1 CHAPTER 1

Cardiovascular anatomy and physiology

> **Learning objectives**
>
> - Point out the key landmarks in the human heart relevant to cardiac rhythm management.
> - Name the four chambers of the heart, the four valves, and the major vessels.
> - Describe the flow of blood through the heart.
> - Define AV synchrony and explain why it is important.
> - State the difference between the body's arterial versus venous systems.

Introduction

An encyclopedia could be written on the anatomy and physiology of the human heart, and that is not our purpose. Device clinicians must understand the cardiovascular system to understand arrhythmias and device therapy. This chapter will introduce the important concepts of cardiac anatomy and physiology necessary for an understanding of cardiac rhythm management. To that end, this chapter will describe the chambers, valves, and major vessels of the heart and how these control the flow of blood in the body. Although we think of the heart—rightly—as a pump, it also possesses a complex electrical system. The cells of the human heart are unique in many ways, and how they produce, conduct, and dissipate electrical energy is very important, particularly to pacing. Our goal here is to describe the anatomy and physiology of the healthy heart and cardiovascular system in terms of what device clinicians need to know.

The healthy heart

The human heart is a double pump (right and left) that sits in the middle of the chest, slightly to the left, and rotated so that the right side is more anterior than the left. An average adult human heart is relatively large, about 13 by 9 by 6 cm and weighing about 300 g. The heart is protected by the rib cage and sits directly behind one of the body's thickest bones, the sternum. The bottom of the heart rests on the diaphragm muscle. The heart is encased in this protected but somewhat crowded area—it also contains the lungs (three lobes on the right, two on the left), the stomach, and the intestines.

The bottom tip of the heart (called the apex) taps up against the chest when the heart contracts. By placing his hands on the chest, a physician can feel the place where the apex of the heart makes contact with the chest; this place is called the point of maximal impulse (PMI). Knowing the precise location of the PMI can be very useful in treating cardiology patients, because the PMI of a healthy heart occurs slightly to the left, while the PMI of a person with an enlarged heart is going to occur much farther to the left, even off to the side. A healthy heart is roughly the size of the fist, but when hearts enlarge, such as occurs with disease progression, the enlargement occurs toward the left. Thus, PMI can

The Nuts and Bolts of Implantable Device Therapy Pacemakers, First Edition. Tom Kenny.

provide a fast, noninvasive way of determining if and to what degree the heart has enlarged.

The left ventricle composes most of the mass of the heart, being by far the largest of the four pumping chambers. A healthy heart circulates about 4–6 l of blood a minute—which is the entire blood volume of the body! That means the entire circulating volume of blood in the body moves around every minute or once per beat.

The heart consists of four chambers: two upper chambers called atria (singular atrium) and two lower and larger chambers called ventricles. To understand the healthy heart, it is useful to think of the heart in terms of right side (right atrium and right ventricle) and left side (left atrium and left ventricle). The right side of the heart circulates deoxygenated blood to the lungs (where it can be oxygenated). The left side of the heart pumps oxygenated blood out to the rest of the body (see **Figure 1.1**).

The heart is a muscle and consists of four distinct layers. The endocardium is the innermost layer and composes a lining for the interior of the heart. The epicardium is the outer layer of the heart. Between the endocardium and epicardium lies the myocardium—the thickest layer—which is muscle. The entire heart is encased in a liquid-filled sac called the pericardium, which acts like a shock absorber for the heart. The pericardial sac contains about 15–20 cc of pericardial fluid in a healthy individual. In the event that fluid builds up to abnormally high levels in the pericardial sac (such as might occur when a lead or catheter inside the heart perforates the endocardium, myocardium, and epicardium and goes exterior to the heart), this fluid can place pressure on the heart in a condition known as cardiac tamponade. Since the heart is contained in a relatively small space, this pressure can compromise the heart's ability to fill with blood and pump efficiently. During device implantation, perforation is an important concern because it can lead to cardiac tamponade. In the event that perforation results in cardiac tamponade, a needle is inserted into the pericardial sac (through the chest wall) to drain the blood. Lead perforation does not always result in cardiac tamponade, but it is a serious concern.

Blood flow through the heart

The heart is a pump and it is located amid a network of vessels that carry deoxygenated blood into the right side of the heart and reoxygenated blood into the left side of the heart. The flow is actually

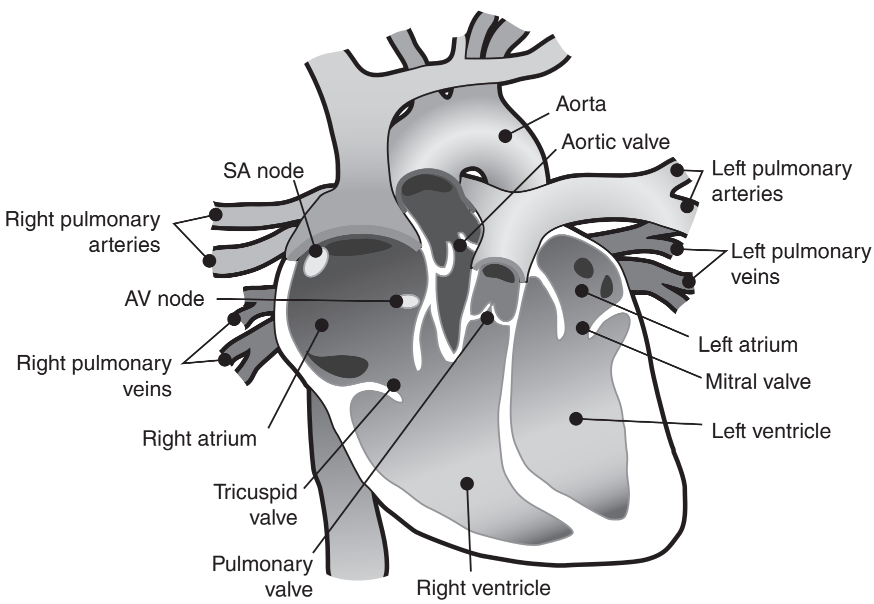


Figure 1.1 Cross section of the heart showing the chambers.

fairly simple. Deoxygenated blood enters the right side of the heart and is pumped over to the lungs via the pulmonary arteries and is returned back (as oxygen-rich blood) to the left side of the heart by way of the pulmonary veins (PV). While both right and left sides of the heart contract at the same time as a single unit, the right side is busy pumping deoxygenated blood to the lungs, while the left side is pumping reoxygenated blood out to the rest of the body.

Deoxygenated blood enters the right side of the heart via the superior vena cava (SVC), but once it has become oxygenated again, blood is pumped back out from the left side of the heart into the aorta. The aorta is the largest vessel in the body, and it forms a U shape at the top of the heart. These portions of the aorta are called the *ascending*, the *descending*, and the *arch*. Coming off the aortic arch are three main arteries: the left subclavian artery, the left common carotid artery, and the brachiocephalic trunk.

To better understand the blood flow through the heart, it is important to review the structure of the heart. The atria or upper chambers of the heart are smaller, have thinner walls, and are smoother on the inside than the ventricles. Within the ventricles is a network of fibrous strands known as trabeculae. These structural differences become important in lead implantation within the heart; it is much easier to affix or lodge a lead in the trabeculae of the ventricles than to try to anchor the lead to a smooth atrial wall. Historically, atrial leads have almost always been active-fixation screw-in-type leads, while ventricular leads were almost always passive-fixation leads (fins or tines that lodge in the trabeculae). Today, active-fixation leads are often used in both chambers since they facilitate lead removal (**Figure 1.2**).

Overall, blood flow to the heart is discussed, *right* and *left* sides, although it is important to recognize that what happens in the heart, that is, systole (contraction) and diastole (relaxation), are happening on both sides at the same time. The right atrium of the heart receives blood from the SVC, the inferior vena cava (IVC), and the coronary sinus (CS). The CS is technically a vein and it has an opening or ostium (sometimes just called *os*) at the base of the right atrium, slightly posterior. The CS delivers oxygen-depleted blood to the right atrium from the coronary arteries that encircle the exterior of the heart. The CS is of interest in cardiac resynchronization therapy (CRT) because the left ventricular lead is passed through the CS (counter to the flow of blood) in order to be placed into the coronary vessels to pace the left ventricle. CRT is used in patients with heart failure, whose hearts have remodeled, that is, enlarged and changed shape. (It may be said that with heart failure, the heart changes from the shape of a football to the shape of a basketball!) The CS may be relocated in this remodeling, which can be challenging in implanting a CRT lead because the physician must first locate the os of the CS and then navigate through it in order to implant the left ventricular lead.

Anatomically, the heart is dominated by the large muscle mass of the left ventricle, which makes up about two-thirds of the heart in terms of weight and volume. This greater size is typically ascribed to the fact that the left ventricle must pump blood throughout the whole body, whereas the right ventricle only has to pump blood to the lungs. The left and right ventricles pump blood to different destinations, but the left ventricle is larger and more muscular for a reason—pressure. It is important to review the pressures against which the heart must work to understand cardiac blood flow (**Figure 1.3**).

Deoxygenated blood in the right side of the heart must travel over the lungs to pick up oxygen. This means that blood in the right ventricle travels across the pulmonary valve into the pulmonary artery and then out toward the lungs. The pulmonary valve opens automatically when pressure from the contracting right ventricle forces it open. This occurs *when the pressure in the right ventricle exceeds the pressure in the pulmonary artery.* Pressure gradients are key concepts in understanding blood flow. Valves are like gates that open and close in response to pressure. In general, the pressure in the PV is fairly low, around 12 mmHg. Thus, the right ventricle does not need to create a lot of force to open the pulmonary valve.

Meanwhile, as the left ventricle contracts, it creates pressure on the aortic valve, leading to the aorta. In order to open the aortic valve and pump blood out into the aorta, the heart must overcome the pressure in the aortic valve. Pressure in the

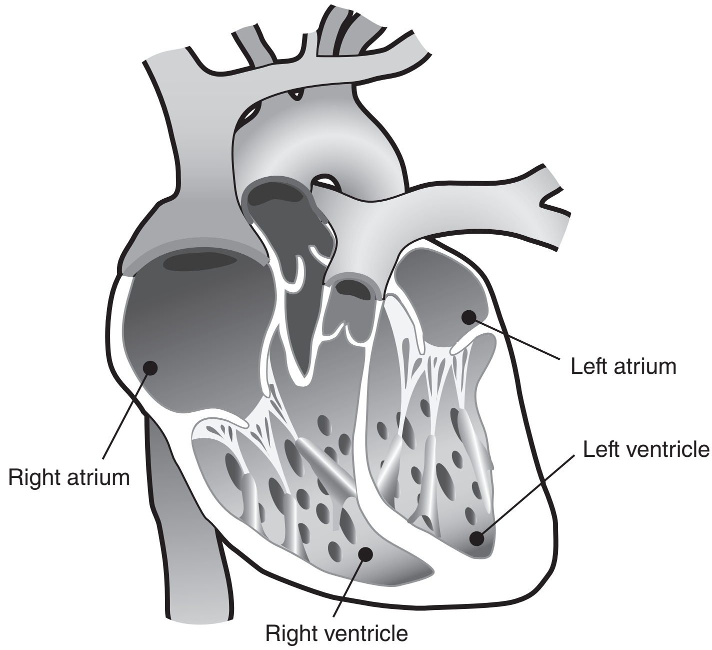


Figure 1.2 Note that the atria are smooth walled, while the ventricles contain a spongelike fibrous network of trabeculae.

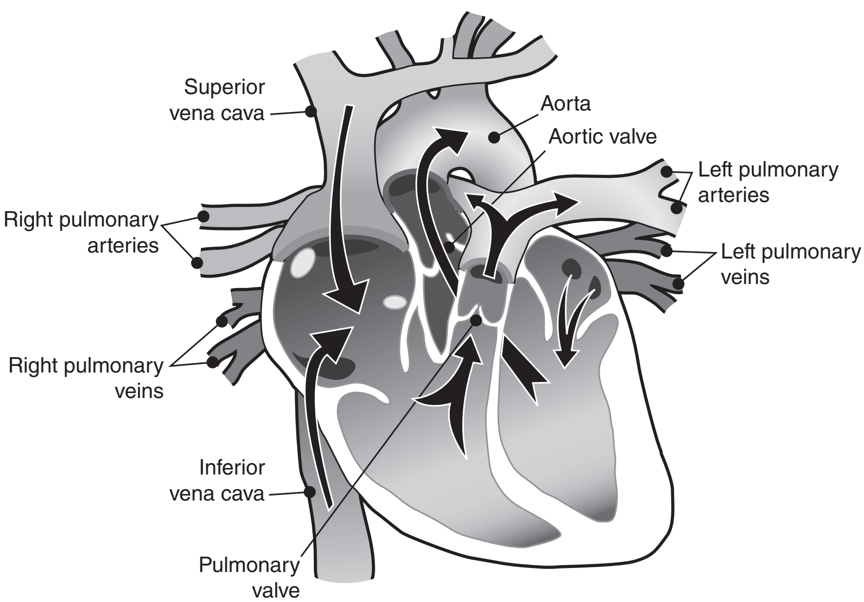


Figure 1.3 The blood flow within the heart takes oxygen-depleted blood from the body into the right atrium, where it flows to the right ventricle and is pumped out over the lungs; the reoxygenated blood from the lungs is pumped into the left atrium where it flows to the left ventricle and is pumped out via the aorta to the body.

aorta is high, around 120 mmHg or *ten times higher* than the pressure in the PV. The left ventricle must therefore work much harder to pump blood than the right ventricle. This requires the left ventricle to be larger and more muscular than the right ventricle (see **Figure 1.4**).

On the right side of the heart, blood travels from the right atrium into the right ventricle via the tricuspid valve. The tricuspid valve gets its name from its characteristic shape involving three leaves or cusps. Attached to these cusps are cords that anchor into the base of the ventricle; known as chordae tendineae, they look almost like little parachutes. The strands of the chordae tendineae attach to tiny papillary muscles. These chords attach to the valve leaves at one end and a papillary muscle at the other end. On the right side of the heart, the tricuspid valve is associated with three papillary muscles. The purpose of these chords and muscles is to assure that the valve is effectively closed and opened at the proper times (**Figure 1.5**).

Figure 1.4 The left ventricular is far more muscular than the right ventricle because it must overcome 10 times the pressure of the right ventricle in order to pump blood out via the aortic valve and into the aorta.

The heart can rightly be thought of as a pump, but it must be remembered that the heart is also a muscle and all muscles need a steady supply of oxygen-rich blood. The heart muscle is supplied with blood through a network of coronary arteries that surround the outside of the heart. Blockage in a coronary artery results in ischemia, which can lead to death of cardiac muscle, including the chordae tendineae and papillary muscles. While the patient may survive such an ischemic event, the damage to the heart may lead to an incompetent valve, that is, a valve that is no longer able to function effectively.

In tracing the blood flow from the right ventricle to the pulmonary artery, it should be clear that the blood has to go from *down* in the right ventricle to *up* through the pulmonary valve and into the pulmonary artery. The blood is able to make this journey because of the pumping pressure of the heart. The route the blood takes as it exits the right ventricle and journeys up toward the pulmonary valve is known as the right ventricular outflow tract (RVOT). On the other side of the heart, there is also a corresponding left ventricular outflow tract (LVOT) of approximately the same size. Cardiac leads are sometimes fixated in the RVOT (see **Figure 1.6**).

Blood pumped out of the right ventricle crosses the pulmonary valve and enters the pulmonary artery, which splits into two branches: right and left. The right pulmonary artery takes blood to the right lung, while the left pulmonary artery takes blood to the left lung. In this respect, the pulmonary artery is unique in the body in that it is an artery but it carries deoxygenated blood! Blood travels through the lung to the alveoli where it gains oxygen and loses carbon dioxide. Once it is reoxygenated, the blood gathers into the PV (which are also unique being the only veins to carry oxygenated blood). There are four PV in total; the two right-sided PV take oxygenated blood from the right lung, while the two left-sided PV take oxygenated blood from the left lung, and they all bring this reoxygenated blood to the left atrium.

The left atrium is smooth walled, like the right atrium, and although the left atrium is much

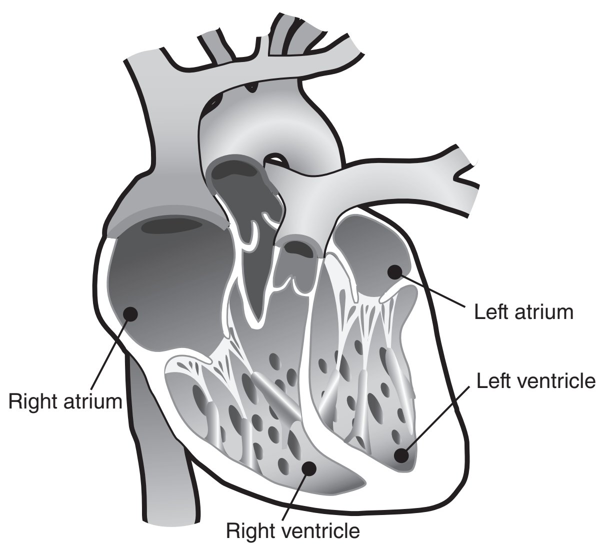


Figure 1.5 The leaflets of the valves are attached by chordae tendineae at one end and papillary muscles on the other, which assure the effective opening and closing of the valves.

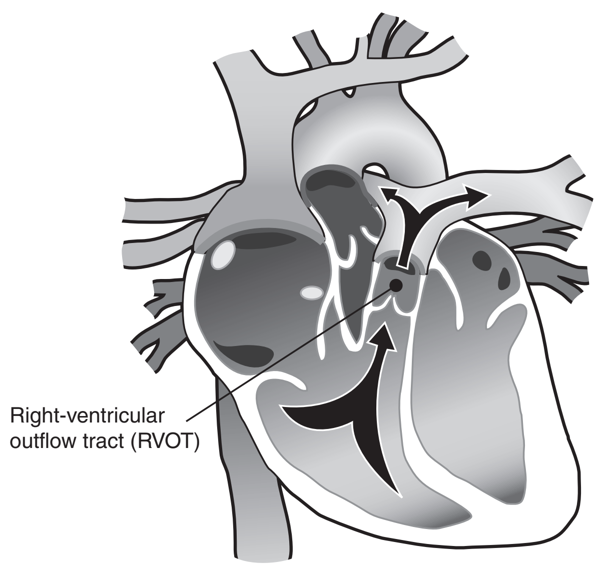


Figure 1.6 There are two outflow tracts in the heart, one associated with the right ventricle and the other the left ventricle. These outflow tracts are roughly the same size. The illustration shows the right ventricular outflow tract (RVOT), a preferred location for right ventricular lead fixation. The left ventricular outflow tract (LVOT) cannot be seen in this illustration, as it is posterior.

smaller than the left ventricle, it is larger than the right atrium. The blood will travel from the left atrium into the left ventricle by way of the mitral valve. The mitral valve gets its name from the miter, a bishop's hat. The mitral valve has two cusps and papillary muscles connected by chordae tendineae. Once blood is in the left ventricle, a contraction will force it toward the aorta by way of the LVOT. In persons with hypertrophic obstructive cardiomyopathy (HOCM), the septum or wall in the heart can become thick and enlarged, effectively narrowing the LVOT. In the healthy heart, the blood flows up the LVOT, across the aortic valve, and into the aorta. From the aorta, blood will be directed upward toward the head, downward toward the legs and feet, and some blood will be redirected back to the coronary arteries of the heart.

The blood flow from the left ventricle to the aorta and back to the coronary arteries is unique in the body in that *most of that flow occurs during diastole rather than systole*. Think of it this way: as blood is pumped by the left ventricle during systole upward and downward, to the brain and the rest of the body, some of that blood flows back during diastole and drains into the coronary arteries. Although it may seem counterintuitive, it is important to remember that coronary artery perfusion occurs primarily during diastole.

Volume, valves, and pressure

While it is tempting to think of the heart as simply a pump with an electrical system, it is more accurate to say that the heart moves blood because of variations in volume and pressure.

The heart has four valves: two are atrioventricular (AV) valves because they connect the atrium to the ventricle and two are semilunar valves, connecting the heart with pulmonary arteries or the aorta. The right AV valve is the tricuspid, while the left AV valve is the mitral valve. The flow or movement of blood is guided and controlled by the heart's muscular action in the form of systole (contraction) or diastole (relaxation).

When blood pours into the right atrium, it distends and expands the right atrium. When this volume of blood creates sufficient pressure, it forces the tricuspid valve open. Think of it as volume creating pressure and pressure opening valves. When the tricuspid valve opens, the blood dumps into the right ventricle. During this period of diastole, blood pours into the right ventricle, creating volume and expanding it. As blood pours in and ventricular diastole nears the end, the atria contract while the AV valves are still open in something nicknamed *atrial kick*. *Atrial systole occurs at the end of ventricular diastole*. Atrial kick forces the maximum amount of blood from the atria into the ventricles. It is estimated that atrial kick delivers 20–30% of cardiac output.

The atrial contribution to ventricular filling (atrial kick) is of enormous clinical significance. Patients with certain atrial arrhythmias, such as atrial fibrillation (AF), lose atrial kick. Even milder forms of atrial tachyarrhythmias may compromise atrial kick. Moreover, patients who do not have AV synchrony (one atrial beat corresponding to one ventricular beat) will lose atrial kick. The loss of atrial kick can reduce cardiac output by 20–30%.

Once the atria have contracted and the ventricles are filled with blood, the AV valves snap closed. The ventricles now start to contract and push open the semilunar valves. For example, as the right ventricle contracts (systole), it opens the PV. (The PV is sometimes called the pulmonic valve; it's the same thing.) The whole process works on volume, pressure, and contraction/relaxation.

Of the four valves in the heart, the tricuspid valve is of most interest to device specialists, because at least one lead will be placed into the right ventricle. This means that pacing and defibrillation leads typically cross the tricuspid valve. These leads may interfere with the proper closing of the tricuspid valve, particularly if the lead is large diameter or several leads are passed over the tricuspid valve. A single lead through the tricuspid valve is likely to cause minimal to no dysfunction. However, it is not unusual to see patients with three or more leads in the right ventricle, and these leads may hamper the tricuspid valve in its closing, leading to tricuspid regurgitation or backflow of blood. Patients with multiple leads (such as children who grow up with pacemakers) may need to have some of them removed to avoid tricuspid regurgitation.

Right ventricular leads are typically fixated at the right ventricular apex or in the RVOT and may be

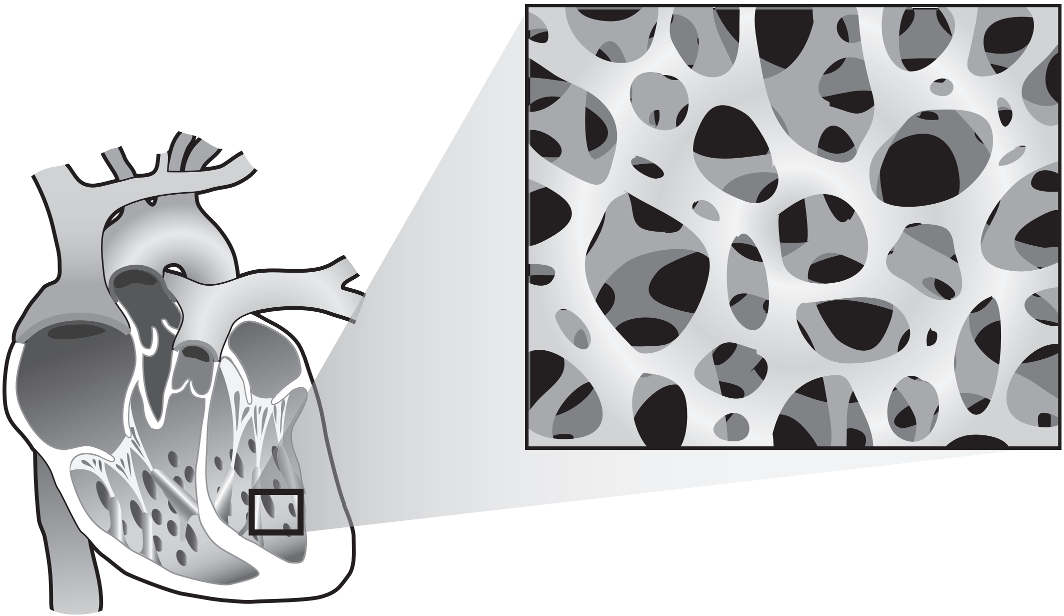


Figure 1.7 Trabeculae form a fibrous network within the ventricles. Passive-fixation ventricular leads are held in place by lodging their tines or fins in the trabeculae.

lodged in the trabeculae. Trabeculae are a fibrous network that could be described as similar to the pores of a sponge (see **Figure 1.7**).

On the left side of the heart, the blood flow pattern is similar. Blood flows into the left atrium, over the open mitral valve, and into the left atrium. At the end of ventricular diastole, as the ventricle is distended and stretched, atrial kick delivers more blood into left ventricle. The volume of blood creates pressure. The mitral valve closes. As the left ventricle contracts, the growing pressure overcomes the resistance on the aortic valve and it opens, allowing blood to flow out into the aorta and beyond.

While any valve can become diseased or dysfunctional, valvular disease more commonly affects the mitral and the aortic valves (left-sided valves) than the right-sided valves (tricuspid and pulmonary). These left valves are more likely to suffer damage or disease because of the high-pressure environment in which they function, exposing them to more potential damage. Other damage can occur when plaque builds up in the coronary arteries and the aorta. The aorta can become diseased, typically in the case of an aortic aneurysm or dissection. Carotid arteries in the neck are also frequently a site for atherosclerotic disease.

The right atrial appendage

The right atrial appendage (RAA) is an area near the right atrium, which is a preferred site for attaching active-fixation atrial leads (see **Figure 1.8**). The RAA serves no obvious purpose and may be sacrificed in certain heart surgeries, such as a coronary artery bypass graft (CABG) procedure. CABG or *bypass* surgery involves stopping the heart and running the blood through a machine to reoxygenate it during the course of the procedure. This is done by attaching a large-diameter hose to the RAA; when surgery concludes and this hose is removed, it can damage the RAA to the point that it is completely or partially surgically removed. In patients who have had a CABG procedure, the RAA may not be available for right atrial lead placement. For such patients, the right atrial lead is often placed against the lateral wall of the right atrium. It is sometimes possible to fixate a right atrial lead in the remnants of the RAA, if a portion of it is preserved.

Arteries and veins

Any discussion about the heart necessarily involves the vasculature, which is why we commonly refer to our circulatory system as the *cardiovascular* system. As most of us remember from anatomy classes, arteries carry blood away from the heart, while veins transport blood back to the heart. (The exceptions are the PV and arteries described earlier.) Arteries carry oxygen-rich blood, while veins carry deoxygenated blood. What is of importance to device clinicians is that arteries are *high-pressure* vessels, while veins are *low-pressure* vessels. Arteries tend to be more muscular in structure and muscular contractions of the arteries help to move blood outward into the body. Veins tend to be less muscular than arteries, but unlike arteries, they contain a system of tiny interior valves. The purpose of these little valves is to maintain a unidirectional flow of blood (see **Figure 1.9**).

Some of the most important veins in the body are the SVC and its counterpart, the IVC. The SVC takes blood from the upper part of the body and delivers it into the right atrium, with the IVC doing the same for blood from the lower part of the body. The coronary veins, networked around the outside of the heart, carry blood from the heart tissue and deliver it back to the right atrium; they are closely linked to the coronary arteries, which carry reoxygenated blood from the left ventricle back to the heart muscle. The CS is the site where

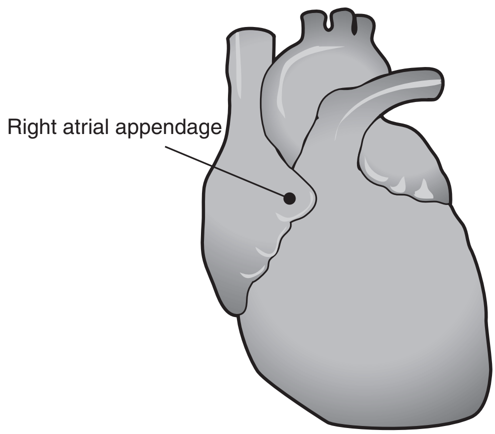


Figure 1.8 The right atrial appendage serves no obvious hemodynamic purpose, but is often the site of fixation of atrial leads.

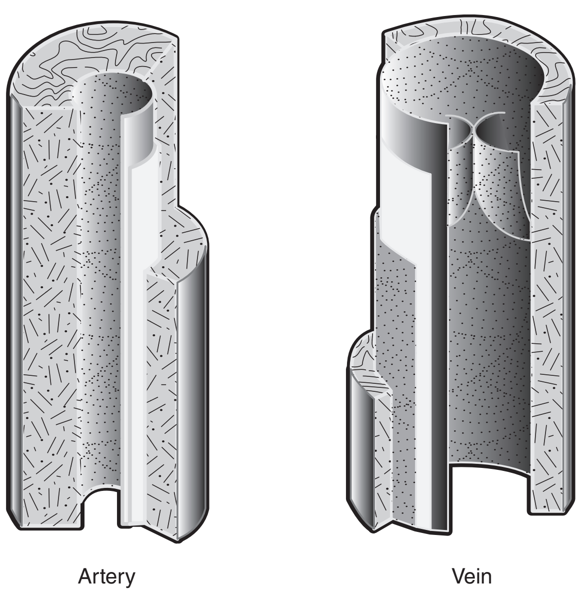


Figure 1.9 Veins and arteries have different purposes, different anatomical structure, and different pressures. Overall, veins are low-pressure systems that move blood by a series of little valves that keep blood flowing in the same direction. Arteries are high-pressure systems and are more *muscular*, so that they force blood forward by squeezing.

the great, middle, and small cardiac veins all drain; the CS takes this blood and delivers it back to the right atrium.

The PV carry reoxygenated blood from the lungs and deliver it to the left atrium so that it can be pumped back out to the body by the left ventricle.

The most important artery in the body is by far the aorta. The aorta is connected to the left ventricle, and it is the first and main conduit that takes reoxygenated blood from the left ventricle and sends it out to the body. As this reoxygenated blood makes its way out into the body, its first two stops are the head (brain) and the heart muscle. Inadequate oxygenated blood to the brain can very quickly provoke symptoms. This is the reason that depressed cardiac output is associated with symptoms like dizziness, light-headedness, feeling woozy, and fatigue. Severe symptoms might include syncope.

The coronary arteries arise from the root of the aorta, just above the cusps of the aortic valve. Coronary arteries receive most blood during diastole, so blood is more or less *pouring back into these vessels*. The coronary artery system is a network—almost a mesh—of middle-sized to very small vessels that cover the exterior surface of the heart (see **Figure 1.10**).

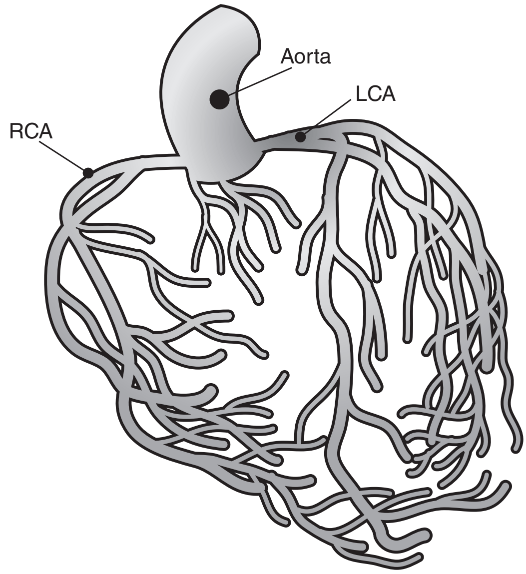


Figure 1.10 The coronary arteries of the heart branch out to surround the entire heart muscle. The two most prominent coronary arteries are the right coronary artery (RCA) and the left coronary artery (LCA).

Coronary arteries get their name from the Latin word for *crown* (such as in our word *coronation*) because this network of vessels sits like a crown atop the heart and encircles it. The heart gets blood *from outside in* as oxygen-rich blood in these coronary arteries is delivered to the exterior of the heart muscle. Coronary arteries are not within the heart; they are epicardial structures. The two main coronary arteries are the right coronary artery (RCA) and the left coronary artery (LCA). The RCA and LCA come off the aorta and are located in the AV groove, an exterior structure below the atria and above the ventricles. The RCA runs from the aorta in the right AV groove, while the LCA comes off the aorta and quickly branches to the left main. The left main is a very short artery (about the size of a thumbnail), which branches quickly into the left anterior descending artery (LAD) and the circumflex artery. The LAD travels down the front of the left side of the heart. The circumflex artery can be found in the left AV groove.

The RCA bifurcates to the posterior descending artery. The right atrium and right ventricle get their supply of oxygen-rich blood from the RCA. Much of the cardiac conduction system is right sided, that is, it commences with the sinoatrial (SA) node in the high right atrium and travels down to the AV node on the right side of the septum. These important electrical structures get their oxygen-rich blood supply from the RCA. The electrical system travels down the ventricles to the inferior wall of the left ventricle (located at the bottom of the heart but belonging to the left ventricle); the inferior wall is also fed oxygen-rich blood by the RCA. An occlusion of the RCA, such as might occur in a myocardial infarction (MI), may result in death of the heart muscle it feeds, which includes the right atrium, the right ventricle, and the inferior wall of the left ventricle, and it might affect the conduction system, including the SA node and the AV node. An inferior wall MI is typically the result of a clogged RCA.

For an MI, the more distal the occlusion (that is, further from the aorta), the less potential damage the heart attack will have. In other words, the worst occlusions are proximal. Whether or not a patient survives an MI comes down to the numbers. The loss of over 40% of the left ventricular muscle mass results in death. However, that 40% is cumulative. For example, a person can survive an MI that costs him 30% of left ventricular muscle mass, but if that heart attack is followed by another that kills 15% of the left ventricular muscle mass, the second (milder) heart attack will prove fatal. This is the reason many people survive a first heart attack but die of a second or third attack, even though their fatal MI may be relatively mild.

The LCA branches quickly to the left main, which branches almost at once to the LAD. The LAD runs on the outside of the heart along the front of the heart along the septum. The left main supplies the left atrium and the majority of the left ventricle, in other words, the major pumping portion of the heart. An occlusion in the left main can be particularly disastrous because it is so far upstream and affects the heart's left ventricular muscle mass. No wonder they call the left main the *widow maker*!

The coronary arteries do not run in straight lines; they twist and turn and sometimes make very sharp bends. People with coronary artery disease (CAD) typically have plaque buildup in the areas where the coronary arteries bend at sharp angles. These are areas where the blood flow creates a lot of turbulence and plaque and other substances can collect and build up. It is typically to find blockage and occlusions at these places.

The LAD supplies the anterior wall of the left ventricle and the septum with oxygen-rich blood. Since part of the heart's conduction system runs through the septum (the right and left bundle branches), an LAD occlusion can damage the heart's ability to conduct electricity properly.

The circumflex artery runs along the AV groove laterally and thus supplies oxygen-rich blood to the lateral wall of the left ventricle along with the left atrium. The circumflex runs along the AV groove to the left, heading toward the back of the heart, where it meets with the RCA, which travels along the AV groove to the left toward the back of the heart. Both the circumflex and the RCA are responsible for providing oxygenated blood to the posterior wall of the ventricle. But which is the more important provider? That depends on *crux* and whether the heart is right or left dominant.

The *crux* refers to an imaginary line drawn exactly down the middle of the ventricular posterior wall without any regard to anatomical landmarks. If the RCA crosses the crux, then the heart is said to be *right dominant*, and the RCA is the greater supplier of oxygenated blood to the ventricular posterior wall. On the other hand, if the circumflex crosses the crux, then the heart is said to be *left dominant*, and the circumflex is the more significant provider. Roughly 60% of the population is right dominant.

While this information about the vasculature is important, it is even more important for clinicians to recognize that there is tremendous interpatient variability in terms of venous anatomy. While we can describe major structures and typical venous formations, anomalies are very common. These anomalies may be minor variations or they can be very pronounced, such as missing veins and arteries. Clinicians who deal with the cardiovascular system must be prepared for large and small differences in vascular anatomy. The cardiovascular system is incredibly resilient and can adapt to some anomalies by building up collateral circulation. For example, a person with a missing or incompetent vessel may over time build up a network of smaller collateral vessels that compensates by doing the same job. It is not unusual to see vessels grow larger or branch out to compensate. Sometimes, when an artery is blocked, collateral circulation will build up and compensate by delivering oxygen-rich blood to the heart muscle.

Every artery in the body has a matching or corresponding vein, usually located in close proximity. This applies to the coronary system as well. Note that there are great differences in coronary venous anatomy among patients, which becomes important when implanting left ventricular leads for CRT devices (see **Figure 1.11**).

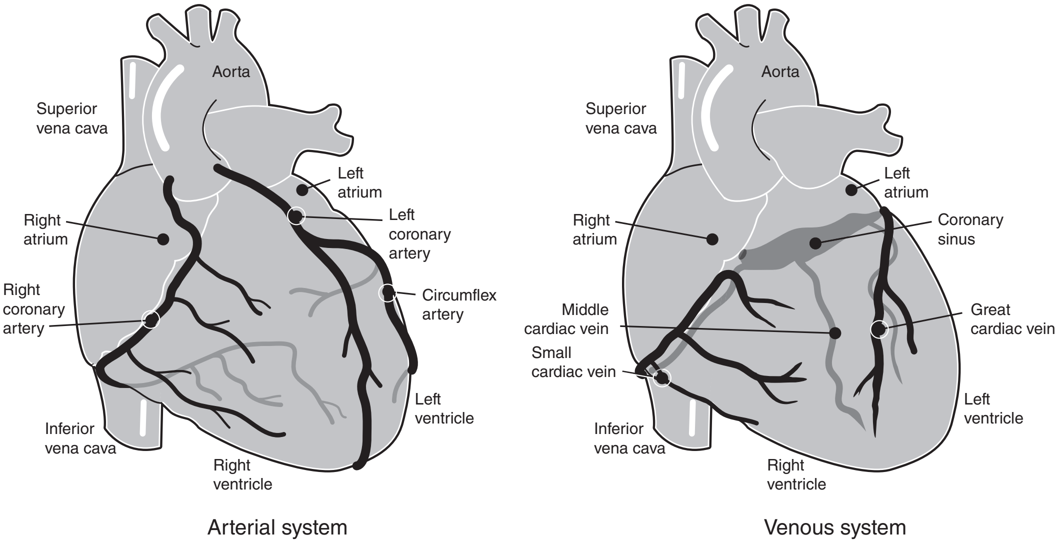


Figure 1.11 The coronary artery system is matched by a coronary venous system.

The nuts and bolts of cardiovascular anatomy and physiology

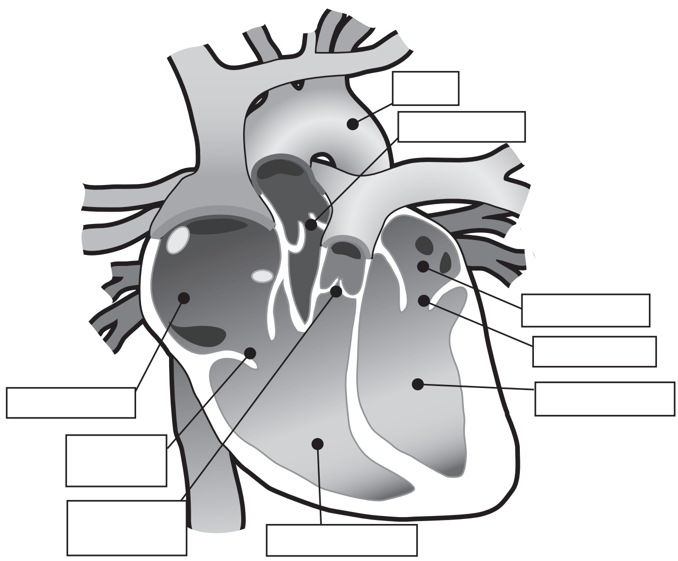
- The heart consists of four chambers, which may be considered the upper chambers (right atrium and left atrium) and lower chambers (right ventricle and left ventricle) or may be thought of as the right heart (right atrium and right ventricle) and left heart (left atrium and left ventricle).
- Deoxygenated blood enters the right atrium, flows to the right ventricle, and is pumped out via the pulmonary valve to the lungs. The blood is reoxygenated in the lungs and then enters the left atrium and flows to the left atrium and out of the aortic valve into the aorta and the rest of the body.
- The heart has two outflow tracts: a right ventricular outflow tract (RVOT) and a left ventricular outflow tract (LVOT).
- The largest chamber of the heart is the left ventricle, making up about 2/3 of the cardiac mass. The left ventricle is muscular and massive because it must pump against approximately 10 times the pressure against which the right ventricle pumps (120 vs. 12 mmHg).
- The two cardiac valves most susceptible to dysfunction and disease are the mitral and aortic valve because they function in a high-pressure environment.
- The chordae tendineae connect the leaflets of the valves to the papillary muscles and look like little parachutes. These help the valves open and close properly.
- In general, arteries transport blood away from the heart, are muscular and contract to help move the blood on its way, and have thicker walls than veins. Veins have thinner, less muscular walls and carry oxygen-depleted blood back to the heart using tiny interior valves to keep the blood flow moving forward. Arteries transport oxygenated blood and can be considered high-pressure systems, while veins transported deoxygenated blood in a low-pressure system.
- Cardiac contraction is systole; cardiac relaxation is diastole. Atrial systole occurs at the very end of ventricular diastole in something nicknamed *atrial kick*. In a healthy individual, about 20–30% of cardiac output comes from atrial kick.
- The heart is a muscle that is fed with oxygenated blood through a network of coronary arteries. Coronary arteries get oxygen-rich blood from the aorta, and they perfuse the heart muscle during diastole as blood drains back.
- Although arteries and veins generally take blood away from or to the heart, respectively,

the pulmonary vessels are the exception. The pulmonary artery transports deoxygenated blood, while the pulmonary veins carry oxygenated blood. This is because of their special location and the fact that their work is taking blood from the right side to the left side of the heart.

- The main coronary arteries are the right coronary artery and the left coronary artery. The left coronary artery branches quickly to a short vessel known as the left main (the *widow maker*) and the circumflex artery.
- A myocardial infarction can kill the heart muscle. The clogged arteries determine the location of the affected muscle. A right coronary artery occlusion will affect the right atrium and ventricle and the inferior wall of the left ventricle, while a left coronary artery occlusion will affect the left atrium and most of the left ventricle. By far the most dangerous occlusion is in the left main because it feeds the majority of the heart muscle with oxygen-rich blood.

Test your knowledge

Fill in these anatomical landmarks of the heart. They include the four chambers, the four valves, and the body's main artery.



Answer the following questions

1 What are the names of the two atrioventricular valves of the heart?
- **A** Atrial and ventricular
- **B** Tricuspid and mitral
- **C** Pulmonary and pulmonic
- **D** Aortic and superior vena cava

2 Which chambers of the heart contain trabeculae?
- **A** Atria
- **B** Ventricles
- **C** Right-sided chambers only
- **D** Left-sided chambers only

3 Why can trabeculae be important to device clinicians?
- **A** They are good places to secure a passive-fixation lead
- **B** They help regulate blood pressure
- **C** They prevent atherosclerosis
- **D** All of the above

4 Which of the following is *not* true about the aorta?
- **A** It is an artery.
- **B** It consists of an ascending portion, a descending portion, and an arch.
- **C** It carries only oxygenated blood.
- **D** It is the largest vein in the body.

5 From which artery does blood enter the right atrium?
- **A** Superior vena cava
- **B** Inferior vena cava
- **C** Coronary sinus
- **D** All of the above

6 What is *atrial* kick?
- **A** Ventricular pressure on the tricuspid valve, forcing it shut
- **B** Electrical impulses originating in the atrium to cause the heart to beat faster
- **C** Atrial systole that forces the most blood possible into the already-full and diastolic ventricles
- **D** A type of arrhythmia

7 Why would a person with chronic AF likely have decreased cardiac output?
- **A** AF is associated with low blood volume.
- **B** AF causes the heart to beat very slowly.
- **C** AF may cause the heart to experience frequent pauses.
- **D** AF reduces or eliminates atrial kick—and atrial kick contributes to cardiac output.

8 Which of the following is often a preferred location for affixing a cardiac pacing lead?
- **A** The right ventricular outflow tract (RVOT)
- **B** The left ventricular outflow tract (LVOT)
- **C** The excised right atrial appendage
- **D** The tricuspid valve

9 What connects the valve leaflets to the papillary muscles?
- **A** Trabeculae
- **B** Arteries
- **C** Chordae tendineae
- **D** Tiny valves

10 Which coronary artery is nicknamed the *widow maker* because an occlusion in this vessel will deprive the majority of the heart's muscle mass of oxygen-rich blood?
- **A** Left main
- **B** Circumflex
- **C** Right coronary artery
- **D** Inferior vena cava