

## Section I

### Cardiac Anatomy and Physiology

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## 1

## Cardiac Anatomy

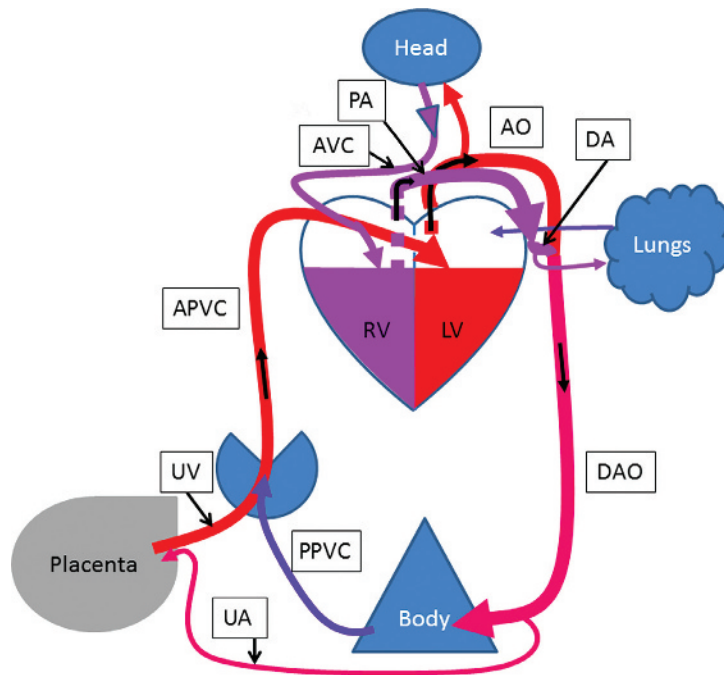
*H. Edward Durham, Jr.*

### Fetal Circulation and Transition to Adult Circulation

Any study of cardiology begins with a complete and thorough understanding of the anatomy of the heart and its physiology. Understanding the arrhythmias, the cardiac disease process, congenital heart conditions and mechanisms of treatment all stem from a working knowledge of the cardiac anatomy and physiology. The general arrangement of the circulatory system is two circuits in series; two separate circulatory paths where the end of one feeds into the beginning of the other. However, the circulation did not start out this way.

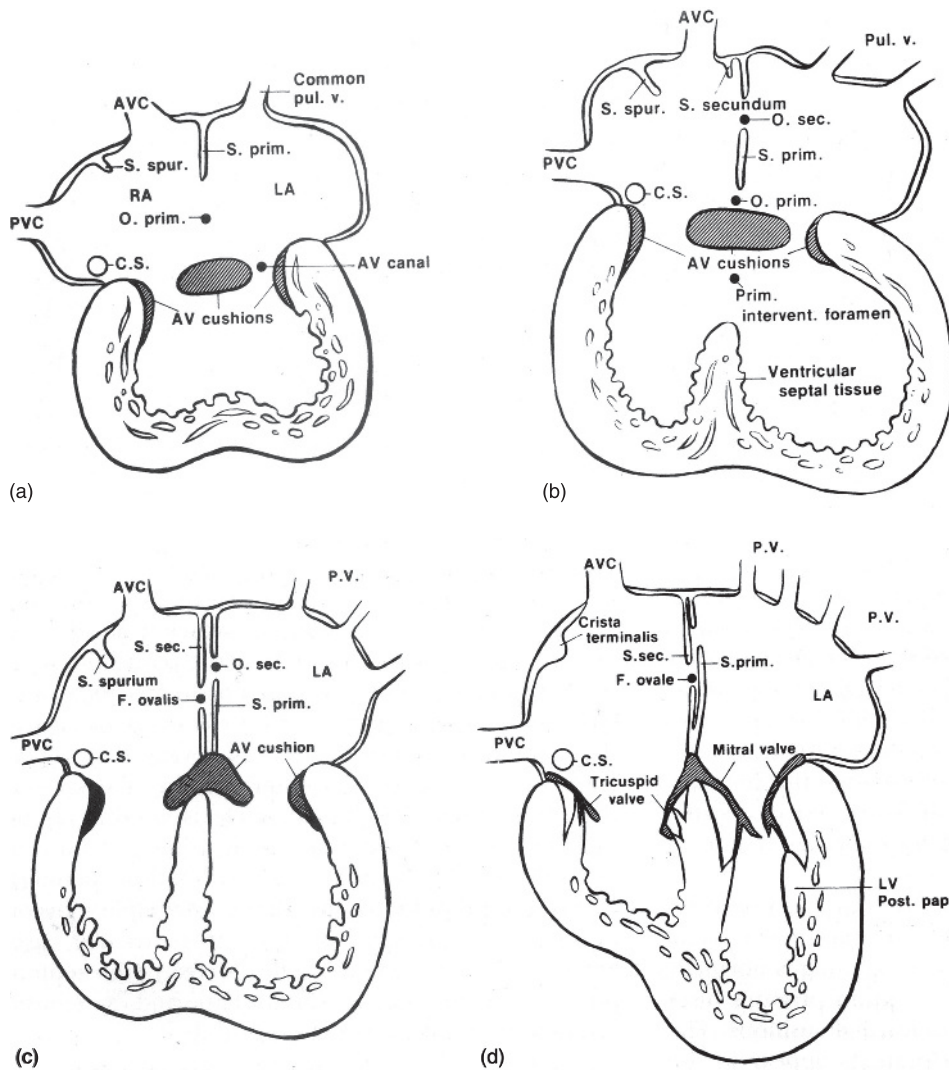
In the fetus, circulation is a double circulation in parallel or two circulatory paths that cross over each other at strategic areas to incorporate placental blood flow and bypass the unused lungs (Figure 1.1). As highly oxygenated blood enters the fetus from the placental vein (*vein* because it carries blood toward the heart), it passes through the liver where it mixes with the deoxygenated blood of the lower body. From here it travels to the right atrium and is shunted almost directly into the left atrium. At this point, there is very little mixing with deoxygenated blood from the head and forelimbs due to the anatomic proximity of the posterior vena cava to the fossa ovalis, which channels the blood almost directly into the left atrium. This blood is still highly oxygenated and travels to the left ventricle and out of the aorta. At this stage, further mixing occurs, with some highly oxygenated blood travelling to the head and some mixing with deoxygenated blood from the right ventricle via the pulmonary artery and then the ductus arteriosus. This mixed blood then travels to the lower body and to the placenta to be remixed into the maternal circulation. It still carries enough oxygen to supply the lower extremities with all the nutrition that is needed. The highly oxygenated blood from the left ventricle flows directly to the head and forelimbs to ensure a highly oxygenated blood supply to the developing brain. Deoxygenated blood from the head and forelimbs then returns to the right atrium of the fetal heart and out of the pulmonary artery to mix as previously described. The circulation continues in this manner until birth.

During the last phases of cardiac development, as the atrial septum develops, the fossa ovalis transforms into the foramen ovale (Figure 1.2). The foramen ovale develops as a one-way valve through the interarterial septum that allows oxygenated blood to pass from the right atrium to the left, as the fossa ovalis did. The valve eventually closes to stop blood from shunting from the left atrium to the right in the adult.



**Figure 1.1** A simplified schematic of circulation in the fetus. Oxygenated blood enters the fetal circulation from the *umbilical vein* (UV) via the *ductus venosus* into the anterior portion of the *caudal vena cava* (APVC) in the liver. The oxygenated blood travels to the *right atrium* where the majority is shunted through the *foramen ovale* to the *left atrium* then into the *left ventricle* (LV). A small portion mixes with venous blood returning from the head, then travels to the *right ventricle* (RV). During fetal cardiac systole, the mixed oxygenated/deoxygenated blood from the right ventricle is pumped into the *main pulmonary artery* (PA) through the *ductus arteriosus* (DA) and into the *descending aorta* (DAO). A very small portion of this mixed blood bypasses the ductus arteriosus and enters the pulmonary arterial system (PA) to provide oxygen to the lung tissue and returns to the left atrium through the *pulmonary veins*. Simultaneously, the fully oxygenated maternal blood is pumped from the left ventricle into the aorta (AO), up the carotid arteries to the cranial fetus, as well as to the caudal portion of the fetus. The blood delivered to the cranial fetus has the most oxygen content; while the blood delivered to the caudal fetus carries less oxygen because of the mixing that occurs in the descending aorta distal to the ductus arteriosus. Although this blood has less oxygen than the cranial blood, it will still deliver sufficient oxygen to the caudal fetus to nourish the tissue before passing through the caudal capillary vessels and returning through the posterior portion of the caudal vena cava (PPVC) to the liver. Blood from the fetus is returned to the placenta through the *umbilical artery* (UA), which exits the fetal circulation at the iliac arteries. Red, fully oxygenated blood. Purple, mostly deoxygenated blood. Red–Purple, mixed oxygenated/deoxygenated blood. AVC, anterior caudal vena cava.

It is at parturition and shortly thereafter that two systems in series finally develop. This process starts with the first breath, which drops pulmonary vascular resistance dramatically. Simultaneously, the placental circulation is removed, which increases systemic vascular resistance and reverses the blood flow through the ductus arteriosus to move blood from the aorta to the pulmonary artery. The tissue of the ductus arteriosus is highly sensitive to oxygen. When exposed to the increased oxygen content of the arterial blood in the aorta, the musculature of the ductus arteriosus constricts and closes



**Figure 1.2** (a–d) Septal development of the heart. The development of ventricular and atrial septa and formation of atrioventricular valves by the AV endocardial cushions (from the post-loop stage to late fetal development). AVC, anterior vena cava; CS, coronary sinus; LA, left atrium; LV left ventricle; PV, pulmonary veins; PVC, posterior vena cava; RA, right atrium; Common pul. v., common pulmonary vein; S. spur., septum spurium; S. prim., septum primum; O. prim., ostium primum; S. secundum, septum secundum; O. sec, ostium secundum; Prim. Intervent. foramen, primary interventricular foramen; Pul.v./P.V., PV; F. ovalis, fossa ovalis; F. ovale, fossa ovale; Post. Pap, posterior papillary muscle. Source: Fox (1999) [1]. Reproduced with permission of Elsevier.

the communication. The net effect of these changes is to decrease the volume of blood flowing through the right side of the heart and increase it in the left. These changes cause the pressure in the left atrium to increase which functionally closes the foramen ovale and finally separates the two circulations.

In the fetus the size of the individual ventricles is equal and their relationship stays the same for about 10 days after parturition. Over the first few weeks of life, the systemic blood pressure rises and pulmonary pressures remain static; this increased workload changes the size of the left ventricle. By about 2 weeks of age, the proportions of the two ventricles are that of an adult with the right ventricle being about one-third as thick as the left. During the next 4 weeks cardiac growth converts from *hyperplasia* to *hypertrophy* (growth in cardiac mass by myocyte enlargement rather than division). From this stage on all increases in cardiac mass are related to hypertrophy, either concentric or eccentric, which will be discussed in Chapter 2 (Cardiac Physiology).

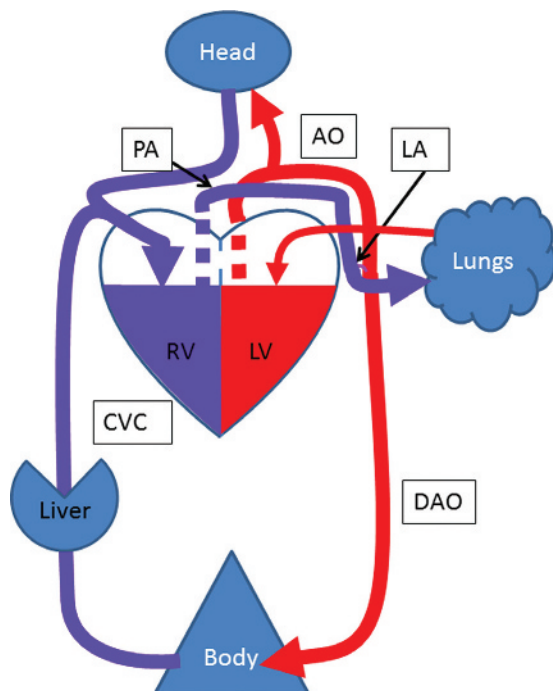
## Anatomy of the Adult Heart [1]

The purpose of the heart is to move blood through the circulatory system. To accomplish this, the heart utilizes a muscular contraction (a pump) activated by an electrochemical stimulus. This electrostimulus is conducted down special conduction tissue within the muscular pump. Understanding the structure of both of these components (the electrical conduction and the muscular pump) is critical for understanding cardiac physiology. In this chapter they will be discussed separately.

The heart is situated within the cranial thoracic cavity between the third and sixth rib spaces, with the base (top) dorsal to the costochondral junction near the cranial midline, and the apex (bottom) slightly toward the left thoracic wall caudally. It is completely surrounded by the lungs except for a small inverted “v” shaped notch in the right hemithorax between the right cranial and right caudal lung lobes. The great vessels carrying blood from the left and right ventricles, the aorta and pulmonary artery respectively, leave the heart at the craniodorsal aspect.

The heart is enclosed in a tough fibrous sac known as the pericardium. The pericardium contains a very small amount of fluid; approximately 0.2–5 mL depending on body size. The pericardium is composed of three layers: the outer fibrous layer, and the serous layer which is further divided into the parietal and visceral layers. The visceral layer is the outer layer of the heart itself and is called the *epicardium*. The pericardium is attached to the cranial mediastinum and the diaphragm which helps hold the heart in place within the thoracic cavity. The vagus nerve runs over the pericardium to the diaphragm and gut. A branch of the vagus nerve innervates the heart.

The heart itself is a four-chambered muscular structure that moves blood throughout the body and lungs, and as mentioned earlier, it constitutes the pump of a double circulation in series (Figure 1.3). The path of blood flow through the system begins with the left ventricle, proceeds to the aorta, and is distributed throughout the arterial vasculature, also referred to as the *systemic circulation*. Arteries are defined as vessels moving blood away from the heart, and veins are the vessels that return blood toward the heart. Blood then moves into progressively smaller arteries, arterioles and eventually into the capillaries to transfer nutrients and oxygen to the tissues. Also in the capillary system, waste byproducts of metabolism are collected and transported away from the tissues. The blood is then moved into venous capillaries, venules and finally to larger veins to be carried back to the heart through systemic veins.

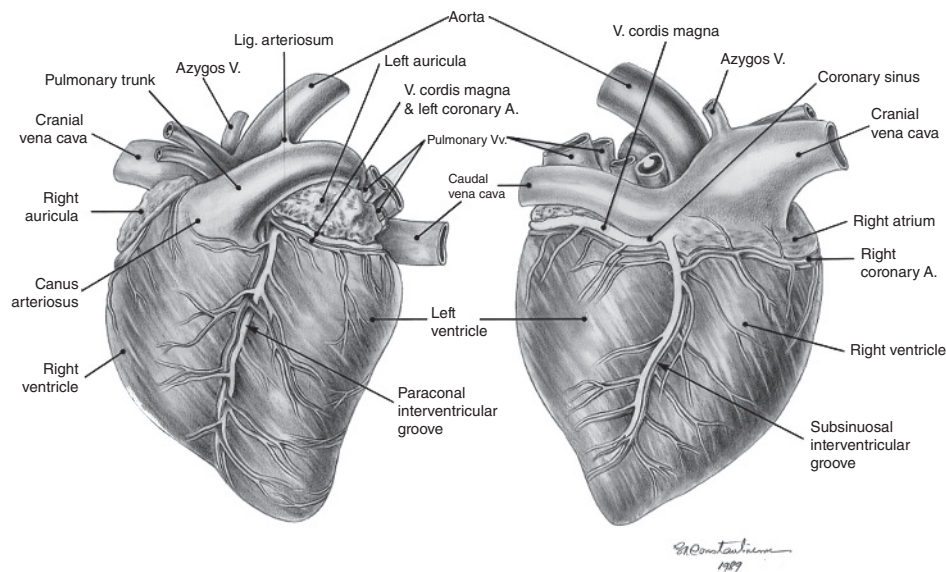


**Figure 1.3** Post-parturition circulation. Starting in the left ventricle (LV), blood is ejected past the aortic valve and into the ascending aorta during ventricular systole. This oxygenated blood is distributed to the organs and tissues through the branching of the systemic arterial system from the aorta (AO). The first branches off the aorta are the left subclavian and common carotid arteries, exiting at the aortic arch, in most mammalian species. The other arteries exit the aorta from the descending aorta (DAO). As the oxygenated blood distributes through the body it passes through the arterioles then finally into the capillaries of each individual tissue. In the capillaries, oxygen is delivered and carbon dioxide is taken up. The blood then travels back toward the right atrium via the venous capillaries, venules and eventually veins, which drain in the venae cavae. There are two venae cavae in mammals; the cranial vena cava, and the caudal vena cava (CVC), which both return deoxygenated blood to the right atrium. During ventricular diastole, the deoxygenated blood passes through the tricuspid valve into the right ventricle (RV). From the right ventricle the blood is pumped into the lungs through the pulmonary artery (PA) where carbon dioxide is released through the blood-gas barrier in the alveoli and oxygen is taken up. After parturition the ductus arteriosus closes becoming the ligamentum arteriosum (LA), allowing blood to circulate through the pulmonary vasculature. The newly oxygenated blood is returned to the left atrium through the pulmonary veins. Blood then moves from the left atrium to the left ventricle past the mitral valve during ventricular diastole, to start the cycle anew.

The heart is divided along its long axis by two septa, the *interventricular*, that divides the ventricles or pumping chambers and the *interatrial* that divides the atria, the receiving chambers. The heart is additionally divided transversely by two valves that direct flow from the atria to the ventricles.

In viewing the exterior of the heart, multiple structures can be readily identified. From the ventral surface the auricular appendages are pointing at the observer. The right atrial appendage is more prominent than the left since the right atrium is positioned more to the dextralateral aspect of the heart and the left is positioned more to the posterior. The

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**Figure 1.4** A horse heart: left (auricular) aspect, and right (atrial) aspect. The drawing on the left shows the ventral surface of the heart. The *paraconal interventricular groove* demarcates the separation of the right and left ventricles. The interventricular septum is beneath this groove. The main pulmonary artery can be seen exiting the right ventricle arching dorsal over the left ventricle to the lungs. Note the *ligamentous arteriosum* connecting the pulmonary artery and the aorta. This is the location of the *ductus arteriosus* in the fetus. The illustration on the right depicts the dorsal aspect of the heart. Notable features include the cranial and caudal vena cavae, and the coronary sinus. Azygos V., azygos vein; Lig. arteriosum, ligamentous arteriosum; V. cordis magna and left coronary A., vena cordis magna and left coronary artery; Pulmonary Vv., pulmonary veins; V. cordis magna, vena cordis magna; Right coronary A., right coronary artery. Source: courtesy of Constantinescu (1991) [3].

left coronary artery is apparent coursing toward the apex of the heart in the *paraconal groove* separating the right and left ventricles (Figure 1.4). Several smaller branches of the left coronary artery can also be appreciated. The cardiac apex consists of the bottom portion of the left ventricle divided from the right ventricle along the *paraconal groove*. Running parallel with the left coronary artery is the great coronary vein. Cranial to the *paraconal groove* is the right ventricular outflow tract leading to the pulmonary artery. The aorta exits the heart at the central cranial aspect.

From the dorsal surface the other coronary arteries can be seen, including the circumflex branch of the left coronary artery and the *subsinuosal interventricular branch*. The cranial and caudal vena cava can be identified entering the right atrium. The four pulmonary veins returning blood from the lungs entering the left atrium are also noted just above the coronary sinus as it traverses the heart bringing blood from the left ventricle to the right atrium (Figure 1.4). From this view the left auricle is seen beneath the pulmonary trunk, as well as the posterior portion of the right atrium as it extends laterally then anteriorly.

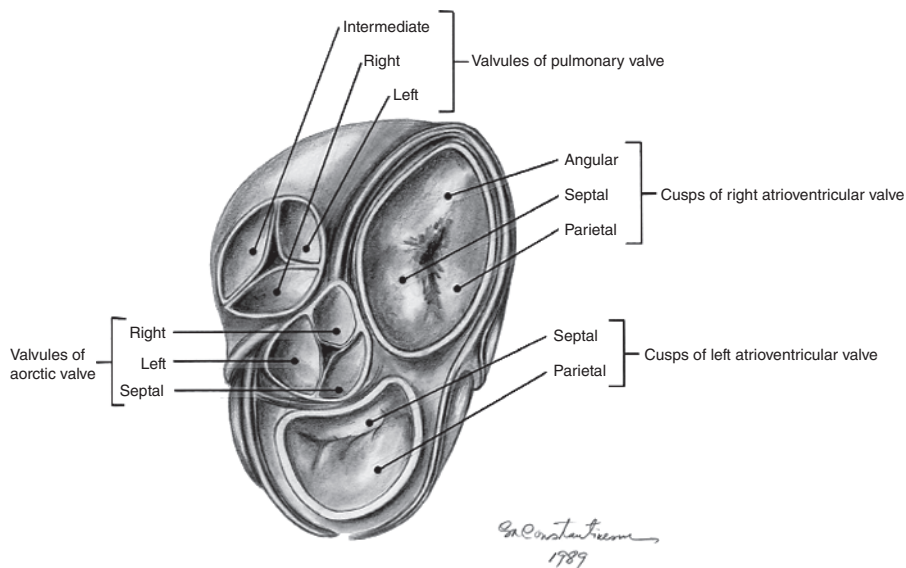


## Internal Structure

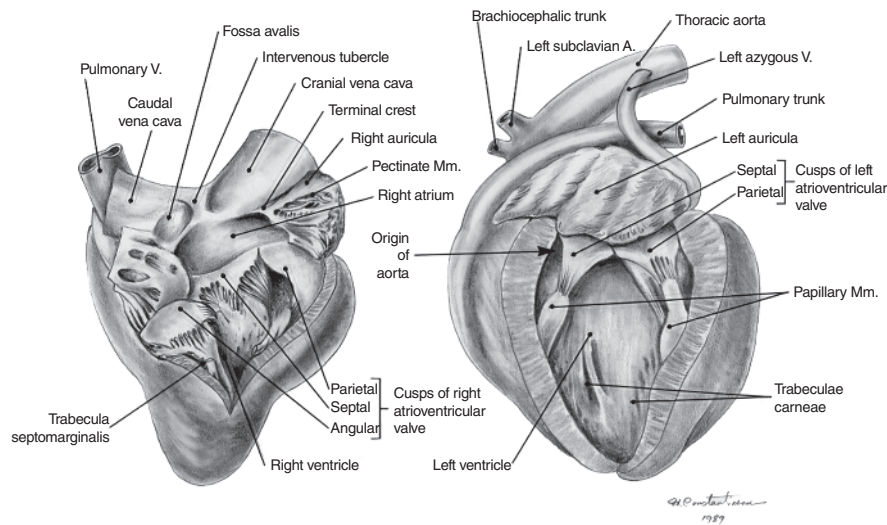
Histologically, the heart is made up of three layers: the *endocardium*, which lines the inner surfaces, the *myocardium* which is the muscular portion, and the *epicardium* which is also the visceral pericardium. The heart has a fibrous “skeleton” that helps form the structure at the base of the heart and insulates the atrial tissue from ventricular tissue electrically. In doing so, all supraventricular electrical impulses are directed into the atrioventricular (AV) node of the conduction system which will be discussed on p. 17. The fibrous skeleton also forms the framework from which the valves are attached. The formation of the *AV fibrous rings*, *aortic fibrous ring* and the *pulmonic fibrous ring* create the annulus for each valve, to which the valve leaflets are attached (Figure 1.5).

At the top of the heart, cranial to the valves, are the right and left atria. The atria function as the collecting chambers that hold blood during ventricular systole to fill the ventricle during the next ventricular diastole. Both atria are thin walled (0.5–2 mm thick depending on species and breed) and have auricular appendages that project ventrally which are lined with pectinate muscles.

The left atrium receives oxygenated blood returning from the pulmonary circulation via the pulmonary veins of which there are typically four to six. The inflow to the left



**Figure 1.5** A horse heart: atrioventricular and arterial valves and the individual cusps of the four cardiac valves. This view of the heart shows the dorsal aspect of the ventricle, with the atria removed at the level of the valve orifices. Using the clock face analogy: the tricuspid valve is at 6 o'clock, the pulmonic valve is at 9 o'clock to 10 o'clock, the mitral valve runs from around 1 o'clock to around 3 o'clock. The aortic valve is situated in the middle. The inlet and outlet of the right ventricle are further apart than the inlet and outlet of the left ventricle, which are in extreme proximity. Individual leaflets or *cusps*, of the valves are labeled. The coronary arteries can be seen exiting from the near aortic valve; the *right main* coronary artery coming off at ~9 o'clock, and the *left main* coronary artery from ~12 o'clock. Source: courtesy of Constantinescu (1991) [3].



**Figure 1.6** Interior of a pig heart with the right ventricle opened, and left ventricle opened. The left image shows the right ventricle open to reveal the interior structures. The right atrium is also open to show the interior of the right atrium and vena cavae. The individual features are labeled including the cusps of the tricuspid valve. The right illustration is of the interior of the left ventricle, showing the mitral apparatus; papillary muscles, chordae tendineae, and cusps of the valve. The aorta is seen running behind the left atrium and pulmonary artery, exiting from the left ventricle deep to the mitral valve in this view. Pulmonary V., pulmonary vein; Pectinate Mm., pectinate muscles; Left subclavian A., left subclavian artery; Left azygous V., left azygous vein; Papillary Mm., papillary muscles. Source: courtesy of Constantinescu (1991) [3].

ventricle is controlled by the *left AV valve* or *mitral valve*. The right atrium receives blood from the systemic venous system for delivery to the right ventricle. It has three inlets: the cranial vena cava, the caudal vena cava and the coronary sinus. It also has one outlet through the right AV valve or *tricuspid valve*. Another noteworthy structure of the right atrium is the *interventricular tubercle* (Figure 1.6); a small ridge of tissue which is a remnant of the *septum spurium* of cardiac development and helps direct blood returning from the vena cava toward the tricuspid valve. The fossa ovalis can be seen along the interatrial septum, on the right atrial side.

The ventricles constitute the majority of the heart and together form its conical shape. The two ventricles share a common muscular *interventricular septum* (IVS). The IVS contributes to the interlinking of the ventricular contraction maximizing energy consumption. The left ventricle forms the cardiac apex with the right ventricle wrapped around it. The left ventricle normally has the greater mass. The left ventricular inflow and outflow tracts are in extreme proximity with the anterior leaflet of the mitral valve separating the two during diastole making a cone like configuration; in contrast to the right ventricle in which the inflow portion and the outflow tract are at opposite ends of the “U” shape of the ventricle, creating a crescent shaped chamber “wrapping around” the left ventricle. The left ventricle is situated caudodorsal to the right.

The left ventricle is the high pressure system of the two circulations as it moves blood from the low pressure of the pulmonary system to the relatively high pressure of the systemic circulation. The free wall is approximately two-and-a-half to three times the thickness of the right ventricular free wall; left ventricular diastolic wall thicknesses

range from 0.5 cm in small breed dogs to 1.0 cm or more in giant breeds. The left ventricle contains, within its lumen, papillary muscles with attached *chordae tendineae* leading to the mitral valve (Figure 1.6). Two papillary muscles are most common, but split or triple papillary muscles are not uncommon. The papillary muscles project from the apical portion of the ventricle toward the AV valves. The chordae tendineae are fibrous strands that attach the papillary muscles to the mitral valve leaflets. Blood flow into the ventricle enters via the mitral valve and exits out of the aorta. Forward flow is maintained by closure of the mitral valve during systole and closure of the aortic valve during diastole. The area immediately leading to the aortic valve narrows, forming a funnel shape, and is known as the left ventricular outflow tract.

The right ventricle pumps blood from the systemic venous circulation to the lungs. Along the inner surface of the right ventricle are muscular ridges known as *trabeculae carneae*, which are not typically present in the left ventricle. Papillary muscles and chordae tendineae are also attached to the tricuspid valve from the apex of the right ventricle. Additionally, *trabeculae septomarginalis* or moderator bands may at times be seen traversing the right ventricle. These thin bands of tissue often contain conduction tissue and can lead to the free wall or papillary muscles. They can also be present in the left ventricle.

The four cardiac valves (Figure 1.5) control the direction of blood flow through the heart. The right and left AV valves are also known as the tricuspid and mitral valves respectively. *Semilunar valve* is a term sometimes used to refer to the ventricular outflow valves collectively due to the half-moon shape of their cusps. The left ventricular outflow valve is the *aortic valve*, and the right ventricular is the *pulmonic valve*.

The AV valves are more accurately a valve apparatus, consisting of several components. The valve annulus is the anchor point for the valve leaflets or *cusps* and is part of the fibrous skeleton of the heart. The leaflets physically retard blood flow when they are closed. The cusps are attached on their ventricular surface to papillary muscles by the chordae tendineae. During systole, the papillary muscles contract, tightening the chordae tendineae and keeping the cusps closed against the rising ventricular pressure. If any of these components are damaged then the function of the valve may be compromised.

The mitral valve is the more robust of the two AV valves, and unless diseased is able to remain competent under pressures over 200 mmHg. It is sometimes referred to as the *bicuspid* valve since it has two leaflets: an anterior leaflet that is nearly contiguous with the aortic valve and a posterior leaflet attached near the left ventricular free wall. During systole the mitral valve prevents blood from the left ventricle flowing into the left atrium. This also protects the pulmonary venous circulation from the relatively high pressures of the left ventricle during systole.

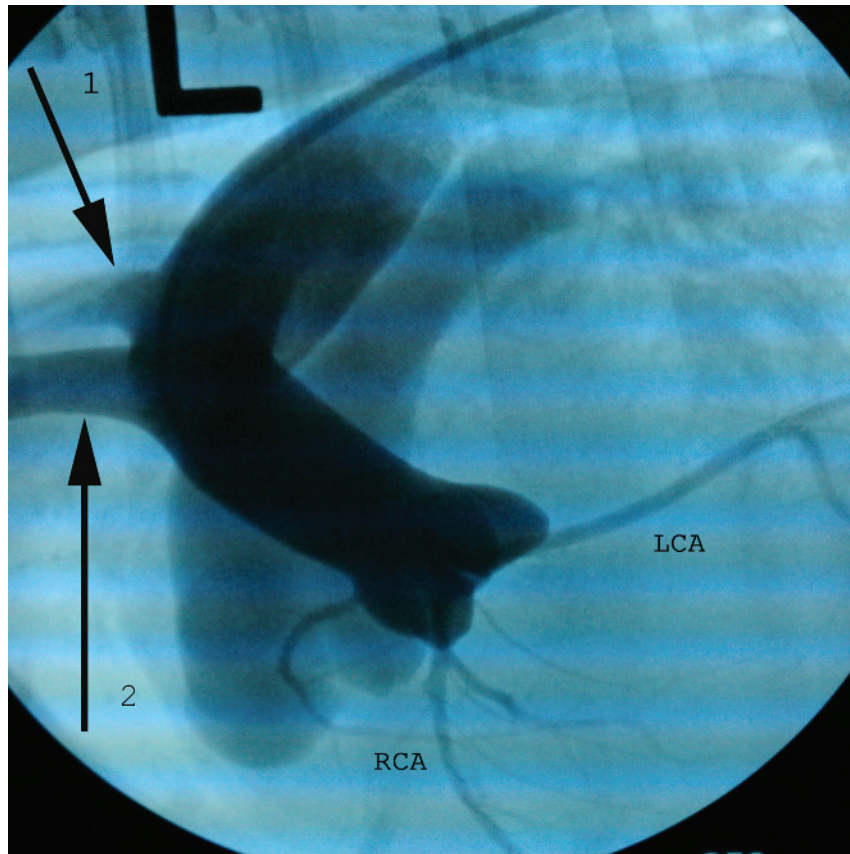
The tricuspid valve of the right heart is similar to the mitral valve in that it also has two leaflets. The term “tricuspid” is borrowed from human medicine to indicate the right AV valve; although in some dogs an extra smaller cusp of tissue can be appreciated. The tricuspid valve is suitably strong to withstand normal right ventricular pressure (25–35 mmHg systolic) but will often become incompetent at pressures much above this.

Semilunar valves have a fibrous annulus and three cusps, but do not have associated chordae tendineae or papillary muscles. In the pulmonic valve the cusps are named *right*, *left* and *septal semilunar* cusps; for the aortic they are called *right coronary*, *left coronary* and *non-coronary* cusps (Figure 1.5). They are operated by the flow of blood through their associated vessels. As blood is ejected from the ventricle the valves open, then as

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flow ceases and the residual pressure in the great vessels allows blood to flow backward toward the ventricle, the valves close from this pressure. This closure stops the blood from returning to the ventricle and in doing so maintains a diastolic pressure in the circulation necessary for a pressure gradient across the capillary bed while allowing left ventricular pressure to fall to zero or below.

The great vessels carry blood from the heart beyond the semilunar valves. The aorta transports blood from the left ventricle to the systemic circulation of the body. The pulmonary artery carries blood from the right ventricle to the lungs or pulmonary circulation. The aorta leaves the cranial aspect of the ventricle from the center of the heart (*ascending aorta*) and arches (*aortic arch*) toward the caudal body running down the length of the torso along the spine (*descending aorta*). Branches exit the aorta along the arch to supply blood to the head and forelimbs. The number and configuration of these branches varies among species, but typically a *left subclavian trunk* and *brachiocephalic* branches are typically the first two major arteries to exit the aorta (Figure 1.7). Proximal



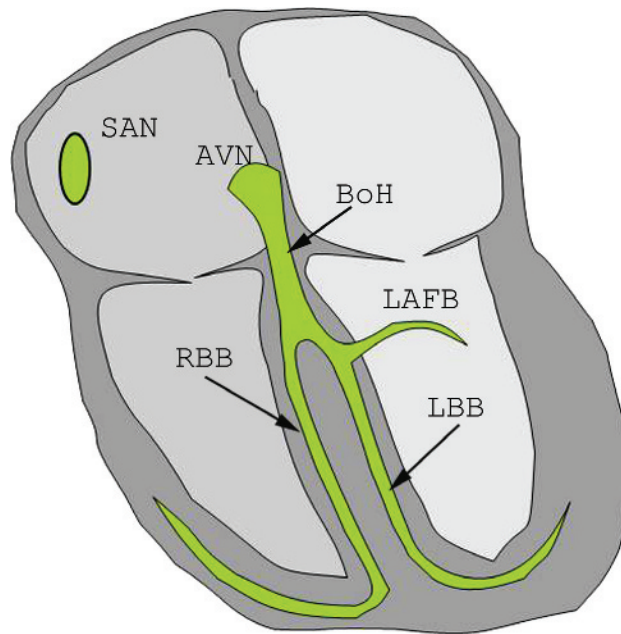
**Figure 1.7** A contrast angiogram of the proximal aorta and its arteries. The left subclavian artery (arrow 1) and brachiocephalic trunk (arrow 2) bifurcate from the aorta at the craniodorsal aortic arch. The left coronary artery (LCA) and the right coronary artery (RCA) can be seen exiting the aortic sinuses, demarcating the outer edge of the respective ventricles.

to the arch, the aorta widens just distal to the valve itself forming the *aortic sinuses* from which the coronary arteries arise (Figures 1.5 and 1.7).

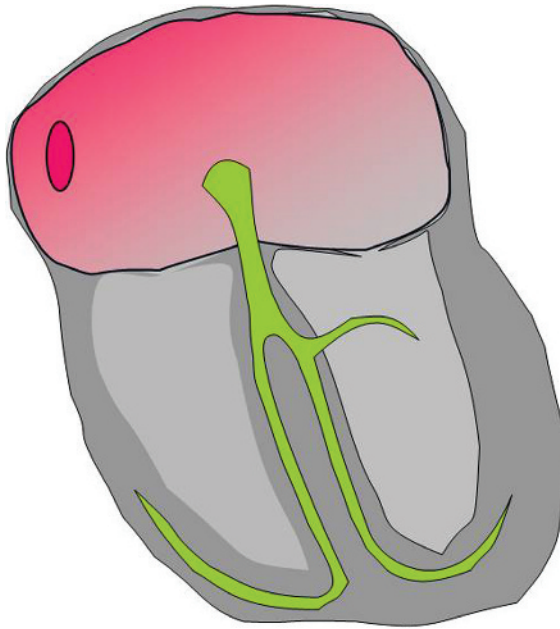
The pulmonary artery exits the right ventricle on the craniodorsal aspect of the heart and branches into two large arteries that carry blood to the right and left set of lungs (Figure 1.4). The section from the pulmonic valve to the bifurcation is called the *main pulmonary artery* and each branch is named for which lung group it feeds; the *right pulmonary artery* or *left pulmonary artery*. Just proximal to the bifurcation the *ligamentum arteriosum* can be seen attached to the aorta, where these two vessels cross at nearly right angles. This structure is the remnant of the *ductus arteriosus* seen in the fetal circulation.

### Cardiac Conduction System

An important part of cardiology and cardiac anatomy is the electrical conduction system of the heart (Figure 1.8). This specialized tissue within the heart allows for very rapid yet controlled depolarization of the myocardium. The cells that make up the



**Figure 1.8** The cardiac conduction system. The sinoatrial node (SAN) is located in the right atrial wall. This cluster of cells has the fastest automaticity and generally drives the intrinsic heart rate. The SA node is innervated by both the sympathetic and parasympathetic nervous systems. The atrioventricular node (AVN) is located at the posteroventral region of the interatrial septum near the opening of the coronary sinus. This location puts it very close to the ventricle. The depolarization impulse is transferred through the fibrocardiac skeleton via the bundle of His (BoH). The bundle of His then divides into the right bundle branch (RBB) and the left bundle branch (LBB), which further splits off to a left anterior fascicle branch (LAFB) and a left posterior fascicle (not shown). Image courtesy of Virginia Luis-Fuentes, MRCVS, DACVIM.



**Figure 1.9** Atrial depolarization, showing the atria in red as the depolarization waves move from the sinoatrial node across the atrial wall and toward the atrioventricular node. Image courtesy of Virginia Luis-Fuentes, MRCVS, DACVIM.

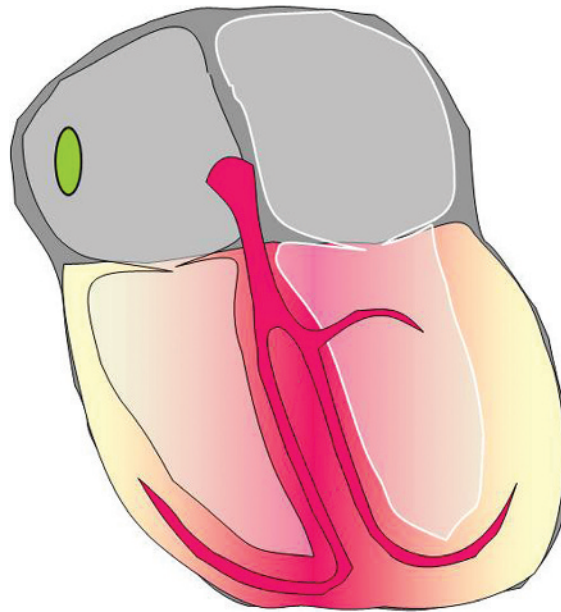
cardiac conduction system are non-contractile, but are designed to depolarize very rapidly, transmitting the current to the next cell.

Cardiac depolarization originates within the *sinoatrial node* (SAN) located at the confluence of the right atrium, the right auricular orifice, and the cranial vena cava. This small wedge-shaped group of cells is made up of histologically discreet specialized cells that demonstrate *automaticity*. Automaticity is the inherent property of a cell to depolarize itself over a period of time if it is not stimulated from an outside source first. The exact mechanism of this function will be discussed in Chapter 2.

The presence of specialized conduction tissue in the atria is not entirely clear. Some cells within the atrial myocardium have a propensity for electrical conduction and may serve as functional conductive pathways, but these cells are not histologically different than the other atrial myocardium. The Bachmann's Bundle was identified as a potential interatrial conduction group of cells. These are parallel aligned myocytes running between the atria, and have been associated with some atrial arrhythmias [2]. Their exact role and function is controversial, but they may assist moving the SAN depolarization through the atrial tissue. The depolarization wave generated by the SAN travels through the atrial myocardium spreading outward throughout the tissue and is re-concentrated at the AV node (Figure 1.9).

The ventricles have a complex conduction system that begins with the AV node (Figure 1.10). The AV node is situated just at the top of the ventricles in the intra-atrial septum, as it attaches to the ventricles. This mass of Purkinje cells conducts the depolarization wave somewhat slower than the rest of the conduction system. This allows for all the depolarization waves of the atria to collect in the AV node before passing through the fibrous skeleton to the faster conduction of the *bundle of His* or *common AV bundle*. The bundle of His then divides into the bundle branches near the top of the inner ventricular

**Figure 1.10** Ventricular depolarization, showing the depolarization of the bundle branches in red as the impulse is conducted out of the bundle branches to the ventricular Purkinje fibers, then to the myocytes. The sinoatrial node rests in the right atrium awaiting its next depolarization. Image courtesy of Virginia Luis-Fuentes, MRCVS, DACVIM.



septum. The right and left bundle branches can be identified and both run just beneath the subendocardium. The left further divides into posterior, anterior, and septal fascicles as it cascades toward the left ventricular apex finally spreading to the ventricular myocardium; each fascicle innervating a different portion of the left ventricle. The right bundle branch courses down the IVS subendocardially fanning out into the right ventricular free wall. Toward the ends of the bundle branches they become finer Purkinje fibers, finally terminating in the endocardium. The cardiac conduction system allows for rapid depolarization and contraction of all the myocytes nearly simultaneously.

Control of cardiac rate is accomplished with both sympathetic and parasympathetic innervations. The vagal nerves originating in the medulla oblongata provide the parasympathetic stimulation. Sympathetic stimulation is from nerves arising from the lateral reticular formation of the vasomotor center of the brain and relays signals through the central nervous system and thoracic ganglion exiting the spinal column between the first and fourth thoracic vertebrae.

A small ganglion between the pulmonary veins and the two vena cava is present near the SAN that the right-sided vagal nerve enters. Fibers from this ganglia innervate the SAN and when stimulated slow heart rate. The left vagal nerve courses to a corresponding fat pad ganglia near the AV node and slows AV nodal conduction when stimulated; however, there is overlap of these two nerves and one side of the vagal nerve does not innervate only one portion of the heart. Other parasympathetic innervations can be seen in the atrial myocardium. The ventricular myocardium itself has only a very small parasympathetic connection, but the ventricular conduction is heavily parasympathetically innervated.

Sympathetic nerves leading to the heart contain both afferent and efferent fibers. The afferent fibers carry signals from the heart itself back to the brain. The efferent fibers return impulses to the heart which are actually modified reflexively by afferent input

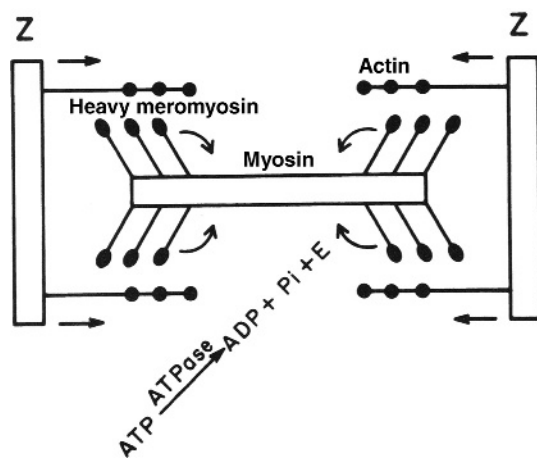
from the heart and receptors in the great vessels, such as the baroreceptors located in the aorta. Stimulation from the sympathetic nervous system increases heart rate and contractility, in addition to the vasoconstrictive action exhibited on the blood vessels. The two systems work in concert to change heart rate and cardiac function by the suppression of one system and the stimulation of the other to maintain blood pressure.

### Microscopic Structure

The secret to the contractile function of the heart lays in its specialized striated muscle. The cardiac myocardium is composed of fiber-like bands of muscle tissue arranged in overlapping multidirectional layers. This arrangement allows for contraction in three directions at once. Each muscular band is composed of many fibrous strands arranged longitudinally. These branching fibrous bands are composed of individual myocytes. Cardiomyocytes are tubular, approximately 50–100  $\mu\text{m}$  long and 10–25  $\mu\text{m}$  wide, and are arranged in a longitudinal pattern with one cardiac cell abutted end to end with the next. Between each myocyte are the *intercalated discs*. The intercalated discs serve to connect two myocytes, allowing for communication of two cells and establishing an anchor for the contractile mechanism within the myocytes. The cells are held as fibrous groups by collagen connective tissue interspersed with a high concentration of capillaries.

Within the myocyte, a high number of mitochondria can be found along with the nucleus and other organelles. The functional unit of the cardiac myocyte and of contraction is the *sarcomere*. The sarcomere is a segment of contractile fibers bordered by transverse discs, known as *Z-bands*, within each myocyte. There are many sarcomeres inside each myocyte, with individual sarcomeres stacked end to end and circumferentially to form a “cable effect” within the cell.

Each individual sarcomere is made up of thin actin bands attached to the Z-bands and a thick myosin band that sits between the actin fibers. The myosin fibers extend from the Z-band about two-thirds of the way towards the center of the sarcomere; the actin fibers are positioned between the myosin fibers, extending from the center outward, but not fully to the Z-bands, bridging the gap between the actin fibers from each end of the



**Figure 1.11** An individual sarcomere: the myosin molecule in the center is stationary. Contraction occurs when the heavy meromyosin and the actin react to depolarization; the heavy meromyosin pulls toward the center, shortening the cell, and draws the Z-bands closer together. When coupled with millions of other sarcomeres depolarizing rapidly, the heart contracts in unison. Source: Fox (1999) [1]. Reproduced with permission of Elsevier.



sarcomere (Figure 1.11). When the cell is depolarized, proteins along the length of the actin and myosin fibers shift position causing the fibers to slide along each other, pulling the Z-bands closer together and making the overall length of the sarcomere and thus the cell shorter and thicker. When done in unison, the overall effect will reduce the internal dimensions of the ventricle by 50%.

## References

- 1 Fox, P.R., Sisson, D. and Moïse, S.N. (1999) Cardiac anatomy, in *Textbook of Canine and Feline Cardiology: Principles and Clinical Practice* (eds P.R. Fox, D. Sisson and S.N. Moïse), 2nd Edition. W.B. Saunders Company, Philadelphia.
- 2 van Campenhout, M.J.H., Yaksh, A., Kik, C. *et al.* (2013) Bachmann's bundle: a key player in the development of atrial fibrillation? *Circulation: Arrhythmia and Electrophysiology*, **6**, 1041–1046.
- 3 Constantinescu, G.M. (1991) *Clinical Dissection Guide for Large Animals*. Mosby-Year Book, St Louis.

