Fundamentals

1 Overview of cardiac anatomy relevant to catheter ablation

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Every new diagnostic technique and every new surgical or interventional procedure in the heart leads to a review of the organ's anatomy relevant to that particular technique or procedure. Although the anatomy of the heart has remained unchanged, the perspectives from which clinicians can approach the heart have evolved through the ages. Catheter ablation for cardiac arrhythmias is the relatively "new boy on the block" that has led to a new perception of cardiac anatomy in the normally structured as well as the congenitally malformed heart. In this chapter, I hope to provide an overview of the fundamentals in anatomy of the normally structured heart, with emphasis on features relevant to catheter ablation. Necessarily, much of the information is basic, although crucial to knowing where the ablation catheter is—particularly for beginners who may be literally in the dark in the catheter laboratory.

The heart within the body

The concept of viewing the heart *in situ* in the body is crucial to understanding the relationships between its chambers and structures, as well as the relationships between the heart and other anatomical structures. According to Walmsley [1], descriptions of cardiac anatomy disregard the cardinal principle of using terms in relation to anatomic position. He noted that many textual descriptions and innumerable figures throughout the medical literature view the heart as if it could be held in the hand, with the atria above the ventricles and the left and right hearts lying alongside each other in a sagittal plane—basic and false concepts that have caused untold confusion in the past. Standing the heart on its apex, it is easy to see how the anterior and posterior descending coronary arteries acquired their names. Yet, these same arteries have correct appellations—the superior and inferior interventricular arteries, respectively—in some of the older literature. In his elegant atlas, McAlpine [2] also emphasized the importance of describing the heart in its anatomical location

for appropriate clinical correlations. He termed the orientation of the heart, seen in its living condition, as "attitudinal." Since electrophysiologists "view" the patient with the heart *in situ*, it is essential that the attitudinal approach [3] should be adopted when describing the spatial relationships of chambers and structures. The names of the chambers remain unaltered, although right heart chambers are not strictly to the right nor left heart chambers strictly to the left.

The heart lies in the mediastinum of the thoracic cavity, between the left and right lungs. When viewed from the front, the heart has a trapezoidal silhouette. Two-thirds of its bulk lies to the left of the midline of the chest, with its apex directed to the left and inferiorly. The fibrous pericardium enclosing the heart has as its inner lining a thin membrane, the serous pericardium, which also lines the outer surface of the heart as the epicardium. The pericardial cavity is the space between the parietal lining and the epicardium (Fig. 1.1, upper panel). These layers are continuous at two cuffs, one around the aorta and pulmonary trunk and the other around the veins. Two recesses are found within this pericardial cavity. One, termed the transverse sinus, lies between the posterior aspect of the arterial trunks and the anterior aspect of the atrial chambers. The other, the oblique sinus, is behind the left atrium and limited by the right pulmonary veins and the caval veins to the right side and the left pulmonary veins to the left side (Fig. 1.1). For the ablationist, it is important to note that the right phrenic nerve descends along the lateral aspect of the superior caval vein to pass in front of the hilum of the right lung and then along the fibrous pericardium lateral to the right atrium to reach the diaphragm (Fig. 1.1, lower panel). Its course in front of the hilum can be as little as 1 or 2 mm from the right upper pulmonary vein, although it is frequently 0.5–1 cm or more distant [4]. The left phrenic nerve usually descends along the pericardium over the left atrial appendage, the obtuse cardiac margin and the left obtuse marginal vein and artery, or over the anterior descending artery and great cardiac vein [4].
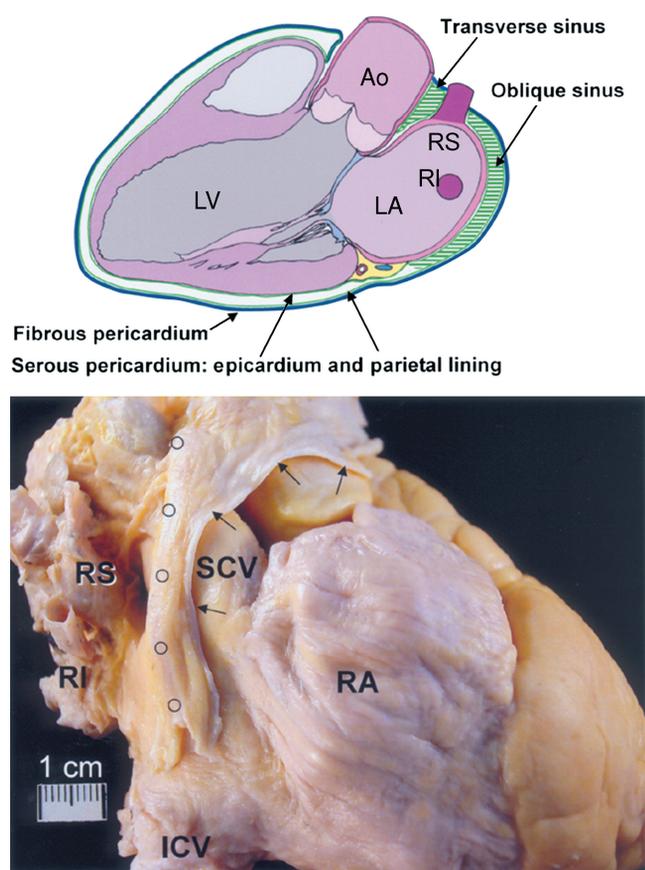
Figure 1.1 The diagram (*top*) shows the components of the pericardium and the pericardial sinuses. The specimen (*bottom*), viewed from the right, shows the cut edge of the pericardium (arrows) and the course of the right phrenic nerve (open circles). Ao, aorta; ICV, inferior caval vein; LA, left atrium; LV, left ventricle; RA, right atrium; RI, inferior right pulmonary vein; RS, superior right pulmonary vein; SCV, superior caval vein.

Relationships of cardiac chambers

The relative positions of the cardiac chambers and great vessels are readily displayed with an endocast (Fig. 1.2). The so-called right heart chambers are anterior and to the right (Fig. 1.2A). From the frontal aspect, the right border of the cardiac silhouette is formed exclusively by the right atrium, with the superior and inferior caval veins joining at its upper and lower margins (Fig. 1.2B). The inferior border of the silhouette is marked by the right ventricle. The left border is made up of the left ventricle, but it merges with the pulmonary trunk near the upper border. Apart from the tip of its appendage curling around the edge of the pulmonary trunk, the left atrium is not visible from the frontal aspect (Fig. 1.2B, C). Being the most posterior of the cardiac chambers, the left atrium lies directly in front of the esophagus (Fig. 1.2D–F). While the esophagus is a useful portal for the echocardiographer monitoring procedures, potential risk of damage to the esophagus and

vagus nerves of the esophageal plexus must be a consideration when ablating from within the left atrium (Fig. 1.2F). A view from the posterior aspect shows the relationships between the great veins (Fig. 1.2D). The left and right pulmonary veins enter the "corners" of the left atrium, and there is considerable variability in the number and orientation of the veins. The right superior pulmonary vein passes behind the right superior caval vein, and the lower pulmonary vein courses behind the intercaval area of the right atrium.

Viewing the endocast from the right aspect shows the location of the right atrium posterior and to the right of the right ventricle (Fig. 1.2A). The plane of the right atrioventricular junction, containing the annular insertion of the tricuspid valve, is orientated nearly vertically. In contrast, the plane of the pulmonary valve is nearly horizontal and located well cephalad, making the pulmonary valve the most superiorly situated of the cardiac valves. On the epicardial side, the root of the aorta is embraced by the musculature separating the inlet and outlet valves of the right ventricle (Fig. 1.2A). Thus, the right ventricle sweeps from posterior to anterior and passes cephalad, such that its outflow tract lies superior to that of the left ventricle (Fig. 1.2A, C, E).

From the left aspect, the left ventricle can be seen projecting forward and leftward with the apex, directed inferiorly (Fig. 1.2C). The finger-like left atrial appendage points toward the pulmonary trunk. Unlike the right atrial appendage, the left appendage has a narrow neck, and its entrance (os) is related to the upper left pulmonary vein. As it passes cephalad, the right ventricular outflow tract wraps over the left ventricular outlet. The latter projects rightward and cephalad into the aortic arch, which in turn is directed leftward. Thus, the left and right ventricular outlets have a spiral spatial relationship. The aortic root is located centrally in the heart, with the aortic valve immediately adjacent to the mitral valve. Like the tricuspid valve, the plane of the annular insertion of the mitral valve, marking the atrioventricular junction, is more nearly vertical than horizontal. The great cardiac vein and its continuation into the coronary sinus pass along the epicardial side of the inferior wall of the left atrium (Fig. 1.2C–F). Although related to the posteroinferior and inferior quadrants of the mitral "annulus," this venous structure does not run directly epicardial to the annulus, but is usually a centimeter or so away (Fig. 1.2F).

The atrial chambers

Both the right and left atrial chambers lie to the right of the ventricular chambers that they open into. Each atrium has three components—the appendage, the venous part, and the vestibule. They share a septum that separates their

Figure 1.2 A–E. The endocast, viewed from different perspectives, shows the spatial relationships between the right (colored blue) and left (colored red) cardiac chambers. **F.** The section through a specimen is in the same orientation as the endocast viewed from the left. It shows the course of the esophagus, running directly behind the left atrium. Note the distance between the hinge of the mitral leaflet (black arrow) and the great cardiac vein/coronary sinus (white arrow). Ao, aorta; E, esophagus; ICV, inferior caval vein; LA, left atrium; LB, left bronchus; LI, left inferior pulmonary vein; LS, left superior pulmonary vein; LV, left ventricle; PT, pulmonary trunk; RA, right atrium; RI, right inferior pulmonary vein; RS, right superior pulmonary vein; RV, right ventricle; SCV, superior caval vein.
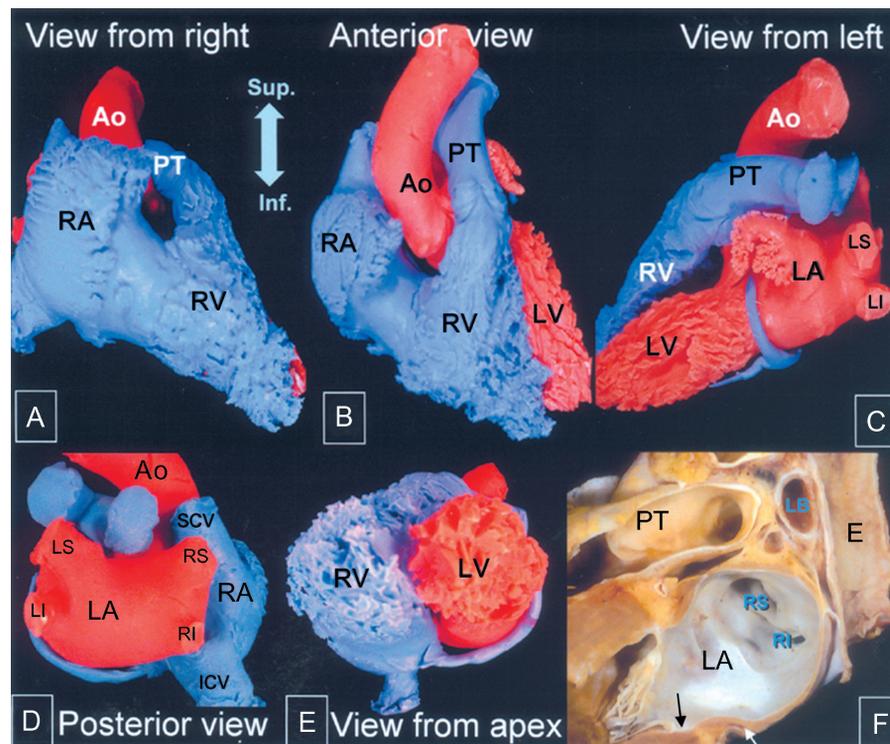
cavities. Each atrium has morphologically distinct features, primarily based on the extent of pectinate muscles on the endocardial surface, the presence or absence of the terminal crest, and the shape of the appendage [5].

The right atrium

Characteristically, the appendage of the right atrium is triangular in shape, with a broad base that meets with the venous component (Fig. 1.3A). In contrast to the smooth endocardial surface of the venous component and the septum, the atrial appendage contains a vast array of interleaving fronds of pectinate muscles that are separated by thin, almost membranous, atrial wall (Fig. 1.3A, B). The pectinate muscles can be traced as offshoots from one side of the terminal crest. On the epicardial aspect, a fat-filled groove corresponding to the terminal crest is a landmark for the location of the sinus node (Fig. 1.3C). The crest is a raised muscular ridge that springs medially from the septal aspect, curves around the anterior quadrant of the entrance of the superior caval vein, and then descends along the posterolateral wall of the atrium toward the entrance of the inferior caval vein (Fig. 1.3D). Its most distal part branches into narrower bundles that blend into the pectinate muscles. The array of pectinate muscles does not reach the hinge line (annular insertion) of the tricuspid valve, but is separated from it by the smooth wall of the vestibule (Fig. 1.3D, E). The area of the atrial wall between the orifice of the inferior caval vein and the hinge line or

annular insertion of the tricuspid valve is dubbed the "flutter isthmus" (or inferior isthmus). Morphologically, it has three zones. The posterior zone, closest to the inferior caval vein, is often fibrous, while the anterior zone is the vestibule (Fig. 1.3E). The middle zone contains the distal branches of the terminal crest and pectinate muscles, with fibrous tissue in between. Frequently, the middle zone is pouch-like, and the depression is known as the sinus of Keith or subeustachian sinus [6,7]. Anatomically, this appears to be the best isthmus to target for ablation, since it is shorter than a more laterally located isthmus and is further from the compact atrioventricular node than the so-called septal isthmus, which is located more medially (Fig. 1.3E).

The triangle of Koch is a landmark on the endocardial aspect of the right atrium for locating the atrioventricular node and penetrating the atrioventricular bundle of His. These important structures lie within the superior apex of the triangle in the attitudinally oriented heart (Fig. 1.3F). The anterior border of the triangle is the hinge line of the septal leaflet, while the tendon of Todaro, buried in the musculature of the eustachian ridge, marks the posterior border [8]. At the superior apex of the triangle, the tendon inserts into the central fibrous body, whereas inferiorly the tendon continues into the free margin of the eustachian valve that guards the entrance of the inferior caval vein [8,9]. The ridge is prominent in some hearts, but flat in others. The orifice of the coronary sinus marks the inferior border of the triangle. The vestibule directly anterior
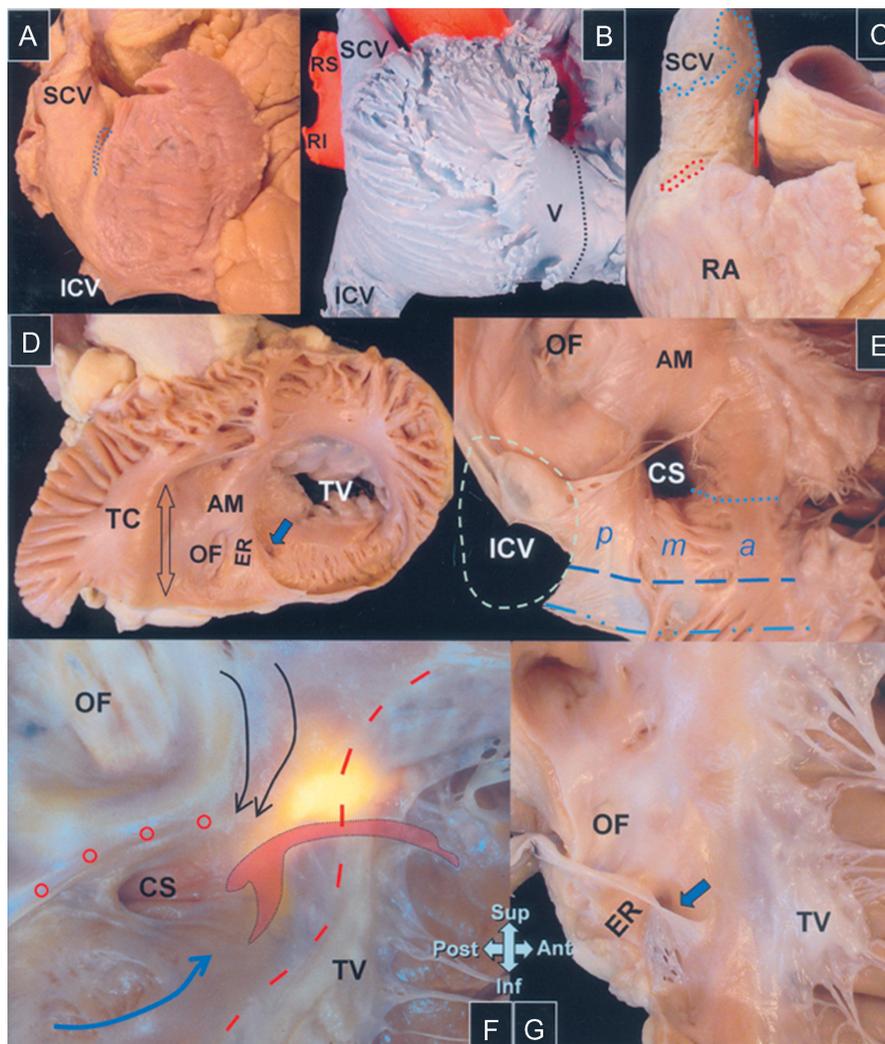
Figure 1.3 **A.** View of the right atrium from the right, with the location of the sinus node (dotted line) marked in the terminal groove. **B.** The endocast shows the impressions made by the pectinate muscles in comparison with the smooth surface of the vestibule, just proximal to the tricuspid valve (dotted line). **C.** The distal margin (blue dotted line) of the myocardial sleeve on the wall of the superior caval vein extends beyond 1 cm (red line) in this heart. The sinus node (red dotted line) is at the venoatrial junction. **D.** The right atrium is displayed to show the terminal crest separating the pectinate muscles from the smooth venous component (open arrows) between the orifices of the caval veins. The intercaval area, aortic mound, eustachian ridge, and vicinity of the coronary sinus orifice (blue arrow), together with the oval fossa, give the erroneous impression of an extensive septal aspect. **E.** The area between the orifice of the inferior caval vein (green broken line) and the hinge of the tricuspid valve is the region of the flutter isthmus. The anterior zone (a) is the vestibule of the tricuspid valve; the middle zone (m) is a fibromuscular area; and the posterior zone (p) is usually fibrous, with scanty muscle fibers. The shortest distance (blue dotted line) is the so-called septal isthmus, while the longest distance (line with blue dashes and dots) is more laterally situated. The inferior isthmus (blue broken line) lies in between. **F.** The triangle of Koch is delineated anteriorly by the hinge line of the septal leaflet of the tricuspid valve (broken line) and posteriorly by the tendon of Todaro (row of circles), glistening in the musculature of the eustachian ridge. Transillumination shows the membranous septum at the apex of the nodal triangle. The atrioventricular node and bundle are superimposed. The putative slow pathway (blue arrow) approaches from inferior, and the fast pathway (double arrows) approaches from anterior and superior. **G.** An extensive valve, with small perforations, guards the orifice of the coronary sinus (arrow). AM, aortic mound; CS, coronary sinus; ER, eustachian ridge; ICV, inferior caval vein; OF, oval fossa; RA, right atrium; RI, right inferior pulmonary vein; RS, right superior pulmonary vein; SCV, superior caval vein; TC, terminal crest; TV, tricuspid valve; V, vestibule.

to the orifice is the area commonly known as the septal isthmus, which is ablated to eliminate the so-called slow pathway in atrioventricular nodal reentrant tachycardia (Fig. 1.3F) [10,11]. The so-called fast pathway, on the other hand, putatively sweeps from the anterior and superior part of the atrium to approach the apex of the triangle of Koch [12,13]. Owing to its proximity, the atrioventricular node is at risk of damage, accounting for the higher incidence of postprocedural heart block in patients undergoing fast-pathway ablation [14].

The orifice of the coronary sinus marking the posterior part of the base of the nodal triangle is usually guarded by a flimsy crescent-shaped valve, the thebesian valve. This valve is attached posteroinferiorly and has variable morphologies, ranging from fibrous bands to a filigree network (Fig. 1.3G) [15]. Hellerstein and Orbison [16] reported large flap-like valves that may present as obstacles to intubation in 25% of hearts.

Posterior and inferior to the coronary sinus is the orifice of the inferior caval vein. This venous opening is guarded by the eustachian valve, which attaches to its anterolateral borders. This valve is usually thin and membrane-like, but is muscular in some hearts. Occasionally, it is a Chiari network that may extend to cover the orifice of the coronary sinus.

The entrance of the superior caval vein into the roof of the right atrium is not guarded by a valve. Instead, the terminal crest passes around its anterior and lateral borders. While the wall of the inferior caval vein is seldom covered by muscle on the outside, the superior cavoatrial junction is usually invested in a muscular sleeve that extends from the atrial wall to various lengths along the superior caval vein (Fig. 1.3C). This is clearly shown in an illustration in the paper by Keith and Flack [17] on their discovery of the sinus node.

On the endocardial surface, the terminal crest demarcates the pectinated portion of the right atrium from the smooth-walled intercaval area, the venous component (Fig. 1.3D). The crest is the thickest part of the parietal wall [18]. The sinus node is located in the terminal crest in the anterolateral part of the junction [19,20]. In approximately 10% of hearts, however, the sinus node is horseshoe-shaped and located in the anterior quadrant [21]. The septal aspect of the right atrium appears to be rather extensive at first sight. Walmsley and Watson [22] emphasized the importance of distinguishing between the "medial wall of the right atrium" and the "interatrial septum." The anterior part of the "medial wall" is termed the aortic mound, on account of its close relationship to the right coronary aortic sinus (Fig. 1.3D, G). Perforation of the atrial wall in this region leads to the transverse pericardial sinus and the aortic root. The true extent of the atrial septum is discussed below.

The left atrium

This chamber has an appendage that is characteristically narrow in humans and shaped like a crooked finger [5]. The appendage has a crenellated appearance externally and can give the appearance of lobes (Fig. 1.4A). The tip of the appendage can be directed anterosuperiorly, superiorly, inferiorly, or even curling over the body of the appendage (Fig. 1.4B) [23]. The appendage overlies the left atrioventricular groove containing the circumflex artery.

In the majority of cases, it also overlies the left main stem or proximal portion of the anterior descending coronary artery and the left wall of the pulmonary trunk. The junction of the appendage with the rest of the atrial chamber —the os of the appendage—is not marked by a muscle band equivalent to the terminal crest. The endocardial surface of the appendage is irregular, with an array or whorls of muscle bundles that occasionally extend beyond the os into the adjacent atrial wall. In between the muscle bundles, the wall of the appendage is thin, almost membranous. The os of the appendage is anterior to the orifice of the left superior pulmonary vein. The isthmus, the so-called left atrial ridge, between the pulmonary vein and the os varies from approximately 0.5 to 2.5 cm in the adult heart (Fig. 1.4C, D).

The remainder of the left atrial wall has a fairly smooth endocardial surface that belies the complexity of its myocardial structure [24–26]. Since there are no pectinate muscles to provide the contrast in topography, the vestibular portion can only be described as that part of the atrial wall immediately proximal to the insertion of the mitral valve. This includes the so-called mitral isthmus, which is the atrial wall between the orifice of the left inferior pulmonary vein and the mitral valve (Fig. 1.4C, D). When ablating the left atrium for atrial fibrillation, many operators now add an ablation line in this isthmus in the posteroinferior wall of the left atrium. It is relevant to note that the circumflex artery and the great cardiac vein, in continuity with the coronary sinus, run along the epicardial side (Fig. 1.4C). Furthermore, small pits and crevices are found occasionally in this otherwise smooth isthmic region. These crevices are in thin areas in the atrial wall, resembling the thin walls that are between pectinate muscles. Since the mitral orifice is kidney-shaped rather than circular, the vestibule is similarly shaped. The gentle inner curvature accommodates the root of the aorta on the epicardial aspect.

The venous component is the largest part of the left atrium. The superior wall of the left atrium is related to the bifurcation of the pulmonary arteries (Fig. 1.2D). The posterior atrial wall lies between the orifices of the pulmonary veins (Fig. 1.2D). While there are usually four veins, each inserting into a corner of the venous component, there is also considerable variation [27,28]. Where there are fewer than four orifices, this is due to two or more veins on the same side coming to a confluence before entering the atrium [29]. The orientation and configuration of the venous insertions also vary, and five types have been described [30]. The venoatrial junctions often are not discrete, especially when the veins widen as they approach the atrium. However, with respect to ablating the atrial wall in order to isolate the pulmonary veins, it is pertinent to note that the distance between left and right veins is wider than that between superior and inferior veins when there is the usual arrangement of four venous orifices.
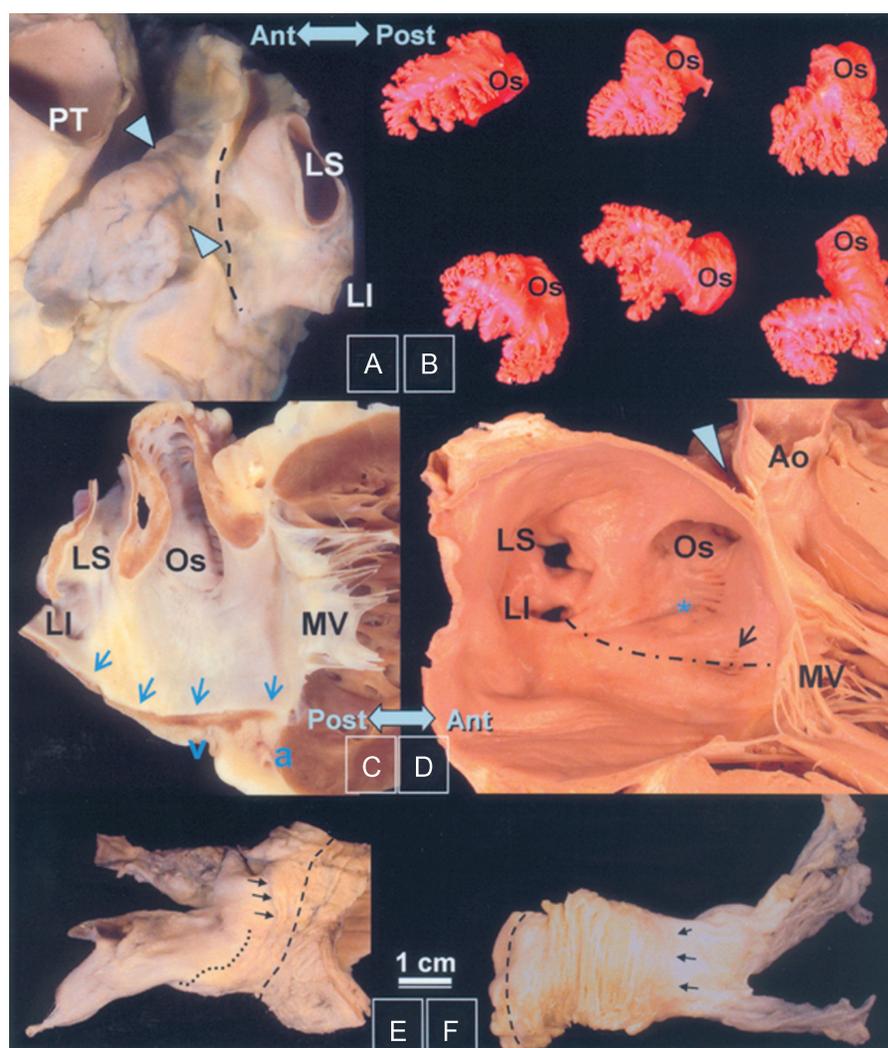
Figure 1.4 **A.** The left atrial appendage, viewed from the left, shows the narrow neck (between the triangles) and the course of the oblique left atrial vein or ligament of Marshall (broken line). **B.** Endocasts of atrial appendages, showing the different shapes and angles relative to the os. **C.** The left atrial isthmus (blue arrows) lies between the orifice of the left inferior pulmonary vein, and the mitral valve is of variable thickness. On the epicardial side run the great cardiac vein (v) and the coronary artery (a). Note in this heart that the os of the appendage is adjacent to the orifice of the left superior pulmonary vein. **D.** This heart, sectioned in the same orientation as the previous one, shows a wide separation between the os and the left superior pulmonary vein. The left atrial isthmus (dashed and dotted line) passes through several small pits (arrow). A thin part of the atrial wall (pale color) is indicated by the asterisk. Note the transverse sinus (triangle) between the aortic root and the anterior left atrial wall. **E, F.** The right and left superior pulmonary veins, respectively, have been dissected from the outer surface to show the myocardial sleeves that extend beyond the venoatrial junction (broken line). The distal margin of the sleeves ends abruptly (small arrows) or fades out gradually (dotted line). Ao, aorta; LI, left inferior pulmonary vein; LS, left superior pulmonary vein; MV, mitral valve; PT, pulmonary trunk.

Moreover, muscular sleeves that continue from the atrial wall to the outer side of the venous wall are longer and occupy more of the circumference in the upper pulmonary veins than the lower veins (Fig. 1.4E, F) [25,28,31,32]. The sleeves are thickest at the venoatrial junctions and become thinner distally, where they terminate in a discrete margin or else taper and fade away (Fig. 1.4E, F). The posterior wall of the left atrium is adjacent to the esophagus (Fig. 1.2F), separated only by the fibrous pericardium and periesophageal tissues of esophageal arteries, fibrofatty tissues, nerve plexus, and lymph nodes. The minimal distance between the endocardial surface and the esophageal wall is approximately 3.5 mm, as measured in cadavers in a recent study [33].

The atrial septum

Partitioning the atrial chambers, the atrial septum is not as extensive as is usually perceived [5]. The true septum,

which can be crossed without exiting the heart or traversing through epicardial tissues, is limited to the flap valve of the oval fossa and the immediate muscular rim that surrounds it on the right atrial aspect (Fig. 1.5A, B). The normal configuration of the septum can be likened to a door drawn tightly against and overlapping the door frame. The frame is an infolding of the right atrial wall, forming the rim (or limbus), while the door is the flap valve (Fig. 1.5C).

While most hearts have a well-defined muscular rim on the right atrial aspect, allowing the operator to "feel" the "jump" from firm muscular rim to tenting of the thin valve with the catheter for safe transseptal puncture, some hearts have little change in topography and the valve is thicker (Fig. 1.5A, B). Using transesophageal echocardiography, Schwinger and colleagues [34] found an abrupt change from thick rim to thin valve in 82% of patients and gradual thinning in 18%. They also found that the valve had a mean thickness of 1.8 ± 0.7 mm on

Figure 1.5 **A.** This view into the right atrium shows a small oval fossa (between the arrows) without distinct margins. The eustachian valve is a Chiari network. **B.** The atrial chambers, sectioned through the oval fossa (open arrow) to show the fold (broken arrows) of the superior rim and the epicardial fat in the inferior rim (*). Note the proximity of the right pulmonary veins to the plane of the septum. **C.** This right atrial view shows a large oval fossa with a well-defined muscular rim. The aortic mound lies anteriorly. The open arrow indicates the site of probe patency in the fossa. **D.** The same heart, sectioned to show the left atrial aspect of the septum, shows the location of the crescentic opening (open arrow), corresponding to the probe patency. Note the thin atrial wall (red arrow) immediately opposite the crescentic opening and the proximity of the aortic root. The blue circles correspond to the muscular rim in the right atrium. AM, aortic mound; Ao, aorta; CS, coronary sinus; I, orifice of the inferior caval vein; ICV, inferior caval vein; MV, mitral valve; RI, right inferior pulmonary vein; RS, right superior pulmonary vein; S, orifice of the superior caval vein; SCV, superior caval vein; TC, terminal crest; TV, tricuspid valve.
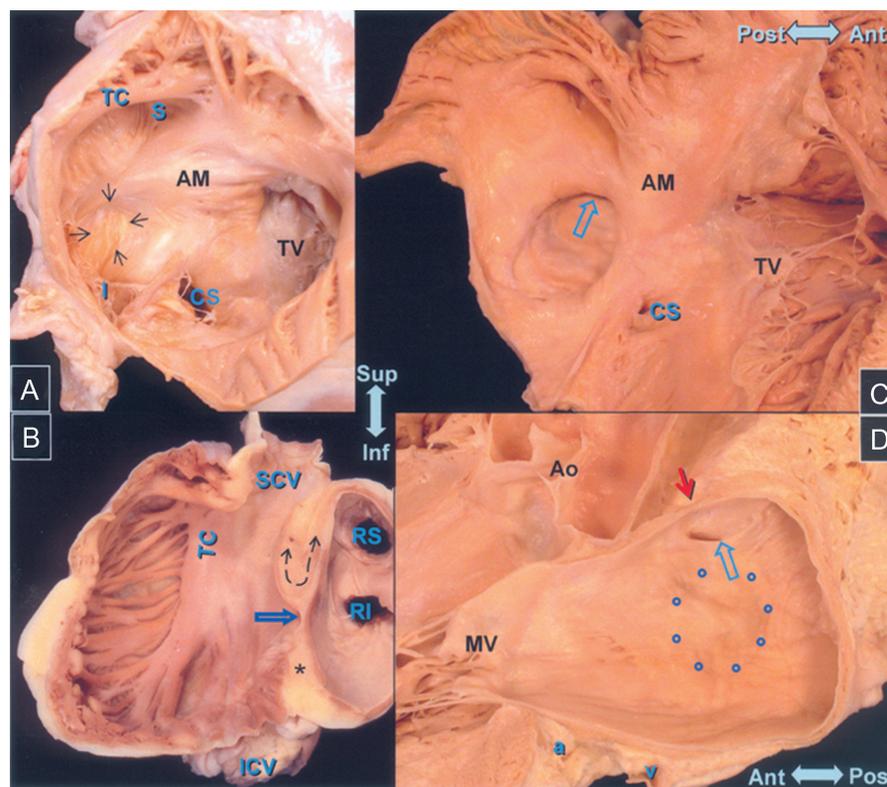
echocardiographic assessment, whereas Shirani *et al.* [35] reported a mean thickness of 1.9 ± 0.99 mm in hearts from postmortems.

Using intracardiac echocardiography to guide transseptal puncture in 19 patients, Hanaoka and colleagues [36] found that the needle entered the middle of the valve in only two cases. They commented that due to angulation of the sheath, the needle drifted cranially to be trapped in the upper edge of the fossa in the majority of patients. The anterior margin of the upper edge is where a probe-patent foramen ovale is sited, a regular finding in 27% of individuals at postmortem (Fig. 1.5B) [37]. This nonadherent margin of the valve has a C-shape (Fig. 1.5D). A catheter lodged in this crevice will have its tip directed toward the anterior wall of the left atrium. This part of the wall, just inferior to Bachmann's bundle, can be very thin (Fig. 1.5D; see below).

The atrioventricular junctions

The atrioventricular junctions are guarded by the tricuspid and mitral valves. The walls of the atria and ventricles are contiguous and without myocardial continuity, except for one point—i.e., at the site of the penetrating bundle of the atrioventricular conduction tissues. Importantly, it is at the atrioventricular junction that anomalous mus-

cular atrioventricular connections are found, which produce the Wolff–Parkinson–White variant of ventricular preexcitation [38]. In describing the location of the accessory bundles, attitudinal terminology is desirable [3]. Furthermore, the true septal component is limited to the area of the central fibrous body. The so-called "anterior septum" is contiguous with part of the supraventricular crest of the right ventricle, while the "posterior septum" is formed by the muscular floor of the coronary sinus overlying the diverging posterior walls of the ventricular mass, and the vestibule of the right atrium overlapping ventricular myocardium. Thus, anatomically, the atrioventricular junction can be described as comprising extensive right and left parietal junctions that meet with a small septal component (Fig. 1.6A, B). The right parietal junction is relatively circular and occupies a near-vertical plane in the heart, marked by the course of the right coronary artery in the atrioventricular groove. On the endocardial surface, the tricuspid vestibule overlies the ventricular wall (Fig. 1.6C). The superior and most medial part of the junction abuts directly on the membranous septum.

The left parietal junction surrounds the orifice of the mitral valve, and part of it is the area of fibrous continuity between mitral and aortic valves (Fig. 1.6A). The potential for accessory atrioventricular connections is mainly limited to the junction supporting the hinge line of the mural leaflet of the mitral valve. This runs from
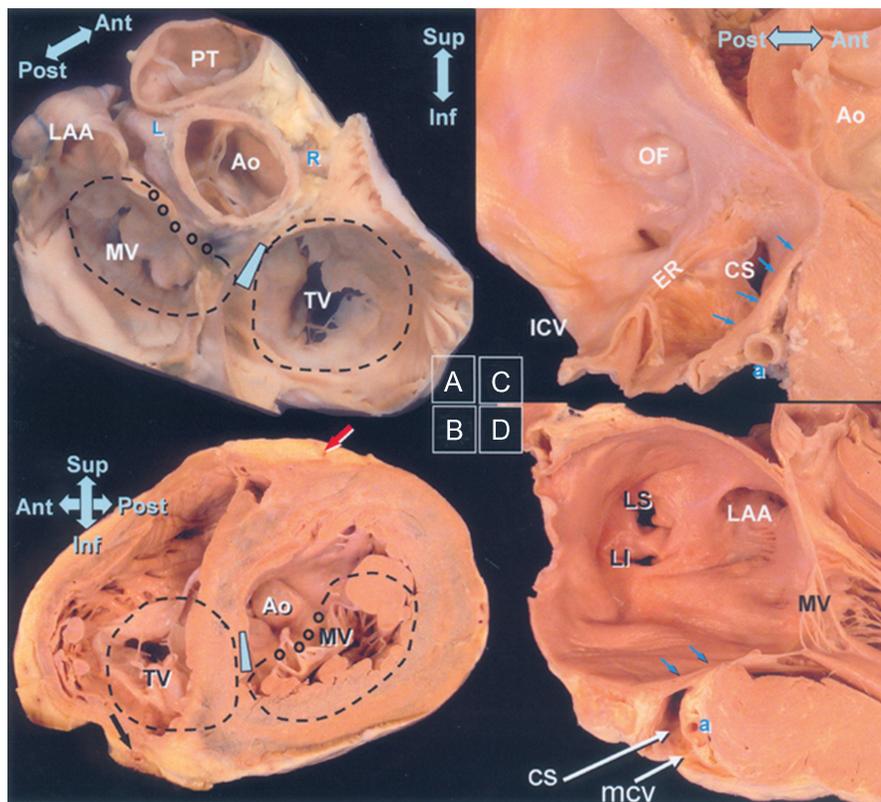
Figure 1.6 A. This view of the base of the heart shows the relative locations of the four cardiac valves. The left (L) and right (R) coronary arteries arise from the facing aortic sinuses. The orifices of the tricuspid and mitral valves are marked by the broken lines. The row of circles marks the span of fibrous continuity between the aortic and mitral valves. The filled shape indicates the membranous and muscular septal areas at the atrioventricular junction. The atrioventricular conduction bundle of His penetrates through this area. **B.** This heart, sectioned through the sagittal plane of the body and displayed in attitudinal fashion, has the right and left atrioventricular junctions superimposed to show that the greater parts of the junction are parietal. In this orientation, the tricuspid junction occupies the anterior, superior, and inferior parts parietally, while the mitral junction occupies the superior, posterior, and inferior parts. The red and black arrows indicate the locations of the "anterior" and "posterior" descending interventricular coronary arteries. **C.** This section through the tricuspid vestibule (blue arrows) shows a gap between its underside and the ventricular wall. This inferior pyramidal space contains fatty tissues of the epicardium and the coronary artery (a). The eustachian ridge is prominent in this heart. **D.** This section through the left atrioventricular junction shows the mitral vestibule (blue arrows), overlying the inferior pyramidal space. Note the relationship of the middle cardiac vein (mcv) entering the coronary sinus (cs) and the coronary artery (a). Ao, aorta; CS, coronary sinus; ER, Eustachian ridge; ICV, inferior caval vein; L, left coronary artery; LAA, left atrial appendage; LI, left inferior pulmonary vein; LS, left superior pulmonary vein; MV, mitral valve; OF, oval fossa; PT, pulmonary trunk; R, right coronary artery; SC, supraventricular crest; TV, tricuspid valve.

posterosuperior to posterior and inferior when the heart is viewed in a left anterior oblique projection (Fig. 1.6B). The inferior area harbors the coronary sinus and its tributary, the great cardiac vein (Fig. 1.6D). The inferior paraseptal region, called the "posterior septum," is the inferior pyramidal space, which contains epicardial fibrofatty tissues together with the artery supplying the atrioventricular node (Fig. 1.6C, D) [39,40].

The ventricles

Like the atrial chambers, each ventricle is best described as having three components: the inlet containing the atrioventricular valve, the outlet leading to the arterial valve, and the apical trabecular component. In the normal adult heart at autopsy, the parietal wall of the right ventricle is 3–5 mm thick, excluding trabeculations, and that of the left ventricle is 12–15 mm thick. Conventionally, these wall measurements are taken at 2 cm proximal to the pulmonary valve and 2 cm distal to the mitral valve. The ventricular septum curves as it is traced from the inlet toward the outlet portions, allowing the right ventricle to "wrap" over the left ventricle (Fig. 1.2E).

The right ventricle

The inlet portion of the right ventricle extends from the hinge line of the tricuspid valve to the papillary muscles that anchor the leaflets, via the tendinous cords, to the

ventricular wall. The leaflets can be distinguished as septal, anterosuperior, and inferior or mural. The septal leaflet, with its cords inserting directly into the ventricular septum, is characteristic of the tricuspid valve. The medial papillary muscle, a small out-budding from the septum, supports the zone of apposition (or commissure) between the septal and anterosuperior leaflets (Fig. 1.7A). A larger papillary muscle, the anterior papillary muscle, supports

the extensive anterosuperior leaflet and its zone of apposition with the inferior leaflet. The zone of apposition between the anterosuperior and inferior leaflets is supported by a group of small papillary muscles, the inferior papillary muscles.

Coarse muscular trabeculations criss-cross the apical portion. One of them, the moderator band, is characteristic of the right ventricle (Fig. 1.7A). This arises from the

Figure 1.7 **A.** The right ventricle, displayed to show its component parts. The supraventricular crest (SC) is clasped between the limbs (broken arrows) of the septomarginal trabeculation (SMT). The moderator band (MB) arises from the SMT, and the anterior papillary muscle (a) inserts into it. The stars mark the course of the atrioventricular conduction bundle in the myocardium behind the tricuspid valve, and the dark circles trace the course of the right bundle branch after it emerges at the base of the medial (m) papillary muscle. **B.** This section shows the relationship between the pulmonary infundibulum (blue arrows) and the left ventricular outlet, with the heart viewed from the front. The infundibulum adjacent to the aortic outlet is not septal (green arrows). **C.** The leaflets of the pulmonary valve have been removed to show the small semilunar areas of myocardium (*) enclosed within the sinuses, as distinct from the paler color of the arterial wall. **D.** This dissection of the atrioventricular junctions, with removal of two sinuses of the aortic valve, shows the relationship between the membranous septum (green dots) and the left ventricular outflow tract (LVOT). The mural leaflet of the mitral valve is extensive (broken arrows). The fibrous continuity between the aortic or anterior leaflet (AL) and the aortic valve lies between the left (l) and right (r) fibrous trigones (triangles). **E.** This view of the left ventricular outflow tract shows the membranous septum transilluminated and the span of valvar fibrous continuity (arrow). The atrioventricular conduction bundle penetrates the right margin of fibrous continuity, and the left bundle branch descends in the subendocardium. **F.** A false tendon (open arrows) crosses from the septum to the medial papillary muscle. AL, anterior leaflet; Ao, aorta; L, left coronary leaflet; LC, left coronary orifice; LV, left ventricle; LVOT, left ventricular outflow tract; MB, moderator band; MV, mitral valve; N, noncoronary leaflet; PT, pulmonary trunk; R, right coronary leaflet; SC, supraventricular crest; Sep, septum; SMT, septomarginal trabeculation; TV, tricuspid valve.
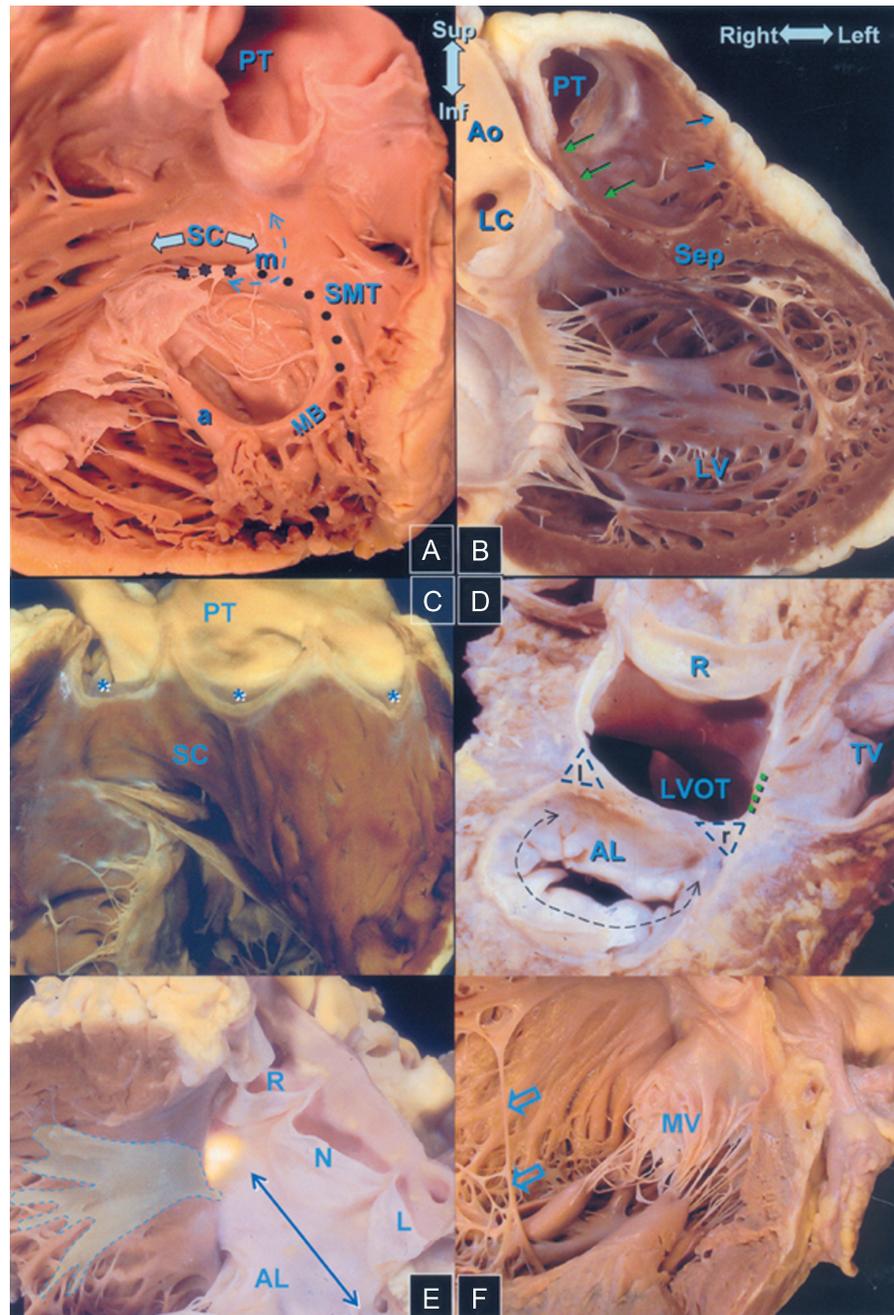
body of the septomarginal trabeculation to span the ventricular cavity and inserts into the parietal wall. The moderator band carries within its musculature a major fascicle of the right bundle branch. The anterior papillary muscle arises from the moderator band. The septomarginal trabeculation itself is a Y-shaped strap of muscular band that is adherent to the septal surface. It clasps between its limbs the infolding of the heart wall forming the ventricular roof, an area also known as the supraventricular crest (Fig. 1.7A). This crest separates the two right heart valves and is an integral part of the outlet, blending into the free-standing subpulmonary muscular infundibulum, which is a tube-like structure supporting the pulmonary valve (Fig. 1.7B). Although ablationists refer to septal and free wall portions of the right ventricular outflow tract, it should be noted that the infundibulum does not have a septal component—a fact well known to cardiac surgeons, who harvest the pulmonary valve for the Ross procedure [41]. The septal component is only in its most proximal part, at the branch point of the septomarginal trabeculation. Furthermore, the right ventricular outlet curves to pass anterior and cephalad to the left ventricular outlet (Fig. 1.2C). Any perforation in the "septal" part is more likely to go outside the heart than into the left ventricle (Fig. 1.7B).

From the anterior surface of the septomarginal trabeculation run further muscular bands called the septoparietal trabeculations, which insert into the parietal wall. The infundibulum immediately proximal to the pulmonary valve has a smoother wall. Since the crescentic hinge lines of the pulmonary leaflets cross the anatomic junction between the ventricular musculature and the arterial wall, they enclose within the sinuses small semilunar areas of myocardium (Fig. 1.7C) [42]. Two of the pulmonary sinuses are adjacent to two aortic sinuses, although the planes of the aortic and pulmonary valves are at an angle to one another (Fig. 1.6A). The adjacent or "facing" aortic sinuses are those giving origin to the coronary arteries. The third pulmonary sinus is unrelated to the aorta.

The left ventricle

The left ventricle has an approximately conical shape and is located posteriorly within the ventricular mass. Viewed from the frontal aspect, its outlet overlaps its inlet. The hinge of the mitral leaflets at the entrance to the inlet has a very limited attachment to septal structures. Compared with that of the tricuspid valve, its septal attachment is further from the apex. The larger portion of the valve is hinged to the parietal atrioventricular junction, and one-third is the span of fibrous continuity with the aortic valve (Fig. 1.7D, E). The latter is attached to the septum at the right fibrous trigone and to the parietal musculature at the left fibrous trigone (Fig. 1.7D). The right trigone, in continuity with the membranous septum, forms the central fibrous body. The two leaflets of the mitral valve are disproportionate in size. The "anterior" leaflet, in continuity with the aortic valve, is deep, whereas the mural (or "posterior") leaflet is shallow (Fig. 1.7D). The latter leaflet frequently has a scalloped appearance. Unlike the tricuspid valve, the tension apparatus of both mitral leaflets inserts exclusively into two groups of papillary muscles.

The apical component of the left ventricle extends out from the level of the origins of the papillary muscles to the ventricular apex. At the apex, the muscular wall tapers to only 1–2 mm thick. The trabeculations are finer than those found in the right ventricle. Occasionally, fine muscular strands or so-called false tendons extend between the septum and the papillary muscles or the parietal wall (Fig. 1.7F) [43,44]. These strands often carry the distal ramifications of the left bundle branch. Writing in *Quain's Anatomy* in 1929, Walmsley [45] commented, "Tawara, however, gave them a new significance by stating that they [false tendons] were anomalies in the distribution of the atrioventricular bundle tissues." In recent years, they have been implicated in idiopathic left ventricular tachycardia [46].

The left ventricular outlet is bordered by the muscular ventricular septum anterosuperiorly and the aortic ("anterior") leaflet of the mitral valve posteroinferiorly. The upper part of the ventricular septum leading to the aortic valve is smooth. The common atrioventricular conduction bundle emerges from the central fibrous body to pass between the membranous septum and the crest of the muscular ventricular septum (Fig. 1.7E). From here, the left bundle branch descends in the subendocardium and usually branches into three main fascicles, which interconnect and further divide into finer and finer branches as the Purkinje network (see below).

In the outlet, the landmark for the site of the atrioventricular conduction bundle is the fibrous body that adjoins the crescentic hinge lines of the right and noncoronary leaflets of the aortic valve (Fig. 1.7). Two leaflets of the aortic valve have muscular support, these being the ones adjacent to, or facing, the pulmonary valve. As discussed above, these two aortic sinuses give rise to the right and left coronary arteries. Like the pulmonary valves, these two sinuses contain small segments of ventricular myocardium within [47]. The third sinus, the noncoronary sinus, does not have muscular support. The musculature in the aortic sinuses may be a source of repetitive monomorphic ventricular tachycardia. Owing to the spatial relationship of the subpulmonary infundibulum and the left ventricular outlet (Fig. 1.7B), the foci may be ablated from within the part of the right ventricular outlet that overlies the adjacent aortic sinuses [48]. Since the main coronary arteries arise from the arterial part of the sinuses, they are not in the immediate field. Ablations

within the sinuses without trauma to the coronary arteries have also been reported [49,50].

The coronary arteries

As described above, the two major coronary arteries arise from the aortic sinuses (the Valsalva sinuses). The course and distribution of these two arteries allow designation of the sinuses as right and left coronary, with the third sinus being noncoronary (Fig. 1.6A). Only the right coronary sinus is situated anteriorly [51]. The arterial orifices are usually located eccentrically in the sinuses, close to the sinotubular junction [52]. Origin just above the junction is not unusual. Having emerged from the right coronary aortic sinus, the right coronary artery is directly related to the supraventricular crest, the muscular structure forming the roof of the right ventricle. In this region, it gives rise to a prominent infundibular branch and, in 55–60% of individuals, also a branch that supplies the sinus node [19,53]. Passing within the fatty tissues of the right atrioventricular groove, the right coronary artery gives off the acute marginal branch before turning posteriorly to the cardiac crux to give rise to the posterior descending coronary artery, which runs in the inferior interventricular groove. The right coronary can also be traced into the left atrioventricular groove to supply the inferior wall of the left ventricle. This coronary arrangement, known as right coronary arterial dominance, is found in 90% of individuals. In this arrangement, the right coronary also gives origin to the artery supplying the atrioventricular node in the majority of cases, but variations in origins have been described [39,40].

The left coronary artery, having emerged from its aortic sinus, enters the space between the left atrial appendage and the pulmonary trunk. Within 1 cm of its origin in most cases, the main stem usually divides into the anterior descending and the circumflex arteries. It is worth noting that the terms "anterior descending" and "posterior descending" reflect the previous anatomical practice of standing the heart on its apex and having the "anterior" interventricular groove in the midline. With the heart *in situ*, the "anterior" artery runs in the superior interventricular groove and the "posterior" artery runs in the inferior groove (Fig. 1.6B) [54]. McAlpine preferred to describe the two main branches of the left coronary artery as anterior and posterior divisions, to clarify their course and relations [55]. Be that as it may, the major branches of the "anterior" interventricular artery are the diagonal, septal perforating, and infundibular branches. The diagonal branches supply the anterior wall of the left ventricle, while the infundibular branches pass to the right ventricular outlet. The septal perforators pass perpendicularly into the ventricular septum. The circumflex artery supplies a branch to the sinus node in 45% of individuals. Its extent around the left atrioventricular junction is limited to supplying the obtuse margin of the left ventricle. Only in about 10% of individuals does it reach the cardiac crux to give rise to the "posterior" interventricular artery and a branch to the atrioventricular node at this juncture.

The coronary veins

The venous return from the heart muscle is either channeled via small thebesian veins that open directly into the cardiac chambers or, more significantly, is collected by the greater coronary venous system, which drains 85% of the venous flow [56,57]. The main coronary veins in the greater system are the great, middle, and small cardiac veins. The great and middle veins run alongside the "anterior" interventricular and "posterior" interventricular, respectively, and drain into the coronary sinus. As the great cardiac vein turns into the left atrioventricular groove, it passes close to the first division of the left coronary artery and under the cover of the left atrial appendage. Approaching 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. The left ventricular veins may be utilized for ablating ventricular tachycardia from a source close to the epicardium [58]. However, although coronary veins are usually superficial to arteries, cross-overs are not uncommon [15]. Furthermore, care should be taken when catheters or wires are being deployed in superficial veins, since the venous wall is thin and "unprotected" by muscle on the epicardial side.

The entrance of the vein of Marshall, or oblique left atrial vein, marks the venous end of the tube-shaped coronary sinus. When persistent, this is the left superior caval vein, which courses epicardially between the left atrial appendage and the superior pulmonary vein. In most individuals, the vein is a fibrous ligament, or if a lumen is present it is narrow, rarely exceeding 2 cm in length, before tapering to a blind end. If accessible, this channel may be entered for ablating the left atrial wall. In the absence of the vein of Marshall or its remnant, Vieussens' valve is taken as the anatomic landmark for the junction between the coronary sinus and the great cardiac vein. This very flimsy valve has one to three leaflets, which can provide some resistance to the catheter. Another marker for the junction is the end of the muscular sleeve around the coronary sinus. However, in a proportion of cases, the sleeve may extend to 1 cm or more beyond the junction [59]. Bundles from the sleeve sometimes run into the left atrial wall and also cover the outer walls of adjacent coronary arteries [59,60].

Close to its right atrial orifice, the coronary sinus receives the middle cardiac vein. The middle vein passes

just superficial to the right coronary artery at the cardiac crux. It is a useful portal for ablating accessory atrioventricular pathways located in the inferior pyramidal space [61]. Very rarely, the entrance of the middle vein is dilated and surrounded by a cuff of muscle, giving the potential for accessory atrioventricular connections [62].

The small vein receives tributaries from the right atrium and the inferior wall of the right ventricle before coursing in the right atrioventricular junction to open to the right margin of the coronary sinus orifice, or into the middle cardiac vein. When joined by the acute marginal vein, or vein of Galen, the small vein becomes larger in size. Several other veins, from the anterior surface of the right ventricle and from the acute margin, drain directly into the right atrium. In some hearts, the anterior veins merge into a venous lake in the right atrial wall.

The cardiac conduction system

Although the cardiac conduction system has been mentioned in the previous sections, it is appropriate to summarize the key features and put them in the context of the overall anatomy of the heart. Much has been written about "specialized internodal tracts" connecting the sinus node to the atrioventricular node. However, their existence in the form as originally defined by early anatomists has never been demonstrated [63–65]. The myocardium between the nodes bears no histological characteristic of specialization or cable-like arrangement that in any way resembles the ventricular bundle branches [66,67]. Instead, the internodal myocardium is arranged in broad bands that surround the orifices of the large veins, the tricuspid valve, and the oval fossa. Bands like the rim of the oval fossa and the terminal crest are raised ridges on the endocardial aspect and tend to have an orderly alignment in the myocardial fibers. The major interatrial band is Bachmann's bundle, located anterosuperiorly in the subepicardium. Again, this bundle is not insulated by a fibrous sheath, nor does it have well-defined margins (Fig. 1.8A). There are further smaller muscular bundles that cross the interatrial groove to connect the right and left atrial walls anteriorly, superiorly, posteriorly, and inferiorly, the right atrium to the right pulmonary veins, the wall of the coronary sinus to the left atrium, and so on (Fig. 1.8B, C) [24–26]. Fine bridges connecting the remnant of the vein of Marshall to the left atrial myocardium have also been demonstrated [68].

The sinus node

The sinus node is crescent-like in shape, with a mean length of 13.5 mm in the adult heart [69]. It is usually described as having a head, body, and tail, with the head
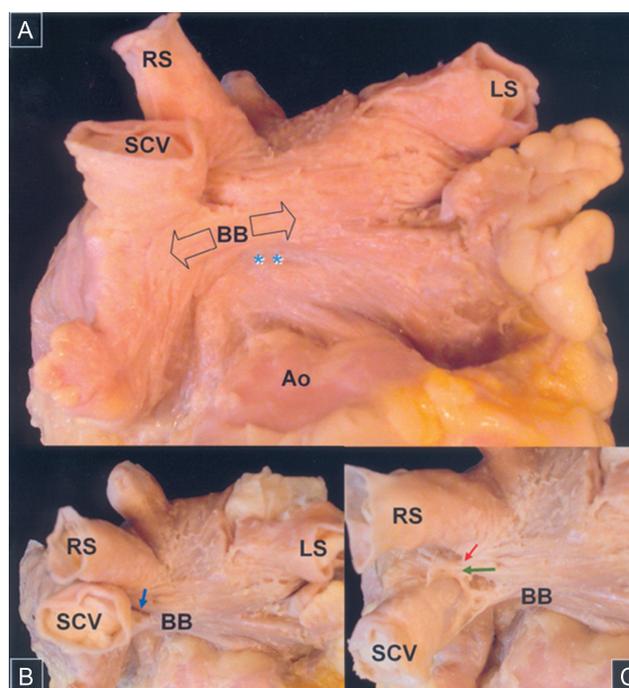
Figure 1.8 **A.** This dissection shows Bachmann's bundle crossing the interatrial groove (open arrows). Usually, it is a broad band of aligned myofibers that blends into the right and left atrial myocardium. It is not encased in a fibrous sheath. The area of the left atrial wall immediately inferior to the bundle can be very thin in some hearts (pale area marked by ******). **B.** This view from above shows Bachmann's bundle crossing the interatrial groove (arrow). **C.** The superior caval vein, pulled forward, reveals smaller interatrial bridges from the left atrium (green arrow) and from the right superior pulmonary vein (red arrow). Ao, aorta; BB, Bachmann's bundle; LS, left superior pulmonary vein; RS, right superior pulmonary vein; SCV, superior caval vein.

portion situated cephalad and close to the superior margin of the terminal groove. In most cases, the head is subepicardial, while the tail penetrates inferiorly into the myocardium of the terminal crest to lie closer to the subendocardium. The node is richly supplied with nerves from both the sympathetic chains and the vagus nerve. Nodal tissues are usually penetrated by a prominent nodal artery [70]. Although the specialized myocytes of the nodal cells are set in a fibrous matrix, the node is not encased in a fibrous sheath. The borders of the node are irregular, with frequent interdigitations between nodal and ordinary atrial myocytes, facilitating communication between node and right atrium [20,71].

The atrioventricular conduction system

In the normal situation, the atrioventricular conduction system provides the only pathway of muscular continuity between atrial and ventricular myocardium (Fig. 1.9A, B)
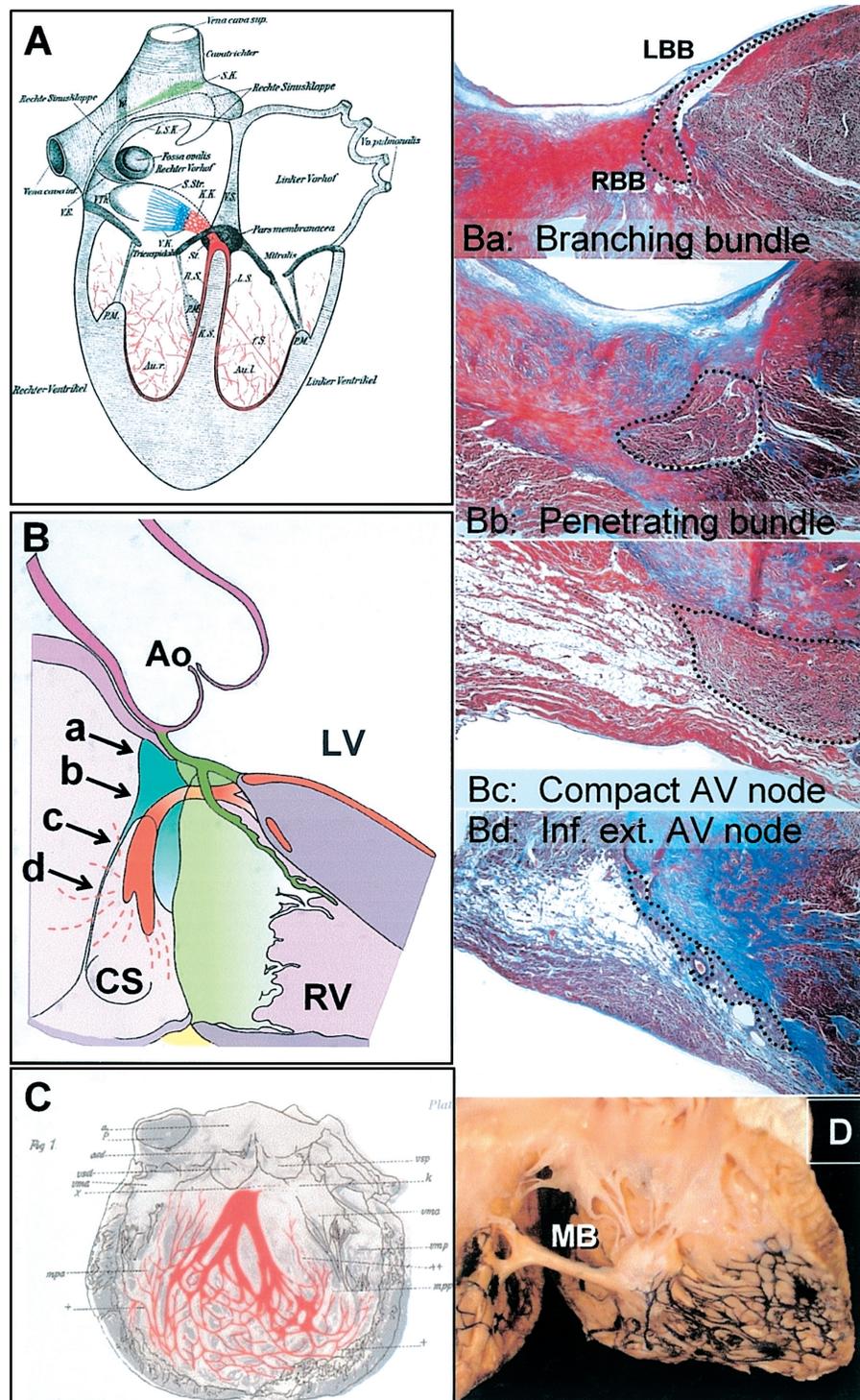
Figure 1.9 A. This diagram from Walter Koch's monograph [72, plate 13] depicts in exquisite detail the cardiac conduction system, but with the heart standing on its apex. **B.** The triangle of Koch and the proximal parts of the atrioventricular conduction system in this diagram are orientated more attitudinally. The arrows (a–d) indicate the corresponding levels of the histological sections (Ba–Bd), in which the conduction tissues are delineated with dotted lines. **C.** This diagram from Tawara's monograph [73, plate 1] depicts the left bundle branch and its interconnecting ramifications. **D.** The Purkinje fiber network is displayed in the right parietal wall of a sheep heart. Ao, aorta; AV, atrioventricular; CS, coronary sinus; LBB, left bundle branch; LV, left ventricle; MB, moderator band; RBB, right bundle branch; RV, right ventricle.

[72]. Thus, there is an interface of transitional cells between ordinary atrial myocardium and the histologically specialized cells that make up the atrioventricular node. These cells are arranged to provide anterior, inferior, and deep inputs to the compact atrioventricular node. The anterior input sweeps from the anterior margin of the oval fossa deep to the ordinary myocardium of the tricuspid vestibule. The inferior input approaches the compact node from the musculature in the floor of the coronary sinus and from the Eustachian ridge. The deep input bridges the compact node with the left atrial vestibule and inferior rim of the oval fossa.

Located at the apex of Koch's triangle is the atrioventricular node, described as the *"Knoten"* by Tawara [73] in his extensive monograph published in German in 1906 (Fig. 1.9B). The compact part of the node in the adult is approximately 5 mm long and wide [39]. In the majority of hearts, inferior extensions from the node pass to the right and left sides of the artery, which penetrates the compact node [74]. The right extension courses parallel and adjacent to the hinge of the tricuspid valve, while the left extension projects toward the mitral vestibule. The distance of the right inferior extension to the endocardial surface is approximately 1–5 mm. Put in the context of the right atrial landmarks of the triangle of Koch, right inferior extensions extend to the mid-level of the triangle, but may even extend to the vicinity of the coronary sinus in cases with a small triangle [39]. Ueng and colleagues [75] cautioned that ablation of slow pathways will only be successful in the "mid-septal" area in patients with larger nodal triangles.

Superiorly, at the apex of Koch's triangle, the penetrating atrioventricular conduction bundle of His passes through the central fibrous body to be sandwiched between the interventricular component of the membranous septum and the crest of the muscular ventricular septum, encased in a fibrous sheath (Fig. 1.9B). This short bundle of specialized myocardium is a direct extension of the compact atrioventricular node, enabling atrial activity to be conveyed to the ventricles. As discussed previously, the emergence of the bundle in the ventricles is directly related to the membranous septum and the aortic outflow tract. After a short distance, the bundle bifurcates into the left and right bundle branches (Fig. 1.9B). The left bundle branch fans out as it descends in the subepicardium of the septal surface of the left ventricle (Fig. 1.9C). In contrast, the right bundle branch is cord-like and descends the musculature of the ventricular septum to emerge in the subendocardium at the base of the medial papillary muscle, to run in the septomarginal trabeculation (Fig. 1.7A). Along the way, a prominent branch crosses to the parietal wall within the moderator band. Both bundle branches are insulated as they descend toward the apical parts of the ventricles. The branches then ramify as the Purkinje fibers, which run in the subendocardium and into the myocardium like a network. These have been shown in the diagrams drawn by Tawara [73] (Fig. 1.9C) and can be demonstrated in animal hearts by injections (Fig. 1.9D). In the subendocardium of the ventricular walls, they can be traced crossing the ventricular cavities in "false tendons" (Fig. 1.7F) and up the outflow tracts. Recently, triggers of ventricular fibrillation have been mapped to the Purkinje system in the right ventricular outflow tract and successfully ablated [76].

In some hearts, the atrioventricular bundle itself continues beyond the bifurcation as a third bundle. Termed the dead-end tract, this runs on the crest of the septum and has not yet had any function ascribed to it [77].

Fat pads and innervation

Extracardiac nerves from the mediastinum reach the heart through the areas bounded by the serous pericardium. These sites around the great veins at the cardiac base and around the pulmonary trunk and aorta are referred to as the hilum of the heart [78]. Nerves from the venous part of the hilum extend mainly to the atria, while those from the arterial pole predominantly reach the ventricles, but there are also multiple connections. Several branches of mediastinal nerves between the aorta and the pulmonary trunk connect with the aortic root and the superior region of the left atrium [79]. Six to ten collections of ganglia—ganglionated subplexuses of the epicardiac neural plexus—have been described in the human heart [79,80]. Half of the subplexuses are located on the atria and the other half on the ventricles. Occasional ganglia are located in other atrial and ventricular regions of the epicardium [79]. The ganglionated subplexuses are generally associated with islands of adipose tissue, referred to as fat pads, that serve as visual landmarks for cardiac surgeons [81]. The locations described by Armour and colleagues [79] are depicted in Fig. 1.10. Pauza and colleagues [80] found up to 50% of all cardiac ganglia on the posterior and posterolateral surfaces of the left atrium, whereas Singh and colleagues [81] reported that the largest populations of ganglia are adjacent to the sinus and atrioventricular nodes. However, the studies are not comparable, since Pauza and colleagues [80] rejected counts from regions covered by abundant fat. The ganglia within each subplexus are interconnected by thin nerves, while ganglia of adjacent subplexuses are also interconnected, forming the meshwork of the epicardiac neural plexus. Further nerves penetrate into the myocardium, becoming thinner and thinner and devoid of ganglia [80]. Recent experimental and clinical studies will help clarify the functional nature of the different epicardial ganglionated subplexuses [82–84].

Conclusions

Whilst the structure of the heart has remained unchanged over the ages, understanding of its anatomy has evolved over time, particularly with the development of new imaging methods and therapeutic strategies, each of which has required a review of the anatomy. The development of catheter ablation techniques has in many ways outpaced the understanding of relevant anatomy. Attitudinal orientation, as originally promoted by McAlpine [2], is crucial in understanding living anatomy. This chapter has
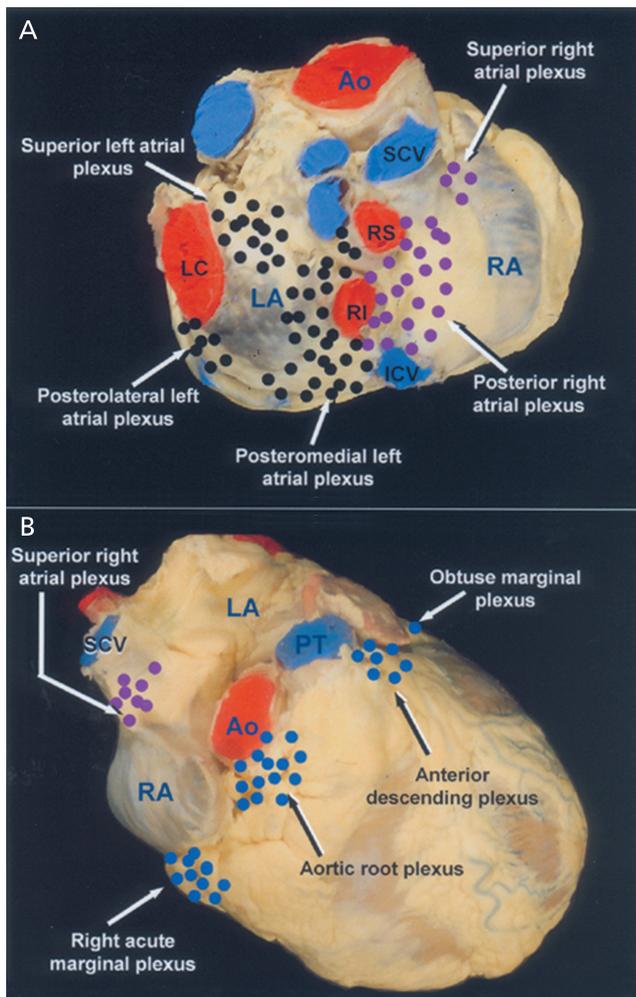
Figure 1.10 The dots depict the areas of fat pads containing ganglionated plexuses of the epicardial neural plexus. The nomenclature follows Armour *et al.* [79]. **A.** A sealant-filled heart specimen, viewed from the back. **B.** The frontal aspect. The posteromedial left atrial plexus and the posterior right atrial plexus invaginate into the interatrial groove, fusing to form the interatrial septal plexus. Ao, aorta; ICV, inferior caval vein; LA, left atrium; LC, left coronary orifice; PT, pulmonary trunk; RA, right atrium; RI, right inferior pulmonary vein; RS, right superior pulmonary vein; SCV, superior caval vein.

reviewed only hearts with normal connections and relations in the cardiac chambers. Postoperative arrhythmias are an increasing problem in adults with congenital heart disease. The complexities of the malformations can be daunting for ablationists, and the anatomy of the lesions will also need to be addressed.

For advances in this field to be achieved, synergy and collaboration between anatomists and practitioners of catheter ablation are essential. In this chapter, I have drawn freely from many such collaborations and I acknowledge the help of all who have contributed, and are continuing to contribute, to our understanding of the heart.

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