Section 1 **Anatomy and physiology**

Chapter 1

Cardiac embryology and anatomy

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An appreciation of the normal development of the heart and great vessels and normal adult cardiac anatomy is essential to the understanding of congenital and acquired heart disease.

Embryology

The heart develops predominantly from splanchnic mesoderm, together with some influx of neural crest cells, which contribute to endocardial cushions. Union of the left and right endothelial channels results in the primitive heart tube, which starts to beat in the third week of gestation. The "arterial" end of the tube lies cephalad while the "venous" end lies caudad. A series of dilatations form the primitive heart chambers (Figure 1.1).

The initially straight heart tube transforms into a helically wound loop, normally with a counterclockwise winding (Figure 1.2). Such cardiac looping

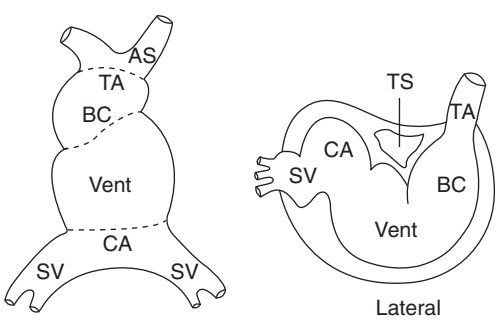


Figure 1.1 The primitive heart at around 3 weeks' gestation. The sinus venosus (SV) has left and right horns, and receives blood from the vitelline and umbilical veins. The common atrium (CA) lies between the SV and single ventricle (Vent). The bulbus cordis (BC) is divided into a proximal and distal portions. The outflow tract, composed of the distal BC and the truncus arteriosus (TA), is in continuity with the aortic sac. The transverse sinus (TS) is the area of pericardial cavity lying between the arterial and venous ends of the heart tube.

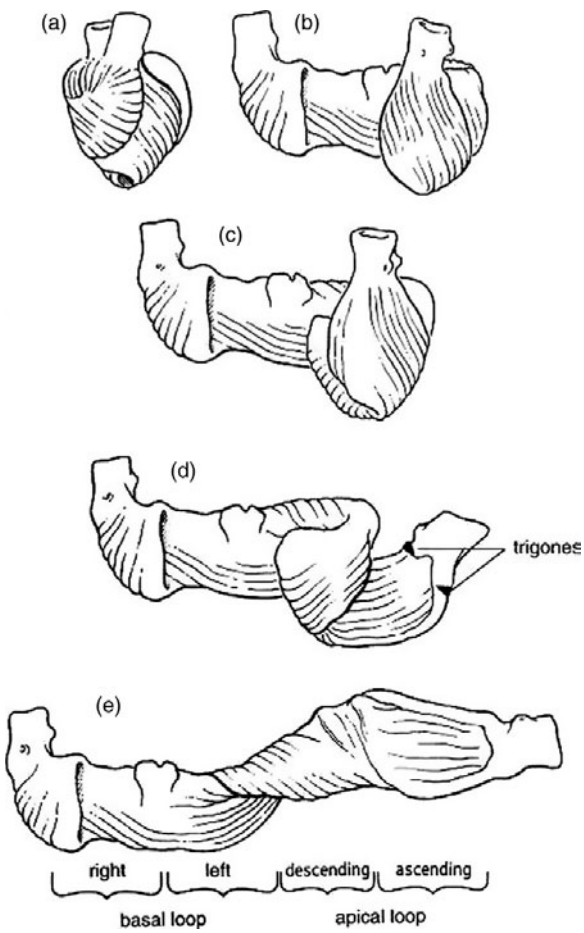


Figure 1.2 Schematic representation of the ventricular myocardial band. (a) Normal position. (b) Pulmonary artery separated. (c) Complete separation of right free wall showing 90° crossing of horizontal fibers with vertical ones. (d) Dismounting of the aorta separates vertical fibers. (e) Extended myocardial band. Reproduced with permission from Buckberg GD. *Semin Thorac Cardiovasc Surg* 2001; 13(4): 320–32.

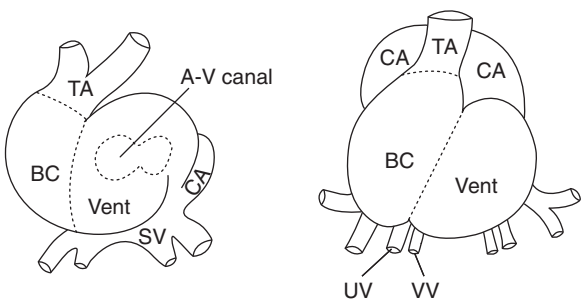


Figure 1.3 The primitive heart during the fourth and fifth weeks of gestation. The left horn of the SV receives blood from the left common cardinal vein. The right horn of the SV receives blood from the hepato-cardiac canal and the right common cardinal, umbilical (UV) and vitelline (VV) veins.

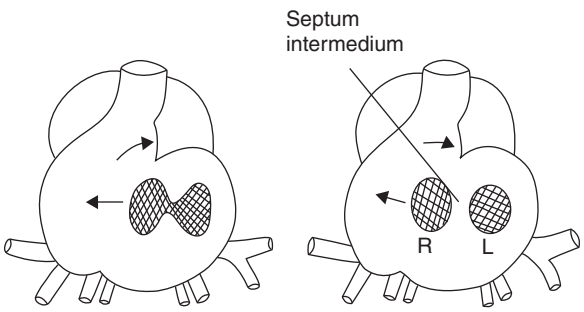


Figure 1.4 Fusion of the dorsal and ventral endocardial cushions forms the septum intermedium that divides the atrioventricular canal into left and right channels.

establishes the basic topological left-right asymmetry of the ventricular chambers, and brings the segments of the heart tube and the developing great vessels into their topographical relationships. This cardiac looping is regarded as an important process in cardiac morphogenesis and several of the well-described congenital cardiac malformations (e.g. topological left-right asymmetry) may result from disturbances in this looping process.

Lengthening of the heart tube and differential growth cause buckling of the tube within the pericardial cavity. As a result the common atrium and sinus venosus come to lie behind the bulbus cordis and common ventricle (Figure 1.3).

Further development consists of division of the atrioventricular (A-V) canal, formation of the interatrial and interventricular septa and partition of the outflow tract. Development and fusion of dorsal and ventral endocardial cushions divide the A-V canal into left and right channels. During this division, enlargement of the endocardial cushions forces the channels apart while the distal bulbus cordis migrates to the left (Figure 1.4).

Partition of the atrium begins with development of the sickle-shaped septum primum, which grows down from the dorsal wall to fuse with the septum intermedium. Before complete obliteration of the foramen primum by the septum primum, degenerative changes in the central portion of the septum result in the formation of the foramen secundum. The thicker septum secundum grows downward from the roof on the right side of the septum primum to overlie the foramen secundum. As the lower edge does not reach the septum intermedium a space between the free margin of the septum

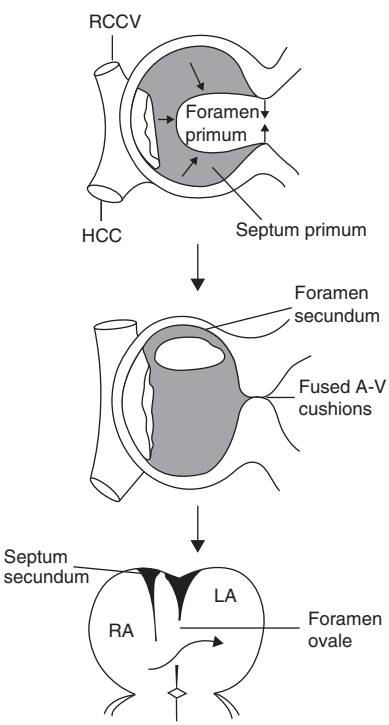


Figure 1.5 Formation of the intra-atrial septum. In the upper diagrams, the developing septum primum (shaded) is viewed from the right side of the common atrium. RCCV, right common cardinal vein (primitive SVC); HCC, hepatocardiac channel (primitive IVC).

secundum and foramen secundum (known as the foramen ovale) persists (Figure 1.5). The right horn of the sinus venosus becomes incorporated into the RA (as the vena cavae) and the left horn becomes the coronary sinus.

The interventricular septum is formed by the fusion of the inferior muscular and the membranous (bulboventricular) septa. The primary interventricular foramen, which is obliterated by formation of the septum, is bounded posteriorly by the A-V canal. The resulting separation of the bulbus cordis

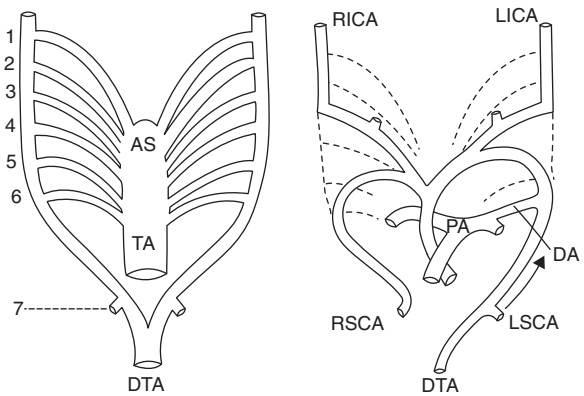


Figure 1.6 The fate of the pharyngeal arch arteries and development of the great arteries. The pharyngeal arch arteries coalesce to form the left and right dorsal aortae, which join to form the primitive descending thoracic aorta (DTA). The aortic sac (AS) becomes the right half of the aortic arch, and brachiocephalic and common carotid arteries. The left dorsal aorta forms the left half of the aortic arch. The third arch arteries form the internal carotid arteries (LICA and RICA). The sixth arch arteries and truncus arteriosus (TA) form the pulmonary arteries (PA). The distal portion of the left sixth arch artery forms the ductus arteriosus (DA). The seventh intersegmental arteries form the subclavian arteries (LSCA and RSCA).

from the ventricle results in the formation of the RV and LV.

The truncus arteriosus (TA), aortic sac, pharyngeal arch arteries (Figure 1.6) and dorsal aortae develop into the great vessels of the superior mediastinum.

Partition of the outflow tract begins during formation of the interventricular septum as two pairs of ridges grow into the lumen. The left and right bulbar ridges unite to form the distal bulbar septum and the left and right aorticopulmonary ridges fuse to divide the TA into the aorta and main pulmonary trunk (Figure 1.7).

Differentiation of the thick myoepicardial mantle that surrounds the primitive endocardial tube results in formation of the epicardium, myocardium and fibrous tissue of the heart. The myocardium further differentiates into a spongy, trabeculated inner layer and a compact outer layer. In the atria, the trabeculae form the pectinate muscles, whereas in the ventricles they form the chordae tendinae and papillary muscles. The myocardium of the atria remains in continuity with that of the ventricles until separated by the development of fibrous tissue in the A-V canal. The small strand of myocardium that bridges this fibrous tissue differentiates into the cardiac conducting system.

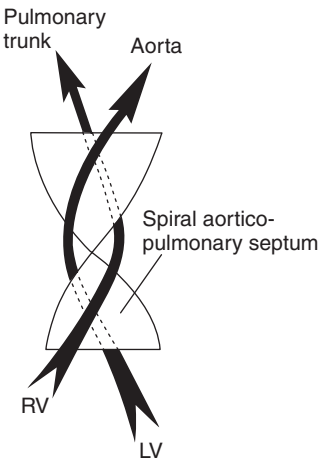


Figure 1.7 Partition of the truncus arteriosus by the helical aorticopulmonary septum into the ascending aorta and main pulmonary trunk.

Raised folds arising from the margins of the distal ventricular outflow tracts and A-V channels become excavated on their downstream surfaces to form the pulmonary, aortic, tricuspid and mitral valves.

Fetal circulation

The fetal circulation (Figure 1.8) differs from the adult circulation in the following respects:

- *Umbilical vein* and *ductus venosus* Carries oxygenated placental blood to the IVC via the ductus venosus.
- *Foramen ovale* The opening of the IVC lies opposite the foramen ovale. Oxygenated blood is directed across the foramen by the Eustachian valve into the LA and distributed to the head and arms.
- *Pulmonary circulation* High pulmonary vascular resistance (PVR) results in minimal pulmonary blood flow and physiological RVH.
- *Ductus arteriosus* Venous blood returning from the head and arms enters the RA via the SVC. The majority of blood ejected into the main pulmonary trunk is directed into the descending thoracic aorta via the wide ductus arteriosus.
- *Umbilical arteries* These paired vessels, arising from the iliac arteries, return deoxygenated blood to the placenta.

At birth the cessation of umbilical blood flow, coupled with lung expansion and respiration, yields the so-called transitional circulation. This circulation is inherently unstable and may persist for a few hours or several weeks.

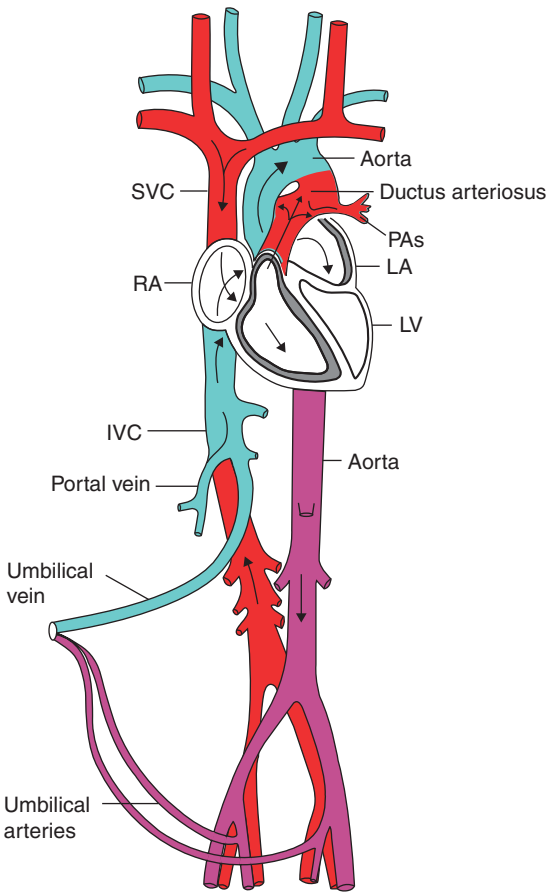


Figure 1.8 The fetal circulation.

- *Umbilical vessels* Close shortly after birth.
- *Ductus venosus* Becomes ligamentum venosum.
- *Foramen ovale* When LA pressure > RA pressure, flow across the foramen effectively ceases. May remain patent into adulthood.
- *Pulmonary circulation* Pulmonary blood flow increases with rapid decline in PVR. PVR ≈ SVR at 24 h. PVR continues to fall for several months.
- *Ductus arteriosus* Functional closure at birth as blood is diverted to the pulmonary circulation. Anatomical closure may take several weeks.

Normal cardiac anatomy

Pericardium

The pericardium is a cone-shaped structure, composed of fibrous and serosal parts, that encloses the heart and the roots of the great vessels. The fibrous part consists of dense connective tissue that merges superiorly with the adventitia of the great arteries, and inferiorly with the central tendon of the diaphragm. The inner surface of the fibrous pericardium is lined by the parietal layer of serous pericardium, which is reflected over the surface of the heart as the visceral layer or epicardium. A thin film of pericardial fluid separates the two serosal layers. The pericardial reflections create the oblique sinus, a blind recess behind the LA bounded by the four pulmonary veins and the IVC, and the transverse sinus between the aorta and PA in front and the SVC and LA behind.

Heart borders

- Right SVC, RA, IVC
- Left Edge of LV
- Anterior RA, RV, small strip of LV
- Posterior LA, pulmonary veins (× 4)
- Inferior RV
- Superior LA appendage.

Right heart chambers

The RA receives the SVC superiorly, and the coronary sinus and IVC, both guarded by rudimentary valves, inferiorly. A superior elongation, the RA appendage, overlies the root of the aorta. The sulcus terminalis is a groove on the surface of the RA running from the junction of the SVC and RA appendage to the IVC. The sulcus is reflected on the inner surface of the RA as a ridge of muscle; the crista terminalis. The character of the inner surface of the RA reflects its embryological origins. The surface posterior to the crista terminalis originates from the sinus venosus and is smooth, whereas that anterior to the crista originates from the primitive atrium and is trabeculated by bands of pectinate muscle. The interatrial septum forms the posteromedial wall of the RA. A shallow depression in the center of the septum, the fossa ovalis, represents that part of the septum primum not covered by the septum secundum (Figure 1.9).

The tricuspid valve separates the RA and RV. The three cusps – septal, inferior and anterior – are attached at their bases to the fibrous A-V ring. The free edges and inferior surfaces of the cusps are attached via chordae tendinae to papillary muscles from the trabeculae of the RV wall.

On the surface of the heart, the RA is separated from the crescent-shaped RV by the right A-V groove in which the right coronary artery lies. The ventricular

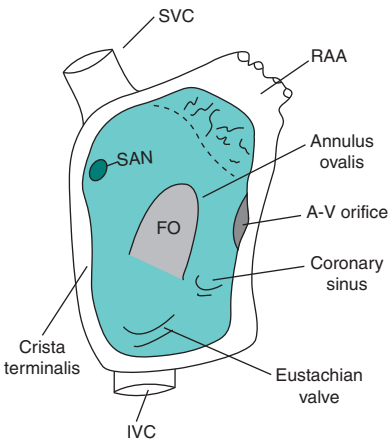


Figure 1.9 The interatrial septum viewed from the right side of the heart. The annulus ovalis is a sickle-shaped ridge of tissue in the septum secundum that surrounds the fossa ovalis (FO). Posterior to the crista terminalis the lining of the atrium is smooth. SAN, sinoatrial node; RAA, right atrial appendage.

cavity is lined by a series of ridges known as the trabeculae carnae. One of these trabeculae, the moderator band, lies free within the cavity and carries part of the RV conducting system. The smooth-walled outflow tract or infundibulum leads to the main pulmonary trunk.

The pulmonary valve consists of three semi-lunar cusps, two anterior and one posterior, attached at their bases to a fibrous ring.

Left heart chambers

The LA lies directly behind the RA, from which it is separated by the interatrial septum. The small LA appendage arises from the superior aspect of the LA and overlies the RV infundibulum. The four pulmonary veins, namely – left and right, superior and inferior – drain into the posterior wall of the LA. With the exception of the LA appendage, which is trabeculated by pectinate muscles, the LA cavity is smoothwalled.

The mitral valve is a complex structure composed of both valvular and subvalvular components. The valve apparatus comprises two asymmetrical leaflets attached to a flexible, saddle-shaped annulus. The subvalvular apparatus comprises chordae tendinae, papillary muscles and adjacent LV myocardium.

The LA is separated from the LV by the left A-V groove, in which the left circumflex coronary artery lies. The ventricle is circular in cross section and has a wall thickness three to four times that of the RV. With the exception of the aortic vestibule, which has smooth walls, the lining of the LV cavity has prominent trabeculae carnae.

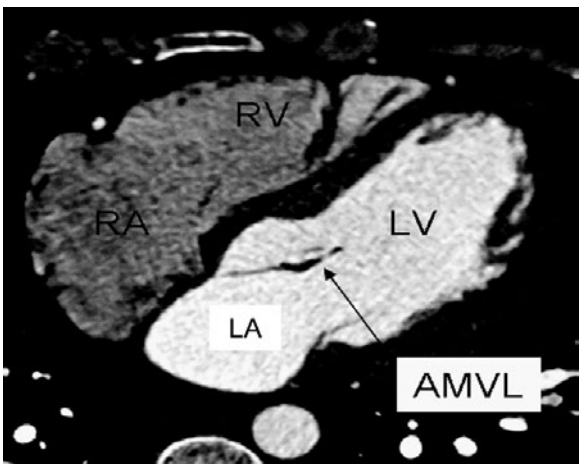


Figure 1.10 CT image showing a four-chamber view of the normal heart. AMVL, anterior mitral valve leaflet.

Structure–function relationships

As a consequence of the looping of the heart tube (Figure 1.2) the ventricular myocardium consists of a continuous muscular band that extends from the PA to the aorta. This band is curled in a helical manner that describes two spirals – a basal loop, with right and left segments, and an apical loop. During the cardiac cycle myocardial contraction begins in the right basal segment, followed by the left segment, so that the basal loop contracts, leading to narrowing of the ventricular mass – the pre-ejection phase. The wave of contractile activity then spreads to the descendant limb, causing the base and apex to rotate in opposite directions. This twisting of the descendant segment causes axial ventricular shortening – the ejection phase. After activation of the ascendant segment there is reciprocal rotation of the base and the apex (Figure 1.2). This "untwisting" leads to axial lengthening of the ventricles, implying a descent of the base of the ventricles, elongation and an associated drop in intra-ventricular pressure – the pre-suction phase. The atrioventricular valves open and the suction phase begins when ventricular pressure falls below atrial pressure. Relaxation of the ventricular myocardium leads to further filling – the drainage phase.

Nerve supply

The heart is innervated by afferents and efferents of both the sympathetic and parasympathetic nervous system. The parasympathetic supply comes from the

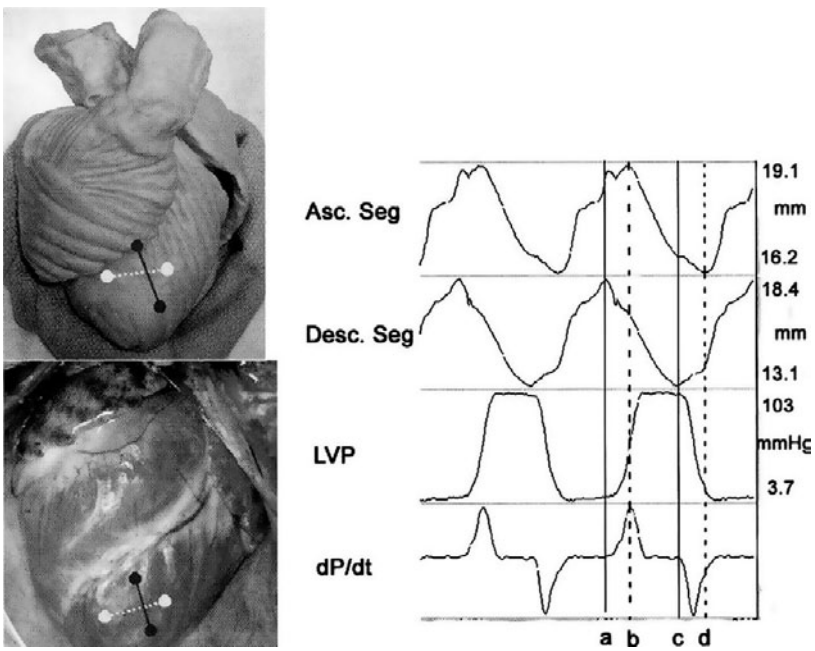


Figure 1.11 Contraction of the myocardium comprises rotary torsion (shortening the ventricular cavity) and thickening (narrowing the ventricular cavity to compress the ventricular contents). At the LV apex, superficial segments ascend toward the base (darker vertical lines) whilst deep segments descend away from the base (lighter horizontal lines). The start (a) and end (c) of contraction of the descending segments precedes the start (b) and end (d) of contraction of the ascending segments. Reproduced with permission from Buckberg GD, *et al. Semin Thorac Cardiovasc Surg* 2001; 13(4): 342–57.

vagus nerves via the cardiac plexuses. Short post-ganglionic fibers pass to the SA and A-V nodes and are only minimally distributed to the ventricles. The sympathetic supply arises from the cervical and upper thoracic sympathetic trunks and supplies both the atria and ventricles. Post-ganglionic fibers arise in the paired stellate ganglia. The right stellate ganglion supplies the anterior epicardial surface and the inter-ventricular septum. The left stellate ganglion supplies the lateral and posterior surfaces of both ventricles. Although the heart has no somatic innervation, stimulation of vagal afferents may reach consciousness and be perceived as pain.

Conducting system

This is discussed in Chapter 2.

Blood supply

The right coronary artery arises from the anterior aortic sinus, passes between the pulmonary trunk and RA appendage and descends in the right A-V groove until it reaches the posterior interventricular groove. In 85% of patients the artery continues as the posterior descending artery (i.e. "right" dominance). In its course, it gives off atrial, SA and A-V nodal, and ventricular branches before dividing into the posterior descending and RV marginal arteries.

The left coronary artery arises from the left posterior aortic sinus and divides into the left anterior (interventricular) descending and circumflex arteries. The LAD descends anteriorly and inferiorly to the apex of the heart. In its course it gives off one or more diagonal branches and a series of septal perforating branches, which supply the anterior interventricular septum. The left circumflex artery runs posteriorly in the left A-V groove until it reaches the posterior interventricular groove, where it may continue as the posterior descending artery in 15% of patients. In its course, the circumflex artery gives off one or more obtuse marginal branches (Figure 1.12 and Figure 1.13).

Venous drainage

The majority (75%) of venous blood drains via the coronary sinus into the RA. The coronary sinus is 2–3 cm in length and lies adjacent to the circumflex artery in the left posterior A-V groove. Its principal tributaries are the great, small, middle and posterior LV cardiac veins (Figure 1.14).

The anterior cardiac veins drain the anterior part of the RV and empty directly into the RA.

The diminutive Thebesian veins may empty into any of the cardiac chambers and account for a small amount of venous drainage. Those draining into the left heart contribute to the "anatomical shunt".

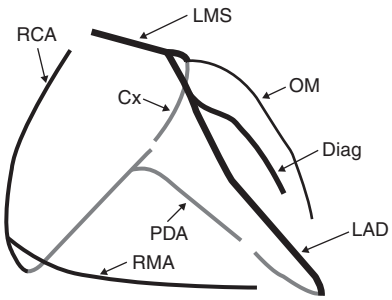


Figure 1.12 The anatomy of the coronary arteries. LMS, left main stem; RCA, right coronary artery; Cx, circumflex; OM, obtuse marginal; Diag, diagonal; LAD, left anterior descending; PDA, posterior descending artery; RMA, right marginal artery.

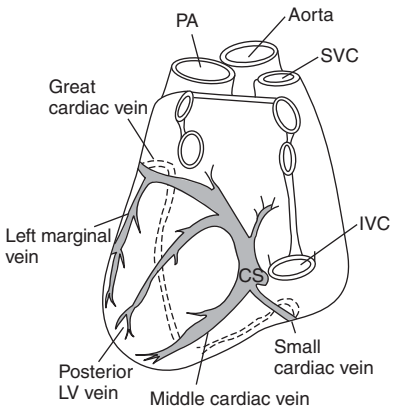
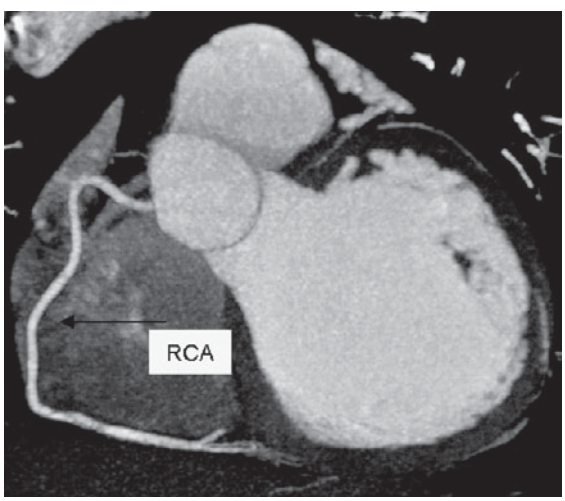


Figure 1.14 Posterior view of the heart showing the anatomy of the coronary sinus (CS) and cardiac veins.



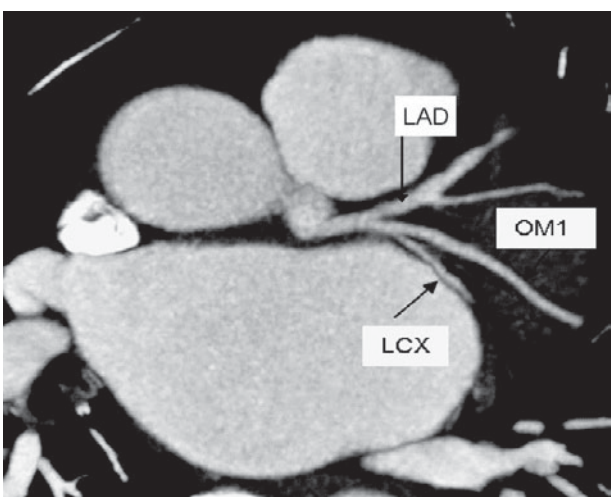


Figure 1.13 CT images showing the right- and left-sided coronary circulation. RCA, right coronary artery; LAD, left anterior descending artery; LCX, left circumflex artery; OM1, first obtuse marginal artery.

Key points

- Knowledge of cardiac embryology is necessary to understand congenital heart disease.
- The spiral pattern of the heart has implications for myocardial structure and function.
- In the fetal circulation, oxygenated blood is directed across the foramen ovale into the LA to supply the head and arms.
- The posterior descending artery arises from the right coronary artery in 85% of patients.
- The venous drainage of the anterior RV does not enter the coronary sinus.

Further reading

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Section 1 **Anatomy and physiology**

Chapter 2

Cardiac electrophysiology

Stefan G. De Hert

Anesthesiologists may witness cardiac arrhythmias either as an existing comorbidity, or as a perioperative complication. In both instances, the occurrence of such arrhythmias may have significant consequences on outcome.

Anatomy

When in sinus rhythm the heart beats in an orderly sequence. Specialized cardiac muscle cells (myocytes) in the sinoatrial (SA) node generate cardiac action potentials (APs), which cause normal myocytes to contract. APs are transmitted through the heart via the conducting system (Figure 2.1).

The cells of the conducting system are modifications of general cardiac myocytes, and classified; as *nodal*, *transitional* and *Purkinje* myocytes (Table 2.1). All myocytes in the conducting system are capable of spontaneous, rhythmic generation of cardiac APs. The anatomy and physiology of this system ensures

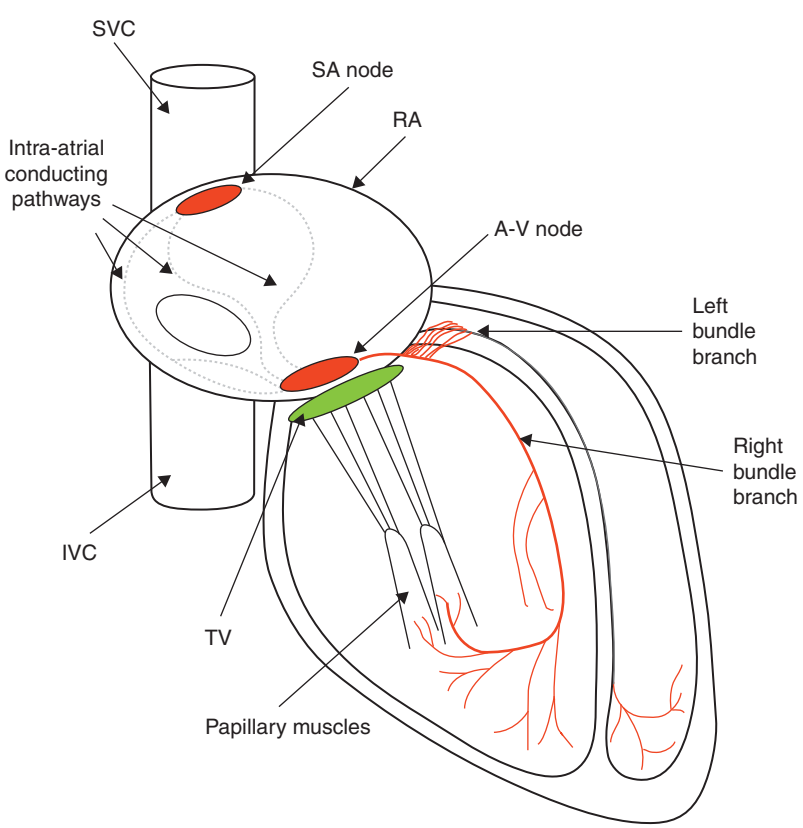

Figure 2.1 The cardiac conducting system.

Core Topics in Cardiac Anesthesia, Second Edition, ed. Jonathan H. Mackay and Joseph E. Arrowsmith. Published by Cambridge University Press.

Table 2.1 AP conduction velocities in the cardiac conducting system

Tissue	Myocyte type	Conduction rate (m s^{-1})
SA node	Nodal	0.05
Intra-atrial pathways	General and Purkinje	1
AV node	Transitional	0.05
Bundle of His	Transitional and Purkinje	1
Purkinje system	Purkinje	4
Myocardium	General	0.6

that atrial systole precedes ventricular systole. Whichever focus produces an AP most frequently acts as the pacemaker – in sinus rhythm this is the SA node.

SA node

The SA node lies within the right atrial (RA) wall in a groove at the junction of the superior vena cava (SVC) and RA. Macroscopically it is a flattened ellipse possessing a "head", "body" and "tail", measuring $10 \times 3 \times 1$ mm and often covered by a plaque of subepicardial fat.

The SA node is supplied by the right coronary artery (RCA) in 65% of hearts, and by the circumflex branch of the left coronary artery (LCA) in 35%. The largest branch of the SA nodal artery – the *ramus cristae terminalis* – runs through the center of the SA node. It has a large lumen and thick adventitia, knitting firmly with a thick collagenous network of connective tissue within the node. It has been suggested that this structure might function as a baroreceptor for the atrial natriuretic peptide homeostatic system. It might be expected that rhythmically discharging excitable cells have a high oxygen demand, but there are surprisingly few branches within the node. The majority of the blood flows onwards to perfuse the RA.

Pacemaker cells are nodal myocytes lying within the core of the node. Arranged in clusters, each cell has one large nucleus and pale cytoplasm containing few organelles. They are non-contractile, possessing a small number of myofibrils arranged randomly.

Intra-atrial conduction pathways

It was initially thought that the cardiac AP was conducted between the SA node and atrioventricular node (AVN) as a wave of depolarization spreading radially via gap junctions between general atrial myocytes. However, the cardiac AP reaches the AVN more quickly than would be expected had it been passing through ordinary myocardium. In fact there are three specialized conducting pathways consisting of Purkinje fibers in the atria; the *anterior*, *middle* and *posterior internodal tracts*.

Atrioventricular node

The AVN is an oval structure measuring $8 \times 3 \times 1$ mm. It lies within the atrial septum and has a surface in the RA near the basal attachment of the septal leaflet of the tricuspid valve, and a surface in the LA adjacent to the mitral valve annulus.

Microscopically the center of the AVN contains a small number of nodal myocytes, surrounded by a fibrous network of long transitional myocytes – similar to that of the SA node but less dense. Transitional myocytes provide an electrical link between the nodal P cells and more distal parts of the conducting system. They have a smaller diameter than general cardiac myocytes but possess similar organelles and contractile apparatus. Cardiac APs are conducted slowly in the AVN and are therefore likely to be responsible for normal A-V conduction delay. Under normal circumstances, these cells are the only electrical link between atria and ventricles, as these chambers are electrically insulated from each other by a fibrous annulus.

The first and largest branch of the posterior septal branch of the RCA supplies the AVN in 80% of hearts; otherwise the node derives its blood supply from the left circumflex artery.

Accessory conducting pathways

In addition to the AVN, accessory conducting pathways may form abnormal electrical connections between the atria and ventricles. These pathways are caused by disordered cardiogenesis and consist of normal cardiac myocytes or specialized conducting tissue. In these circumstances there is incomplete formation of the mitral or tricuspid fibrous annuli that electrically insulate the atria from the ventricles. Depending on the relative refractory periods of the normal AV nodal and the accessory conducting pathways, circumstances may arise when excitation passes retrogradely into the atria through the accessory pathway having already traversed the fibrous annulus via the AVN. This may trigger a re-entrant tachycardia,

such as that seen in patients with Wolff–Parkinson–White syndrome.

His and Purkinje system

The tracts of transitional myocytes running from the AVN narrow quickly as they pass through the fibrous annulus into the interventricular septum (IVS). The common bundle is then said to branch into the left and right bundles at the crest of the IVS. In fact, it is somewhat misleading to consider the branching as a simple bifurcation.

The right bundle runs as a discrete aggregation of fascicles until it reaches the anterior papillary muscle of the tricuspid valve where it splits into a fine network of subendocardial Purkinje fibers, which form a network throughout the RV.

The left bundle is a flat sheet of fine fascicles, which leave the left margin of the common bundle throughout its course towards the IVS. The sheet passes over the LV aspect of the IVS and runs towards the apex of the LV. After 3 cm it splits into anterior and posterior fascicles, maintaining the sheet-like arrangement. The anterior sheet runs towards the anterior papillary muscle of the mitral valve, and the posterior sheet towards the posterior papillary muscle. After reaching the papillary muscles, both sheets split into fine Purkinje networks penetrating the whole of the LV wall and IVS. The networks consist of Purkinje cells, which are wider and shorter than the surrounding general myocytes.

The cytoplasm of Purkinje cells is packed with mitochondria and glycogen, and there is a large sarcoplasmic reticulum, but very few myofibrils. This apparatus provides the copious amounts of energy needed for the rapid conduction of APs. The Purkinje networks have large and numerous nexuses, interdigitating with general cardiac myocytes, allowing efficient conduction of the AP to the myocardium.

Electrophysiology

The cardiac action potential

The normal resting membrane potential (RMP) of cardiac myocytes varies between −60 and −90 mV. The RMP, which is mainly determined by the equilibrium between intracellular and extracellular potassium. The equilibrium potential for potassium (E_K) is given by the Nernst equation:

$$\mathbf{E_K = -61\ log[K^+]_i/[K^+]_e}$$

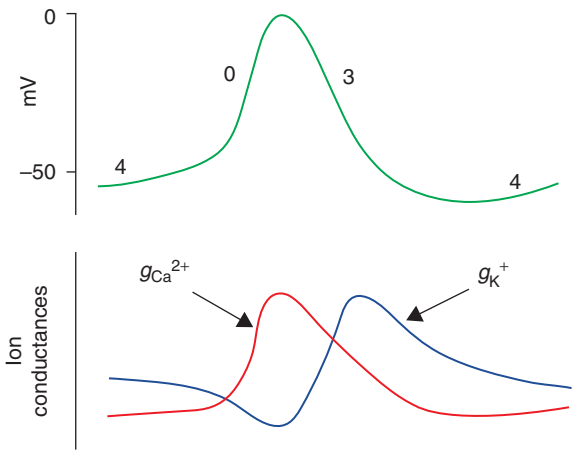

Figure 2.2 The sinoatrial node action potential. Spontaneous diastolic depolarization (the pacemaker potential) is thought to occur as a result of decreasing K^+ conductance and slightly increased Ca^{2+} conductance.

where $[K^+]_i$ and $[K^+]_e$ are the intracellular and extracellular potassium concentrations respectively. For example, if $[K^+]_i = 150$ mM and $[K^+]_e = 4$ mM, then EK = −96 mV. The electrophysiological differences between nodal and ventricular myocytes can be explained on the basis of differences in ion channels and mechanisms of polarization.

The unique property of spontaneous depolarization at the level of the SA node cells (cardiac muscle automaticity) allows for the pacemaker activity. Unlike atrial and ventricular muscle, pacemaker tissue is characterized by an unstable RMP, secondary to a decrease in K^+ conductance (gK^+) and a small increase in Ca^{2+} conductance (gCa^{2+}) through transient (T-type) channels thought to underlie the so-called pacemaker potential or pre-potential (Figure 2.2).

The cardiac AP typically consists of five distinct phases (Figure 2.3).

Phase 0: rapid depolarization phase is due to the rapid influx of Na^+ ions into the myocyte via fast Na^+ channels. The slope of phase 0 represents the maximum rate of depolarization of the cell and is steep (almost vertical) in the ventricle. In atrial pacemaker tissue, depolarization is primarily the result of slower Ca^{2+} influx via L-type channels. As a result, the slope of phase 0 in the sinoatrial and the AVN tissue is flatter than in the ventricle.

Phase 1: early repolarization is caused by an increase in K^+ conductance. Complete repolarization is delayed by a simultaneous increase in Ca^{2+}