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ANATOMY

for **Cardiac**
Electrophysiologists

A PRACTICAL HANDBOOK

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General Anatomy of the Heart

IN RECENT DECADES, DEVELOPMENTS of catheter interventional techniques for arrhythmias have made it necessary to have a sound understanding of cardiac anatomy primarily to avoid or minimize complications during interventional procedures. This knowledge is also relevant in providing the anatomical background for some of the substrates of certain arrhythmias and to fine-tuning interventional strategies and equipment.

This chapter is an overview of the normally structured heart with particular focus on the spatial relationships of the cardiac chambers and neighboring structures relevant to cardiac interventions rather than to provide detailed anatomy of each cardiac chamber. The chambers, cardiac septum, and conduction system will be reviewed more explicitly in later chapters concerning the approaches to specific arrhythmias. We include in this chapter the coronary veins, interatrial connections, and fat pads because these are not covered elsewhere in the handbook, although they are relevant to interventions for arrhythmias.

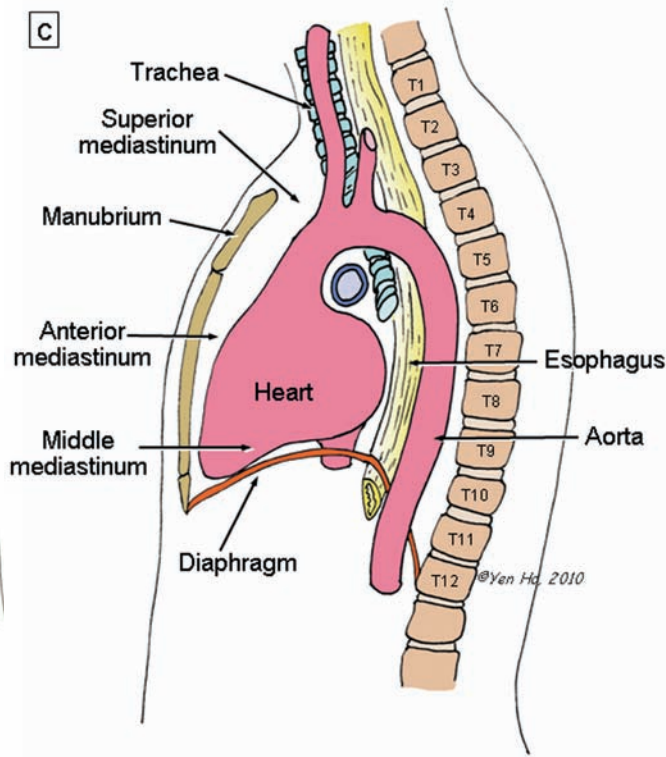
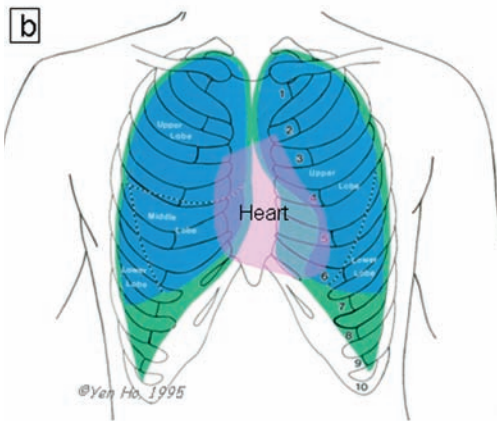
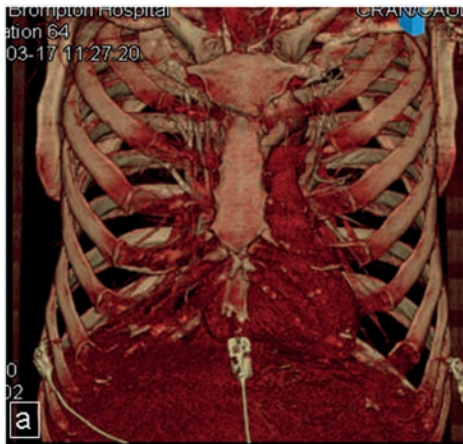


FIGURE 1.1

(a) Anteroposterior (AP) projection of a 3D reconstruction of a computed tomography (CT) scan of the thorax. (b) and (c) Diagrams depicting the location of the heart in AP and left lateral views, respectively.

The Heart and Structures in Its Neighborhood

The heart must be viewed in the context of its location and relationship to surrounding structures. Although the position of the heart varies among people according to their build, in general terms the heart is a mediastinal organ positioned approximately two-thirds to the left and one-third to the right of the midline of the sternum (Figure 1.1). Lying between the lungs, the heart is nearer to the front of the thorax than the back. Its anterior surface, the right ventricle through the fibrous pericardium, lies immediately behind the sternum.

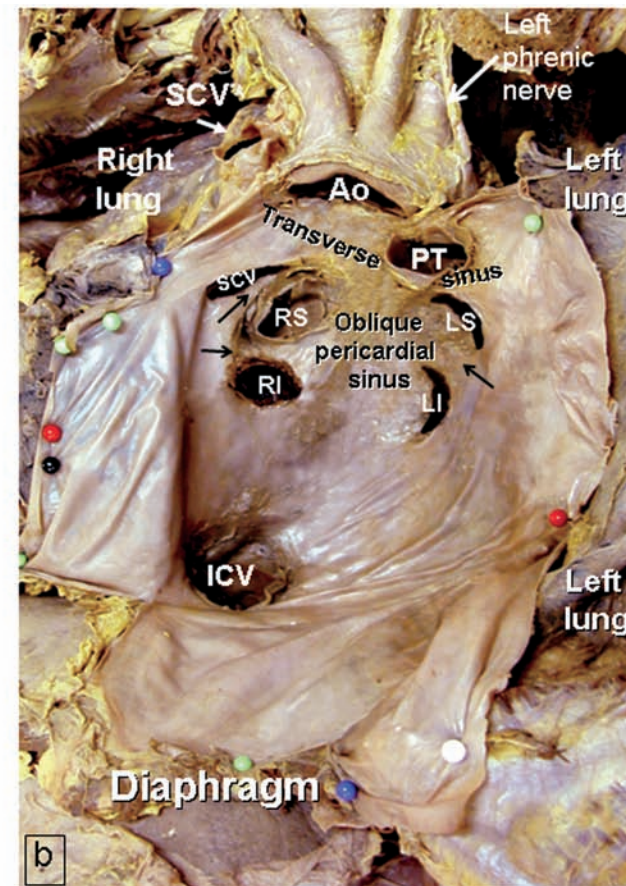
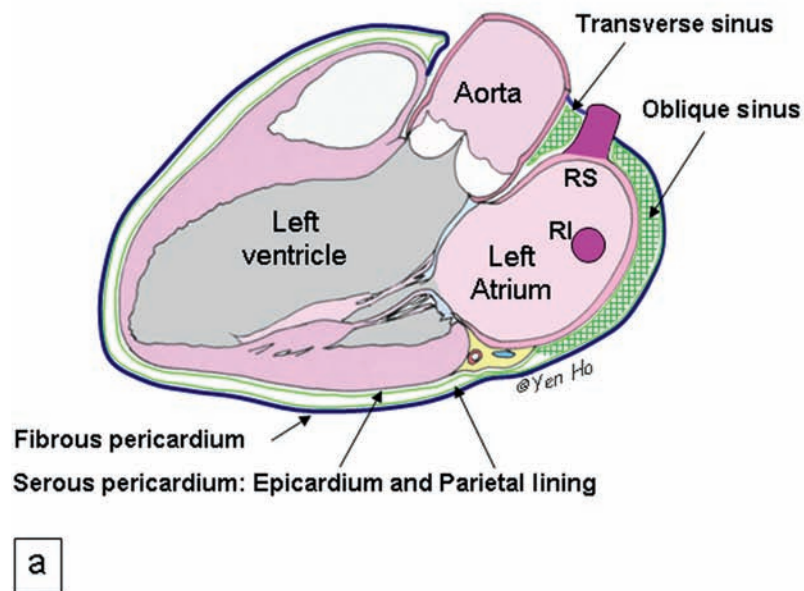


FIGURE 1.2

- (a) The fibrous pericardium encloses the heart and the oblique and transverse sinuses.
 (b) This view from the front after removal of the heart shows the sinuses and recesses between veins (**small arrows**). Ao = aorta; ICV = inferior caval vein; LI, LS, RI, and RS = left inferior, left superior, right inferior, and right superior pulmonary veins, respectively; SCV = superior caval vein. *Photograph courtesy of Professor Damian Sanchez-Quintana, Spain.*

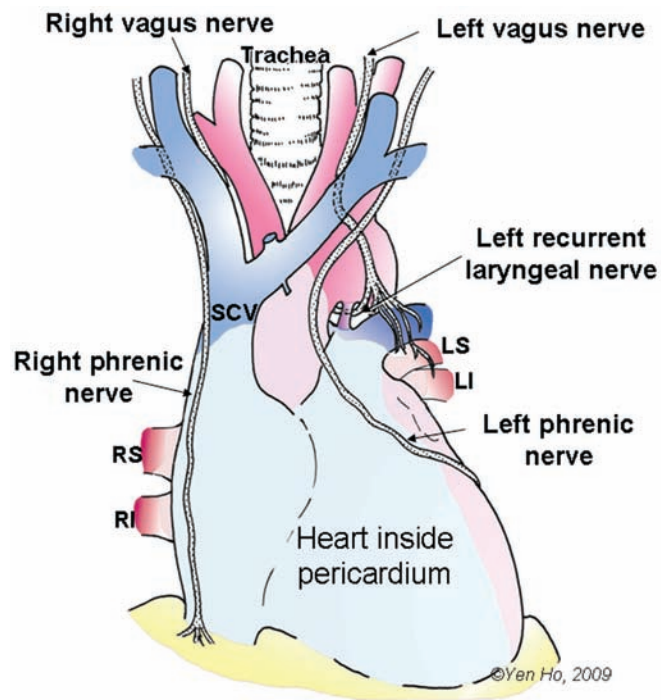


FIGURE 1.3

The phrenic nerves descend bilaterally onto the fibrous pericardium. LI, LS, RI, and RS = left inferior, left superior, right inferior, and right superior pulmonary veins, respectively; SCV = superior caval vein.

The base of the heart lies anterior to the spine from the fifth to eighth thoracic vertebrae. Anteriorly and laterally, the heart is separated from the thoracic wall by the pleura and the thin anterior parts of the lungs. It is enclosed by the fibrous pericardium that separates it from neighboring structures (Figure 1.2).

A fibrous sac, the pericardium, encloses and separates the surface of the heart from adjacent structures. On the outer surface of the pericardial sac descend the right and left phrenic nerves and their accompanying pericardiophrenic vessels, which are branches from the internal mammary vessels (Figure 1.3). There is a variable thickness of fat around each pericardiophrenic neurovascular bundle. The nerves descend into the diaphragm behind the cardiac apex. Along the way, the right phrenic nerve has a close relationship to the superior caval vein and the right upper pulmonary vein, whereas the left phrenic nerve is in the proximity of the left atrial appendage and left ventricle (see Chapter 2 for more details).

The individual course of the phrenic nerves can be located by high-output stimulation capturing the diaphragm (“hiccup”) during an invasive electrophysiology (EP) study. Using colored tags of 3D mapping systems, the 3D relationship, for example with regard to the ostium of the septal (right) pulmonary veins, can be easily depicted (Figure 1.4).

When viewed in situ, the proximity of the esophagus to the posterior and posteroinferior wall of the left atrium is clear (Figure 1.5). Echocardiographers take advantage of this to measure flow and velocities in the left atrial appendage and the pulmonary veins. The esophagus can be located close to the orifices of the right or left pulmonary veins or between the venous orifices. Between the fibrous pericardium and the esophageal wall lie fibrofatty tissues that contain the esophageal arteries, the periesophageal plexus of the vagus nerve, and the lymph nodes.

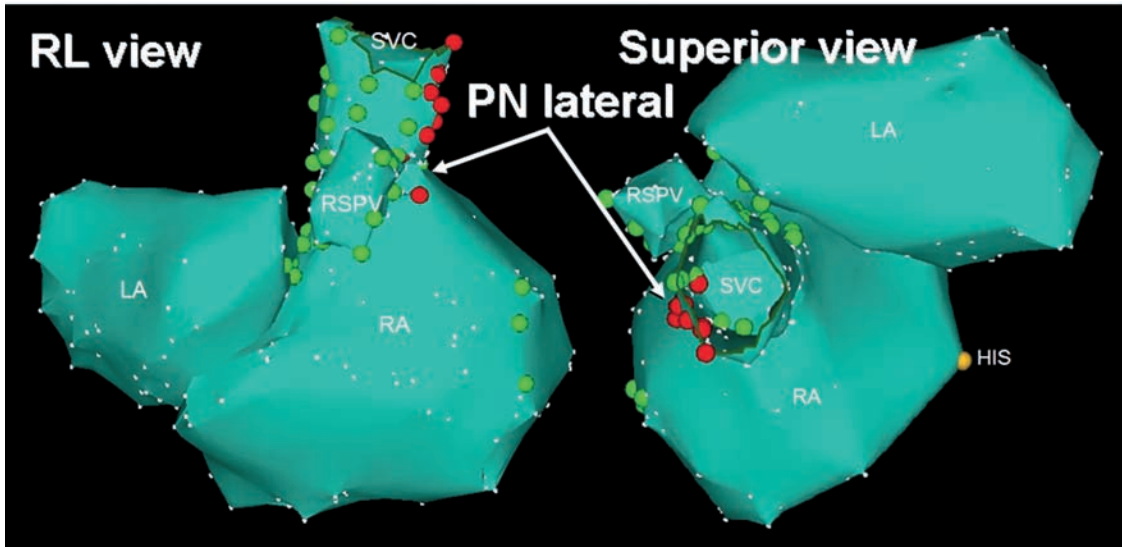


FIGURE 1.4

Position of the phrenic nerve (PN) depicted as **red tags** on a 3D reconstruction of the right atrium (RA) using high-output stimulations. **Green tags** mark sites without PN capture. Note the relationship of the PN to the superior vena cava (SVC) and septal (right) superior pulmonary vein (RSPV), which can be variable. HIS = catheter recording the penetrating bundle (bundle of His); LA = left atrium.

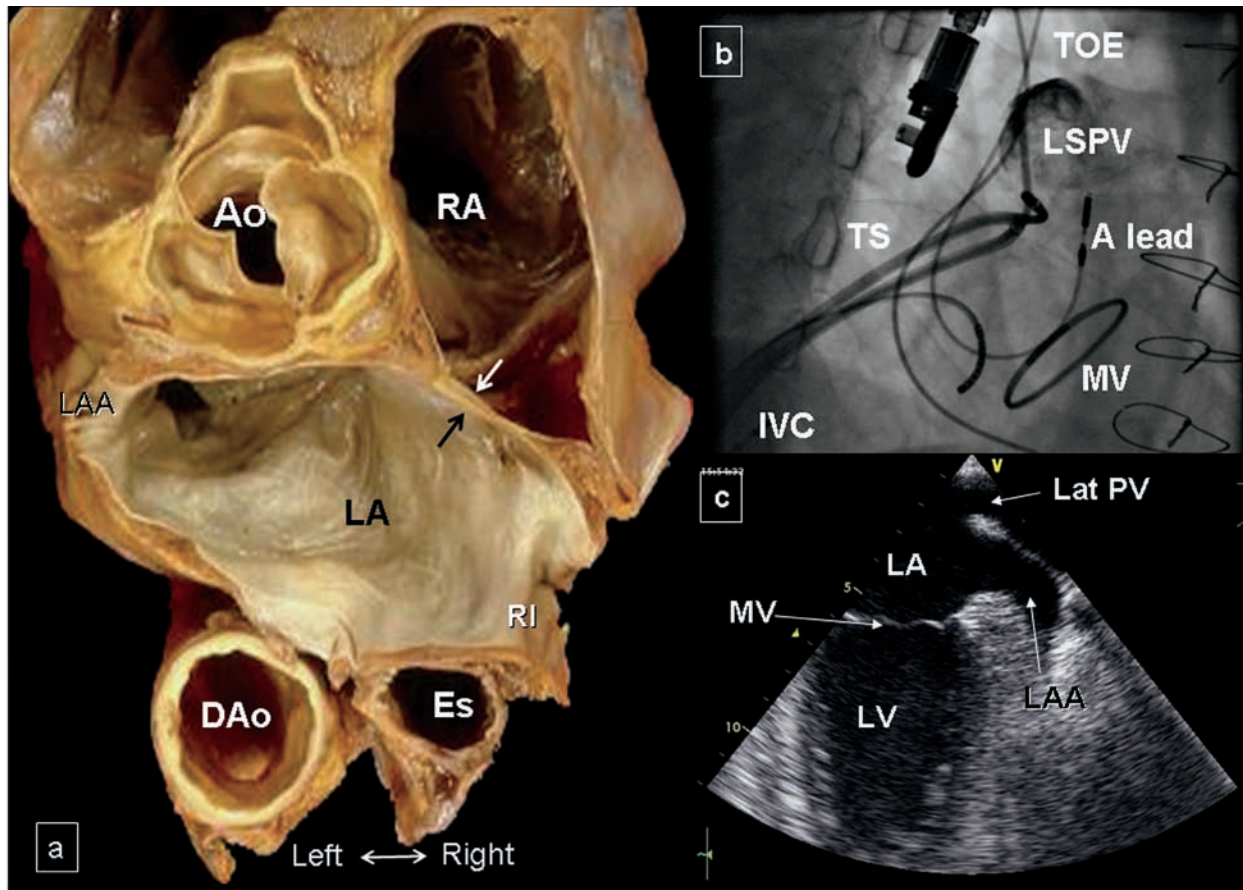


FIGURE 1.5

(a) The transverse cut through a heart specimen shows the relationship of the esophagus (Es) and the descending thoracic aorta (DAo) to the posterior wall of the left atrium (LA). Note the plane of the atrial septum (between arrows) and the central location of

the aortic valve (Ao). (b) Position of the transesophageal echo probe (TOE) in relation to the LA depicted by contrast injection into the left superior pulmonary vein (LSPV) in right anterior oblique (RAO) projection. Note the displaced position of the transeptal sheaths

(TS) in this patient with marked scoliosis, mitral valve (MV) repair, and DDD pacemaker. (c) TOE of MV and left atrial appendage (LAA). IVC = inferior vena cava; Lat PV = lateral pulmonary vein; LV = left ventricle; RA = right atrium; RI = right inferior pulmonary vein.

Understanding the spatial relationship of the esophagus to the left atrium is crucial to reduce the risk of atrioesophageal fistula and gastric hypomotility after ablation for atrial fibrillation (Figures 1.6 and 1.7). The descending aorta usually runs more posteriorly so it is some distance away from the left atrium, but in some patients it may pass close to the orifice of the left inferior pulmonary vein.

The inferior wall of the fibrous pericardial sac is attached to the diaphragmatic pleura, and two-thirds of this wall is to the left of the median plane, corresponding to the location of the heart in the chest. Thus, the part of the diaphragm underneath the heart is mainly related to the left lobe of the liver and the abdominal esophagus, whereas that beneath the cardiac apex overlies the fundus of the stomach. The diaphragm is pierced by the inferior caval vein to the right of the midline of the body, the esophagus to the left of the midline, and the aorta almost at the midline. Accompanying the esophagus through the opening in the diaphragm are the vagal trunks and branches of the left gastric vessels (Figure 1.7).

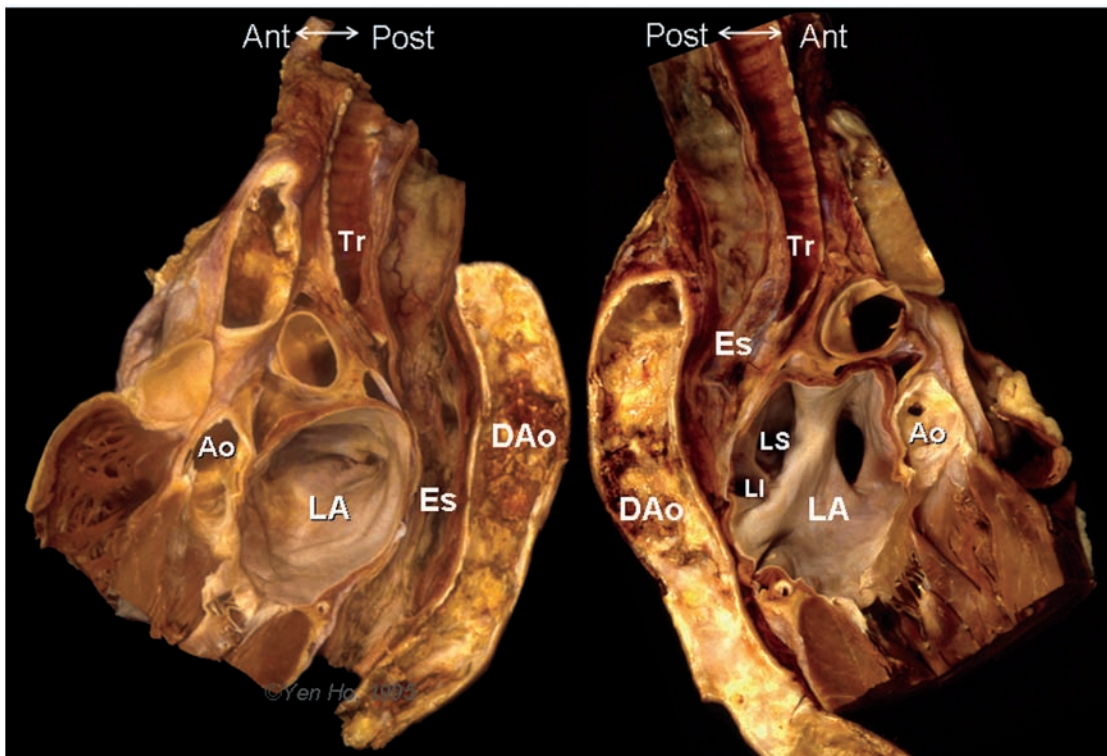
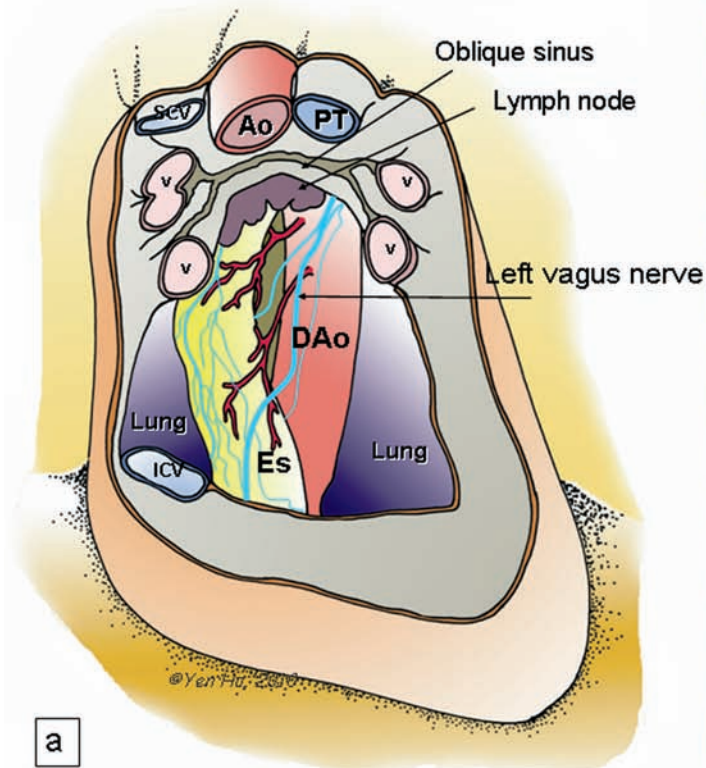


FIGURE 1.6

These two halves of a heart cut longitudinally show the esophagus (Es) curling around the posterior and inferior walls of the left atrium (LA). The *right panel* shows the descending aorta (DAo) adjacent to the left posterior part of the left atrium. Ao = aortic valve; LI and LS = left inferior and left superior pulmonary veins, respectively; Tr = trachea.

Anterior view, heart removed



Posterior view

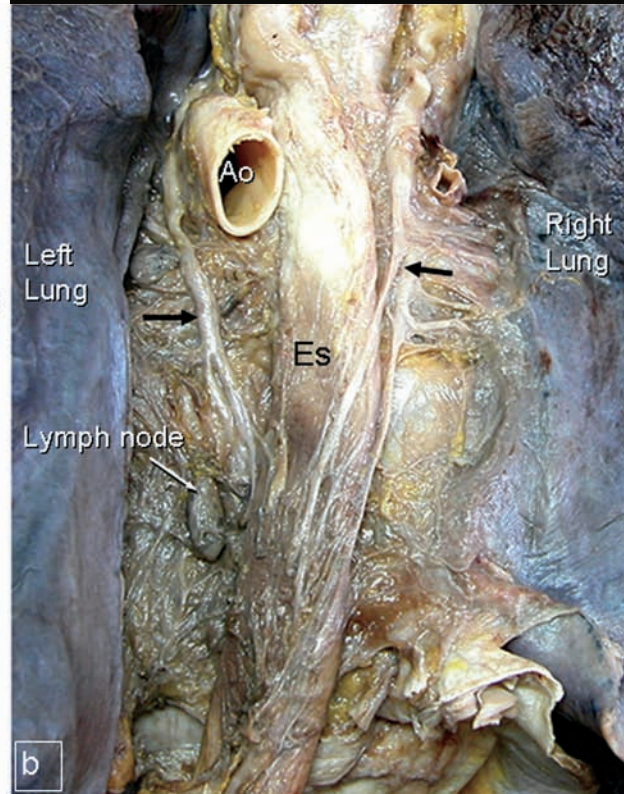


FIGURE 17

(a) This anteroposterior (AP) view of the pericardial sac after removal of the heart and the posterior fibrous pericardium shows the course of the left vagus nerve continuing to the periesophageal plexus at the anterior aspect of the esophagus (Es). Ao = aortic valve; DAo = descending aorta; ICV and SCV = inferior and superior caval veins, respectively; PT = pulmonary trunk. (b) This posteroanterior (PA) view of a cadaver shows the esophagus in situ and its relationship with the vagus nerves (small arrows). Dissection and photograph courtesy of Professor Damian Sanchez-Quintana, Spain.

Relationships of the Cardiac Chambers, Valves, and Septum

Viewing the heart from the front after removal of the fibrous pericardium, it is apparent that the cardiac chambers commonly dubbed the right heart chambers are situated anteriorly relative to the left heart chambers. The frontal silhouette of the heart is nearly trapezoidal, with the upper border being much shorter than the lower. A line joining the upper left and lower right borders of the trapezoid marks the base of the ventricular mass with the silhouettes of the four cardiac valves in the order, from upper left downward, of pulmonary, aortic, mitral, and tricuspid (Figure 1.8). Indeed, the key to understanding the anatomy of the normally structured heart is to appreciate the central location of the aortic valve and hence its close relationship to all four chambers of the heart. The pulmonary valve is the most superiorly sited of the four cardiac valves, and it lies almost horizontally behind the second and third costal cartilages. The orifice of the aortic valve is tilted inferiorly at an angle posterior and to the right of the pulmonary valve. The orifice of the tricuspid valve is separated from that of the pulmonary valve, whereas the orifices

of the aortic and mitral valves are adjacent to each other. The orifices of the tricuspid and mitral valves are offset such that, at their septal insertions, the tricuspid annulus is nearer to the cardiac apex than the annulus of the mitral valve. Thus, the basal portion of the muscular ventricular septum between these two valves has an atrioventricular location being sandwiched between the right atrium and the left ventricle.

The right border of the heart is a more or less vertical line just to the right of the sternum, and it is formed exclusively by the right atrium, with the superior and inferior caval veins joining at its upper and lower margins. The inferior border lying nearly horizontally on the diaphragm is marked by the right ventricle. The left border is made up of the left ventricle, and as it merges with the upper border, the silhouette is formed by the pulmonary trunk. The upper border of the silhouette is made by the arterial trunks with the pulmonary trunk passing to the left of the aorta. Because the left atrium is the most posteriorly situated cardiac chamber, it is barely visible on the frontal silhouette. Only its appendage curling around the edge of the pulmonary trunk forms part of the left heart border.

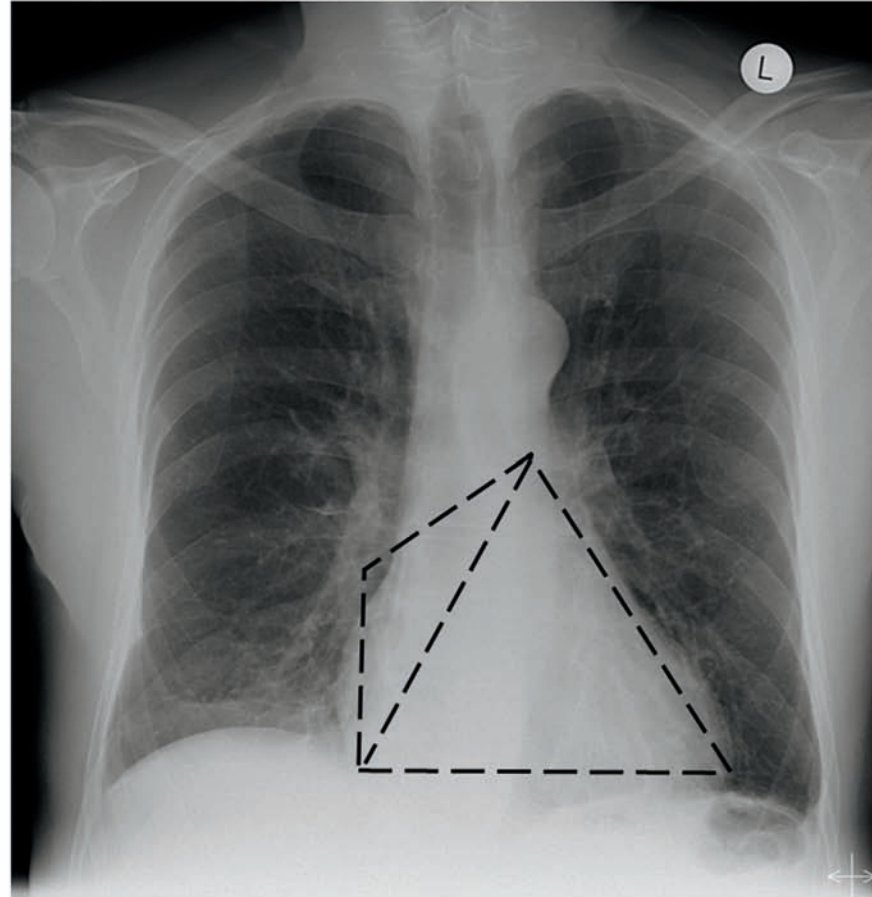
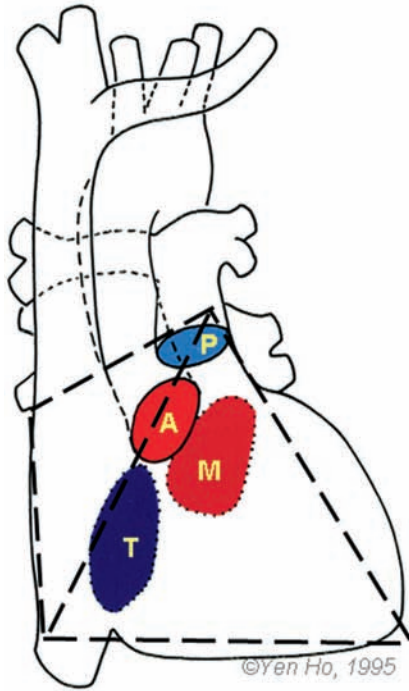


FIGURE 1.8

(a) The diagram shows the location and planes of the four cardiac valves as seen in anteroposterior (AP) projection. The trapezoidal shape of the heart is superimposed. (b) Chest X-ray in AP projection. A, M, P, and T = aortic, mitral, pulmonary, and tricuspid valves, respectively.

Both the right and left atrial chambers are to the right of their respective ventricles. Viewed from the front, the right atrium is right and anterior, whereas the left atrium is situated to the left and mainly posteriorly (Figure 1.9). Consequently, the plane of the atrial septum lies at an angle to the sagittal plane of the body. The front of the left atrium and the medial wall of the right atrium lie just behind the aortic root separated only by the transverse pericardial sinus (see Figure 1.5). The posterior wall of the left atrium is just in front of the tracheal bifurcation and the esophagus with the fibrous pericardium separating the heart from these structures. The bifurcating right and left pulmonary arteries are related to the anterosuperior part of the left atrium. From the atrial chambers, the ventricles project anteriorly and leftward with the tip of the left ventricle forming the cardiac apex. The atrioventricular junctions are marked by the atrioventricular grooves that are filled with fibrofatty tissue and contain the major coronary arteries (Figure 1.10). Positioned just behind the sternum, the right ventricular chamber lies anterior to the left ventricular chamber. Traced from the inferior cardiac border, the right ventricular cavity can be seen to curve and pass superiorly over the left ventricular cavity. This is reflected in the curvature of the ventricular septum. This arrangement results in the right ventricular outflow tract overlapping and crossing the outflow tract from

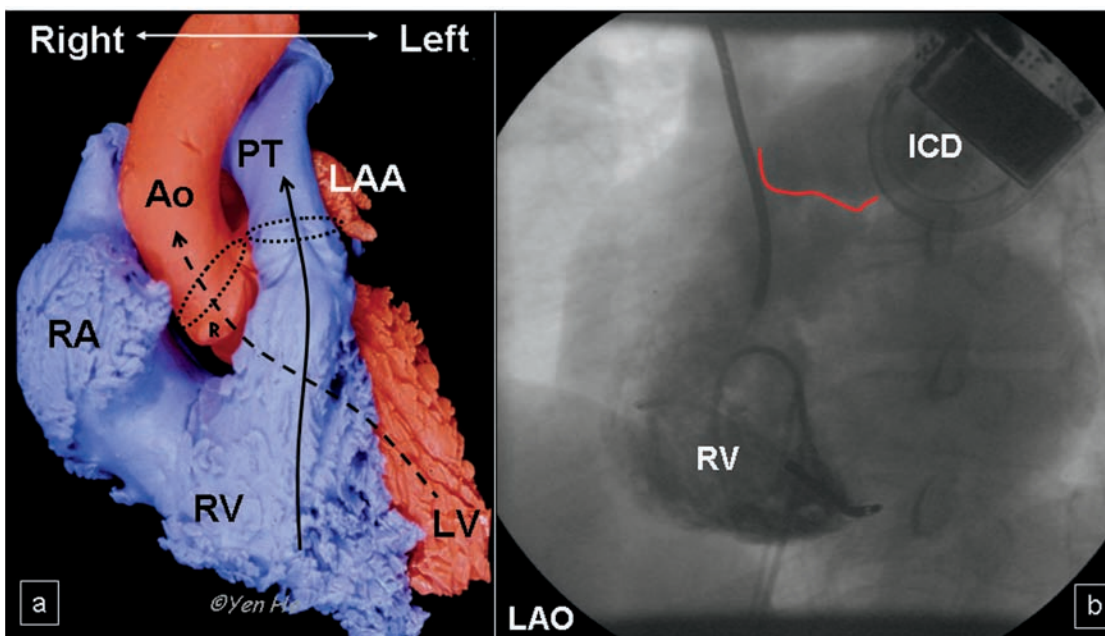


FIGURE 1.9

(a) The different levels and angulations of the planes of the aortic (Ao) and pulmonary valves (PT, or pulmonary trunk) are shown as **dotted ovals** on the endocast, which is displayed at an approximately anteroposterior (AP) view. The right ventricular (RV) outflow tract (**solid arrow**) crosses anteriorly and superiorly relative to the left ventricular (LV) outflow tract (**broken line**). The aortic root is in the center of the heart. LAA = left atrial appendage; R = origin of right coronary artery; RA = right atrium. (b) An RV angiogram in left anterior oblique (LAO) projection in a patient with an implantable cardioverter-defibrillator (ICD). The **red line** marks the pulmonary valve.

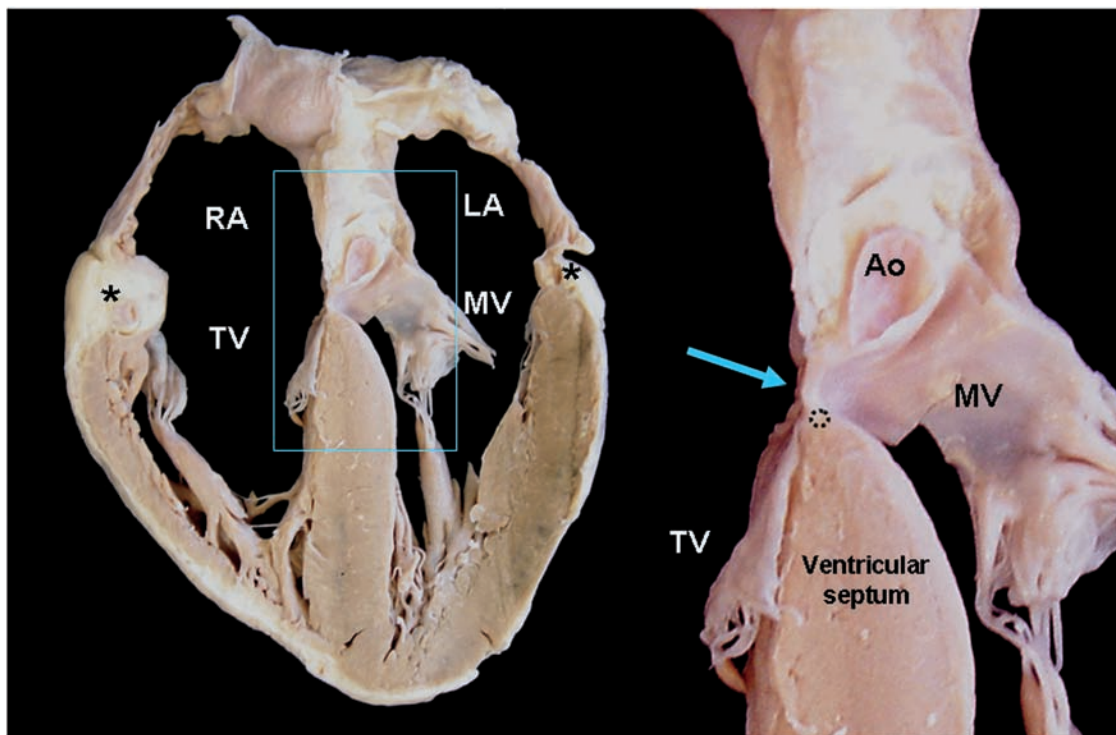


FIGURE 1.10

This section through the four cardiac chambers includes the aortic root. Atrial myocardium is separated from ventricular myocardium by the tissues of the atrioventricular groove (**asterisks**). The enlargement shows the membranous septum (**arrow**) lying between the aortic valve (**Ao**) and the crest of the muscular ventricular septum. The **circle** represents the location of the atrioventricular conduction bundle. **LA** and **RA** = left and right atrium, respectively; **MV** and **TV** = mitral and tricuspid valve, respectively.

the left ventricle when the heart is viewed from the front, an important feature to note when ablating in the ventricular outlets (see Figure 1.9). Detailed description of the outflow tracts follows in Chapters 9 and 10. The pulmonary trunk passes cephalad and to the left of the ascending aorta before branching into the right and left pulmonary arteries. The right pulmonary artery courses rightward over the anterosuperior wall of the left atrium to pass behind the ascending aorta and inferior to the aortic arch.

Although the cardiac septum is mainly muscular, it has a small part that is thin and composed of fibrous tissue. This is the membranous septum of the heart (see Figure 1.10). On the right septal aspect, it is crossed by the hinge line (annulus) of the tricuspid valve, which divides it into atrioventricular and interventricular components. The membranous septum adjoins the right fibrous trigone to form the central fibrous body of the heart, which marks the apex of the nodal triangle of Koch. The membranous septum is a useful guide to the location of the atrioventricular conduction bundle (see Chapter 5). Because the aortic valve borders on the membranous septum, its commissure between the right coronary and noncoronary (posterior) leaflets can help in locating the membranous septum. On the right side of the septum, the commissure between the septal and anterosuperior leaflets of the tricuspid valve can also be used as a guide.

Interatrial Connections

In addition to the atrial septum, muscular continuity between atria can be found peripheral to the septum frequently as bridges in the subepicardium. The most prominent interatrial bridge is Bachmann's bundle (Figure 1.11). This is a broad muscular band that connects the anterior wall of the right atrium with that of the left atrium. It passes in front of the interatrial groove, bifurcating at its rightward and leftward extremities. The bundle is not insulated by a fibrous sheath. Instead, it blends indiscernibly into the atrial walls. The right superior branch passes toward the area of the sinus node at the superior cavoatrial junction, whereas its right inferior branch blends in with the anteroinferior wall of the right atrium. The leftward part of Bachmann's bundle branches to pass around the neck region of the left atrial appendage. The myocardial strands representing the general longitudinal orientation of the myocytes in Bachmann's bundle, as in the terminal crest, are well aligned. Multiple smaller interatrial bridges are frequently present, giving the potential for macroreentry. Some connect the muscular sleeves of the right pulmonary veins and the superior caval vein to the left atrium. In some hearts, there are broad posterior and inferior bridges joining the left atrium to the intercaval area on the right. These could provide the potential for posterior breakthrough of sinus impulse (Figure 1.12).

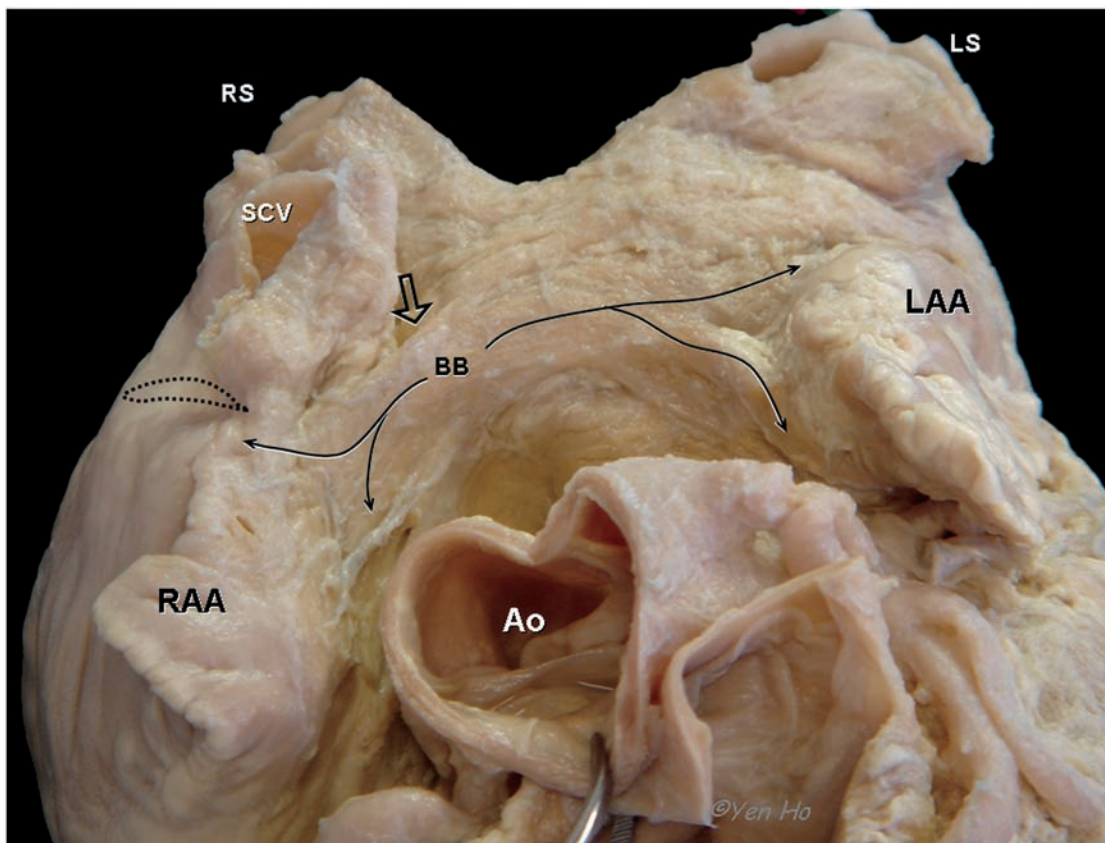


FIGURE 1.11

This anterior view of the heart with the aortic valve (Ao) pulled forward shows the anterior wall of the atria dissected to reveal Bachmann's bundle (BB, thin arrows) crossing the interatrial groove (open arrow). The location of the sinus node is represented by the dotted line. LAA and RAA = left and right atrial appendages, respectively; LS and RS = left and right superior pulmonary veins, respectively; SCV = superior caval vein.

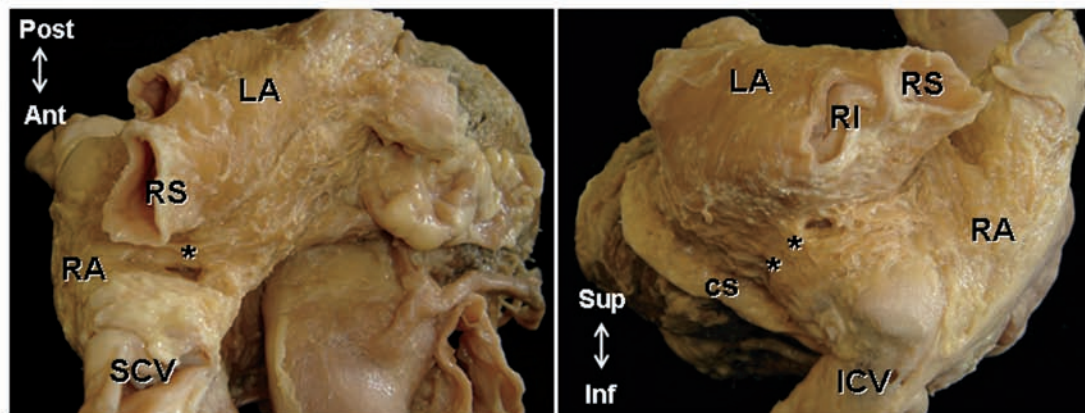
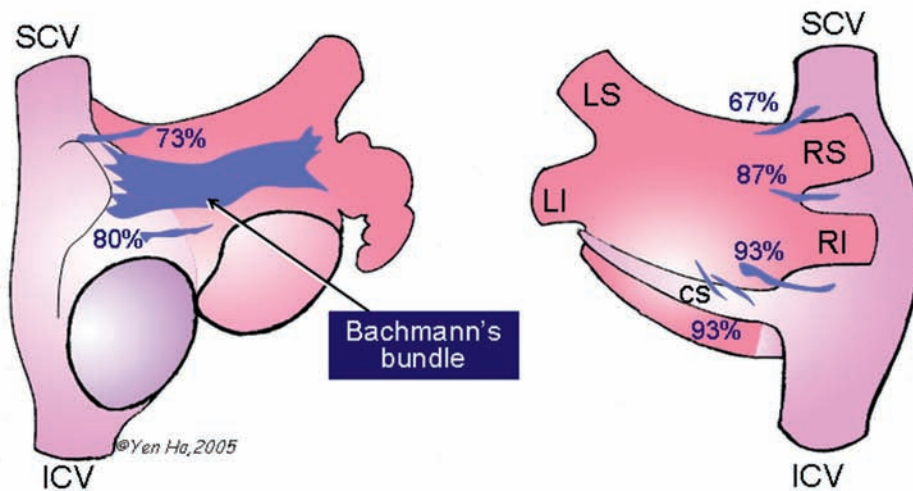


FIGURE 1.12

Bachmann's bundle is not the only interatrial muscular connection. Further connections of varying sizes can exist elsewhere. The diagrams represent anterior and posterior views of the atrial chambers. The percentages refer to the frequency found in a series of 15 heart specimens (Ho SY, Sanchez-Quintana D, Cabrera JA.

J Cardiovasc Electrophysiol. 1999;10:1525-1533). The heart specimens are dissected to show the sub-epicardial musculature of the atria. The *left panel* shows an interatrial muscle bundle (**asterisk**) between the anterior wall of the left atrium (LA) and the intercaval area of the right atrium (RA). The *right panel* shows a

broad interatrial muscle band (**two asterisks**) between the inferior wall of the LA and the RA close to the orifice of the inferior caval vein (ICV). CS = coronary sinus; LI and RI = left and right inferior pulmonary veins, respectively; LS and RS = left and right superior pulmonary veins, respectively; SCV = superior caval vein.

Inferiorly, further muscular bridges from the left atrial wall often overlie and run into the wall of the coronary sinus (Figure 1.13). The coronary sinus itself is invested in a muscular sleeve of varying extent, fading out toward its continuation with the great cardiac vein. There are also fine bridges connecting the remnant of the vein of Marshall to the left atrium.

THE CORONARY VEINS

The venous return from the myocardium either is channeled via small Thebesian veins that open directly into the cardiac chambers or, more significantly, is collected by the greater coronary venous system that drains 85% of the venous flow. The main coronary veins in the greater system are the great, middle, and small cardiac veins (see Figure 1.13). The great and middle veins run alongside the anterior descending and posterior descending coronary arteries, respectively, and drain into the coronary sinus. As the great cardiac vein ascends into the left atrioventricular groove, it passes close to the circumflex artery and under the cover of the left atrial appendage. As it approaches the coronary sinus, the great vein is joined by tributaries from the left ventricular obtuse margin and the inferior wall, as well as veins from the left atrium (see Figure 1.13). The distribution, course, and caliber of the left ventricular veins vary from individual to individual. When utilizing the left ventricular veins for pacing lead implants or for ablating ventricular tachycardia from a source close to the epicardium, it is worth noting that the left phrenic nerve

running in the pericardium may pass in the vicinity (Figure 1.14). Although coronary veins are usually superficial to arteries, crossovers between arteries and veins are not uncommon. When deploying catheters or wires in superficial veins, the operator should be aware that the side of the venous wall farthest from the ventricular wall is thin and unprotected by muscle.

The juncture between the great cardiac vein and the coronary sinus is marked by the entrance of the vein of Marshall, also known as the oblique left atrial vein. When this vein is persistent, it becomes the persistent left superior caval vein opening into the right atrium via the coronary sinus (see Chapter 11). It descends along the epicardium between the left atrial appendage and the left superior pulmonary vein (see Figure 1.13). In the absence of the vein of Marshall or its remnant, the valve of Vieussens is taken as the anatomic landmark for the junction between the coronary sinus and the great cardiac vein. Found in 80% to 90% of hearts, this valve has very flimsy leaflets that can provide some resistance to the catheter (see Figure 1.13). Once past the valve of Vieussens, a sharp bend in the great cardiac vein can cause further obstruction in 20% of cases. Another marker for the junction between vein and coronary sinus is the end of the muscular sleeve around the sinus. In some cases, the sleeve may extend to 1 cm or more over the vein. Muscular bundles and strands from the sleeve can continue onto the left atrial wall and also cover the outer walls of adjacent coronary arteries (see Figure 1.13).

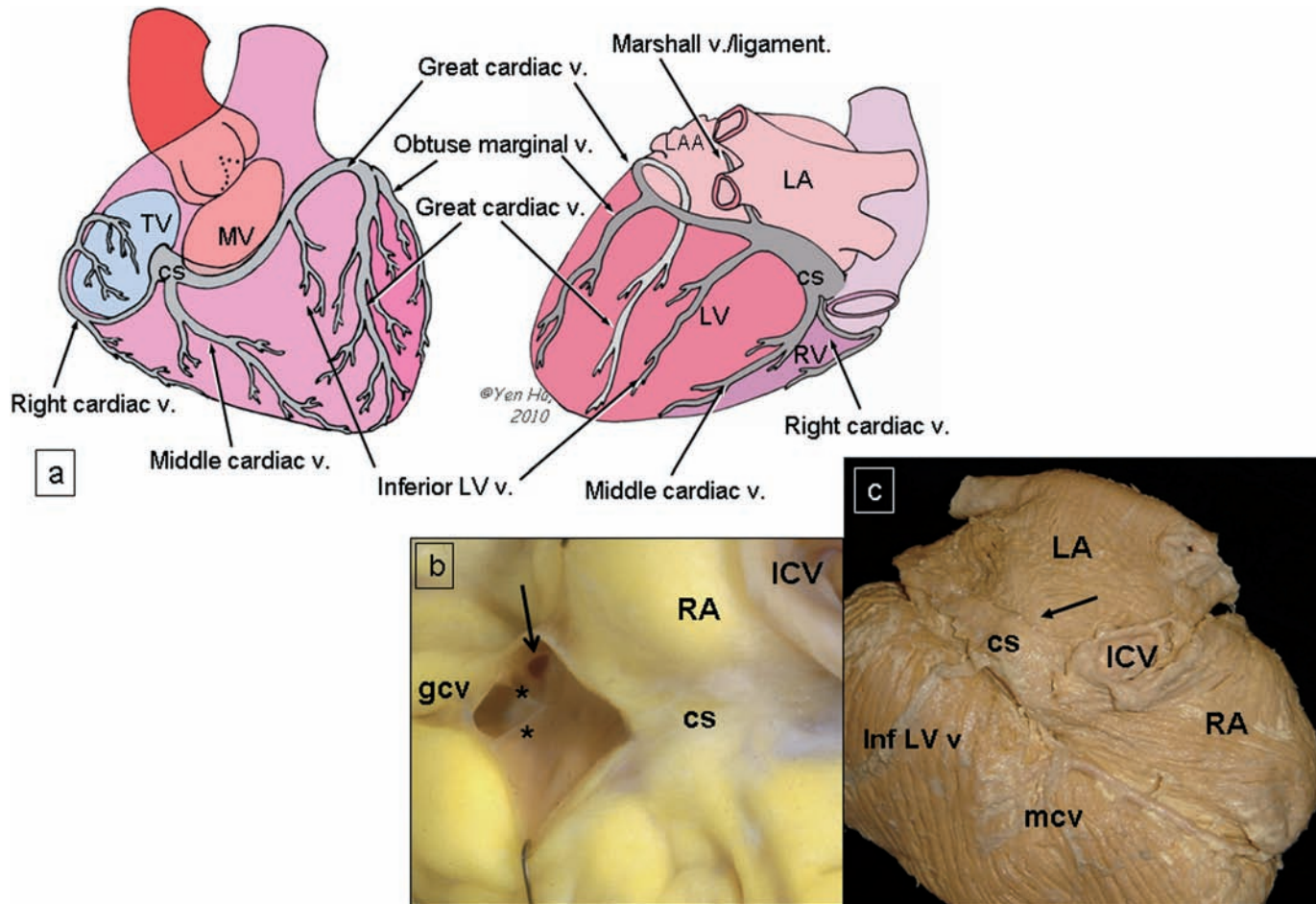


FIGURE 1.13

(a) The coronary venous system in anteroposterior (AP) and tilted posteroinferior (PA) views. (b) This close-up view of a heart specimen approximating to the tilted PA view shows the junction of the coronary sinus (CS) with the great cardiac vein (gcv) guarded

by a flimsy valve of Vieussens (**asterisks**) close to the entrance of the vein of Marshall (**arrow**). (c) This dissection in similar orientation shows the middle cardiac vein (mcv) and inferior left ventricular vein (Inf LV v). The **arrow** indicates a band of muscular

continuity between the CS and the left atrial wall. ICV = inferior caval vein; LA and RA = left and right atrium, respectively; LAA = left atrial appendage; LV and RV = left and right ventricle, respectively; MV and TV = mitral and tricuspid valve, respectively.