5 Anatomy of the Human Heart

Anthony J. Weinhaus

Abstract

This chapter covers the internal and external anatomy of the heart, its positioning within the thorax, and its basic function. Briefly, the heart is a muscular pump, located in the protective thorax, which serves two functions: (1) collect blood from the tissues of the body and pump it to the lungs and (2) collect blood from the lungs and pump it to all the tissues of the body. The heart's two upper chambers (or atria) function primarily as collecting chambers, while two lower chambers (ventricles) are much stronger and function to pump blood. The right atrium and ventricle collect blood from the body and pump it to the lungs, and the left atrium and ventricle collect blood from the lungs and pump it throughout the body. There is a one-way flow of blood through the heart which is maintained by a set of four valves (tricuspid, bicuspid, pulmonary, and aortic). The tissues of the heart are supplied with nourishment and oxygen by a separate vascular supply committed only to the heart; the arterial supply to the heart arises from the base of the aorta as the right and left coronary arteries, and the venous drainage is via cardiac veins that return deoxygenated blood to the right atrium.

Keywords

Cardiac anatomy • Mediastinum • Pericardium • Atrium • Ventricle • Valves • Coronary artery • Cardiac veins • Cardiac skeleton • Cardiopulmonary circulation

5.1 Introduction

The heart is a muscular pump which serves two functions: (1) collect blood from the tissues of the body and pump it to the lungs and (2) collect blood from the lungs and pump it to all of the tissues of the body. The human heart lies in the protective thorax, posterior to the sternum and costal cartilages, and rests on the superior surface of the diaphragm. The heart assumes an oblique position in the thorax, with two-thirds to the left of midline. It occupies a space between the pleural cavities called the *middle mediastinum*, defined as the space inside of the pericardium, the covering around the heart. This serous membrane has an inner and an outer layer, with a lubricating fluid in between. The fluid allows the inner visceral pericardium to "glide" against the outer parietal pericardium.

The internal anatomy of the heart reveals four chambers composed of cardiac muscle or myocardium. The two upper chambers (or atria) function mainly as collecting chambers; the two lower chambers (ventricles) are much stronger and function to pump blood out of the heart. The role of the right atrium and ventricle is to collect blood from the body and pump it to the lungs. The role of the left atrium and ventricle is to collect blood from the lungs and pump it throughout the body. There is a one-way flow of blood through the heart; this flow is maintained by a set of four valves. The atrioventricular or AV valves (the right tricuspid and left bicuspid or

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mitral) allow blood to flow only from atria to ventricles. The semilunar valves (pulmonary and aortic) allow blood to flow only from the ventricles out of the heart and through the great arteries.

A number of structures that can be observed in the adult heart are remnants of fetal circulation. In the fetus, the lungs do not function as a site for the exchange of oxygen and carbon dioxide, and the fetus receives all of its oxygen from the mother. In the fetal heart, blood arriving to the right side of the heart is passed through specialized structures to the left side. Shortly after birth, these specialized fetal structures normally collapse, and the heart takes on the "adult" pattern of circulation. However, in rare cases, some fetal remnants and defects can occur (see Chap. 37).

Although the heart is filled with blood, it provides very little nourishment and oxygen to the tissues of the heart. Instead, the tissues of the heart are supplied by a separate vascular supply committed only to the heart. The arterial supply to the heart arises from the base of the aorta as the right and left coronary arteries (running in the coronary sulcus). The venous drainage is via cardiac veins that return deoxygenated blood to the right atrium (see Chap. 8).

It is important to note that besides pumping oxygen-rich blood to the tissues of the body for exchange of oxygen for carbon dioxide, the blood also circulates many other important substances. Nutrients from digestion are collected from the small intestine and pumped through the circulatory system to be delivered to all cells of the body. Hormones are produced from one type of tissue and distributed to all cells of the body. The circulatory system also carries waste materials (salts, nitrogenous wastes, and excess water) from cells to the kidneys, where they are extracted and passed to the bladder. The pumping of interstitial fluid from the blood into the extracellular space is an important function of the heart. Excess interstitial fluid is then returned to the circulatory system via the lymphatic system.

5.2 Position of the Heart in the Thorax

The heart lies in the protective thorax, posterior to the sternum and costal cartilages, and rests on the superior surface of the diaphragm. The thorax is often referred to as the thoracic cage because of its protective function of the delicate structures within. The heart is located between the two lungs which occupy the lateral spaces called the *pleural cavities*. The space between these two cavities is referred to as the *mediastinum* ("that which stands in the middle"; Fig. 5.1).

The mediastinum is divided first into the superior and inferior mediastinum by a midsagittal imaginary line called the *transverse thoracic plane*. This plane passes through the sternal angle (junction of the manubrium and body of the sternum) and the space between thoracic vertebrae T_4 and T_5. This plane acts as a convenient landmark as it also passes

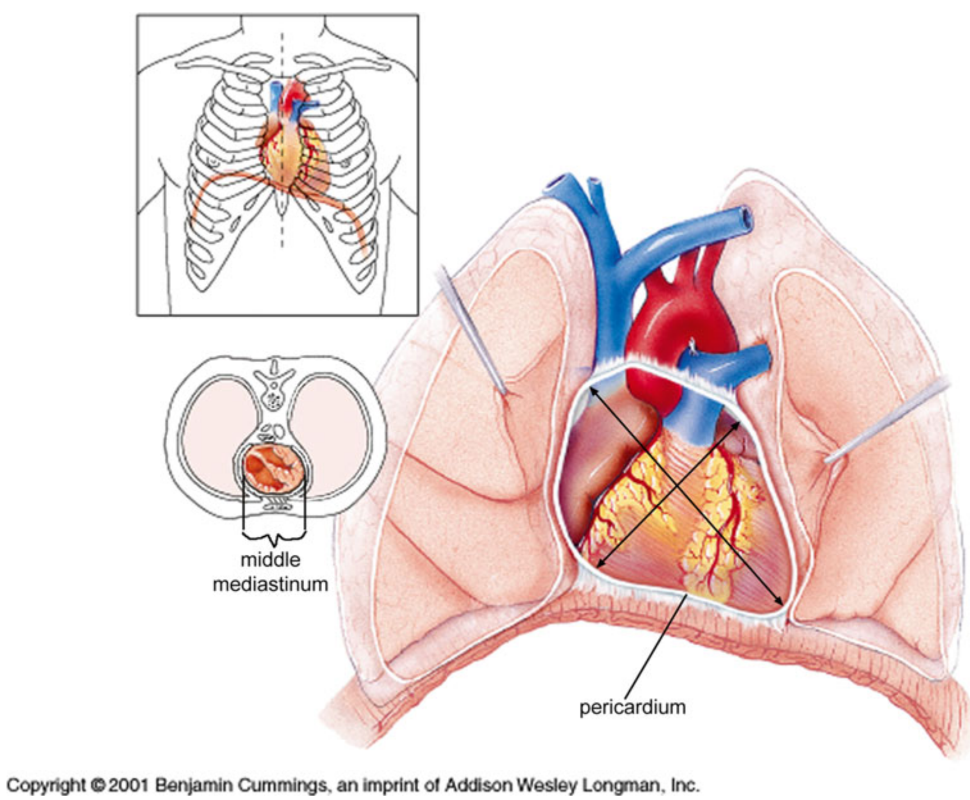

Fig. 5.1 Position of the heart in the thorax. The heart lies in the protective thorax, posterior to the sternum and costal cartilages, and rests on the superior surface of the diaphragm. The heart assumes an oblique position in the thorax, with two-thirds to the left of midline. It is located between the two lungs which occupy the lateral spaces called the pleural cavities. The space between these two cavities is referred to as the mediastinum. The heart lies obliquely in a division of this space, the middle mediastinum, surrounded by the pericardium. Marieb, Elaine N.: Wilhelm, Paticia Brady; Mallatt, Jon B., Human Anatomy, 7th, © 2013. Printed and electronically reproduced by permission of Pearson Education, Inc., New York, New York

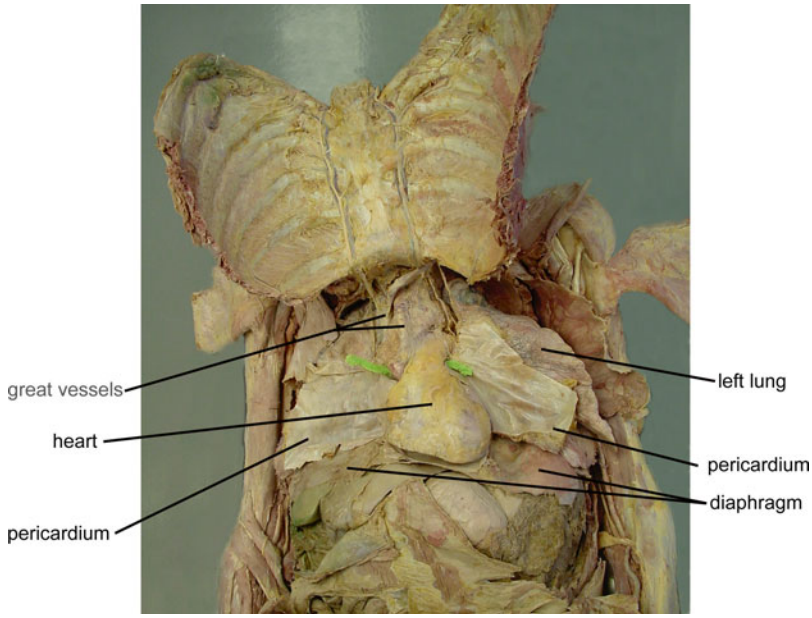

Fig. 5.2 Human cadaver dissection in which the ribs were cut laterally and the sternum and ribs reflected superiorly. This dissection exposes the contents of the thorax (the heart, great vessels, lungs, and diaphragm)

through the following structures: the bifurcation of the trachea, the superior border of the pericardium, the artificial division of the ascending and arch of the aortic artery, and the bifurcation of the pulmonary trunk into the pulmonary arteries.

The human heart assumes an oblique position in the thorax, with two-thirds to the left of midline (Figs. 5.2 and 5.3). The heart is roughly in a plane that runs from the right shoulder to the left nipple. The base is located below the 3rd rib as it approaches the sternum (note that the sternal angle occurs at the level of the 2nd rib). The base is directed superiorly, to the right of midline, and posterior. The pointed apex projects to the left of midline and anterior. Thus, the heartbeat can be easily palpated between the 5th and 6th ribs (just inferior to the left nipple) from the apex of the heart where it comes into close proximity of the thoracic wall. Importantly, the heart lies in such an oblique plane that it is often referred to as being horizontal. Thus, the anterior side may be imagined as the superior and the posterior side as inferior (for additional detail on attitudinally correct cardiac anatomy, see Chap. 2).

The heart is composed of four distinct chambers. There are two atria (left and right) responsible for collecting blood and two ventricles (left and right) responsible for pumping blood. The atria are positioned superior to (or posterior to) and somewhat to the right of their respective ventricles (Fig. 5.3). From superior to inferior down the anterior (or superior) surface of the heart runs the anterior interventricular sulcus ("a groove"). This sulcus separates the left and right ventricles. This groove continues around the apex as the posterior interventricular sulcus on the posterior (inferior) surface. Between these sulci, located within the heart, is the interventricular septum ("wall between the ventricles"). The base of the heart is defined by a plane that separates the atria from the ventricles also called the *atrioventricular groove* or *sulcus*. This groove appears like a belt cinched around the heart. Since this groove appears as though it might also be formed by placing a crown atop the heart, the groove is also called the *coronary* (*corona* = "crown") *sulcus*. The plane of this sulcus also contains the AV valves (and the semilunar valves) and a structure that surrounds the valves called the *cardiac skeleton*. The interatrial ("between the atria") septum is represented on the posterior surface of the heart as the atrial sulcus. Also on the posterior (inferior) side of the heart, the crux cordis ("cross of the heart") is formed from the atrial sulcus, posterior interventricular sulcus, and the relatively perpendicular coronary sulcus.

Note that the great arteries, aorta, and pulmonary trunk arise from the base of the heart and the inferior angle of the heart is referred to as the *apex*; this resembles an inverted pyramid. The right and left atrial appendages (or auricles, so named because they look like dog ears, *auricle* = "little ear") appear as extensions hanging off each atrium.

The anterior (superior) surface of the heart is formed primarily by the right ventricle. The right lateral border is formed by the right atrium, and the left lateral border by the left ventricle. The posterior surface is formed by the left ventricle and the left atrium which is centered equally upon the midline.

The acute angle found on the right anterior side of the heart is referred to as the *acute* margin of the heart and continues toward the diaphragmatic surface. The rounded left anterior side is referred to as the *obtuse* margin of the heart and continues posteriorly and anteriorly. Both right and left ventricles contribute equally to the diaphragmatic surface, lying in the plane of the diaphragm.

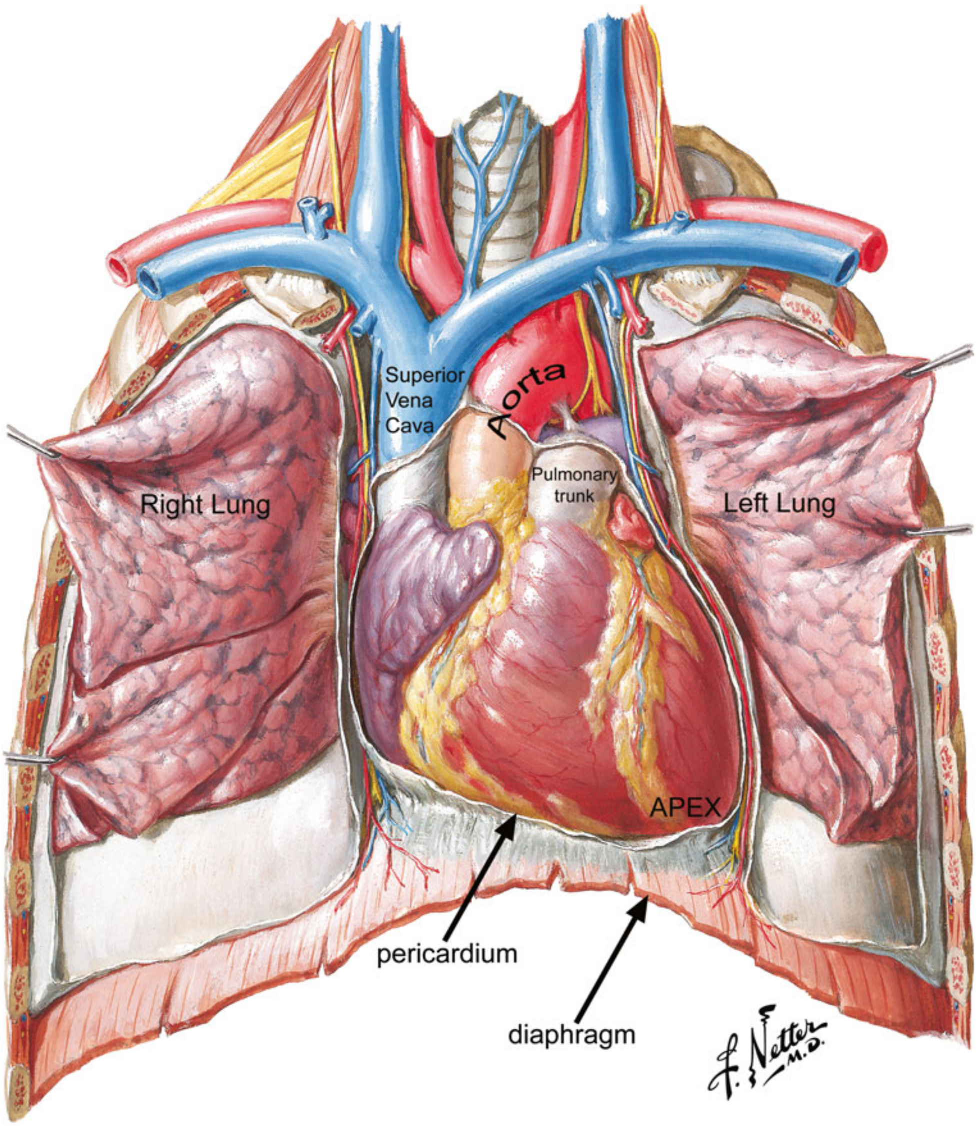

Fig. 5.3 The anterior surface of the heart. The atria are positioned superior to (posterior to) and to the right of their respective ventricles. From superior to inferior, down the anterior surface of the heart, runs the anterior interventricular sulcus ("a groove"). This sulcus separates the left and right ventricles. The base of the heart is defined by a plane that separates the atria from the ventricles called the atrioventricular groove or sulcus. Note that the great arteries, aorta, and pulmonary trunk arise from the base of the heart. The right and left atrial appendages appear as extensions hanging off each atrium. The anterior (superior) surface of the heart is formed primarily by the right ventricle. The right lateral border is formed by the right atrium, and the left lateral border by the left ventricle. The posterior surface is formed by the left ventricle and the left atrium which is centered equally upon the midline midline. www.netterimages.com, Frank Netter

5.3 The Pericardium

The pericardium (peri = "around" + cardia = "heart") is the covering around the heart. It is a serous membrane, composed of two distinct but continuous layers that are separated from each other by a potential space containing a lubricating substance called serous fluid. During embryological development, the heart moves from a peripheral location into a space or cavity. This cavity has a serous fluid-secreting lining. As the heart migrates into the cavity, the serous lining wraps around the heart. This process can be described as being similar to a fist being pushed into a balloon (Fig. 5.4). Note that the fist is surrounded by balloon; however, it does not enter the balloon, and the balloon is still one continuous layer of material. These same properties are true for the pericardium. Furthermore, although it is one continuous layer, the pericardium is divided into two components. The part of the pericardium that is in contact with the heart is called the visceral pericardium (viscus = "internal organ") or epicardium (epi = "upon" + "heart"). The part of the pericardium forming the outer border is called the parietal pericardium (parietes = "walls"). The free or opposing surfaces of these serous membranes (epicardium and parietal pericardium) are covered by a single layer of flat-shaped epithelial cells called mesothelium. The mesothelial cells secrete a small amount of serous fluid to lubricate the movement of the epicardium against the parietal pericardium. The serous surfaces of the epicardium and parietal pericardium are often referred to as the serous pericardium. The outer surface of these serous membranes is a thin layer of fibroelastic connective tissue which supports the mesothelium. The epicardium also

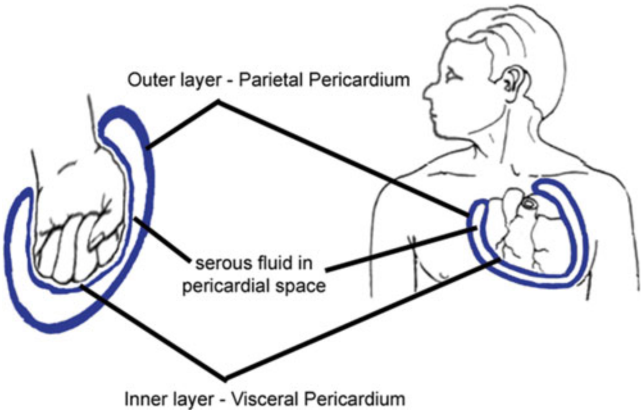

Fig. 5.4 The pericardium. The pericardium is the covering around the heart that is composed of two distinct but continuous layers that are separated from each other by a potential space containing a lubricating serous fluid. During embryological development, the heart migrates into the celomic cavity and a serous lining wraps around it, a process similar to a fist being pushed into a balloon (the balloon and pericardium is one continuous layer of material). The pericardium can be divided into the visceral pericardium (epicardium) and the parietal pericardium. A small amount of serous fluid is secreted into the pericardial space to lubricate the movement of the epicardium on the parietal pericardium. The parietal pericardium contains an epipericardial layer called the fibrous pericardium

contains a broad layer of adipose tissue between the fibroelastic layer and the heart muscle or myocardium. The parietal pericardium contains an additional layer referred to as the fibrous pericardium. This layer contains collagen and elastin fibers to provide strength to the parietal pericardium. It is important to note, however, that there is no potential space between the parietal and fibrous pericardium. The parietal pericardium, together with the fibrous pericardium, is often referred to as the fibrous pericardium.

Inferiorly, the parietal pericardium is attached to the diaphragm. Anteriorly, the superior and inferior pericardiosternal ligaments secure the parietal pericardium to the manubrium and the xiphoid process, respectively. Laterally, the parietal pericardium (specifically, the fibrous pericardium) is in contact with the parietal pleura (the covering of the lungs). Trapped between the fibrous pericardium and the parietal pleura are the phrenic nerves (motor innervation to the diaphragm). Accompanying these nerves are the pericardiacophrenic arteries and veins (supplying the nerve, pericardium, and diaphragm).

Under normal circumstances, only serous fluid exists between the visceral and parietal layers in the pericardial space or cavity. However, the accumulation of fluid (blood from trauma, inflammatory exudate following infection) in the pericardial space leads to the compression of the heart. This condition, called *cardiac tamponade* ("heart" + *tampon* = "plug"), occurs when the excess fluid limits the expansion of the heart (the fibrous pericardium resists stretching) between beats and reduces the ability to pump blood, leading to hypoxia (*hypo* = "low" + "oxygen").

Superiorly, the parietal pericardium surrounds the aorta and pulmonary trunk (about 3 cm above their departure from the heart) and is referred to as the *arterial reflections* or *arterial mesocardium*; the superior vena cava, inferior vena cava, and pulmonary veins are surrounded by the venous reflections or venous mesocardium. The outer fibrous (epipericardial) layer merges with the outer adventitial layer of the great vessels, which is continuous with the visceral pericardium. The result of this reflection is that the heart hangs "suspended" within the pericardial cavity. For more details on the Pericardium, see Chap. 9.

Within the parietal pericardium, a blind-ended saclike recess called the *oblique pericardial sinus* is formed from the venous reflections of the inferior vena cava and pulmonary veins (Fig. 5.5). A space called the *transverse pericardial sinus* is formed between the arterial reflections above and the venous reflections of the superior vena cava and pulmonary veins below. This sinus is important to cardiac surgeons in various procedures when it is important to stop or divert the circulation of blood from the aorta and pulmonary trunk. By passing a surgical clamp or ligature through the transverse sinus and around the great vessels, the tubes of a circulatory bypass machine can be inserted. For more details on cardiopulmonary bypass, see Chap. 33.

5.4 Internal Anatomy of the Heart

A cross-section cut through the heart reveals a number of layers (Fig. 5.6). From superficial to deep, these are (1) the parietal pericardium with its dense fibrous layer, the fibrous pericardium; (2) the pericardial cavity (containing only serous fluid); (3) a superficial visceral pericardium or epicardium (*epi* = "upon" + "heart"); (4) a middle myocardium (*myo* = "muscle" + "heart"); and (5) a deep lining called the endocardium (*endo* = "within"). The endocardium is the internal lining of the atrial and ventricular chambers and is continuous with the endothelium (lining) of the incoming veins and outgoing arteries. It also covers the surfaces of the AV valves, pulmonary and aortic valves, as well as the chordae tendineae and papillary muscles. The endocardium is a sheet of epithelium called *endothelium* that rests on a dense connective tissue layer consisting of elastic and collagen fibers. These fibers also extend into the core of the previously mentioned valves.

The myocardium is the tissue of the heart wall, the layer that actually contracts. The myocardium consists of cardiac muscles which are circularly and spirally arranged networks of muscle cells that squeeze blood through the heart in the proper directions (inferiorly through the atria and superiorly through the ventricles). Unlike all other types of muscle cells, (1) cardiac muscle cells branch; (2) cardiac muscles join together at complex junctions called *intercalated disks*, so that they form cellular networks; and (3) each cell contains

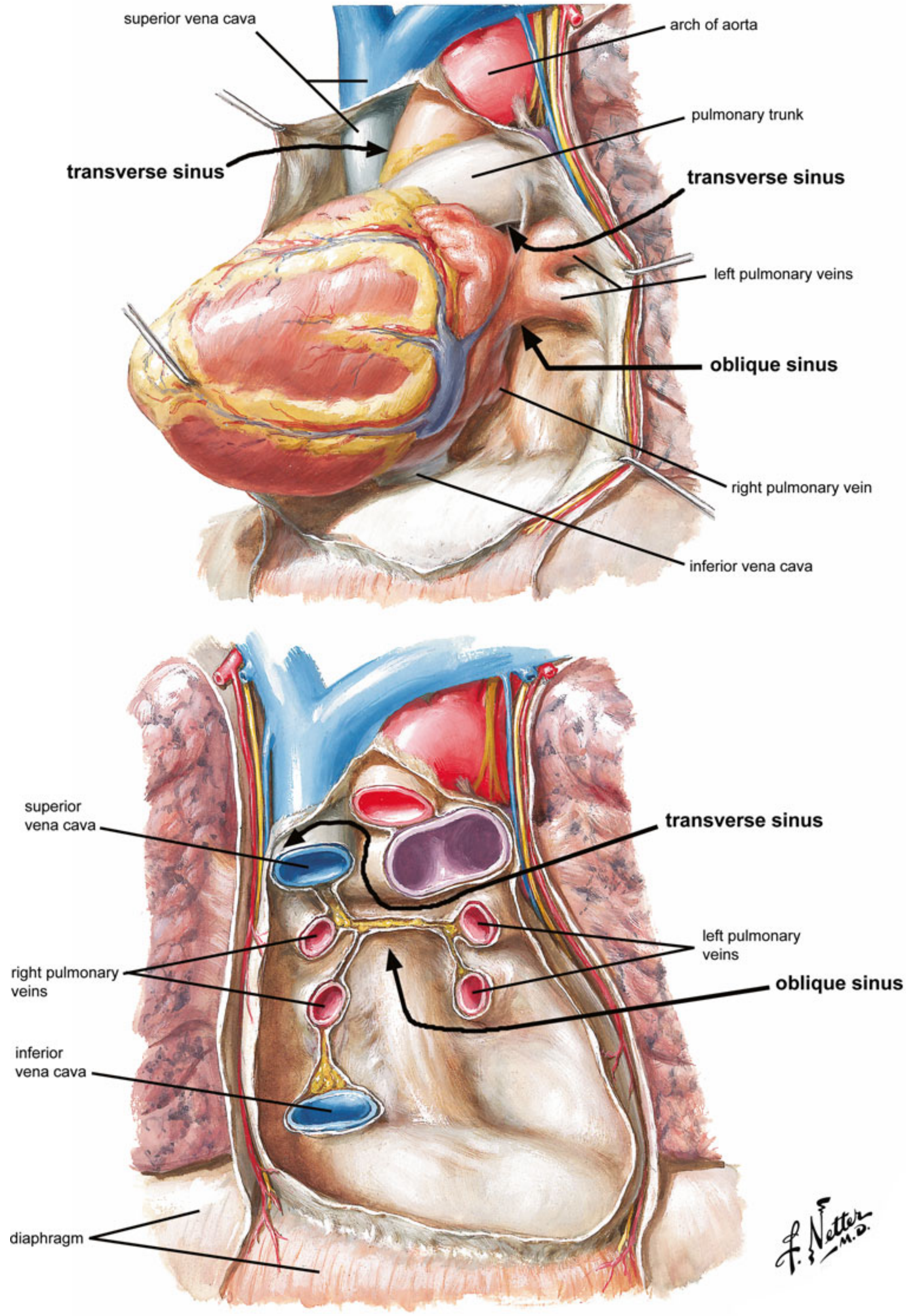

Fig. 5.5 Pericardial sinuses. (**a**) A blind-ended sac called the oblique pericardial sinus is formed from the venous reflections of the inferior vena cava and pulmonary veins. (**b**) Another sac, the transverse pericardial sinus, is formed between the arterial reflections above and the venous reflections of the superior vena cava and pulmonary veins below below. © 2006 Elsevier Inc. All rights reserved. www.netterimages.com, Frank Netter

single centrally located nuclei. A cardiac muscle cell is not called a fiber. The term cardiac muscle fiber, when used, refers to a long row of joined cardiac muscle cells.

Like skeletal muscle, cardiac muscle cells are triggered to contract by Ca^{2+} ions flowing into the cell. Cardiac muscle cells are joined by complex junctions called *intercalated disks*. The disks contain adherens to hold the cells together, and there are gap junctions to allow ions to pass easily between the cells. The free movement of ions between cells allows for the direct transmission of an electrical impulse through an entire network of cardiac muscle cells. This impulse, in turn, signals all the muscle cells to contract at the same time. For more details on the electrical properties of the heart, the reader is referred to Chap. 13.

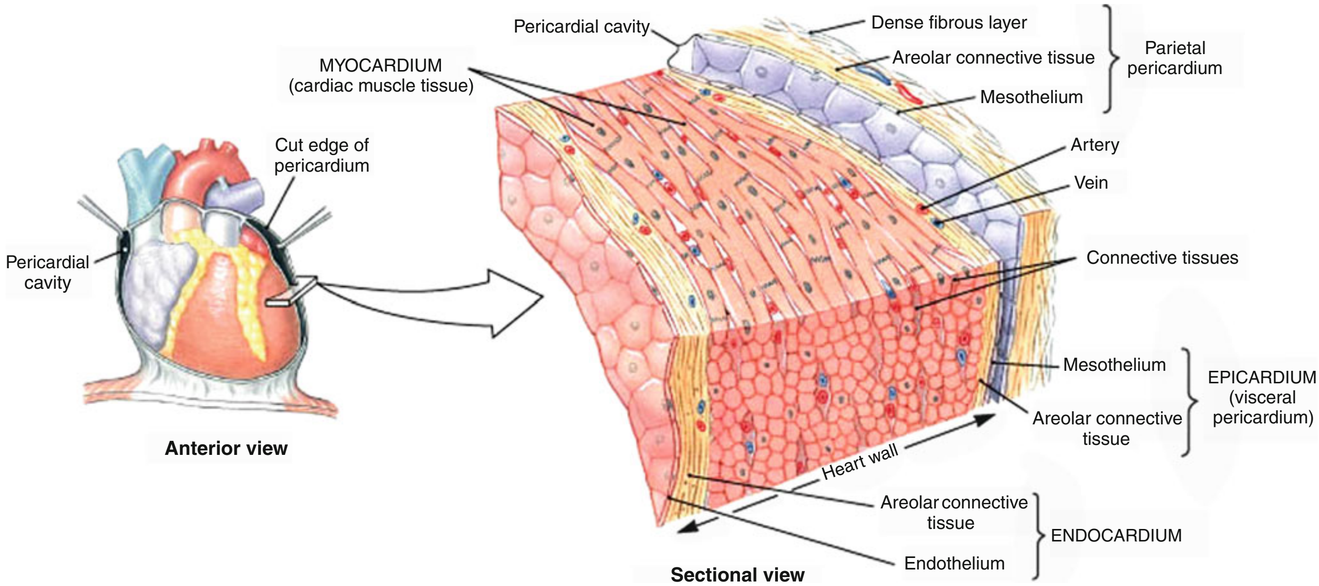

Fig. 5.6 Internal anatomy of the heart. The walls of the heart contain three layers—the superficial epicardium, the middle myocardium composed of cardiac muscle, and the inner endocardium. Note that cardiac muscle cells contain intercalated disks which enable the cells to communicate and allow direct transmission of electrical impulses from one cell to another. Martini, Frederic H.; Timmons, Michael J.; Tallitsch, Robert B., Human Anatomy, 4th, © 2003. Printed and electronically reproduced by permission of Pearson Education, Inc., New York, New York

5.4.1 Cardiopulmonary Circulation

In order to best understand the internal anatomy of the heart, it is desirable to first understand its general function. The heart has two primary functions—collect oxygen-poor blood and pump it to the lungs for the release of carbon dioxide in exchange for oxygen and collect oxygen-rich blood from the lungs and pump it to all tissues in the body to provide oxygen in exchange for carbon dioxide.

The four chambers in the heart can be segregated into the left and the right side, each containing an atrium and a ventricle. The right side is responsible for collecting oxygen-poor blood and pumping it to the lungs. The left side is responsible for collecting oxygen-rich blood from the lungs and pumping it to all tissues in the body. Within each side, the atria are the sites where blood collects and passes through to the ventricles and then they contract to eject the final volumes of blood into the ventricles. The ventricle is much stronger, and it is a site for the pumping of blood out and away from the heart (Figs. 5.7 and 5.8).

The right ventricle is the site for the collection of ALL oxygen-poor blood. The large superior and inferior venae cavae, among other veins, carry oxygen-poor blood from the upper and lower parts of the body to the right atrium. The right ventricle pumps the blood out of the heart and through the pulmonary trunk. The term *trunk*, when referring to a vessel, is a convention that indicates an artery that bifurcates. The pulmonary trunk bifurcates into the left and right pulmonary arteries that enter the lungs. It is important to note that the term "artery" is always used for a vessel that carries blood AWAY from the heart. This is irrespective of the oxygen content of the blood that flows through the vessel.

Once oxygenated, the oxygen-rich blood returns to the heart from the right and left lung through the right and left pulmonary vein, respectively ("vein"—a vessel carrying blood *toward* the heart). Each pulmonary vein bifurcates before reaching the heart. Thus, there are typically four pulmonary veins entering the left atrium. Oxygen-rich blood is pumped out of the heart by the left ventricle and into the aortic artery.

Observing the heart from a superior vantage point, the pulmonary trunk assumes a leftmost anterior location projecting upward from the base of the heart, the aorta is located in a central location, and the superior vena cava has the rightmost posterior location.

5.4.2 The Right Atrium

The interior of the right atrium has three anatomically distinct regions, each a remnant of embryologic development. The posterior portion of the right atrium has a smooth wall and is referred to as the *sinus venarum* (embryologically derived from the right horn of the sinus venosus). The wall of the anterior portion of the right atrium is lined by horizontal, parallel ridges of muscle bundles that resemble the teeth of a comb, hence the name *pectinate* muscle (*pectin* = "a comb," embryologically derived from the primitive right atrium).

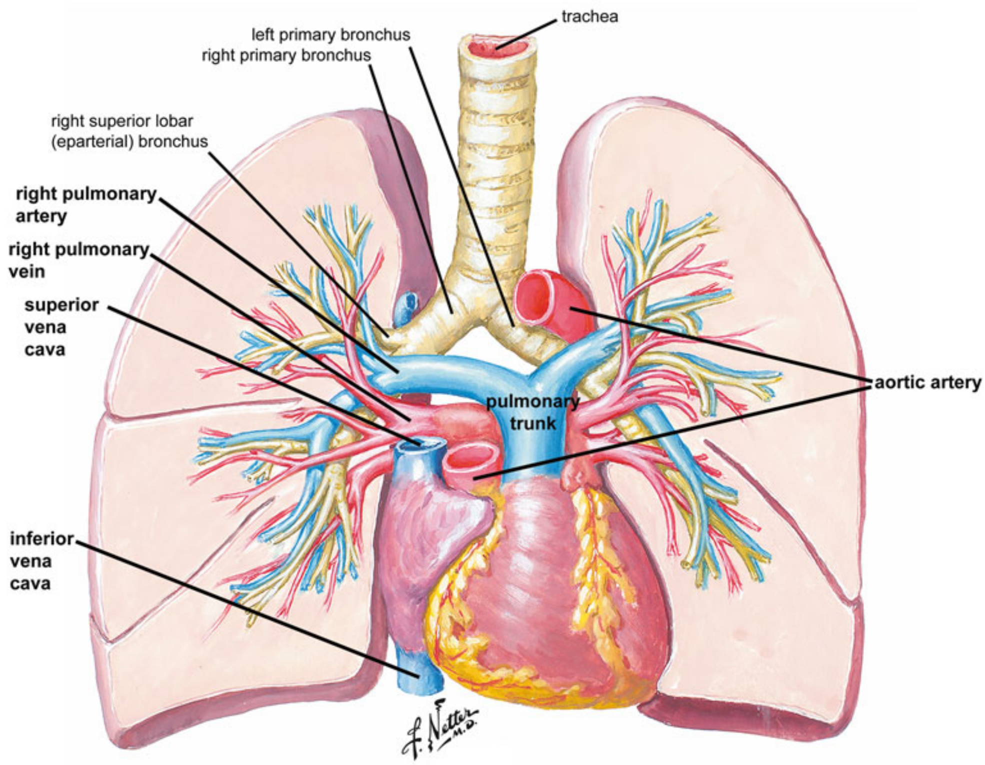

Fig. 5.7 Cardiopulmonary circulation. The four chambers in the heart can be segregated into the left and the right side, each containing an atrium and a ventricle. The *right side* is responsible for collecting oxygen-poor blood and pumping it to the lungs. The *left side* is responsible for collecting oxygen-rich blood from the lungs and pumping it to the body. An artery is a vessel that carries blood away from the heart, while a vein is a vessel that carries blood toward the heart. The pulmonary trunk and arteries carry blood to the lungs. Exchange of carbon dioxide for oxygen occurs in the lung through the smallest of vessels, the capillaries. Oxygenated blood is returned to the heart through the pulmonary veins and collected in the left atrium atrium. www.netterimages.com, Frank Netter

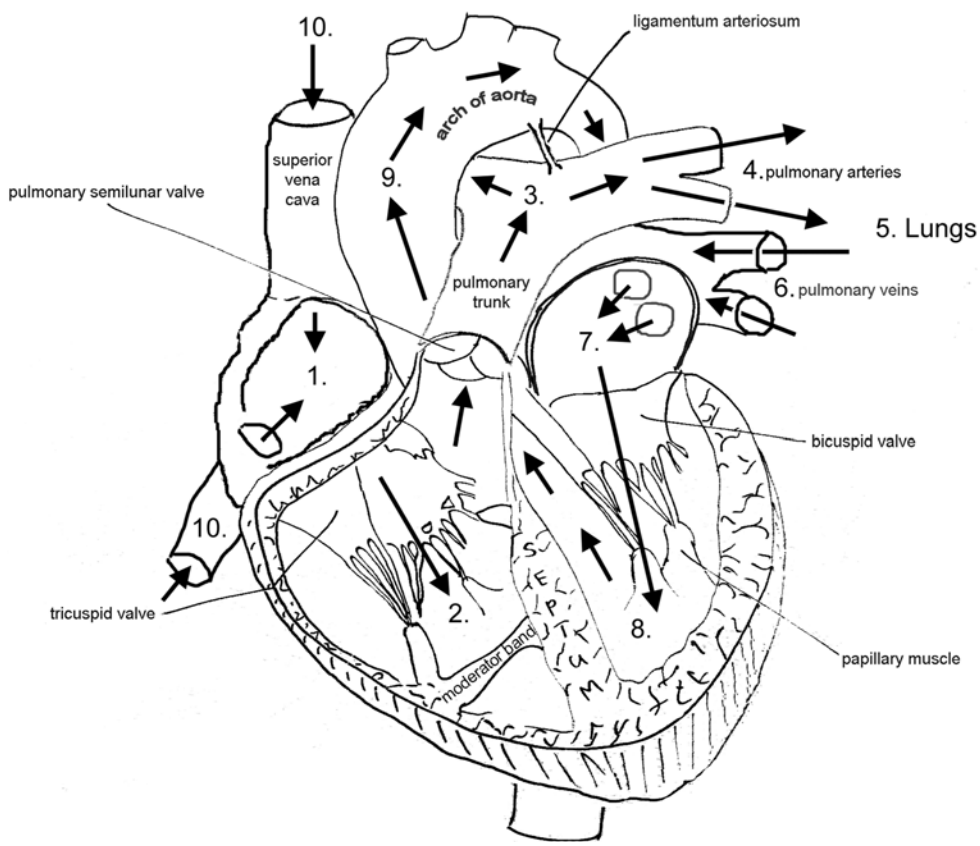

Fig. 5.8 Cardiac circulation. Blood collected in the right atrium is pumped into the right ventricle. Upon contraction of the right ventricle, blood passes through the pulmonary trunk and arteries to the lungs. Oxygenated blood returns to the left atrium via pulmonary veins. The left atrium pumps the blood into the left ventricle. Contraction of the left ventricle sends the blood through the aortic artery to all tissues in the body. The release of oxygen in exchange for carbon dioxide occurs through capillaries in the tissues. Return of oxygen-poor blood is through the superior and inferior vena cavae which empty into the right atrium. Note that a unidirectional flow of blood through the heart is accomplished by valves

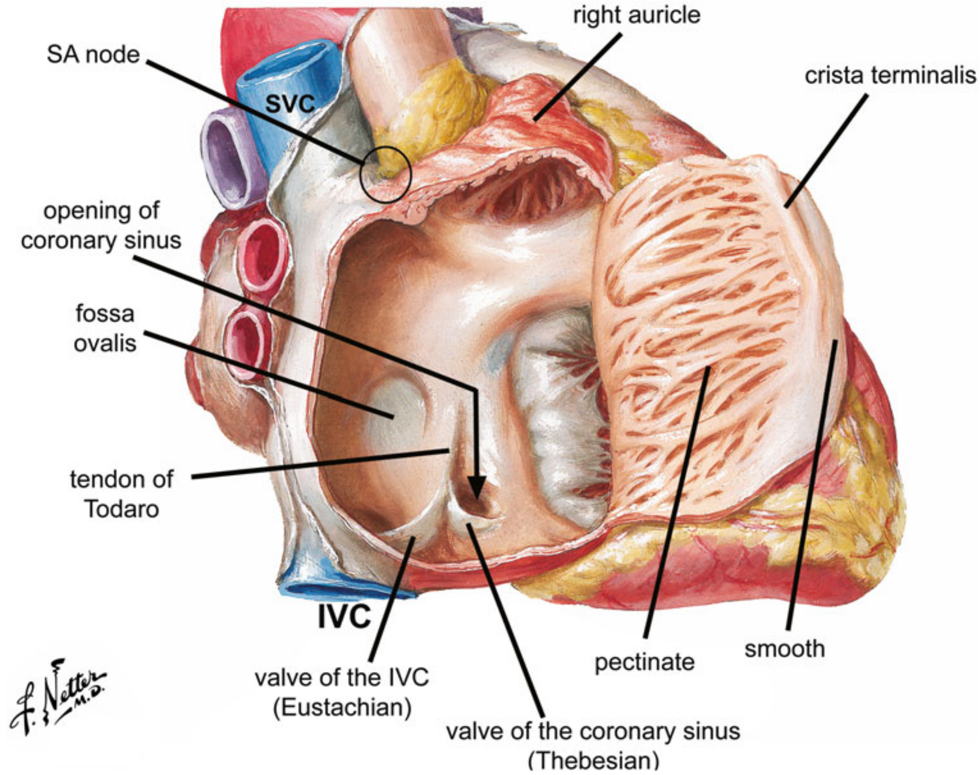

Fig. 5.9 Internal anatomy of the right atrium. The interior of the right atrium has three anatomically distinct regions: (1) the posterior portion (sinus venarum) which has a smooth wall; (2) the wall of the anterior portion which is lined by horizontal, parallel ridges of muscle referred to as pectinate; and (3) the atrial septum septum. www.netterimages.com, Frank Netter

Finally, the interatrial septum is primarily derived from the embryonic septum primum and septum secundum. For more details on the embryology of the heart, refer to Chap. 3.

The smooth posterior wall of the right atrium holds the majority of the named structures of the right atrium. It receives both the superior and inferior vena cavae and the coronary sinus. It also contains the fossa ovalis, the sinoatrial (SA) node, and the AV node.

The inferior border of the right atrium contains the opening or ostium of the inferior vena cava and the os or ostium of the coronary sinus (Fig. 5.9). The coronary sinus is located on the posterior (inferior) side of the heart and receives almost all of the deoxygenated blood from the vasculature of the heart. The os of the coronary sinus opens into the right atrium anteriorly/inferiorly to the orifice of the inferior vena cava. A valve of the inferior vena cava (Eustachian valve, a fetal remnant) guards the orifice of the inferior vena cava (Bartolommeo E. Eustachio, Italian Anatomist, 1520–1574). The valve of the coronary sinus (Thebesian valve) covers the opening of the coronary sinus (fetal remnant to prevent backflow, Adam C. Thebesius, German physician, 1686–1732). Both of these valves vary in size and presence. These two venous valves insert into a prominent ridge, the Eustachian ridge (sinus septum), that runs medial–lateral across the inferior border of the atrium and separates the os of the coronary sinus and inferior vena cava. For more details on the valves of the heart, refer to Chap. 34.

On the medial side of the right atrium, the interatrial septum (atrial septum) has an interatrial and an atrioventricular part. The fossa ovalis (a fetal remnant) is found in the interatrial part of the atrial septum. It appears as a central depression surrounded by a muscular ridge or limbus. The fossa ovalis is positioned anterior and superior to the ostia of both the inferior vena cava and the coronary sinus. A tendinous structure, the tendon of Todaro, crosses the floor of the right atrium. It connects the valve of the inferior vena cava to a portion of the interventricular septum (between ventricles). More specifically, the tendon connects to the central fibrous body (the right fibrous trigone) as a fibrous extension of the membranous portion of the interventricular septum. It courses obliquely within the Eustachian ridge and separates the fossa ovalis above from the coronary sinus below. This tendon likely has a structural role to support the inferior vena cava via the Eustachian valve and is a useful landmark in approximating the location of the AV node (conduction system).

To approximate the location of the AV node, found in the floor of the right atrium and the atrial septum, it is necessary to form a triangle (triangle of Koch; Walter Koch, German surgeon, unknown–1880) using the following structures: (1) the os of the coronary sinus, posteriorly; (2) the right AV opening, anteriorly; and (3) the tendon of Todaro, posteriorly (Fig. 5.10).

In the lateral wall and the septum of the smooth portion of the right atrium are numerous small openings in the endocardial surface. These openings are the ostia of the smallest cardiac (Thebesian) veins. These veins function to drain deoxygenated blood from the myocardium to

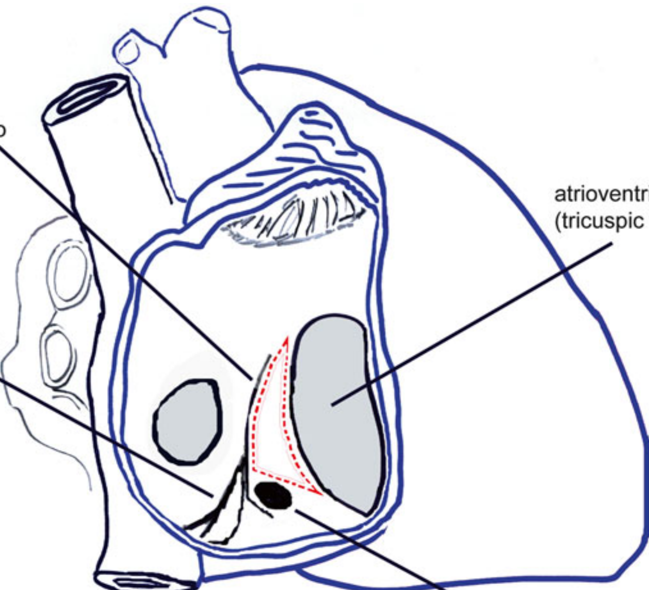

Fig. 5.10 Koch's triangle. Three landmarks are used to triangulate (*dotted red lines*) the location of the atrioventricular node (Taware's node) of the conduction system: (1) coronary sinus, (2) atrioventricular opening, and (3) tendon of Todaro

empty into the right atrium which is the collecting site for all deoxygenated blood (for more details on cardiac vasculature, see Chap. 8).

In the anterior–superior portion of the right atrium, the smooth wall of the interior becomes the pectinate portion of the right atrium. The smooth and pectinate regions are separated by a ridge, the *crista terminalis* (*crista* = "crest" + "terminal"). The ridge represents the end of the smooth wall and the beginning of the pectinate wall. It begins at the junction of the right auricle with the atrium and passes inferiorly over the "roof" of the atrium. The crista runs inferiorly and parallel to the openings of the superior and inferior vena cavae. As early as the developing embryo, the crista terminalis separates the sinus venosus and the primitive atrium and remains to separate the smooth and the pectinate portion of the right atrium in the definitive heart. The crista terminalis on the internal side results in a groove on the external side of the atrium called the sulcus terminalis.

The SA node is the "pacemaker" of the conduction system. The SA node is located between the myocardium and epicardium in the superior portion of the right atrium. The intersection of three lines indicates the location of the SA node: (1) the sulcus terminalis, (2) the lateral border of the superior vena cava, and (3) the superior border of the right auricle (Fig. 5.11). The name of the SA node is derived from its location between the sinus venarum and primitive atrium. The crista terminalis is the division between these two components in the fetus and adult. It seems logical that the sulcus terminalis is a useful landmark for the approximation of the location of the SA node.

5.4.3 The Right Ventricle

The right ventricle receives blood from the right atrium and pumps it to the lungs through the pulmonary trunk and arteries. Most of the anterior surface of the heart is formed by the right ventricle (Fig. 5.12). Abundant, coarse trabeculae carneae ("beams of meat") characterize the walls of the right ventricle. Trabeculae carneae are analogous to pectinate muscle of the right atrium and are found in both the right and left ventricles. The outflow tract, conus arteriosus ("arterial cone"), and infundibulum ("funnel") carry blood out of the ventricle in an anterior–superior direction and can be quite variable in structure—smooth walled or highly trabeculated. A component of the conus arteriosus forms part of the interventricular septum. This small septum, the infundibular (conal) septum, separates the left and right ventricular outflow tracts and is located just inferior to both semilunar valves. Four distinct muscle bundles, collectively known as the *semicircular arch*, separate the outflow tract from the rest of the right atrium. These muscle bundles are also known as the *supraventricular* crest and the *septomarginal trabeculae*.

5.4.3.1 Tricuspid Valve

Blood is pumped from the right atrium through the AV orifice into the right ventricle. When the right ventricle contracts, blood is prevented from flowing back into the atrium by the right AV valve or *tricuspid* ("three cusps") valve. The valve consists of the annulus, three valvular leaflets, three papillary muscles, and three sets of chordae tendineae (Figs. 5.12 and 5.13). The AV orifice is reinforced by the annulus fibro-

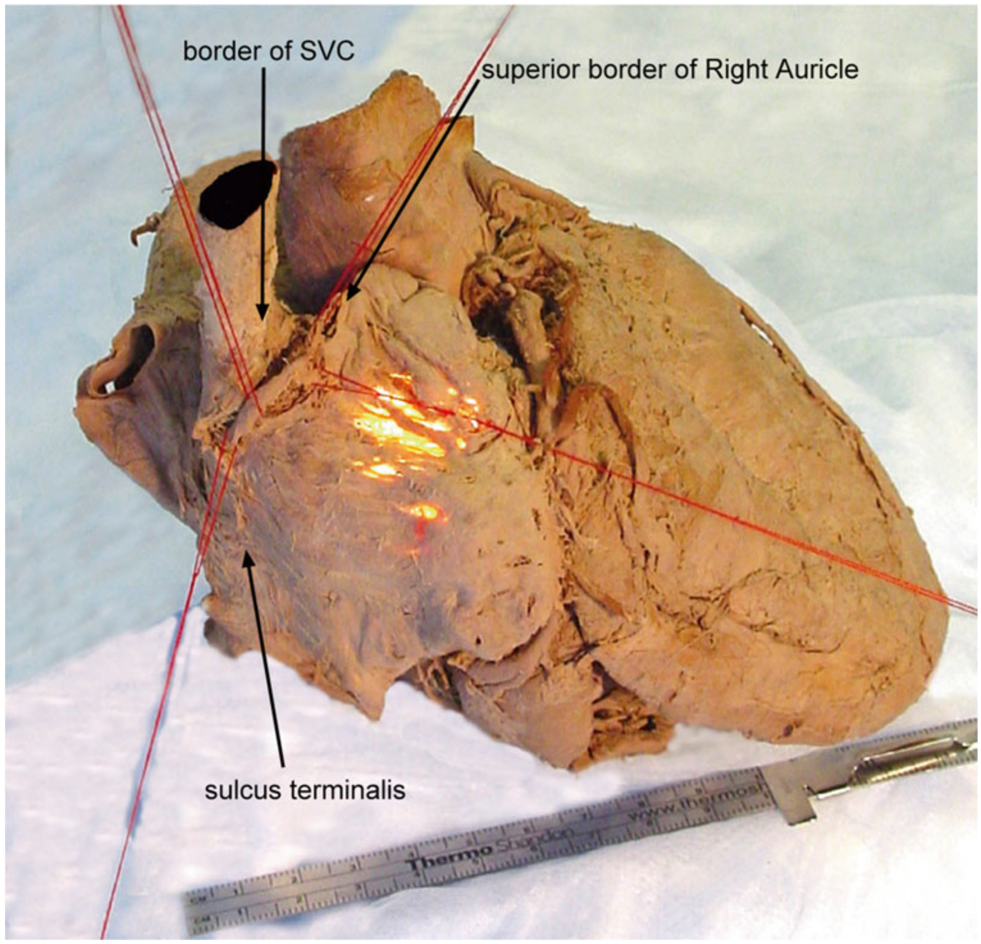

Fig. 5.11 Location of the sinoatrial node. Human cadaver heart demonstrating that the intersection of three lines indicates the position of the sinoatrial node (pacemaker of the conduction system) in the smooth muscle portion of the right atrium: (1) the sulcus terminalis, (2) the lateral border of the superior vena cava, and (3) the superior border of the right auricle. Note the muscle fiber bundles in the wall of the pectinate portion of right atrium. *IVC* inferior vena cava, *SVC* superior vena cava

sus of the cardiac skeleton (dense connective tissue). Medially, the annulus is attached to the membranous interventricular septum.

The tricuspid valve has three leaflets—anterior (superior), posterior (inferior), and septal. The anterior leaflet is typically the largest and extends from the medial border of the ventricular septum to the anterior free wall. This, in effect, forms a partial separation between the inflow and outflow tracts of the right ventricle. The posterior leaflet extends from the lateral free wall to the posterior portion of the ventricular septum. The septal leaflet tends to be somewhat oval in shape and extends from the annulus of the orifice to the medial side of the interventricular septum (on the inflow side), often including the membranous part of the septum (see also Chaps. 2 and 7 for other nomenclature describing these leaflets).

Papillary ("nipple") muscles contract and "tug" down on chordae tendineae ("tendinous cords") that are attached to the leaflets, in order to secure them in place in preparation for the contraction of the ventricle. This is done to prevent the prolapse of the leaflets up into the atrium. This is somewhat analogous to the tightening of the sails on a yacht, in preparation for a big wind. Note that the total surface area of the cusps of the AV valve is approximately twice that of the respective orifice, so that considerable overlap of the leaflets occurs when the valves are in the closed position. The leaflets remain relatively close together even during ventricular filling. The partial approximation of the valve surfaces is caused by eddy currents that prevail behind the leaflets and by tension that is exerted by the chordae tendineae and papillary muscle. As the filling of the ventricle reduces, the valve leaflets float toward each other, but the valve does not close. The valve is closed by ventricular contractions, and the valve leaflets, which bulge toward the atrium but do not prolapse, stay pressed together throughout ventricular contraction. The junction between two leaflets is called a *commissure* and is named by the two adjoining leaflets (anteroseptal, anteroposterior, and posteroseptal). Each commissure contains a relatively smooth arc of valvular tissue that is delineated by the insertion of the chordae tendineae.

There are three papillary muscles, just as there are three leaflets or cusps. The anterior papillary muscle is located in the apex of the right ventricle. This is the largest of the papillary muscles in the right ventricle, and it may have one, two, or more heads. When this papillary muscle contracts, it pulls on chordae tendineae that are attached to the margins of the anterior and posterior leaflets. The posterior papillary

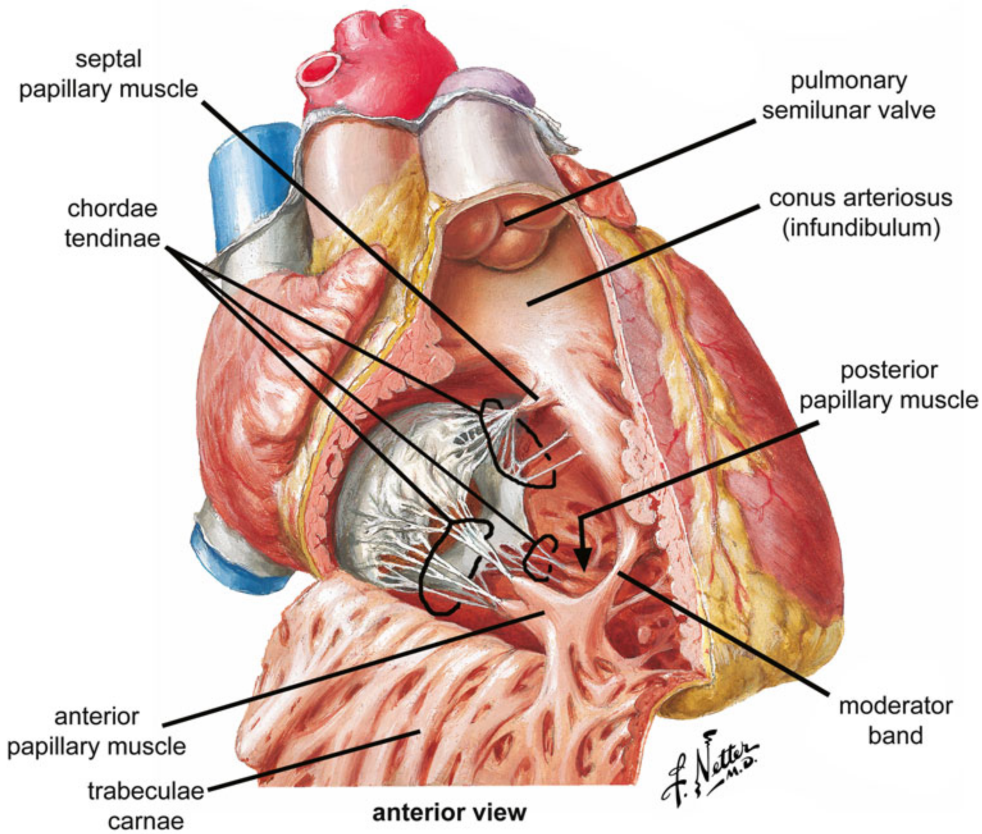

Fig. 5.12 Internal anatomy of the right ventricle. Coarse trabeculae carneae characterize the walls of the right ventricle. The conus arteriosus makes up most of the outflow tract. The right atrioventricular or tricuspid valve is made up of three sets of cusps, chordae tendineae, and papillary muscles. www.netterimages.com, Frank Netter

muscle is small and located in the posterior lateral free wall. When this papillary muscle contracts, it pulls on chordae tendineae that are attached to posterior and septal leaflets. The septal papillary muscle (including the variable papillary of the conus) arises from the muscular interventricular septum near the outflow tract (conus arteriosus). This papillary muscle may consist of a collection of small muscles in close proximity and has attachments to the anterior and septal valve leaflets. In addition, chordae tendineae in this region may extend simply from the myocardium and attach to the valve leaflets directly without a papillary muscle. The most affected is the septal leaflet which has restricted mobility due to extensive chordae tendineae attachment directly to the myocardium. In addition, there is a variable set of papillary muscles that should be considered. The medial papillary muscle complex is a collection of small papillary muscles with chordae attachments to septal and anterior cusps. This complex is located in the uppermost posterior edge of the septomarginal trabeculae, just inferior to the junction of the septal and anterior leaflets of the tricuspid valve, and is superior and distinct from the septal papillary muscles. An important feature of this complex is that it serves as an important landmark for identification of the right bundle branch as it runs posterior to it, deep to the endocardium [1].

Near the anterior free wall of the right ventricle is a muscle bundle of variable size, the *moderator band*, which is occasionally absent. This muscle bundle extends from the interventricular septum to the anterior papillary muscle and contains a primary portion of the right bundle branch of the conduction system. It seems logical that the anterior papillary muscle, with its remote location away from the septum, would need special conduction fibers in order for it to contract with the other papillary muscles and convey control of the valve leaflets equal to the other valve leaflets. The moderator band is a continuation of another muscle bundle, the septal band (septal trabeculae). Together they are called *septomarginal trabeculae* and are components of the semicircular arch (delineation of the outflow tract).

5.4.3.2 Pulmonary Semilunar Valve

During ventricular systole, blood is pumped from the right ventricle into the pulmonary trunk and arteries toward the lungs. When the right ventricle relaxes, in diastole, blood is prevented from flowing back into the ventricle by the pulmonary semilunar valve (Figs. 5.12 and 5.13). The semilunar valve is composed of three symmetric semilunar-shaped cusps. Each cusp looks like a cup composed of a thin membrane. Each cusp acts like an upside-down parachute facing into the pulmonary trunk, opening as it

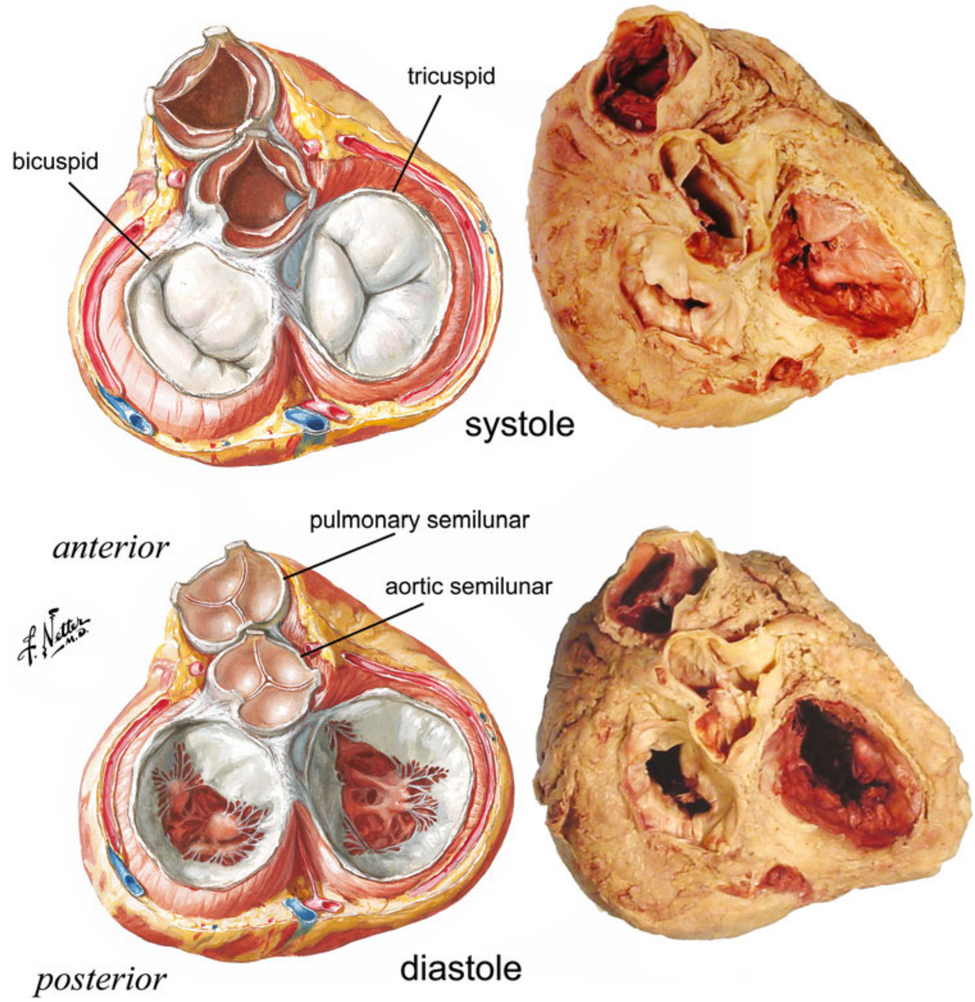

Fig. 5.13 Valves of the heart. During ventricular systole, atrioventricular (AV) valves close in order to prevent the regurgitation of blood from the ventricles into the atria. The right AV valve is the tricuspid valve; the left is the bicuspid valve. During ventricular diastole, the AV valves open as the ventricles relax, and the semilunar valves close. The semilunar valves prevent the backflow of blood from the great arteries into the resting ventricles. The valve of the pulmonary trunk is the pulmonary semilunar valve, and the aortic artery has the aortic semilunar valve. To the right of each figure are human cadaveric hearts. © 2006 Elsevier Inc. All rights reserved. www.netterimages.com, Frank Netter

fills with blood. This filled space or recess of each cusp is called the *sinus of Valsalva*. Upon complete filling, the three cusps contact each other and block the flow of blood. Each of the three cusps is attached to an annulus ("ring") such that the cusp opens into the lumen, forming a U shape. The annulus is anchored to both the right ventricular infundibulum and the pulmonary trunk. The cusps are named according to their orientation in the body—anterior, left (septal), and right.

During ventricular systole, as the right ventricle contracts, the cusps collapse against the arterial wall as blood is flowing past them. When the ventricle rests (diastole), the cusps meet in the luminal center. There is a small thickening on the center of the free edge of each cusp, at the point where the cusps meet. This nodule (of Arantius or Morgagni) ensures central valve closure (Giulio C. (Aranzi) Arantius, Italian anatomist and physician, 1530–1589; Giovanni B. Morgagni, Italian anatomist and pathologist, 1682–1771). Radiating from this nodule around the free edge of the cusp is a ridge, the *linea alba* ("line" + "white").

5.4.4 The Left Atrium

The left atrium (Fig. 5.14) receives oxygenated blood from the lungs via the left and right pulmonary veins. The pulmonary veins typically enter the heart as two pairs of veins inserting posteriorly and laterally into the left atrium (individuals with 3 or 5 pulmonary veins have also been identified).

The left atrium is found midline, posterior to the right atrium and superior to the left ventricle. Anteriorly, a left atrial appendage (auricle) extends over the atrioventricular (coronary) sulcus. The walls of the atrial appendage are pectinate, and the walls of the left atrium are smooth, reflecting their embryological origin. The atrial appendage is derived from the primitive right atrium (which was pectinate). The left atrium is derived from the fetal pulmonary vein as a connection with the embryonic pulmonary venous plexus. These venous structures are absorbed into the left atrium, resulting in the posterolateral connections of the right and left pulmonary veins.

The portion of the interatrial septum on the left atrial side is derived from the embryonic septum primum. In the left

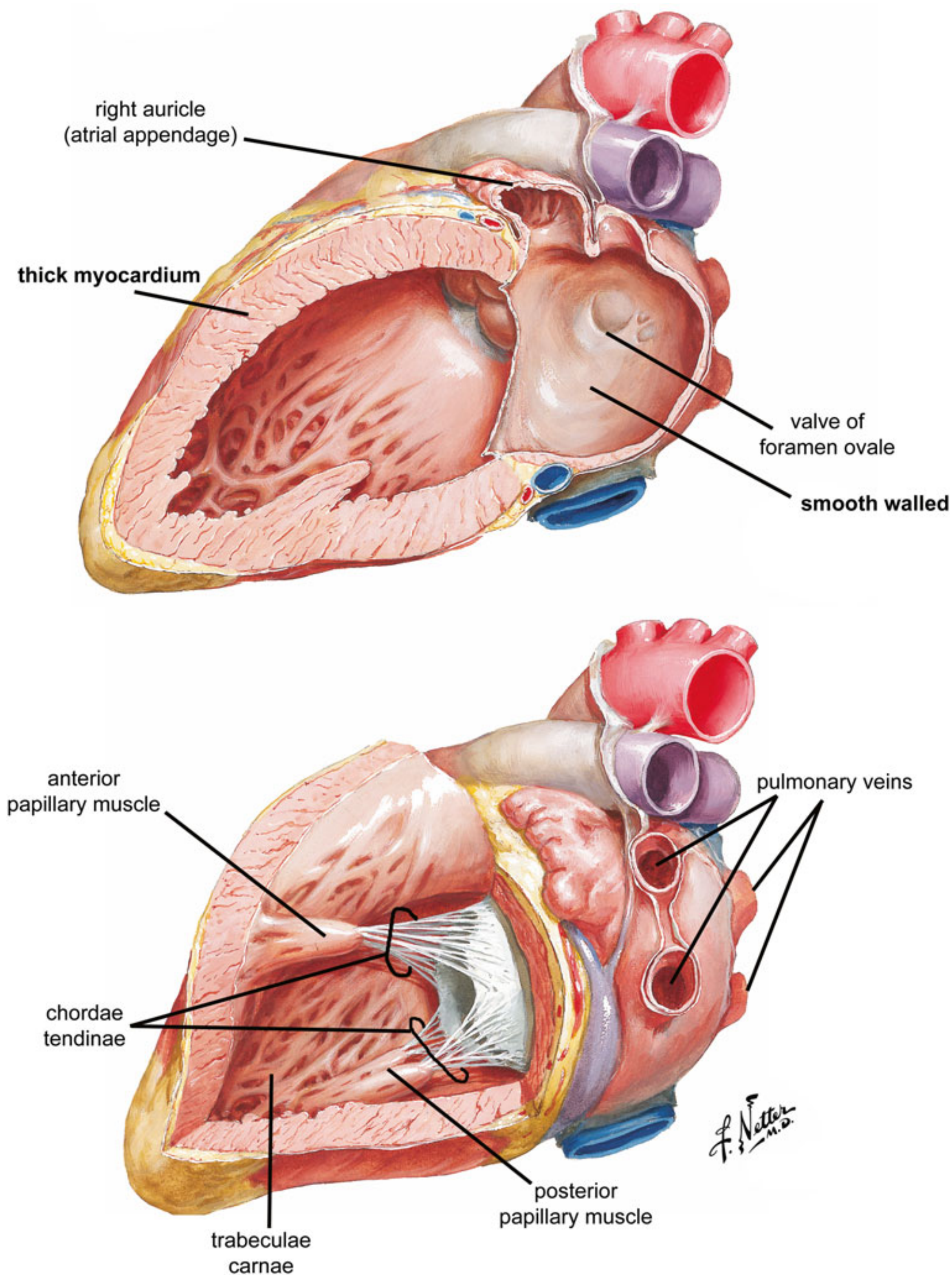

Fig. 5.14 Internal anatomy of the left atrium and ventricle. The left atrium receives oxygenated blood from the lungs via the left and right pulmonary veins. The pulmonary veins enter the heart as two pairs of veins inserting posteriorly and laterally. Anteriorly, the pectinate left auricle extends over the smooth-walled atrium. Most of the left lateral surface of the heart is formed by the left ventricle. Trabeculae carneae characterize the walls and the myocardium is much thicker than the left ventricle. The interventricular septum bulges into the right ventricle, creating a barrel-shaped left ventricle. © 2006 Elsevier Inc. All rights reserved. www.netterimages.com, Frank Netter

atrium, the resulting structure in the adult is called the *valve of the foramen ovale* (a sealed valve flap).

5.4.5 The Left Ventricle

The left ventricle receives blood from the left atrium and pumps it through the aortic artery to all the tissues of the body (Fig. 5.14). Most of the left lateral surface of the heart is formed by the left ventricle, also forming part of the inferior and posterior surfaces. As with the right ventricle, abundant trabeculae carneae ("beams of meat") characterize the walls of the left. However, in contrast to the right ventricle, the muscular ridges tend to be relatively finer. Also in contrast to the right ventricle, the myocardium in the wall of the left ventricle is much thicker. The interventricular septum appears from within the left ventricle to bulge into the right ventricle. This creates a barrel-shaped left ventricle.

5.4.5.1 Bicuspid (Mitral) Valve

Blood is pumped from the left atrium through the left AV orifice into the left ventricle. When the left ventricle contracts, blood

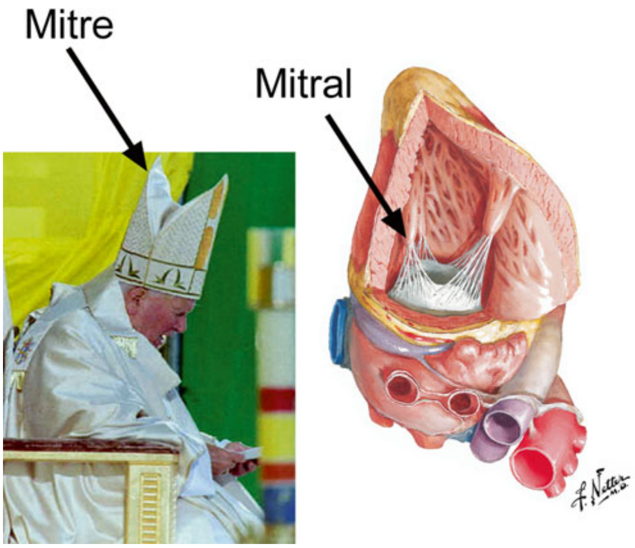

Fig. 5.15 The mitral valve. The mitral (left atrioventricular or bicuspid) valve is so named because of its resemblance to a cardinal's hat, known as a miter. *Left*: Photo of Pope John Paul II from the Vatican web site; *Right*: © 2006 Elsevier Inc. All rights reserved. www.netterimages.com, Frank Netter

is prevented from flowing back into the atrium by the left AV valve or bicuspid ("two cusps") valve (Figs. 5.13 and 5.14). The valve consists of the annulus, two leaflets, two papillary muscles, and two sets of chordae tendineae.

The atrioventricular orifice is partly reinforced by the annulus fibrosus of the cardiac skeleton. The annulus fibrosus supports the posterior and lateral two-thirds of the annulus. The remaining medial third is supported by attachment to the left atrium and by fibrous support to the aortic semilunar valve.

The bicuspid valve typically has two leaflets—anterior (medial or aortic) and posterior (inferior or mural, "wall"). The two opposing leaflets of the valve resemble a bishop's hat or miter. Thus, the bicuspid valve is often referred to as the *mitral valve* (Fig. 5.15).

The anterior leaflet is trapezoidal-shaped. The distance from its attachment on the annulus to its free edge is longer than the length of attachment across the annulus. In contrast, the posterior leaflet is relatively narrow, with a very long attachment distance across the annulus. The distance from annulus to free edge in the anterior cusp is twice as long as the posterior cusp. The posterior cusp is so long and narrow that the free edge is often subdivided into the anterior, central, and posterior crescent shapes. Note that each of these two leaflets may also have numerous scallops within them (see also Chap. 7).

Papillary muscles, in conjunction with chordae tendineae, attach to the leaflets in order to secure them in place. This is done in preparation for the contraction of the ventricle to prevent the prolapse of the leaflets up into the atrium. As with the other AV valve, the total surface area of the two cusps of the valve is significantly greater than the area described by the orifice. There is considerable overlap of the leaflets when the valves are in the closed position (Fig. 5.13).

As with the tricuspid valve, the leaflets remain relatively close together even when the atrium is contracting and the ventricle is filling. The partial approximation of the valve surfaces is caused by eddy currents that prevail behind the leaflets and by tension that is exerted by the chordae tendineae and papillary muscle. In the open position, the leaflets and commissures are in an oblique plane of orientation that is roughly parallel to the ventricular septum. The valve is closed by ventricular contractions. The valve leaflets, which bulge toward the atrium, stay pressed together throughout the contraction and do not prolapse. The junctions of the two leaflets are called the *anterolateral* and the *posteromedial* commissures. The line of apposition of the leaflets during valvular closure is indicated by a fibrous ridge.

There are commonly two papillary muscles of the left ventricle that extend from the ventricular free wall toward and perpendicular to the atrioventricular orifice. The anterior papillary muscle is slightly larger than the posterior, and each papillary muscle consists of a major trunk that often may elicit multiple heads from which extend the chordae tendineae. The chordae tendineae of each papillary muscle extend to the two valvular commissures and to the multiple crescent shapes of the posterior cusp. Thus, each papillary muscle pulls on chordae from both leaflets. In addition, the posterior leaflet occasionally has chordae that extend simply from the ventricular myocardium without a papillary muscle.

5.4.5.2 Aortic Semilunar Valve

During ventricular systole, blood is pumped from the left ventricle into the aortic artery to all of the tissues of the body. When the left ventricle relaxes in diastole, blood is prevented from flowing back into the ventricle by the aortic semilunar valve (Figs. 5.13 and 5.14). Like the pulmonary semilunar valve, the aortic valve is composed of three symmetric semilunar-shaped cusps, and each cusp acts like an upside-down parachute facing into the aortic artery, opening as it fills with blood. The filled space or recess of each cusp is called the *sinus of Valsalva* (Antonio M. Valsalva, 1666–1723). Upon complete filling, the three cusps contact each other and block the flow of blood. Each of the three cusps is attached to an annulus ("ring") such that the cusp opens into the lumen forming a U shape. The cusps are firmly anchored to the fibrous skeleton within the root of the aorta (Fig. 5.16). A circular ridge on the innermost aspect of the aortic wall, at the upper margin of each sinus, is the sinotubular ridge—the junction of the sinuses and the aorta.

At the sinotubular ridge, the wall of the aorta is thin, bulges slightly, and is the narrowest portion of the aortic artery. The cusps are named according to their orientation in the body—left and right (both facing the pulmonary valve) and posterior. Within the sinuses of Valsalva, there are open-

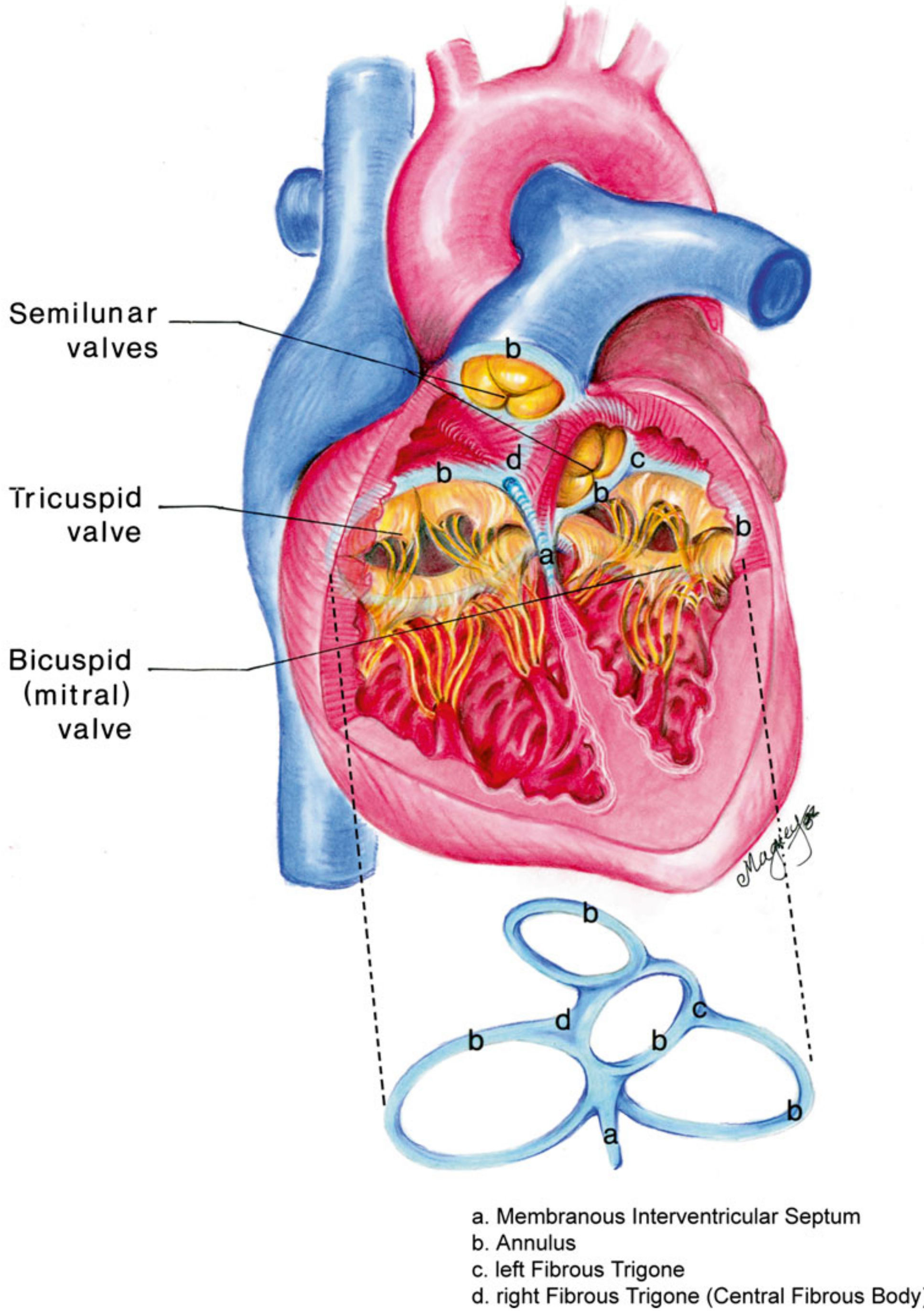

Fig. 5.16 The cardiac skeleton. The cardiac skeleton consists of a dense connective tissue that functions to attach the atrial and ventricular myocardium, support and reinforce the openings of the four valves of the heart, and electrically separate the ventricles from the atria. Courtesy of Jean Magney, University of Minnesota

ings or ostia (*ostium* = "door or mouth") into the blood supply of the heart called *coronary arteries*. These ostia are positioned below the sinotubular junction near the center of the sinuses. Only the two sinuses facing the pulmonary valve (left and right) have ostia that open into the left and right coronary arteries, respectively. Coronary arteries carry oxygenated blood to the myocardium of the heart. During ventricular diastole, the aortic valve snaps shut as pressure in the aorta increases. Under such pressure, the walls of the great artery distend, the sinuses fill, and blood is sent under great pressure through the coronary ostia into the coronary arteries. The posterior (noncoronary) sinus is in a position that it abuts the fibrous skeleton and the annuli of both AV valves (Fig. 5.13).

When the left ventricle contracts, the cusps collapse against the arterial wall as blood flows past them. When the ventricle rests (diastole), the cusps meet in the luminal center. As with the pulmonary valve, there is a small thickening on the center of the free edge of each cusp, at the point where the cusps meet. This nodule (of Arantius or Morgagni) ensures central valve closure. Radiating from this nodule around the free edge of the cusp is a ridge, the *linea alba* ("line" + "white"). This valve is exposed to a greater degree of hemodynamic stress than the pulmonary valve. The aortic cusps can thicken and the linea alba can become more pronounced. For this and other reasons, the aortic pulmonary valve is the most likely valve to be surgically repaired or replaced.

5.5 The Cardiac Skeleton

Passing transversely through the base of the heart is a fibrous framework or "skeleton" made of dense connective tissue, not bone as the name might suggest. The purpose of this tough, immobile scaffold is to (1) provide an attachment for the atrial and ventricular myocardium, (2) anchor the four valves of the heart, and (3) electrically insulate the myocardium of the ventricles from the atria (see also Chap. 13).

The supporting framework of the cardiac skeleton (Figs. 5.13 and 5.16) provides immobile support for the AV openings during atrial and ventricular contractions and support for the semilunar valves against the high pressures generated during and after ventricular contractions. The skeleton is a formation of four attached rings with the opening for the aortic semilunar valve in the central position and the other valve rings attached to it.

The triangular formation between the aortic semilunar valve and the medial parts of the tricuspid and bicuspid valve openings is the right *fibrous trigone* ("triangle") or the central fibrous body, the strongest portion of the cardiac skeleton. The smaller left fibrous trigone is formed between the aortic semilunar valve and the anterior cusp of the mitral valve. Continuations of fibroelastic tissue from the right and left fibrous trigone partially encircle the AV openings to form the tricuspid and bicuspid annulus or annulus fibrosus. The annuli serve as attachment sites for the AV valves as well as atrial and ventricular myocardium. Strong collagenous tissue passes anteriorly from the right and left fibrous trigones to encircle and support the aortic and pulmonary semilunar valve annuli. The membranous interventricular septum is an inferior extension of the central fibrous body that attaches to the muscular interventricular septum. The membranous septum provides support for the medial (right and posterior) cusps of the aortic semilunar valve and continues superiorly to form part of the atrial septum. The tendon of Todaro is a fibrous extension of the membranous septum that is continuous with the valve (Eustachian) of the inferior vena cava. The AV bundle of conduction fibers from the AV node penetrates the central fibrous body, passes through the membranous septum, and splits into left and right bundle branches at the apex of the muscular septum (or the junction of the right and posterior cusps of the aortic semilunar valve).

5.6 The Fetal Heart

By the third month of fetal development, the heart and all major blood vessels are basically formed, and the blood flow is generally in the same direction as the adult. However, there are some major differences between fetal and postnatal circulation (Fig. 5.17). First, oxygenated blood flows toward the fetus and into the heart in umbilical veins, and deoxygenated blood flows away from the fetus in umbilical arteries. Second, the fetus obtains oxygen from the uterus through the placenta, and the fetal lungs are essentially nonfunctional. Therefore, fetal circulation has a number of features to direct most of the blood away from the lungs.

In fetal circulation, oxygenated blood from the placenta flows through the umbilical cord as the umbilical vein. The vein passes through the anterior abdominal wall (umbilicus) and then through the abdomen, into the thorax, and into the heart. As the umbilical vein travels through the abdomen, most of the blood is diverted away from entering the liver (through the ductus venosus) and into the inferior vena cava. Thus, unlike the adult heart, oxygenated blood mixes with deoxygenated blood and collects in the right atrium. Because very little of this blood is required in the lungs, the fetus has three unique features to ensure that the blood is shunted from the right (pulmonary) side of the heart to the left (systemic) side. The first is an oval hole in the interatrial septum called the foramen ovale (the foramen ovale is not really a hole but rather a valve composed of two flaps that prevent the regurgitation of blood). For more information on this topic, the reader is referred to Chap. 3.

Before birth, pressure is higher in the right atrium than in the left because of the large vasculature from the placenta. The foramen ovale is a passage for blood to flow from the right atrium into the left.

A second feature of the fetal heart is the ligament of the inferior vena cava. This ligament is located inferior to the opening of the vena cava and extends medially to the atrial septum, passing inferior to the foramen ovale. It is much more prominent in the fetus than in the adult. It functions in fetal circulation to direct, in a laminar flow, the blood coming into the right ventricle toward the foramen ovale of the interatrial septum, so blood can pass into the left atrium.

The third feature of fetal circulation is a way for oxygenated blood that has been pumped from the right atrium to the right ventricle to be diverted from the pulmonary circulation into the systemic circulation. Despite the shunt from the right atrium to the left, much of the oxygenated blood that enters the right atrium gets pumped into the right ventricle. The ductus arteriosus

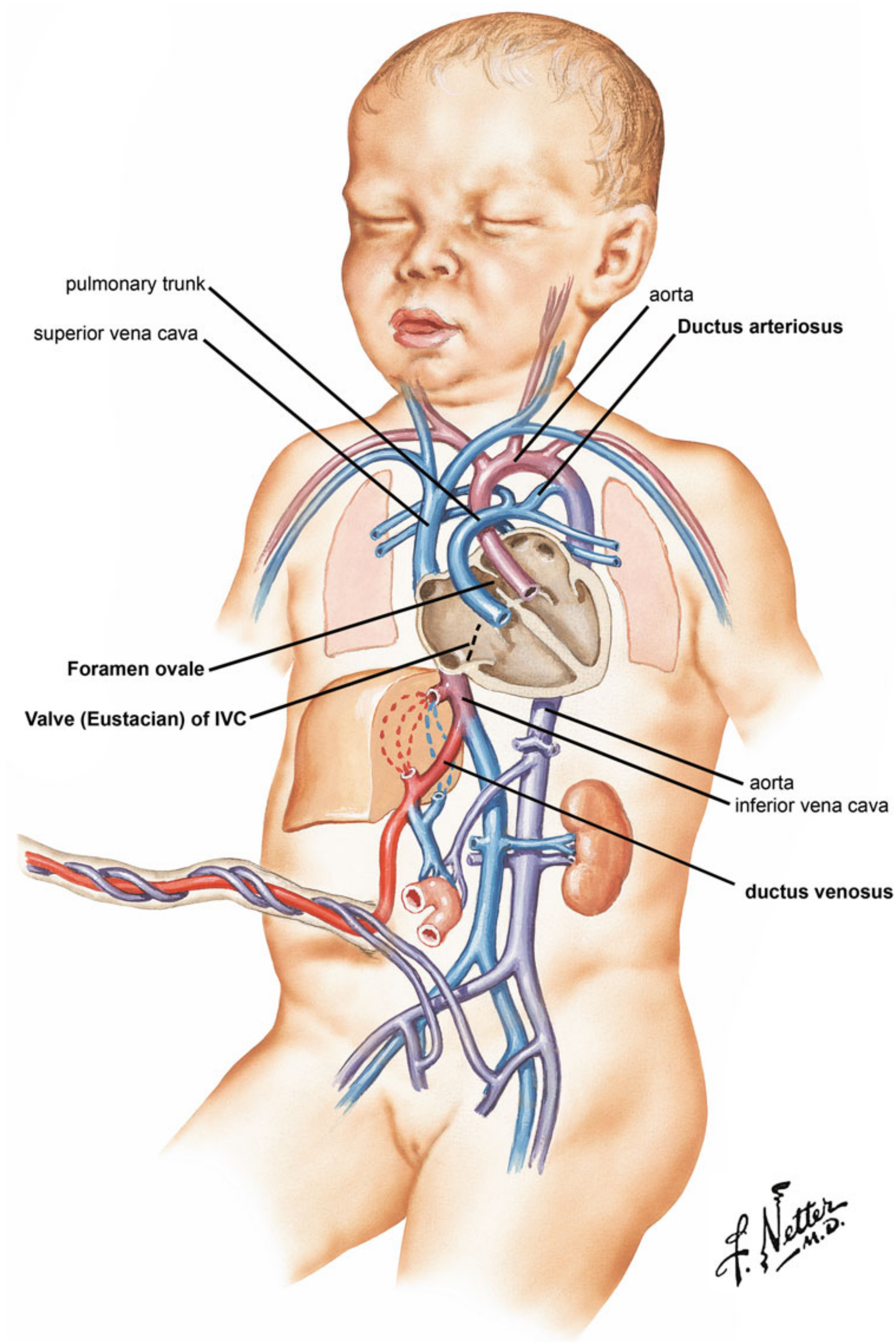

Fig. 5.17 Fetal circulation. The fetal heart has unique features to shunt blood away from the relatively nonfunctional lungs: (1) foramen ovale, (2) ductus arteriosus, and (3) valve (Eustachian) of the inferior vena cava. www.netterimages.com, Frank Netter

("duct of the artery") is a connection between the left pulmonary artery and the aortic artery. Blood is diverted from the pulmonary artery to the aorta so that very little blood reaches the immature lungs. Because the pulmonary vascular resistance of the fetus is large, only one-tenth of right ventricular output passes through the lungs. The remainder passes from the pulmonary artery through the ductus arteriosus to the aorta. In the fetus, the diameter of the ductus arteriosus can be as large as the aorta.

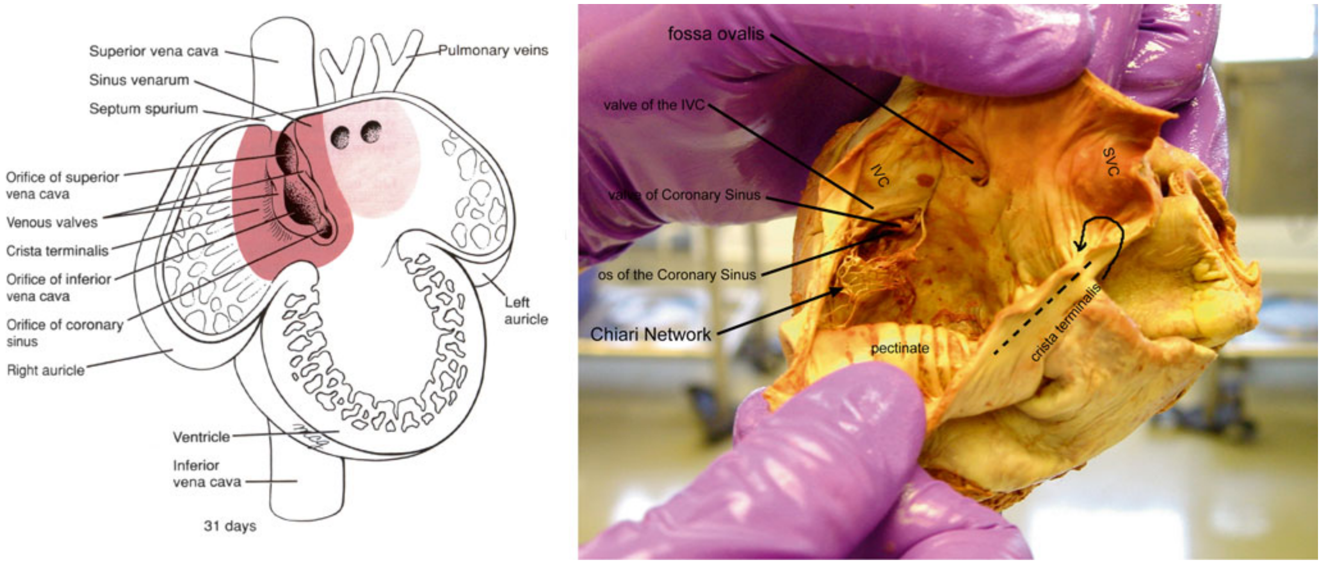

Fig. 5.18 Chiari network. *Left*: The sinus venosus incorporates into the posterior wall of the primitive right atrium. This becomes the sinus venarum (smooth) portion of the right atrium. A pair of tissue flaps, the left and right venous valves, develops on either side of connection between the sinus venarum and the right atrium. The left valve eventually gives rise to the septum secundum (definitive interatrial septum); the right valve gives rise to the valve of the inferior vena cava (Eustachian), the valve of the coronary sinus (Thebesian), and the crista terminalis. Incomplete resorption of the right valve of the embryonic sinus venarum leads to the presence of a meshwork of fibrous strands attached to the edges of the Eustachian valve or the Thebesian valve inferiorly and the crista terminalis superiorly. *Right*: human cadaveric heart. *IVC* inferior vena cava, *SVC* superior vena cava

Shortly after birth, the umbilical cord is cut and the newborn takes its first breath. Rising concentrations of the hormone prostaglandin are believed to result in the closure of the ductus arteriosus (ligamentum arteriosum), and the lungs receive much more blood. The increase in pressure is translated to the left atrium. This pressure pushes together the two valve flaps of the interatrial septum. One of the flaps covers the foramen ovale, thus closing it to form the fossa ovalis. This prevents the flow of blood from the right to the left atrium.

5.7 Other Fetal Remnants: Chiari Network

Around 4–5 weeks of fetal development, the sinus venosus incorporates into the posterior wall of the primitive right atrium. This becomes the sinus venarum (smooth) portion of the right atrium. A pair of tissue flaps, the left and right venous valves, develops on either side of connection between the sinus venarum and the right atrium.

The left valve eventually becomes part of the septum secundum (which becomes a portion of the definitive interatrial septum). The right valve remains intact and forms the valve of the inferior vena cava (Eustachian), the crista terminalis, and the valve of the coronary sinus (Thebesian) (Fig. 5.18).

Infrequently, incomplete resorption of the right valve of the sinus venarum may lead to the presence of a meshwork of fibrous strands attached to the edges of the Eustachian valve or Thebesian valve inferiorly and the crista terminalis superiorly. This is called a “Chiari net or network” (Fig. 5.18). Remnants of the other valve, the left sinus venarum valve, may be found adherent to the superior portion of the atrial septum or the fossa ovalis. For more information on this topic, see Chap. 3.

5.8 Other Fetal Remnants: Atrial Septal Defect

The first step in the separation of the systemic and pulmonary circulation in the fetal heart is the separation of the definitive atrium. The adult interatrial septum is formed by the fusion of two embryonic septa. Note that this embryonic septum always contains a hole such that right-to-left shunting of oxygenated blood remains.

Between 3 and 4 weeks of development, the roof of the atrium becomes depressed and produces a wedge of tissue called the *septum primum* (“first partition”) that extends inferiorly. During the fifth week, this septum reaches the “floor” of the atrium, thus separating the right and left atria. Note that a crescent shape forms along its leading edge. This forms an “arch way” under the septum to function as an opening for the flow of blood called the ostium primum (“first mouth opening”). At the end of the sixth week, the growing edge of the septum primum reduces the ostium primum to nothing. At the same time, the septum primum grows perforations near the superior end of the septum that

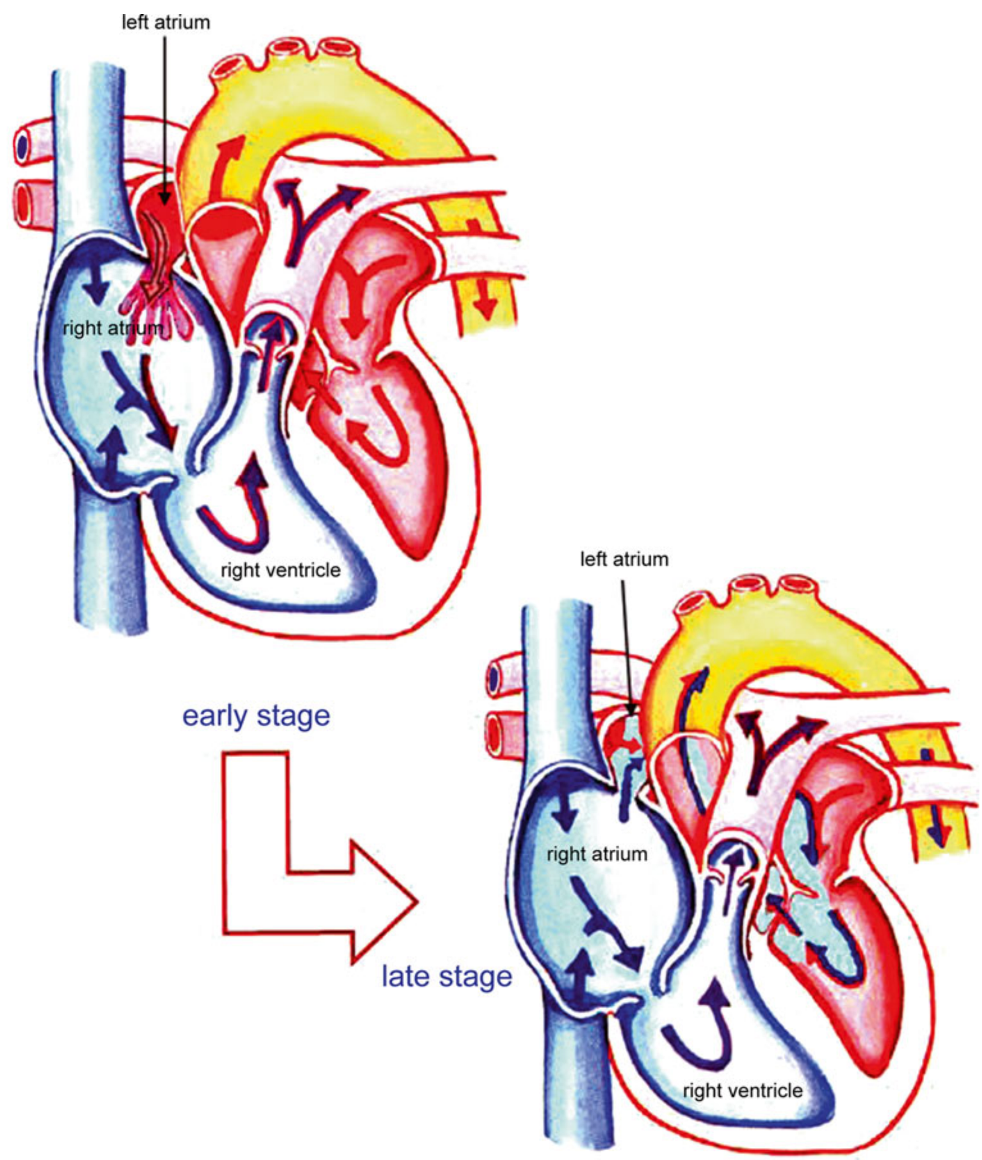

Fig. 5.19 Atrial septal defect (ASD). Incomplete formation of the interatrial septum results in a persistent opening or defect. After birth, the pressure in the left atrium is greater than the right, and there is modest left-to-right shunting of blood. The right atrium will frequently respond to the continuous increases in volume. The result is increased pressure generated by the right atrium and a reverse in the flow from the right to the left atrium. This results in oxygen-poor blood in the left atrium, ventricle, and aortic artery leading to symptoms of hypoxia. Modified from VanDeGraaf KM (ed) (1995) Human anatomy. Wm. C. Brown Publishers, Dubuque, p. 557

coalesce to form a new foramen, the ostium secundum ("second opening"). Thus, a new channel for right-to-left blood flow opens before the old one closes. At the same time, a second crescent-shaped wedge of tissue, the septum secundum ("second partition"), grows from the roof of the atrium. It is located adjacent to the septum primum on the side of the right atrium. Unlike the septum primum, the secundum is thick and muscular as it grows posteroinferiorly. It completely extends to the floor of the right atrium. The crescent shape at the leading edge leaves a hole in the inferior portion called the *foramen ovale* ("oval hole"); this might be considered the third hole. Throughout the rest of fetal development, blood shunts from the right to the left atrium. This shunt closes at birth due to the abrupt dilation of the pulmonary vasculature, combined with the loss of flow through the umbilical vein. The increase in pressure in the left atrium and the loss of pressure in the right pushes the flexible septum primum against the septum secundum. The septum primum covers the foramen ovale as the valve of the foramen ovale.

There are various mechanisms by which an opening can persist in the interventricular septum postnatally. This is referred to as an *atrial septal defect* (Fig. 5.19; see also Chap. 37). This abnormality is generally asymptomatic during infancy. However, the persistent increase in flow of blood into the right atrium can lead to hypertrophy of the right atrium, right ventricle, and the pulmonary trunk. In some cases, the left-to-right flow of blood between the atria converts to right-to-left shunt. This causes oxygen-poor blood to mix with the oxygen-rich blood returning to the left atrium from the lungs. Oxygen-poor blood is then pumped out of the heart through the aortic artery and the symptoms of hypoxia (“low oxygen”) result. Approximately 30 % of normal hearts have a small potency with a valve-competent foramen ovale.

5.9 Other Fetal Remnants: Ventricular Atrial Septal Defect

The developmental formation of the interventricular septum is extremely complex. Simply, the septum forms as the growing walls of the right and left ventricles become more closely apposed to one another. The growth of the muscular septum commences at the inferior end and proceeds superiorly. Septation of the ventricles and formation of the ventricular outflow tracts must occur in tight coordination. Ventricular septal defects can occur because of errors in this complex process. Failure of complete fusion of the membranous septum growing inferiorly from the superior portion of the ventricles and the muscular septum results in one type of ventricular septal defect (Fig. 5.20). Ventricular septal defects are the most common congenital heart defect.

Whatever the origin of a ventricular septal defect, the result is a massive left-to-right shunting of blood due to the ability of the left ventricle to generate higher pressures than the right. This is associated with postnatal pulmonary hypertension and deficient closure of AV valves. This type of condition is often referred to, in lay terms, as “baby being born with a hole in the heart.” Because of extreme hypoxia and

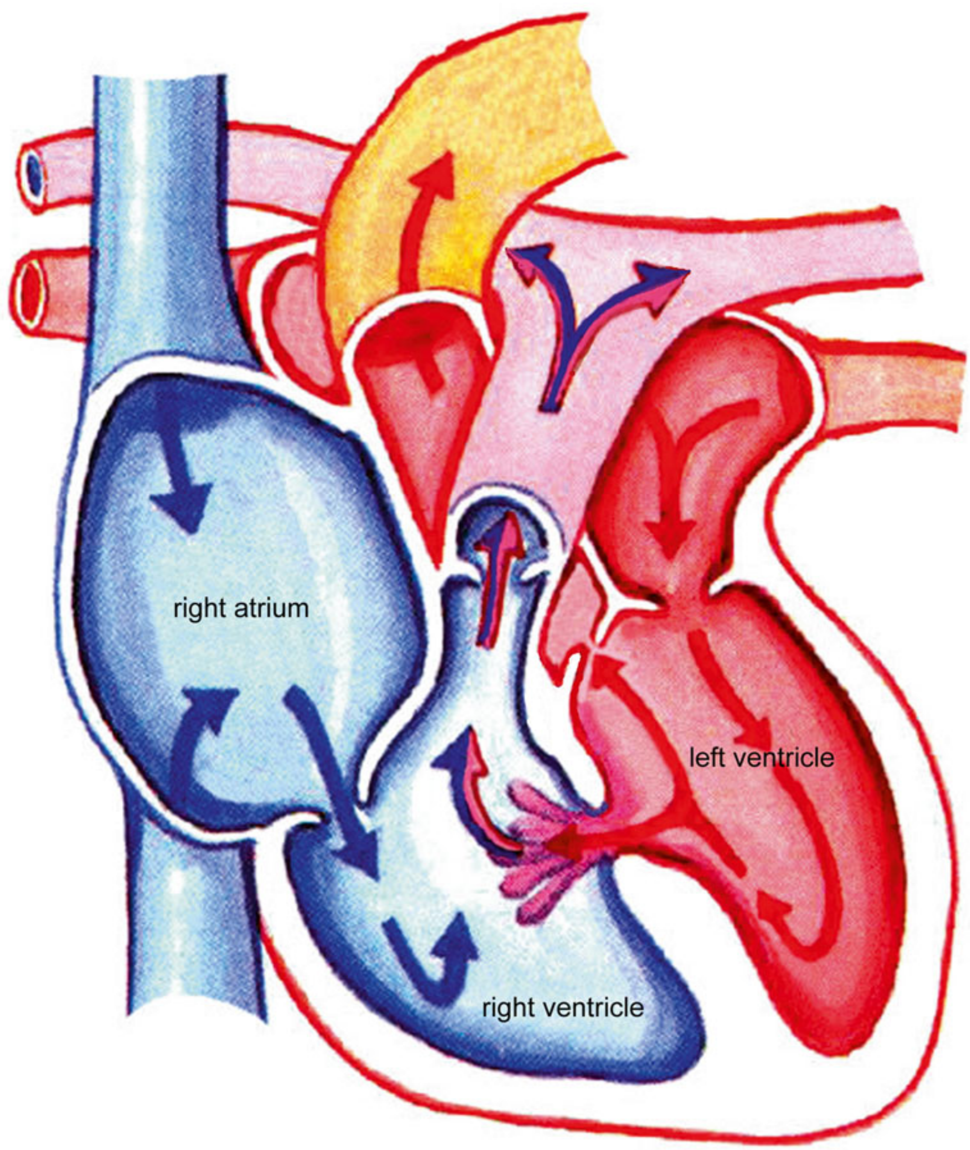

Fig. 5.20 Ventricular septal defect. Caused by abnormal development of the interventricular septum. This condition results in massive left-to-right shunting of blood. This is associated with pulmonary hypertension and deficient closure of atrioventricular valves after birth. Emergent surgical repair of this hole is indicated. Modified from VanDeGraaf KM (ed) (1995) Human anatomy. Wm. C. Brown Publishers, Dubuque

pulmonary hypertension, there is usually immediate surgical repair of the defect. For additional information on ventricular septal defects and their repair, refer to Chap. 37.

5.10 Vasculature of the Heart

The arterial supply to the heart arises from the base of the aorta as the right and left coronary arteries (running in the coronary sulcus). The venous drainage is via cardiac veins that return deoxygenated blood to the right atrium. The coronary arteries arise from the ostia in the left and right sinuses of the aortic semilunar valve, course within the epicardium, and encircle the heart in the AV (coronary) and interventricular sulci (Fig. 5.21).

5.10.1 Right Coronary Artery

The right coronary artery emerges from the aorta into the AV groove. It descends through the groove, then curves posteriorly, and makes a bend at the crux of the heart and continues downward in the posterior interventricular sulcus. Within millimeters after emerging from the aorta, the right coronary artery gives off two branches (Figs. 5.21 and 5.22). The conus (arteriosus) artery runs to the conus arteriosus (right ventricular outflow tract), and the atrial branch to the right atrium. This atrial branch gives off the SA nodal artery (in 50–73 % of hearts, according to various reports), which runs along the anterior right atrium to the superior vena cava, encircling it in a clockwise or counterclockwise direction before reaching the SA node. The SA nodal artery supplies the SA node, Bachman's bundle, crista terminalis, and the left and right atrial free walls. The right coronary artery continues in the AV groove and gives off a variable number of branches to the right atrium and right ventricle. The most prominent of these is the right marginal branch which runs down the right margin of the heart supplying this part of the right ventricle. As the right coronary curves posteriorly and descends downward on the posterior surface of the heart, it gives off two to three branches. One is the posterior interventricular (posterior descending) artery that runs in the posterior interventricular sulcus. It is directed toward the apex of the heart to supply the posterior free wall of the right ventricle. In 85–90 % of hearts, branches of this artery (posterior septal arteries) supply the posterior one-third of the interventricular septum (Fig. 5.23). The second artery is the AV nodal artery which branches from the right coronary artery at the crux of the heart and passes anteriorly along the base of the atrial septum to supply the AV node (in 50–60 % of hearts), proximal parts of the bundles (branches) of His, and the parts of the posterior interventricular septum that surround the

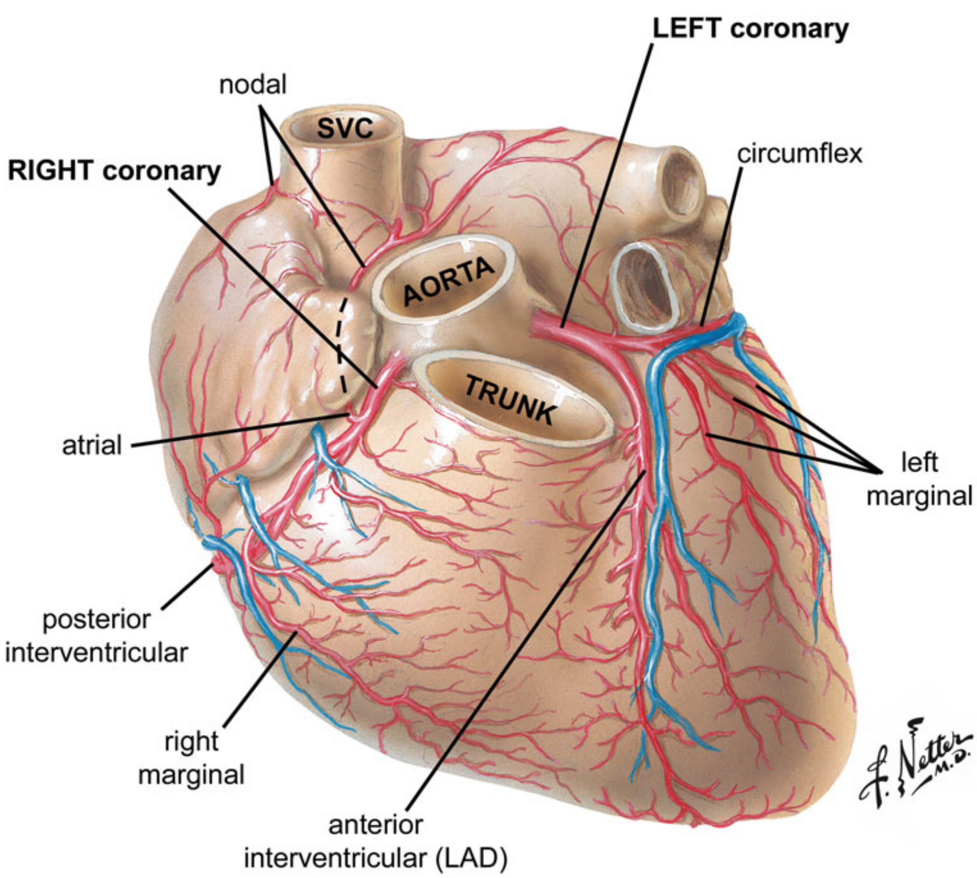

Fig. 5.21 Vascular supply to the heart. Arterial supply to the heart occurs via the right and left coronary arteries and their branches. Venous drainage occurs via cardiac veins. www.netterimages.com, Frank Netter

Fig. 5.22 Atrial branch of right coronary artery. This atrial branch gives off the sinoatrial (SA) nodal artery which runs along the anterior right atrium to the superior vena cava and encircles it in a clockwise, or sometimes counterclockwise, direction before reaching the SA node. The nodal artery can also pass intramurally through the right atrium to the SA node. The SA nodal artery supplies the SA node, Bachman's bundle, crista terminalis, and the left and right atrial free walls

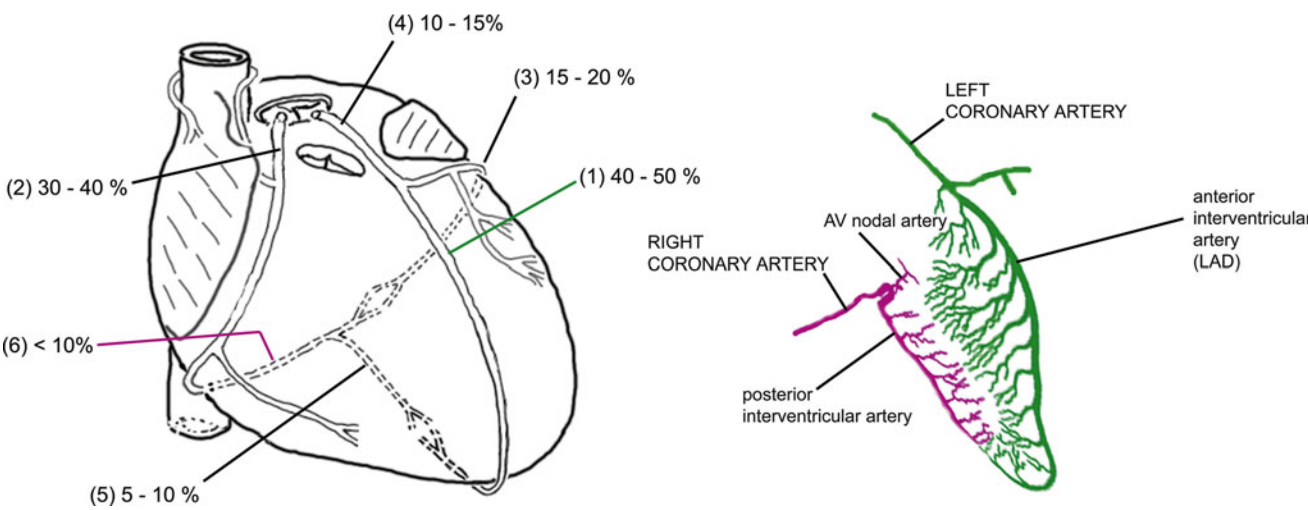

Fig. 5.23 Arterial supply to the interventricular septum. *Left*: Sites of coronary artery occlusion, in order of frequency and percentage of occlusions involving each artery. *Right*: The right coronary artery supplies the posterior one-third of the interventricular septum, and the left coronary supplies the anterior two-thirds. The artery to the atrioventricular node commonly branches off of the posterior interventricular artery. Occlusions occur most frequently in the anterior interventricular artery, which is the primary blood supply to the interventricular septum (and bundle branches within). *AV* atrioventricular

bundle branches. Another artery crosses the crux into the left AV groove to supply the diaphragmatic surface of the left ventricle and the posterior papillary muscle of the bicuspid valve. The right coronary artery also serves as an important collateral supply to the anterior side of the heart, left ventricle, and anterior two-thirds of the interventricular septum via the conus artery and communicating arteries in the interventricular septum (Fig. 5.23). Kugel's artery, which originates from either the right or left coronary artery, runs from anterior to posterior through the atrial septum. This artery serves as an important collateral connection from anterior arteries to the AV node and posterior arteries.

5.10.2 Left Coronary Artery

The left coronary artery (left main coronary artery) emerges from the aorta through the ostia of the left aortic cusp within the sinus of Valsalva (Fig. 5.21). The plane of the semilunar valve is tilted so that the ostium of the left coronary artery is superior and posterior to the right coronary ostium. The left coronary artery travels from the aorta and passes between the pulmonary trunk and the left atrial appendage. Under the appendage, the artery divides (and is thus a very short vessel) into the anterior interventricular (left anterior descending artery) and the left circumflex artery. The left coronary artery may be completely absent, i.e., the anterior interventricular and circumflex arteries arise independently from the left aortic sinus.

The anterior interventricular artery appears to be a direct continuation of the left coronary artery which descends into the anterior interventricular groove. Branches of this artery, anterior septal perforating arteries, enter the septal myocardium to supply the anterior two-thirds of the interventricular septum (in about 90 % of hearts) (Fig. 5.23). The first branch, the first septal perforator, supplies a major portion of the AV conduction system. In about 80 % of hearts, the second or third perforator is the longest and strongest of the septal arteries and is often called the *main septal artery*. This artery supplies the middle portion of the interventricular septum. This artery also sends a branch to the moderator band and the anterior papillary muscle of the tricuspid valve (right ventricle), which is reasonable considering that the moderator band is part of the septomarginal trabeculae of the interventricular septum. This artery is often called the *moderator artery*. Other branches of the anterior interventricular artery extend laterally through the epicardium to supply adjacent right and left ventricular free walls. The anterior interventricular artery also sends a branch to meet the conus artery from the right coronary to form an important collateral anastomosis called the *circle of Vieussens* as well as branches to the anterior free wall of the left ventricle called *diagonal arteries*. These are numbered according to their sequence of origin as first, second, etc. diagonal arteries. The most distal continuation of the anterior interventricular artery curves around the apex and travels superiorly in the posterior interventricular sulcus to anastomose with the posterior descending from the right coronary artery. In summary, the anterior interventricular artery and its branches supply most of the interventricular septum—the anterior, lateral, and apical wall of the left ventricle; most of the right and left bundle branches; and the anterior papillary muscle of the bicuspid valve (left ventricle). It also provides collateral circulation to the anterior right ventricle, the posterior part of the interventricular septum, and the posterior descending artery.

The circumflex artery branches off of the left coronary artery and supplies most of the left atrium—the posterior and lateral free walls of the left ventricle and (with the anterior interventricular artery) the anterior papillary muscle of the bicuspid valve. The circumflex artery may give off a variable number of left marginal branches to supply the left ventricle. The terminal branch is usually the largest of these branches. More likely, the circumflex artery may continue through the AV sulcus to supply the posterior wall of the left ventricle and (with the right coronary artery) the posterior papillary muscle of the bicuspid valve. In 40–50 % of hearts, the circumflex artery supplies the artery to the SA node.

In 30–60 % of hearts, the left coronary artery may give off one or more intermediate branches that originate *between* the anterior interventricular and circumflex arteries. These extend diagonally over the left ventricle toward the apex of the heart and are thus named diagonal or intermediate arteries.

The anterior interventricular artery is the most commonly occluded of the coronary arteries (Fig. 5.23). It is the major blood supply to the interventricular septum and the bundle branches of the conducting system. It is easy to see why coronary artery disease can lead to impairment or death (infarction) of the conducting system. The result is a "block" of impulse conduction between the atria and the ventricles known as "right/left bundle branch block." Furthermore, branches of the right coronary artery supply both the SA and AV nodes in at least 50 % of hearts. An occlusion in this artery could result in necrosis of the SA or AV nodes, thus preventing or interrupting the conduction of electrical activity across the heart. For more details on the coronary arteries, see Chaps. 6 and 8.

5.10.3 Cardiac Veins

An extensive network of intercommunicating veins provides venous drainage from the heart. The venous drainage of deoxygenated blood from the rest of the body is returned to the right atrium, as is the venous drainage of the heart. Venous drainage of the heart is accomplished through three separate systems: (1) the cardiac venous tributaries which converge to form the coronary sinus, (2) the anterior cardiac (anterior right ventricular) veins, and (3) the smallest cardiac (Thebesian) venous system (Fig. 5.24).

Most of the myocardium is drained by the cardiac veins that course parallel to the coronary arteries. These three large veins (the great, middle, and small cardiac veins) converge to form the coronary sinus.

On the anterior side of the heart, the anterior interventricular vein lies within the anterior interventricular sulcus and runs from inferior to superior beside the anterior interventricular artery (Figs. 5.24 and 5.25). At the base of the heart, near the bifurcation of the left coronary artery, it turns and runs within the AV groove as the great cardiac vein around the left side of the heart to the posterior. In the AV groove on the posterior side of the heart, the great cardiac vein *becomes* the coronary sinus, which then empties into the right atrium. From the inside of the right atrium, it can be seen that the coronary sinus opens into the right atrium forming an opening or *os* that is located anteriorly and inferiorly to the orifice of the inferior vena cava. There is a valve (Thebesian valve) that covers the opening of the coronary sinus to prevent backflow. The great cardiac vein is formed

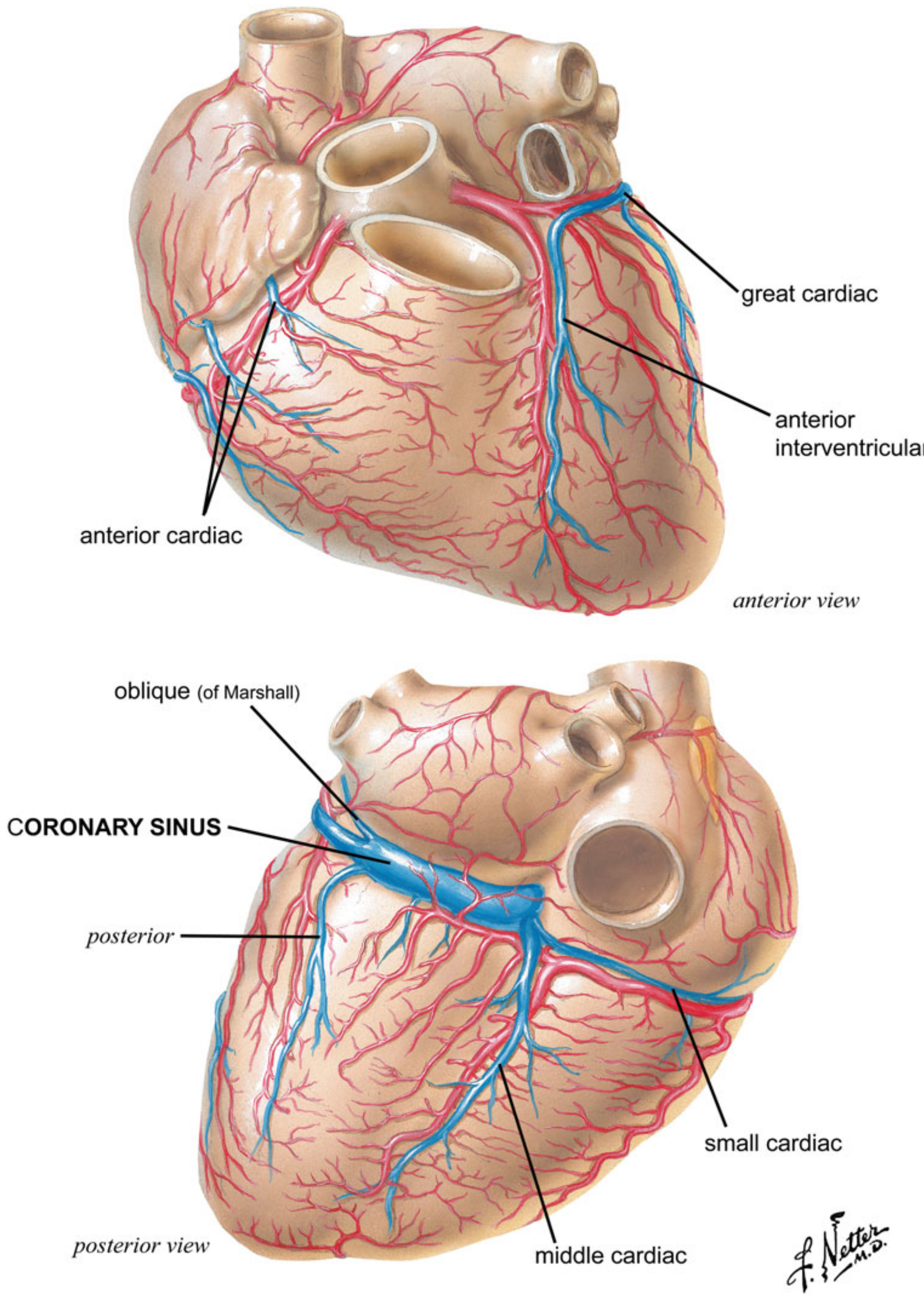

Fig. 5.24 Venous drainage of the heart. Three separate venous systems carry blood to the right atrium—the coronary sinus and its tributaries, the great, middle and small cardiac veins; the anterior cardiac veins; and the smallest (Thebesian) cardiac veins. © 2006 Elsevier Inc. All rights reserved. www.netterimages.com, Frank Netter

by the confluence of small venous tributaries from the left and right ventricles and anterior portion of the interventricular septum. As it ascends toward the coronary sinus, it receives small venous tributaries from the left atrium and left ventricle. It also receives a large left marginal vein, which runs parallel to the left marginal artery.

There are two structures that serve as the boundary between the termination of the great cardiac vein and the beginning of the coronary sinus. The first is the valve of Vieussens, which has the appearance of a typical venous valve and functions to prevent the backflow of blood from the coronary sinus into the great cardiac vein (Raymond Vieussens, French anatomist, 1641–1715). The second is the space between the entry points of the oblique vein of the left atrium (of Marshall) and the posterior (posterolateral) vein of the left ventricle (John Marshall, English anatomist, 1818–1891). The oblique vein of Marshall runs superior to inferior along the posterior side of the left atrium, providing venous drainage of the area. The posterior vein ascends to the coronary sinus from the inferior portion of the left ventricle and provides drainage of the area.

Fig. 5.25 The great cardiac vein. On the anterior side of the heart, the anterior interventricular vein lies within the anterior interventricular sulcus and runs from inferior to superior beside the anterior interventricular artery. At the base of the heart, it changes to the great cardiac vein as it runs within the atrioventricular groove around the left side of the heart to the posterior. In the atrioventricular groove on the posterior side of the heart, the great cardiac vein becomes the coronary sinus and empties into the right atrium

Fig. 5.26 The middle cardiac vein. The middle cardiac vein, located on the posterior surface of the heart, arises near the posterior aspect of the apex of the heart and runs from inferior to superior through the posterior interventricular sulcus before entering the coronary sinus. The middle cardiac vein is formed from venous confluence of tributaries that drain the posterior left and right ventricles and the interventricular septum

In addition to the great cardiac vein, the coronary sinus receives the posterior interventricular (or middle cardiac) vein (Figs. 5.24 and 5.26). Located on the posterior surface of the heart, it arises near the posterior aspect of the apex of the heart and runs from inferior to superior through the posterior interventricular sulcus. It then joins the coronary sinus within millimeters of the sinus entering into the right atrium. The middle cardiac vein is formed from venous confluence of tributaries that drain the posterior left and right ventricles and the interventricular septum.

The coronary sinus also receives the highly variable small cardiac vein. The small cardiac vein arises from the anterior/lateral/inferior portion of the right ventricle. It ascends and runs inferior to and roughly parallel with the marginal branch of the right coronary artery until it reaches the right AV sulcus. At this point, it turns and runs horizontally around to the posterior side of the heart and enters the coronary sinus with the middle cardiac vein. The small cardiac vein is extremely small or absent in 60 % of hearts. In about 50 % of hearts, the small cardiac vein enters the right atrium directly, and it infrequently drains into the middle cardiac vein.

Typically, about 85 % of the venous drainage of the heart occurs through the great, middle, and small cardiac veins through the coronary sinus to the right atrium. This elaborate system of veins drains the left ventricle, some of the right ventricle, both atria, and the anterior portion of the interventricular septum.

The second system of venous drainage of the heart involves the variable and delicate anterior cardiac veins (Figs. 5.24 and 5.27). This system is distinguished from the other cardiac venous system because the anterior cardiac veins do not drain into the coronary sinus. The two to four anterior cardiac veins originate and drain the anterior right ventricular wall, travel superiorly to cross the right AV sulcus, and enter the right atrium *directly*. The sulcus is usually packed with adipose tissue. Through this adipose tissue run the anterior cardiac veins, the right coronary artery, and a branch of the coronary artery, the right atrial or nodal artery. The anterior cardiac veins pass over the right coronary artery in close proximity and in a perpendicular angle. A right marginal vein (when present) runs parallel with the right marginal artery before entering the right atrium directly and is usually considered part of the anterior cardiac venous system.

The third system of venous drainage of the heart is the smallest cardiac venous system (Fig. 5.27). This system is composed of a multitude of small intramural ("within the walls") intramyocardial veins also called Thebesian veins (Adam C. Thebesius, German physician, 1686–1732). These are minute vessels that begin in the capillary beds of the myocardium and open directly into the chambers of the heart. Although called veins, they are valveless communications between myocardial capillaries and a chamber of the heart. Interestingly, ostia of Thebesian veins may be found in all chambers of the heart, but are most prevalent in the atrial and ventricular septa. They are more prevalent on the right side than the left. As much as 17 % of myocardial drainage occurs through these smallest cardiac veins, with 49 % through the cardiac veins and coronary sinus and 24 % through anterior

Fig. 5.27 Anterior cardiac veins. Two to four anterior cardiac veins originate and drain the anterior right ventricular wall. These veins travel superiorly to cross the right atrioventricular sulcus and enter into the right atrium. These veins are part of the smallest cardiac venous system which empties oxygen-poor blood directly into the right atrium without communication with the coronary sinus

cardiac veins. For additional details on the cardiac venous system, see Chap. 8.

5.10.4 Myocardial Bridges

The coronary arteries typically course upon the myocardium or under/within the epicardium of the heart. Frequently, a portion of an artery deviates from its usual subepicardial position to follow an intramyocardial (intramural) course, either by traveling a significant length within the myocardium or beneath an arrangement of muscular slips ("myocardial bridges"). Myocardial bridging is most common in the middle segment of the anterior interventricular artery [2]. The myocardial fibers that cover or "bridge over" the anterior interventricular artery are direct extensions of the myocardium of the conus arteriosus of the right ventricle and cross the artery in a perpendicular direction. Myocardial bridges over the right coronary and the circumflex arteries are much less common. When present, these bridges are extensions of the respective atrial myocardium [3]. The prevalence of myocardial bridges from various sources is reported to occur in 5–85 % of hearts when measured from the cadaver [4–6] and 0.5–16 % when measured from angiography in catheterization labs [4, 5, 7].

Coronary arteries have a tortuous pattern as they run across the heart. Interestingly, studies employing angiography followed by detailed microdissection show that a coronary artery with a typical tortuous shape takes on a perfectly straight pattern when it follows an intramyocardial course [8].

Angiography has also shown that myocardial bridges are associated with narrowing of the lumen of the coronary artery. The narrowing appears during systole and disappears during diastole [2]. The appearance of straight running or systolic narrowing patterns appears to be an important diagnostic technique during angiography to discover intramyocardial segments of coronary arteries [2].

Myocardial bridging is usually a benign condition. Although there is contrasting evidence, atherosclerosis is uncommon within a myocardial bridge [4]; bridging might provide some protection against plaque formation [2].

5.11 Autonomic Innervation of the Heart

The SA node spontaneously produces an impulse for contraction of the atrial myocardium, depolarizes the AV node, and sends an impulse through the bundle fibers to the ventricular myocardium. In addition to the pacemaker activity of the SA node, the heart is also under autonomic, or involuntary, control.

The autonomic nervous system is separated into the *sympathetic* and *parasympathetic* nervous systems. These two systems send neurons to the same target, but convey opposite effects. In emergency situations, sympathetic nerves travel to the heart and innervate the SA and AV nodes in order to increase the rate and force of contraction. In resting situations, parasympathetic nerves that innervate the SA and AV nodes to slow down the heart rate reduce the force of contraction, thus saving energy.

Both the sympathetic and parasympathetic nerves are composed of a two-neuron pathway. These two neurons meet or synapse somewhere in the middle and form a structure called a *ganglion* ("swelling"). Neurons of the sympathetic nervous system emerge from the spinal cord. They emerge from all eight of the cervical segments and the first five of the thoracic spinal cord segments. These neurons travel laterally just centimeters from the spinal cord before they synapse. All of the neurons to the heart are believed to synapse in only two places—the middle cervical ganglion and the cervicothoracic (fused inferior cervical/1st thoracic or stellate "star-shaped") ganglion. Multitudes of fibers then emanate from these ganglia and run to the heart as sympathetic cardiac nerves.

Parasympathetic neurons emerge directly from the brain as part of the vagus nerve or cranial nerve X. The vagus nerve and its branches form the parasympathetic part of the cardiac nerves running toward the heart.

Sympathetic and parasympathetic cardiac nerves interconnect. In addition, nerves of the right and left side have connections. All together, this huge group of connections forms the cardiac plexuses. The dorsal cardiac plexus is located posterior to the arch of the aorta near the bifurcation of the trachea. The ventral plexus is located anterior to the aorta. Nerves from the cardiac plexuses extend to the atria and ventricles, SA node, AV node, coronary arteries, and the great vessels. It is generally believed that there is sympathetic and parasympathetic innervation of the myocardium that forms a network from the atria to the ventricles. For more details about the role of the autonomic nervous system in the physiological control of the heart, refer to Chap. 14.

5.12 Summary

This chapter covered the general internal and external anatomy of the human heart, its positioning within the thorax, and its basic function. It is important to note that this anatomy can be quite varied and also progressively modified by pathophysiologic conditions.

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