Volume 1

Kirklin/Barratt-Boyes

Fourth Edition

Cardiac Surgery

NICHOLAS T. KOUCHOUKOS • EUGENE H. BLACKSTONE
FRANK L. HANLEY • JAMES K. KIRKLIN

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Volume
1

Kirklin/Barratt-Boyes

Cardiac Surgery

Morphology, Diagnostic Criteria, Natural History, Techniques, Results, and Indications

Fourth Edition

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Cardiac Surgery

Morphology, Diagnostic Criteria, Natural History, Techniques, Results, and Indications

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Preface to Fourth Edition

The fourth edition of *Cardiac Surgery* has been prepared without contributions from two of the authors of the third edition, Drs. Robert B. Karp and Donald B. Doty. Dr. Karp was fatally injured in an automobile accident in 2006. Dr. Doty retired from the practice of cardiothoracic surgery in 2004. We are extremely grateful to both of them for their outstanding contributions, many of which remain in the fourth edition. We are equally pleased to welcome as a contributor to the fourth edition, Dr. James K. Kirklin, son of Dr. John W. Kirklin, co-author with Sir Brian Barratt-Boyes of the first two editions of *Cardiac Surgery*.

Except for Dr. Frank Hanley, we received our cardiothoracic surgical education at the University of Alabama Medical Center under the tutelage of John Kirklin, and we were privileged to serve as faculty members in the Department of Surgery at the University of Alabama at Birmingham School of Medicine during his tenure as chair of the department and director of the Division of Cardiothoracic Surgery. James Kirklin currently serves as director of that division.

We have all, including Dr. Hanley, been profoundly influenced by the teachings of John Kirklin, and by his intellect, vision, and clinical skills. His commitment to improving the quality of cardiac surgery through rigorous clinical and laboratory investigations and providing superb clinical care and disciplined training of young surgeons was truly exemplary. Although our interactions with Sir Brian Barrett-Boyes were less frequent and less intense, he possessed these same attributes and was an inspiration to us as well. In the last year of his life, he was engaged in updating the echocardiographic and structural valve deterioration data of the entire Green Lane Hospital experience of aortic allografts, with the intent of transmitting these data for analysis by one of us (EHB).

The systematic approach to cardiac surgery developed and promulgated by these two pioneering surgeons, who both died between publication of the third and this fourth edition of *Cardiac Surgery*, has been a major fixture in our professional careers. The decision to author the third and now fourth editions of *Cardiac Surgery* was in large part influenced by our desire to perpetuate their philosophical approach to this discipline. Thus, the general format of the three previous editions has been maintained.

All chapters present in the third edition have been revised. They have been rearranged so that every chapter relating to surgical treatment of congenital heart disease (except for Chapter 29, "Congenital Heart Disease in the Adult") has been placed in Volume 2. Each chapter was rewritten with input from at least two of the four authors. Chapter 4 ("Anesthesia for Cardiovascular Surgery") was revised by Drs. Colleen G. Koch and Chandra Ramamoorthy. The content, and in some instances the titles, of several chapters have been altered to reflect current knowledge and practice. As an example, the chapter "Heart Failure" in the third edition has been expanded into three chapters in the fourth edition: "Cardiomyopathy," "Cardiac Transplantation," and "Mechanical Circulatory Support." New illustrations and new echocardiographic, computed tomographic, and magnetic resonance images have been added to reflect important advances in the diagnosis and management of congenital and acquired diseases of the heart and great vessels.

We recognize the potential limitation of four authors writing separate portions of this textbook. This challenge was met, in part at least, by dual authorship of each chapter, and by author meetings and correspondence. It was also met by a process of universal review. Specifically, as with the third edition, Dr. Blackstone was designated as the final arbiter. After completion of the revision of each chapter by the primary author, copyedited material was forwarded to Dr. Blackstone in Cleveland, where he and his assistant, Tess Muharsky Parry, reviewed, edited, reorganized, questioned, and adjudicated the entire content of each chapter. It is our hope that this intensive process has improved the accuracy and comprehensiveness of each chapter.

As in the previous editions, Part I of Volume 1 discusses basic concepts of cardiac surgery: anatomy, support techniques, myocardial management, anesthesia, postoperative care, and methodology for generating new knowledge from previous experience. These core chapters are applicable to the broad audience of medical professionals who care for patients with cardiac disease. The remaining chapters of Volume 1 (Parts II to V) discuss specific acquired diseases of the heart and great vessels, and congenital heart disease in adults. This edition has retained, in these later sections and in all of the chapters in Volume 2, presentation of "Indications for Operation" at the end of each chapter, because the indications are the derivatives of comparison of various outcomes (results) of alternative forms of treatments, including no treatment (natural history).

The abbreviation *UAB* has been retained, and is used to identify data and illustrations from the University of Alabama at Birmingham; similarly, *GLH* identifies those from Green Lane Hospital in Auckland, New Zealand. The bibliographic references are again designated using the first letter of the surname of the first author and a number (e.g., L4), rather than simply a number. This convention is simple and convenient, and allows the reader to easily locate a given author's publication among the alphabetically arranged references. The abbreviation *CL* is used throughout to denote 70% confidence limits around the point estimate. The reasons for presenting 70% rather than 95% or 50% confidence limits are presented in Chapter 6.

The fourth edition is written at a time of great change for the specialty of cardiac surgery. Percutaneous catheter-based interventions are being increasingly used to treat patients with

coronary arteriosclerotic heart disease, aortic valve stenosis, mitral valve regurgitation, hypertrophic obstructive cardiomyopathy, diseases of the thoracic aorta, and congenital cardiac lesions such as patent ductus arteriosus, coarctation of the aorta, atrial and ventricular septal defects, and pulmonary valvar stenosis and regurgitation. Less invasive techniques are rapidly being incorporated into cardiac surgical practice for many conditions that continue to require open surgical repair. These advances must be acknowledged and embraced if cardiac surgery is to thrive in the future.

It is our hope that this textbook will be of value to cardiac surgeons who care for patients with congenital and acquired heart disease and with disorders of major blood vessels in the chest, as well as to cardiologists and interventional cardiologists who treat children and adults with these conditions, anesthesiologists, intensivists, pulmonologists, imaging specialists, cardiovascular nurses, trainees in all of these disciplines, and others.

— *Nicholas T. Kouchoukos, MD*
— *Eugene H. Blackstone, MD*
— *Frank L. Hanley, MD*
— *James K. Kirklin, MD*

Contents

VOLUME 1

VOLUME 2

PART I

General Considerations

1 Anatomy, Dimensions, and Terminology

This chapter describes normal cardiac and great artery anatomy and dimensions, as well as the terminology usually employed.

CARDIAC CHAMBERS AND MAJOR VESSELS

Accurate diagnosis of congenital heart defects depends in part on identifying cardiac chambers and major vessels by their morphology, regardless of their spatial positions (Fig. 1-1).

Right Atrium

The right atrium (Fig. 1-2) is the heart chamber that normally receives systemic venous drainage from inferior and superior venae cavae. It also normally receives the major portion of coronary venous drainage from the coronary sinus. Morphologic characteristics important for identifying the right atrium are presence of the limbus of the fossa ovalis, which surrounds the valve of the fossa ovalis (septum primum) superiorly, anteriorly, and posteriorly; a wide-based, blunt-ended, right-sided atrial appendage (auricle); eustachian valve at the orifice of the inferior vena cava and thebesian valve at the orifice of the coronary sinus; and crista terminalis, which separates trabeculated from nontrabeculated (venous) portions of the atrium (Fig. 1-3).

The normal structures are sometimes expressed in an excessive or unusual manner. These are not themselves functionally important abnormalities but are usually associated with cardiac malformations. Thus, the eustachian and thebesian valves may be sufficiently prominent to appear to divide the right atrium into two parts, a common finding in tricuspid atresia.[T6] The right atrial appendage may be juxtaposed leftward, and the left atrial appendage is less frequently juxtaposed rightward. Juxtaposition of the atrial appendages is usually associated with cardiac malformations.[A17]

Radiologically, the definitive morphologic features of the right atrium may be difficult to recognize.[B11] Occasionally, the atrial septum is seen well enough in angiographic profile to delineate the limbus of the fossa ovalis, and sometimes the right atrial appendage is outlined sufficiently to differentiate its shape from that of the left atrial appendage. The fact that the hepatic portion of the inferior vena cava usually drains into the right atrium often makes it possible to determine the location of the right atrium by passage of a catheter from the inferior vena cava to the heart. Cardiovascular magnetic resonance imaging (MRI) and three-dimensional (3D) echocardiographic computed tomography are increasingly able to identify even complex morphologic features of this and other cardiac chambers and their connections.[H3,H6,K4,Y2]

The atria are not in normal position in some patients; in these cases, the wide-based, blunt-ended right atrial appendage is the most secure indicator that an atrium is morphologically a right atrium. Other indicators of the morphology of the atria, and of atrial situs, include venous drainage and the situs indicated by the pulmonary artery and bronchial anatomy.[P1,S23,V3,V4]

Left Atrium

The left atrium (Fig. 1-4) is the cardiac chamber that normally receives pulmonary venous drainage from the four pulmonary veins. Its septal surface is characterized by the flap valve of the fossa ovalis (septum primum), in contrast to the limbus of the fossa ovalis present on the right atrioseptal surface. The left atrial appendage (auricle) is long and narrow, in contrast to bluntness of the right atrial appendage, and is the best indicator that the atrium is morphologically a left atrium. There is no crista terminalis at the base of the left atrial appendage, the only trabeculated structure in the left atrium.

In general, at cardiac catheterization, the location of the left atrium is determined by exclusion after identifying the position of the right atrium as described earlier. With normal pulmonary venous connection, the left atrium may

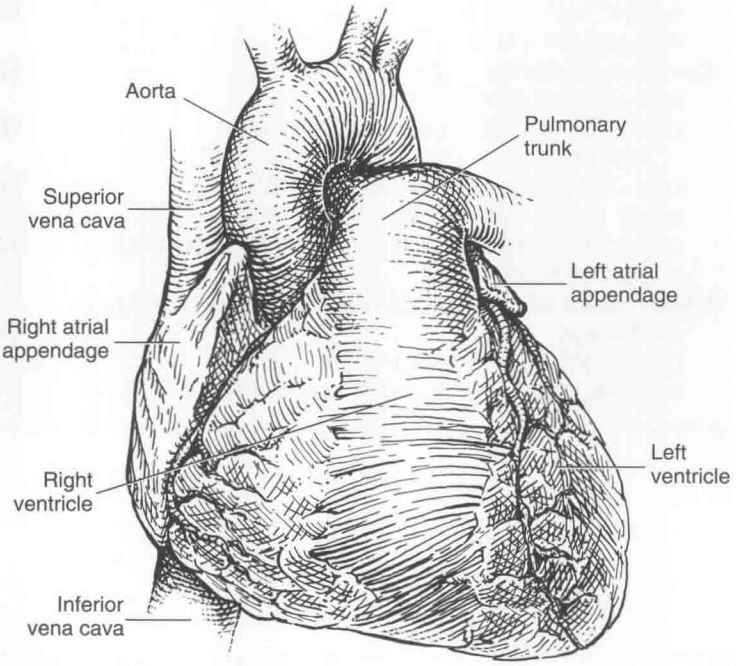

Figure 1-1 Surface anatomy of heart. Left atrial appendage is long and narrow, whereas right atrial appendage is short and blunt. Aorta originates posterior and to the right of the pulmonary trunk at the base of the heart, but is anterior and to the right by the pericardial reflection (not shown). Right ventricle occupies most of anterior aspect of heart, with left ventricle forming the apex and posterior aspects.

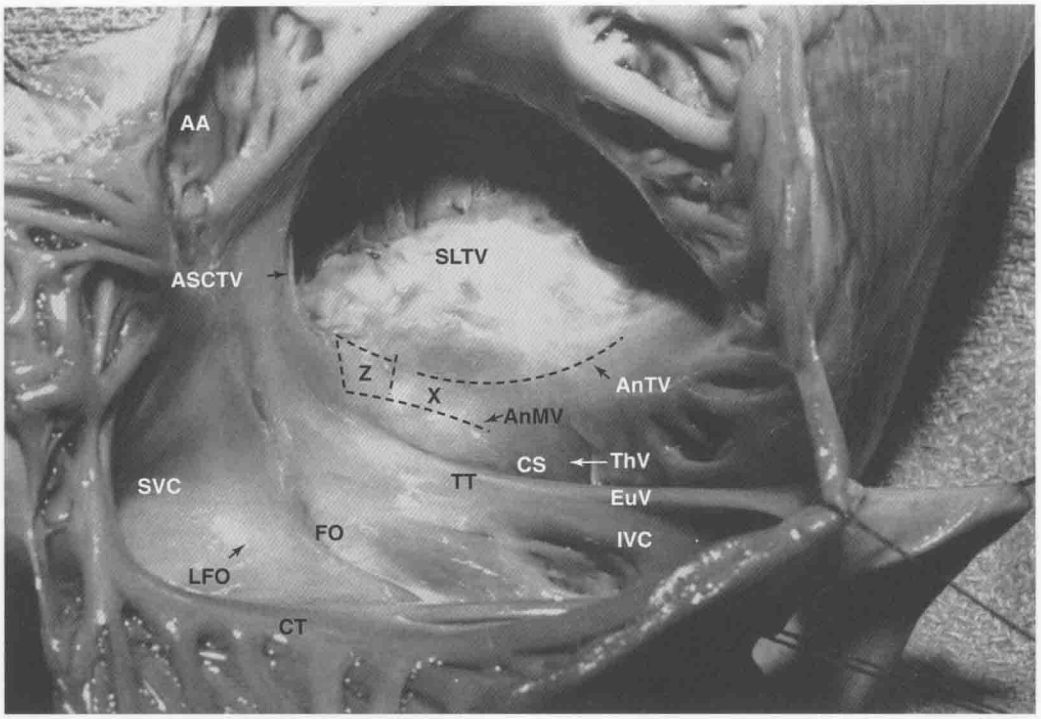

Figure 1-2 Interior of normal right atrium, viewed from right side at operation. Key: *AA,* Atrial appendage; *AnMV,* position of mitral valve anulus on other side of septum, indicated by dotted line; *AnTV,* anulus of tricuspid valve, indicated by dotted line; *ASCTV,* anteroseptal commissure of tricuspid valve; *CS,* coronary sinus orifice; *CT,* crista terminalis (inside of sulcus terminalis); *EuV,* eustachian valve; *FO,* fossa ovalis (sometimes called *septum primum*); *IVC,* inferior vena cava orifice; *LFO,* limbus of fossa ovalis (C-shaped, extending anteriorly and posteriorly to enclose fossa ovalis); *SLTV,* septal leaflet of tricuspid valve; *SVC,* superior vena cava orifice; *ThV,* thebesian valve; *TT,* tendon of Todaro; *X,* muscular portion of atrioventricular septum; *Z,* membranous portion of atrioventricular septum.

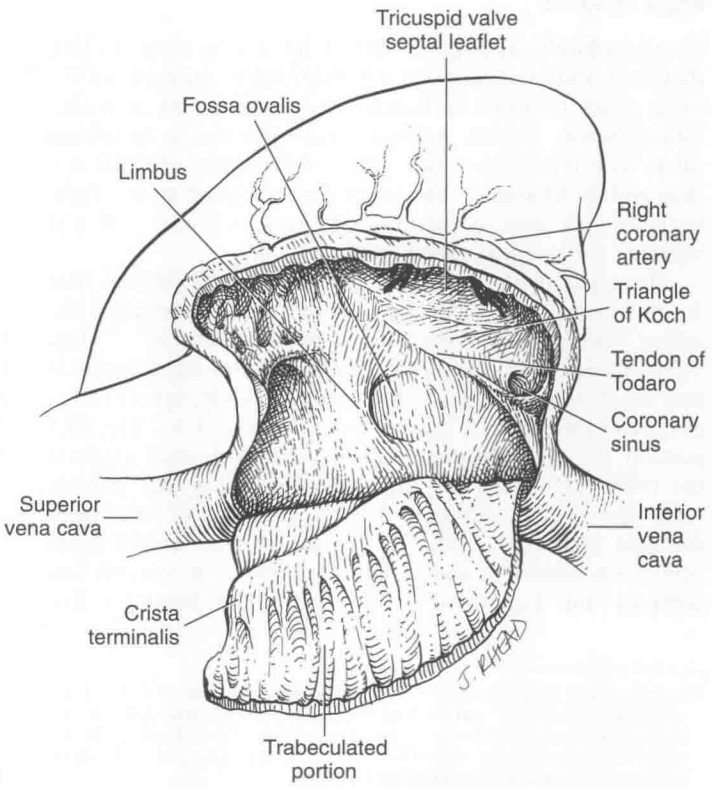

Figure 1-3 Interior of right atrium, oriented as at operation. Right atrium receives superior and inferior venae cavae. Its trabeculated portion is separated from its smooth portion by the crista terminalis. Fossa ovalis is located in center of atrial septum, surrounded on its superior, anterior, and posterior aspects by the limbus. Coronary sinus is positioned inferiorly. Coronary sinus, along with tendon of Todaro and anulus of septal leaflet of tricuspid valve, form the boundaries of triangle of Koch. Atrioventricular node and proximal portions of bundle of His, portions of the specialized conduction system, lie within the triangle of Koch. Right coronary artery lies in atrioventricular groove, the anatomic point of separation of right atrium and right ventricle.

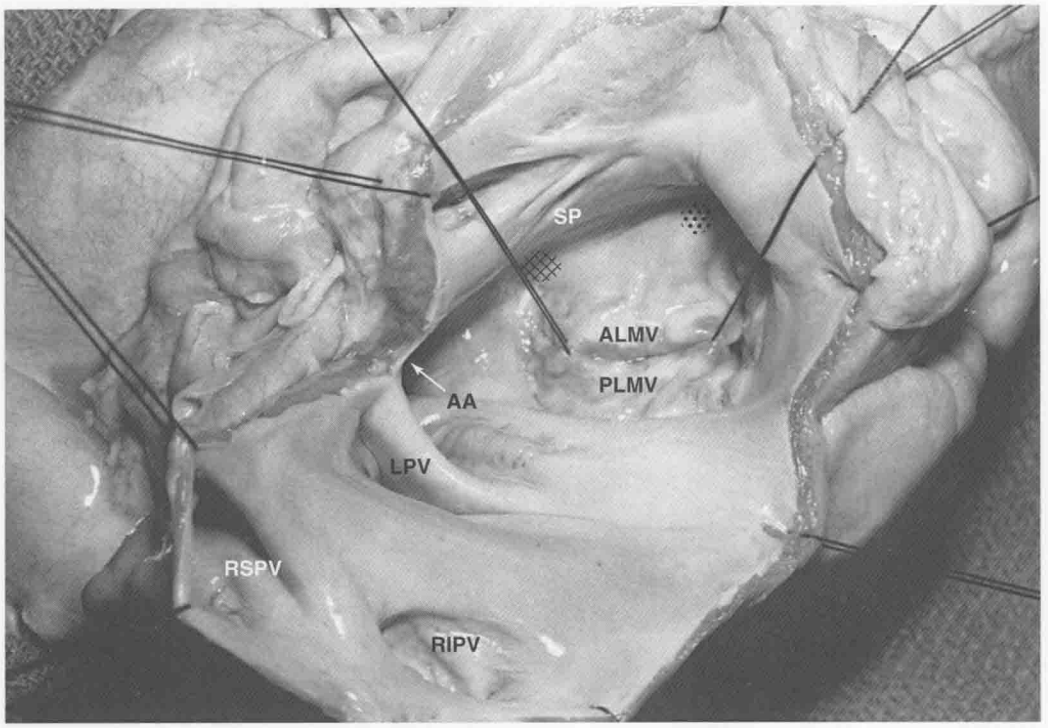

Figure 1-4 Interior of normal left atrium viewed from right side at operation as, for example, during mitral valve operations. Stippled area indicates position of right trigone, which contains bundle of His. Crosshatching marks left trigone, the area of greatest risk to aortic valve during mitral valve replacement. Key: *AA,* Base of atrial appendage; *ALMV,* anterior leaflet of mitral valve; *LPV,* orifices of left pulmonary veins; *PLMV,* posterior leaflet of mitral valve; *RIPV,* orifice of right inferior pulmonary vein; *RSPV,* orifice of right superior pulmonary vein; *SP,* septum primum.

be well opacified after a right ventricular or pulmonary artery injection.

Right Ventricle

Topographically, the right ventricle has a large sinus portion that surrounds and supports a tricuspid atrioventricular (AV) valve (inlet portion) and includes the apex and a smaller infundibulum (outlet portion) that supports a semilunar valve. The inlet and outlet valves of the right ventricle are thus widely separated. The entire sinus portion of the right ventricle and most of the infundibulum (both free wall and septum) are coarsely trabeculated.

The septal surface of the right ventricle is divided into an inlet portion, a trabecular portion (sometimes called the *apical trabecular portion*), and an outlet portion[A9,S29] (Fig. 1-5). Alternatively, the septal surface of the right ventricle may be divided into posterior (basal), middle, apical (anterior), and infundibular (conal) portions (Fig. 1-6). The inlet portion of the ventricular septum surrounds and supports the tricuspid valve.[1] The trabecular portion is that portion with the coarse trabecular pattern typical of the right ventricle (see Fig. 1-6). The outlet portion of the right ventricular aspect of the ventricular septum is smooth but complex and has three components. The largest is the infundibular (conal) septum, which separates the pulmonary from the aortic and tricuspid valves. Only part of the infundibular septum is interventricular (see Fig. 1-5), and in some malformations (e.g., double outlet right ventricle), none of it may be. It must be emphasized that the most distal cephalad portion of the infundibular septum is not, strictly speaking, part of the ventricular septum, because in the normal heart, the pulmonary valve arises from the apex of a cone of muscle and does not have a septal attachment.[A9,B4,C5,V7] A second part of the outlet portion of the septum is the anterior (superior) extension, or division, of the trabecula septomarginalis (septal band). A third small, very anterior portion is a narrow extension superior to the trabecular septum.

Laterally to the right, the infundibular septum imperceptibly merges with the free right ventricular wall immediately beyond its attachment to the membranous septum; at that point, it can be called the *parietal extension of the infundibular septum*[S22] (Fig. 1-7). The parietal band lies anterior to the right aortic sinus (see Fig. 1-7), partially overlying that portion of the free wall of the right ventricle termed the *ventriculoinfundibular fold.* Many surgeons call the infundibular septum and the parietal band the *crista superventricularis.* Medially and to the left, the infundibular septum merges with the trabecular portion of the septum between the limbs of the particularly prominent smooth, Y-shaped muscle bundle called the *trabecula septomarginalis*[A10,T2] (Fig. 1-8). The trabecula septomarginalis extends apically to become continuous with the *moderator band,* a prominent trabeculation running from septum to free wall.

[1]The phrase *inlet septum* is in some ways undesirable because the term has developmental implications,[A7] and the large inlet septum on the right ventricular side is not duplicated on the left side. Use of the term *trabecular* to describe a portion of the sinus septum is also undesirable in some ways because part of the infundibular septum is also trabeculated (see Fig. 1-5).

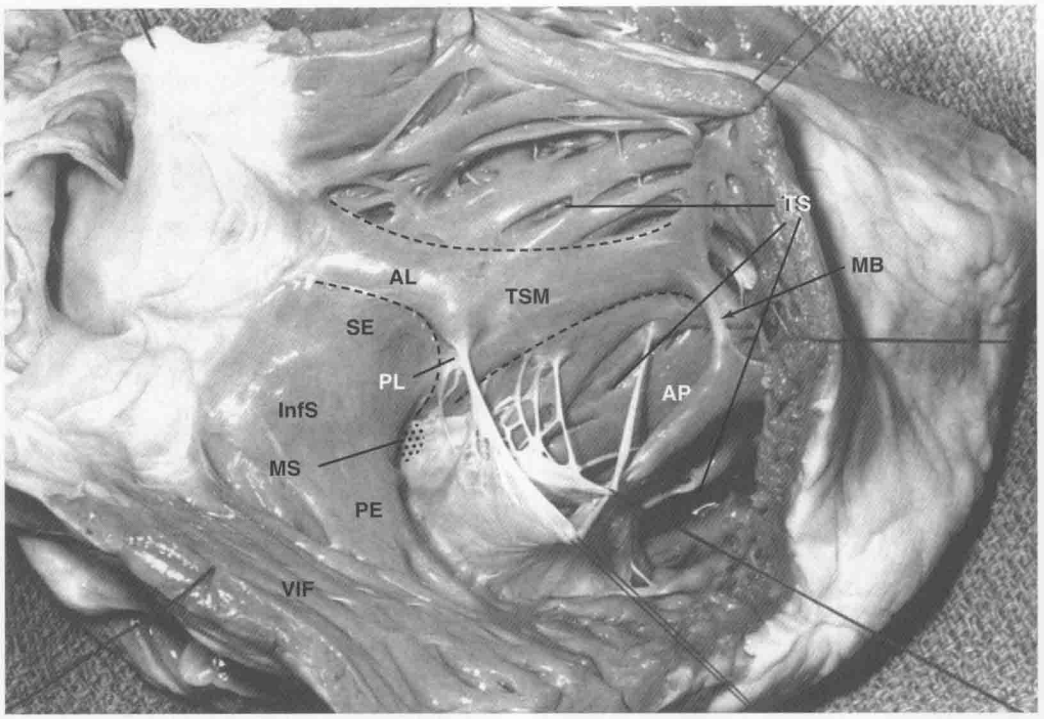

Figure 1-5 Interior of normal right ventricle, particularly trabecular and outlet portions, oriented as at operation. Infundibular (conal) septum separates pulmonary valve from tricuspid valve, and only its rightward portion and inferior part of its central portion form part of the interventricular septum (see also Fig. 1-6). Entire outlet portion of septum of infundibulum is composed of the septal extension of infundibular septum, anterior limb of trabecula septomarginalis (septal band), and in front of that, a heavily trabeculated portion of septum. Key: *AL,* Anterior (superior) limb of TSM; *AP,* anterior papillary muscle; *InfS,* infundibular (conal) septum; *MB,* moderator band; *MS,* position of membranous septum; *PE,* parietal extension of infundibular septum (parietal band); *PL,* posterior limb of TSM, giving origin to medial papillary muscle; *SE,* septal extension of infundibular septum; *TS,* trabeculated portion of septum, part of which lies in infundibulum and remainder in sinus portion of ventricle; *TSM,* trabecula septomarginalis (septal band); *VIF,* ventriculoinfundibular fold.

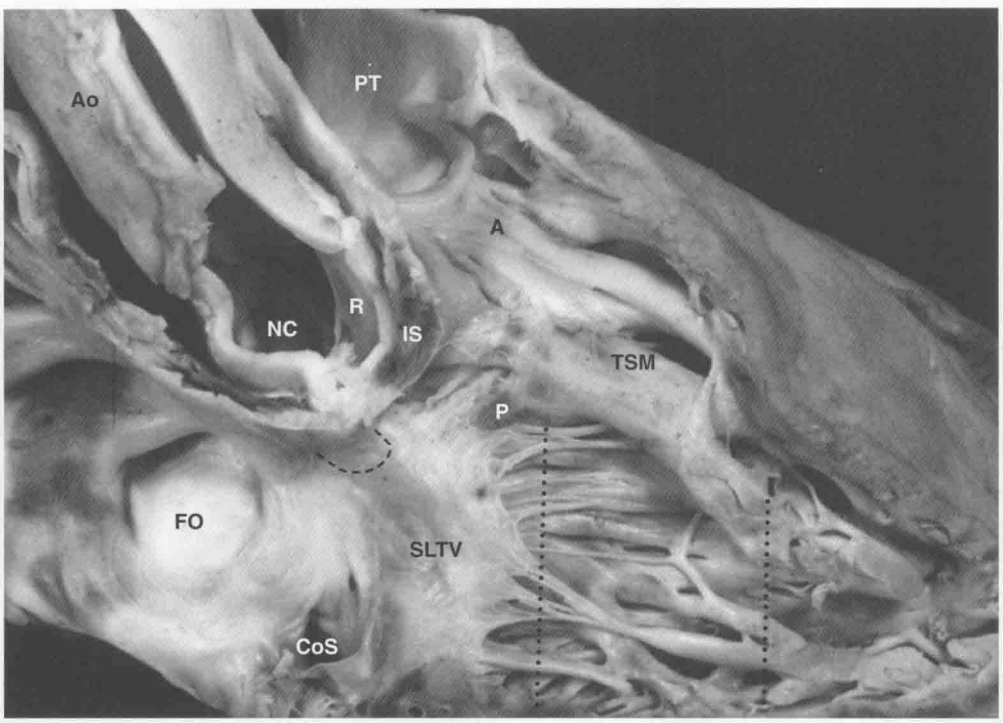

Figure 1-6 Right ventricular side of septum after right atrium, right ventricle, and pulmonary trunk have been exposed by removing their anterior walls and rightward portion of aorta and parietal band (or parietal extension of infundibular septum). Entire right ventricular septum is displayed, together with relationship of infundibular septum to aortic root. In this heart, infundibular septum is less prominent than in some. Dashed line defines atrioventricular portion of membranous septum. Dotted lines define arbitrary division of sinus septum into posterior (beneath septal tricuspid leaflet), middle, and apical portions. Specimen corresponds to a right anterior oblique projection in cineangiography. Key: *A,* Left anterior division septal band; *Ao,* aorta; *CoS,* coronary sinus; *FO,* fossa ovalis; *IS,* cut end of infundibular septum; *NC,* noncoronary aortic sinus; *P,* right posterior division of septal band; *PT,* pulmonary trunk; *R,* right coronary aortic sinus; *SLTV,* septal tricuspid leaflet; *TSM,* trabecula septomarginalis (septal band).

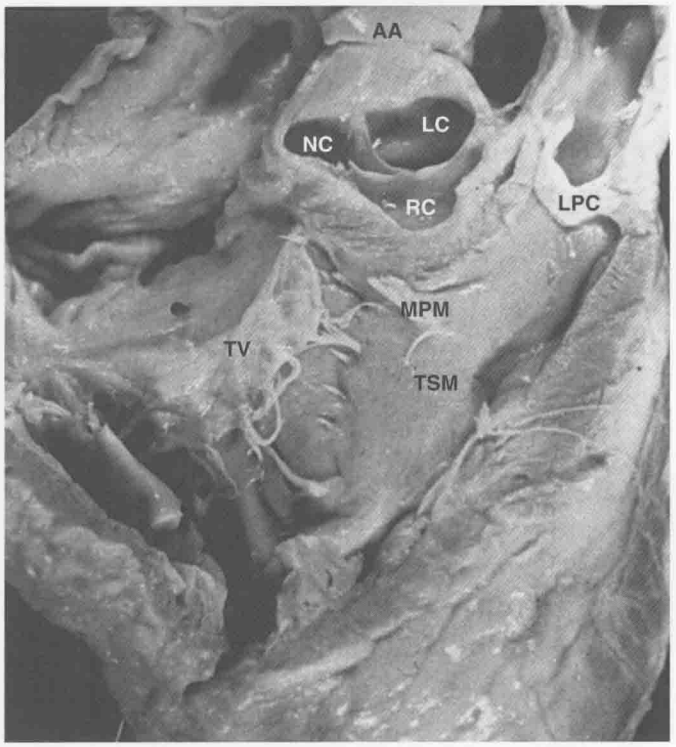

Figure 1-7 Demonstration of interrelationships between right ventricular aspect of ventricular septum and other structures in a longitudinal coronal section through heart. Key: *AA,* Ascending aorta; *LC,* left coronary cusp; *LPC,* left pulmonary cusp; *MPM,* medial papillary muscle; *NC,* noncoronary cusp; *RC,* right coronary cusp; *TSM,* trabecula septomarginalis (septal band); *TV,* tricuspid valve.

The junction between outlet and sinus (trabecular) portions of the right ventricle is clearly demarcated only along the lower margin of the outlet portion of the septum. The incomplete muscular ridge formed by the outlet septum (here, specifically, the infundibular septum) and the parietal band, together with the septal and moderator bands, forms a natural line of division between the posteroinferior sinus portion and the anterosuperior outlet portion of the ventricle.[V2] It is in this area that ventricular septal defects (VSDs) most commonly occur; the morphology of the area gives the name "junctional," or "conoventricular," to these defects.

The papillary muscle arrangement supporting the three leaflets of the tricuspid valve is different from that of the mitral valve in the left ventricle. In the case of the tricuspid valve, in addition to a single large anterior papillary muscle attached to the anterior free wall that fuses with the moderator band, there are multiple smaller posterior papillary muscles attached partly to the posterior (inferior) free wall and partly to the septum, and a group of small septal papillary muscles. The lowermost of these small septal muscles attaches posterior to the trabecula septomarginalis (see Fig. 1-5) and the uppermost, called the *medial (conal) papillary muscle* (muscle of Lancisi or muscle of Luschka), to the posterior limb of the septal band (Fig. 1-9).

Left Ventricle

The left ventricle consists of a larger sinus portion, which supports a bicuspid AV valve and includes the apex, and a much smaller outlet (outflow) portion beneath a semilunar

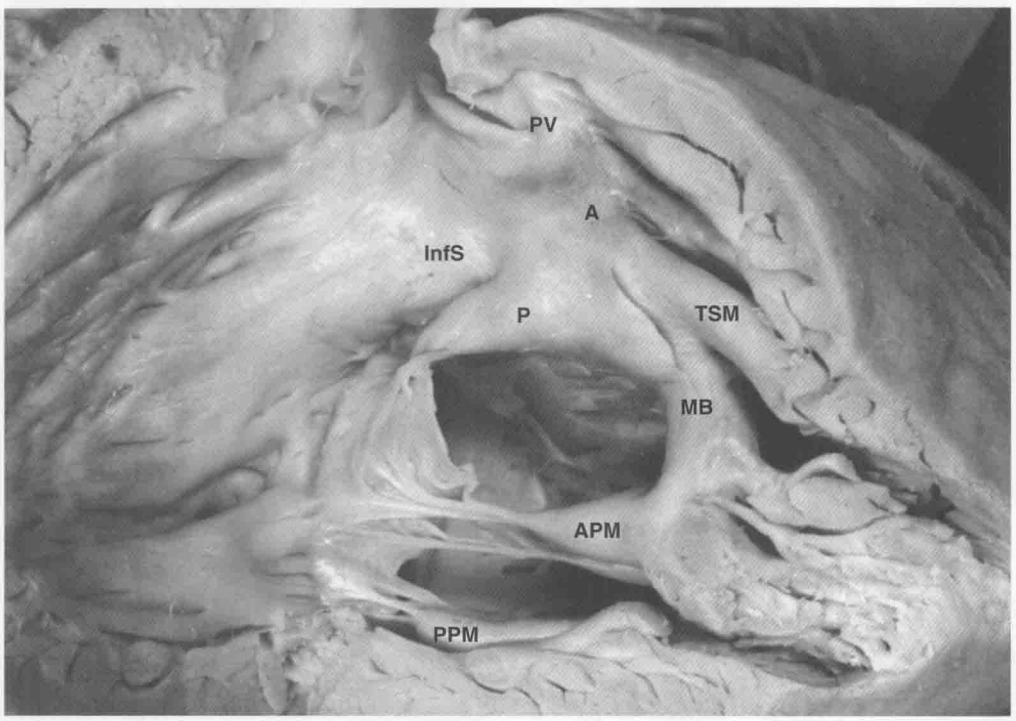

Figure 1-8 Interior of right ventricle after it has been opened close to anterior septal margin and along its acute margin inferiorly, and the anterior wall hinged to the right. Specimen is oriented anatomically, with aorta and pulmonary trunk at top. Pulmonary trunk also has been opened. Attachments of trabecula septomarginalis (septal band) are clearly demonstrated. Key: *A,* Left anterior division of trabecula septomarginalis; *APM,* anterior papillary muscle; *InfS,* infundibular (conal) septum; *MB,* moderator band; *P,* right posterior division of septal band giving origin to medial papillary muscle; *PPM,* posterior papillary muscle; *PV,* pulmonary valve; *TSM,* trabecula septomarginalis (septal band).

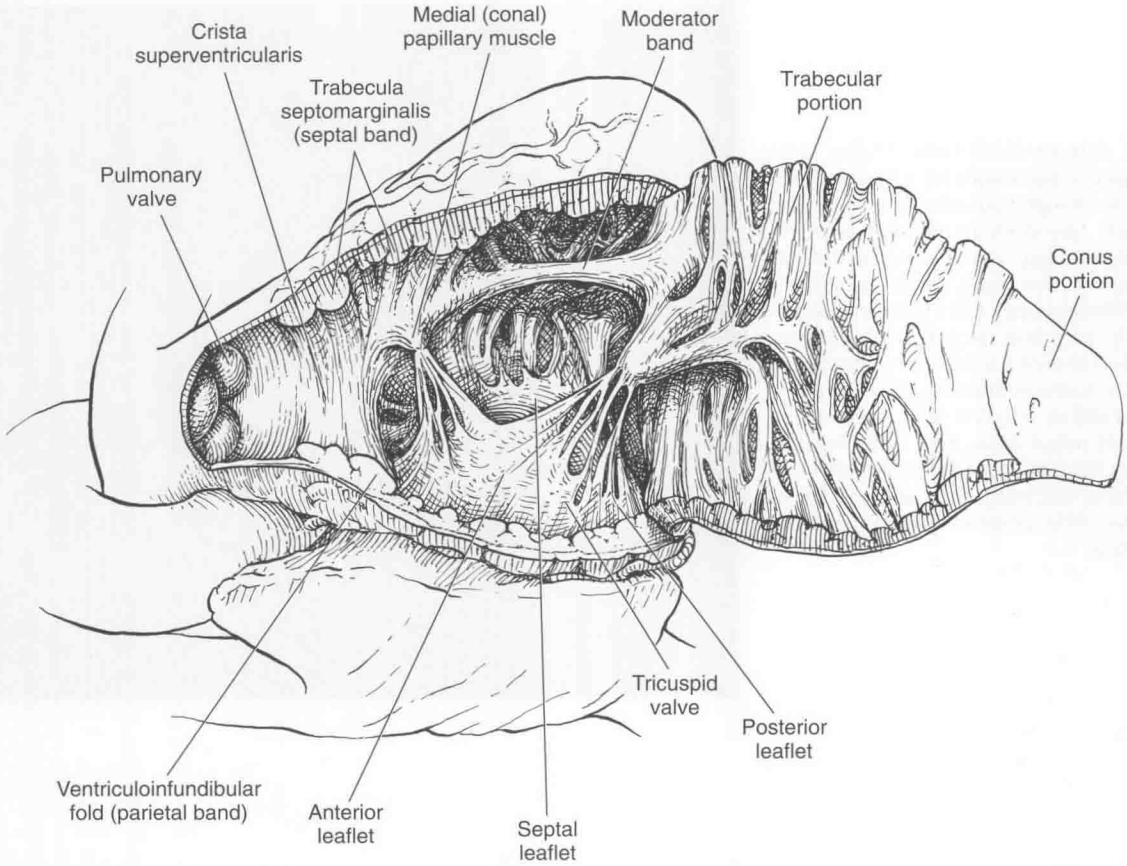

Figure 1-9 Interior of right ventricle, oriented as at operation. Right ventricle is divided into three portions: inlet, containing tricuspid valve and surrounding ventricular septum; sinus, or coarse trabecular portion; and outlet, or conus portion, containing infundibular septum and pulmonary valve. Right lateral extension of infundibular septum merges with right ventricle as ventriculoinfundibular fold (parietal band). Medially and to left, infundibular septum merges with right ventricle to form Y-shaped muscle bundle called *trabecula septomarginalis* (septal band). Trabecula septomarginalis extends to apex as the moderator band. An important landmark is the medial (conal) papillary muscle of the tricuspid valve.

valve. The inlet and outlet valves of the left ventricle lie juxtaposed within its base, and inflow and outflow portions are separated by the anterior mitral leaflet[2] (Fig. 1-10).

The entire free wall of the left ventricle and apical half to two thirds of the septum are trabeculated (Fig. 1-11; see also Fig. 1-10), but the trabeculations are characteristically fine compared with those in the right ventricle.[B11] The septal surface of the left ventricle may be considered to have a sinus portion, most of which is trabeculated, and a smooth outlet (outflow) portion (see Fig. 1-11). The part of the sinus portion of the septum immediately beneath the mitral valve may be termed the *inlet septum*, and the rest of the sinus portion, the *trabecular septum* (Fig. 1-12). The outlet (outflow) portion lies in front and to the right of the anterior mitral leaflet, corresponding to the inlet portion on the right ventricular side of the septum, and includes the AV septum (Fig. 1-13). In contrast to the right ventricular side, where the septal tricuspid leaflet is the only valvar attachment to the septum, on the left ventricular side, the rightward half of the anterior mitral valve leaflet attaches to the septum posteriorly, and the right and part of the noncoronary aortic cusps attach to it anteriorly (see Fig. 1-12). The leftward half of the anterior mitral leaflet is in fibrous continuity with the aortic valve in an area termed the *aortic–mitral anulus* (Fig. 1-14; see also Figs. 1-12 and 1-13). The anteriorly placed right ventricular infundibular (conal) septum lies opposite the aortic valve (Fig. 1-15). It may occasionally be displaced into the left ventricular outflow beneath the aortic valve; occasionally, muscle may also extend between the aortic and mitral valves, forming a true infundibulum to the left ventricle (see Fig. 1-10). The papillary muscles are called *anterolateral* (or simply *anterior*) and *posteromedial (posterior)*. No papillary muscles attach to the left side of the ventricular septum.

Myoarchitecture of the Ventricles

The adult ventricular mass is made up of a three-dimensional network of myocardial cells.[S3] This network is highly structured and arranged in layers in which the myocardial cells have a preferred orientation. In all hearts, the ventricular wall is arranged in three layers: superficial (subepicardial), middle, and deep (subendocardial). Superficial and deep layers are present in both right and left ventricles, whereas the middle layer is only present in the left ventricle. The superficial and deep layers are anchored at the ventricular orifices to fibrous structures of the central fibrous skeleton of the heart. This

[2]In this text, cusps of atrioventricular valves are termed *leaflets*, although current anatomy texts use the term *cusp* for both semilunar and atrioventricular valves.