

~CHAPTER 1~

INTRODUCTION: NORMAL HEARTS — A COMPARISON

Since understanding of the malformed heart requires a prior knowledge of normality, we begin by reviewing the normal heart. Although all mammalian hearts have four chambers, there are, nevertheless, subtle differences between the major groups. More than 3000 animal hearts have been studied, varying in weight from 50 mg in a shrew to 15 kg in a female Indian elephant. The material includes domestic, laboratory and wild terrestrial and aquatic mammals, 50 different species in all. The ten most common species were dogs (755), cats (208), horses (292), cattle (351), pigs (511), sheep (149), lynxes (146), red foxes (94), roe deer (84) and elks (54). Most of the animals were grown-up with the exception of pigs, where piglets, aged two to three weeks, were most frequent. About 60 congenital heart defects were identified, predominantly in domestic animals.

Table 1.1 Heart mass as related to body mass and heart rate.

	Heart Weight/Body Weight Ratio (%)		Heart Rate at Rest
	Mean	Range	Range
Baboon		0.43–0.51	95 – 140
Bat		1.38–1.44	375 – 600
Bottlenose dolphin			70 – 85
Cat	0.40	0.28–1.42	110 – 140
Cow	0.48	0.30–0.87	50 – 80
Dog	0.71	0.43–1.66	70 – 140
Elephant		0.33–0.52	22 – 40
Ermine	1.18		350
European hare	0.77		60 – 70
Goat	0.46	0.26–0.66	70 – 120
Guinea pig	0.42	0.26–0.51	130 – 325
Hedgehog		0.38–0.67	200 – 325
Horse	0.69	0.45–1.20	25 – 50
Man, male, 21–25 yrs	0.55		70
Mole	0.76		250 – 350
Mouse		0.61–0.79	450 – 750
Rabbit, domestic		0.29–0.34	170 – 280
Rat		0.36–0.40	250 – 450
Seal	0.92		60 – 70
Sheep	0.41	0.17–0.82	70 – 120
Shrew	1.35		600 – 1320
Swine	0.40	0.23–0.48	70 – 120
Whale		0.51–0.52	

The table on heart mass as related to body mass and on heart rate (Table 1.1) is compiled from a number of sources^{5–7, 9, 11, 14–17, 23, 25, 27, 29, 32} and is presented with some reservations. The number of animals from which the figures are derived varies between species. The conditions during which the data have been collected is usually not clearly stated. The age of the animal is rarely mentioned. According to the study of Beznák, the relative heart weight in rats is decreasing with increasing body weight in young and in adult animals. Rats weighing 75 g had a ratio of 0.40% and when reaching 270 g, the rats had a ratio of 0.28%.⁴ The technique of weighing the hearts is rarely described. In Schubert's study from 1909, dog hearts with residual blood had ratios of 0.9–2.2% and the empty hearts showed a ratio of 0.85–1.4%.²⁷ Another source of error is pericardial and epicardial fat which can be abundant especially in ruminants. The wide span of heart rates “at rest” can partly be explained by variations in environmental conditions and the degree of excitement of the animal. In a description of feline ECG data, a mean value of 197 was given with a range between 120 and 240,³¹ and in other studies the range of normal heart rates was between 110 and 130 beats per minute²⁹.

Keeping these deficiencies in mind, some undisputable observations could be noted. The smallest animals, the bat and the shrew, have the relatively heaviest hearts and the fastest heart rates. Large animals like elephants have low heart rates and a relatively low heart weight. Allometric equations have been proposed to express heart mass and heart rate as a function of the body mass. The allometric constant for heart weight is given as $0.0058 \times \text{body mass in kg}^{0.98}$ and for rate the formula is $241 \times \text{body mass in kg}^{-0.25}$.⁸ The allometric analysis, however, has serious drawbacks. Examples of deviations from the theoretically derived figures are a comparison between horses and cattle of roughly equal body mass. The heart rate of cattle is twice that of the horse. Another example is a comparison between leporids. The relative mass of the domestic rabbit was 0.24% and that of the wild rabbit 0.28% as compared to the European hare with a ratio of 0.77¹⁵. The heart rate of the hare is said to be 60–70 and that of the rabbit 200–325. Thoroughbred horses and Greyhounds have big hearts, probably explained not only by heavy physical activity but also by genetic predisposition. Many wild animals have a high heart mass/body mass ratio. It could be of interest to study if this ratio is present at birth or if it is explained only by less access to food and a higher physical activity as compared to domestic animals.

Morphology and Function of the Heart and Great Vessels — General Aspects

Information from the literature^{2, 11–13, 28} supplemented with own experience form the basis for the following description. Not surprisingly, the structure and function of mammalian hearts are strikingly similar. There are two suctioning and compressing muscular parts, the ventricles, assisted by the atria and with “back-water valves” preventing backflow in systole to collecting compartments, the atria and the veins and in diastole of blood pumped to peripheral vessels. The thin-walled right ventricle is adapted to great variability in volume and the left ventricular muscle is a high pressure pump allowing less beat-to-beat variations in volume.

A pressure gradient all along the vascular system is the prerequisite for the convection of blood from the heart through the capillary system and back through the veins, atria and ventricles.

The blood pressure is regulated by the flow from the ventricles, the peripheral vascular resistance, the amount of blood in the vascular system, the elasticity of the vessel walls and the viscosity of the blood.

The venous blood draining the body enters the right atrium through the two caval veins and the azygous veins and is pumped to the lungs by the right ventricle with its two backflow valves, the tricuspid leaflets with tendinous cords and papillary muscles and the pulmonary leaflets. The oxygenated blood passes through the pulmonary veins to the left atrium and is pumped into the aorta and its branches by the left ventricle with its two valve systems, the mitral leaflets with tendinous cords and papillary muscles and the aortic leaflets. The heart itself is perfused through the two coronary arteries and the venous heart blood empties into the right atrium via the coronary sinus.

Automatic activity of the specialised pacemaker cells in the sino-atrial node initiates the heart beat. Propagation of the impulse to the atrioventricular node then activates the conduction through the bundle of His with its branches and further via the Purkinje fibers to the myocardium. The existence of internodal pathways has been controversial largely due to misinterpretations of original descriptions of the conduction system. The concept of preferential spread of activation from the sinus node to the atrioventricular node through ordinary myocardium and not through “specialised internodal pathways” is sound and proven.

Neurologic control of the heart action is mediated through parasympathetic and sympathetic branches of the autonomous nervous system.

Pericardium, position and shape of the heart

The heart is located in the lower ventral part of the mediastinum in all mammals and it is covered by lungs apart from a small area ventrally. The organ is suspended within the pericardial cavity. The pericardial sac is fixed to the root of the great arteries and the cranial vein and is attached to the sternum in all animals but the fixation to the diaphragm varies between species. The attachment to the central tendinous aponeurosis of the diaphragm is firm and broad in man but in carnivores a ventral ligament is the only attachment between the pericardium and the diaphragm and in horses and ruminants the caudal part of the pericardium is attached through the sternopericardial ligaments only. The human type of fixation was noted in pigs, seals, phocids and beaver.

Compared to man, quadrupeds have less pronounced left-sided orientation and a more ventrally tilted long axis of the heart. The difference in the *in vivo* orientation of the heart has caused some confusion in the naming of cardiac structures, especially of the leaflets of the aortic valve. A simple way to avoid misunderstanding is to describe the aortic leaflets (and sinuses) as “facing” and “non-facing”. Always, in a valve with three leaflets, two of the leaflets are nearest to the pulmonary valve. Imagining oneself in the aortic valve, looking toward the pulmonary valve, the left and right coronary arteries can then be described as arising from the left- and right-facing sinuses, regardless of the location of the aorta relative to the pulmonary trunk. The third sinus, furthest from the pulmonary valve is non-coronary and non-facing. Ruminants have a relatively larger right lung than other quadrupeds which causes displacement of 3/5 of the heart

to the left of the mid-line. In conformity with the shape of the thorax, the heart is elongated and the apex is pointed in most quadrupeds. The pointing can be pronounced in starving animals due to lack of epicardial fat. Most dogs, on the other hand, have an ovoid heart with a marked interventricular groove and a blunt apex. For reasons unknown, the elephant has a double-pointed apex caused by a prominence of the apical part of the right ventricle and a marked interventricular groove thus creating an extra bulging next to the apex formed by the left ventricular muscle. A similar shape was seen in some piglets and in seals.

The heart contour in seals, dolphins and beaver is similar to dogs but it is broader and flatter. The adaptation to diving seems to be the reason why a bulging of the right ventricle, the main pulmonary artery and the ascending aorta is seen in these marine mammals.

Venous duct (Ductus venosus Arantii)

In foetal life, the venous duct provides passage of blood from mother to foetus by way of the umbilical vein and the caudal caval vein. The venous duct is communicating with the portal vein. The duct closes after birth in man, primates, ruminants, carnivores and rodents. In the horse and the pig the venous duct is closed even before birth. In man, congenital absence of the venous duct is an uncommon anomaly, causing overloading of the sinusoidal circulation of the liver resulting in hepatic and intestinal congestion and portal hypertension. The vascular anatomy and haemodynamics must apparently be different in the horse and the pig in such a way that these complications are avoided.

Caval and azygous veins

In domestic animals the intrathoracic course of the caudal (inferior) caval vein is long. The vein is enclosed in a pleural fold. The orifice of the vein is high in the caudodorsal part of the right atrium. Marine animals have the short caudal caval vein seen in man. The cranial (superior) caval vein drains posteriorly like in man, i.e. close to the crista terminalis. In several species this vein is more muscular than in man, muscularity extending 1 cm or more in the dog. Persistence of the left cranial vein usually draining in the coronary sinus is common in rabbits, rats and mice, is not infrequently seen in dogs and sheep and has been noted in several other species, either as an isolated finding or associated with cardiac malformations. The only significance of the anomaly is during cardiopulmonary bypass surgery.

A left cranial caval vein double the size of the right, was seen in a beaver. Like pinnipeds and phocids the capacity of the venous system seemed unusually large in this animal.

A left azygous vein emptying in the great cardiac vein is seen in pigs and ruminants. A right azygous vein draining the dorsal and lateral part of the thoracic wall is seen in carnivores, ruminants, horses and sometimes in pigs. The right vein drains into the cranial caval vein or directly into the right atrium. In rats and mice, both right- and left-sided azygous veins drain into the left cranial vein.

Right atrium

All mammals studied have principally the same architecture of the venous sinus, terminal crest, oval fossa, valve of the caudal caval vein and the Thebesian valve. These valves show great individual differences and the remnants of the right valve of the venous sinus, the Chiari network, can be extensive. In dogs, division of the right atrium is a frequently described congenital malformation. Therefore, dogs were studied especially with reference to the normal morphology of the right atrium. A marked terminal crest was frequently seen. As compared to man, the oval fossa was more posteriorly (caudally) positioned in dogs and also in horses and ruminants.

Multiple pectinate muscles, more or less marked, extending from the terminal crest, are always seen in the atrial appendage but the shape of the appendage varies between species. In man there is a broad junction with the venous component, and the animals studied showed the same arrangement but often with differently shaped appendages (Fig. 1.1). A “human-like” blunt, triangular and poorly crenellated appendage is found in dogs, elks, bears, wolves and in red foxes. In ruminants and pigs, the appendage is more pointed and crenelated and the external appearance can be similar to the left atrial appendage (Fig. 1.1). The pectinate muscles of the right appendage are extensive in these animals and in seals, in particular, and can be found dorsally in the right atrium as well (Fig. 1.2). In rabbits and hares, the right and left appendages are very similar and have the appearance of a fan with finely crenelated edges (Fig. 1.3). The endocardium of the right atrium is usually thinner than that of the left atrium which has a grey and sometimes whiteish colour.

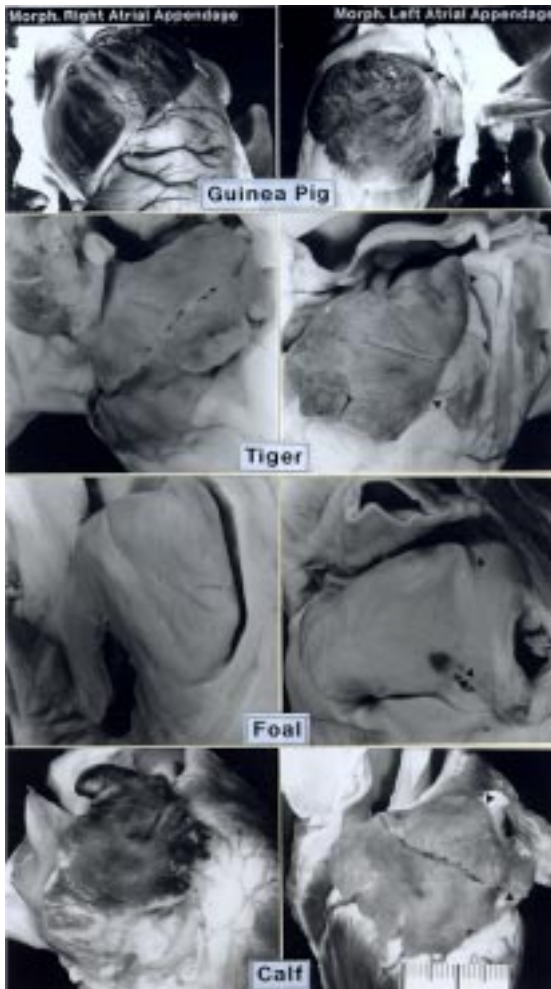


Fig. 1.1 A series of pictures taken from the right and left sides of the hearts of four different animals showing the shapes of the morphologically right and left appendages. The morphologically left appendage has a narrow junction (arrowheads) with the atrium.

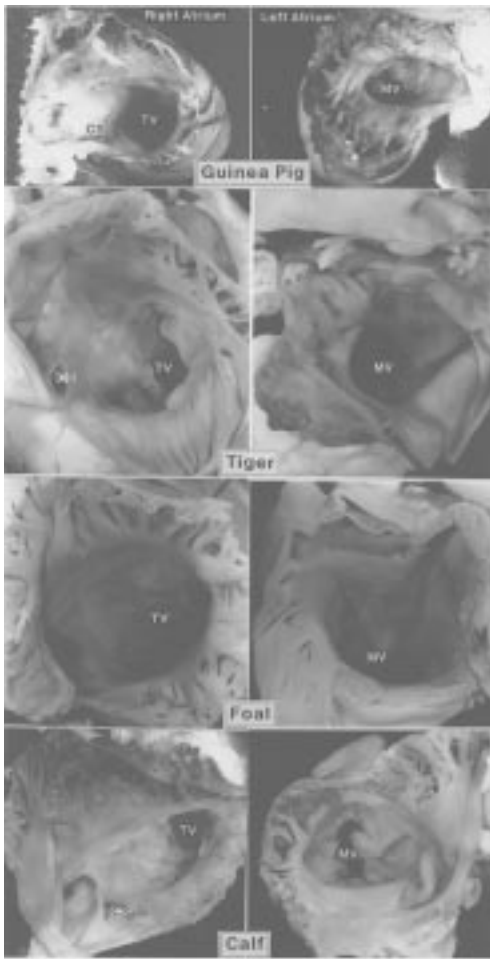


Fig. 1.2 Internal aspects of the right and left atria. The pectinate muscles are distributed extensively in the right atrium. In the left atrium, the posterior wall is smooth because pectinate muscles are limited to the atrial appendage.

Right ventricle

The shape of the ventricle is triangular with three components, the inlet portion with the atrioventricular valve and its tension apparatus, an apical trabecular zone and a tubular outlet part supporting the pulmonary valve, resulting in muscular discontinuity with the tricuspid valve. The variations in site and shape between species, breeds and individuals are considerable with respect to the tricuspid valve, including tendinous chords and papillary muscles, the septomarginal trabeculation with the “moderator band”, the supraventricular crest, the apical trabeculations, the intracavitary Purkinje fibers and the thickness of the right ventricular free wall (Fig. 1.4). Some differences nevertheless are notable. In the dog and cat, the commissures between the

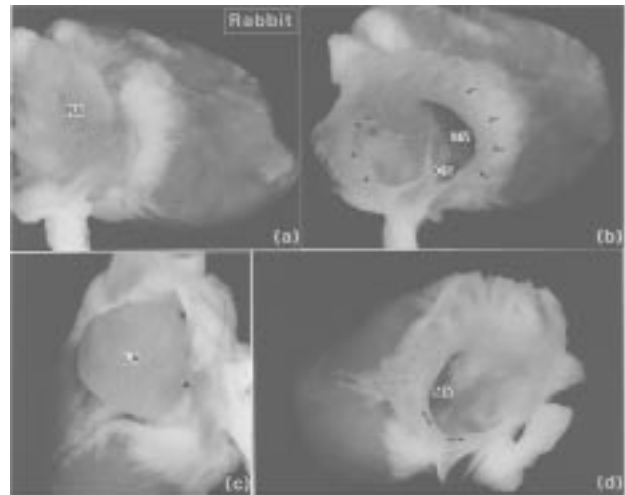


Fig. 1.3 External and internal views of the right [(a) and (b)] and left [(c) and (d)] atria of a rabbit heart. Note the wide junction of the right appendage (a) compared to the narrow junction (arrowheads) of the left appendage (b). The internal view of the right atrium (b) shows the terminal crest (arrowheads) and the extensive array of pectinate muscles (arrows) that arise from it. In contrast, the internal aspect of the left atrium (d) has a smooth posterior wall (double arrows).

anterosuperior and the inferior leaflets are usually fused so that only two leaflets are discernible. The septal leaflet is invariably present separately. This leaflet is usually relatively thick with nodularity in dogs (Fig. 1.5). The same shape has been noted in red foxes and brown bears. The finding should not be misinterpreted as a valvar disease. A medial, a posterior and an anterior papillary muscle can often be identified but interindividual and interspecies variations in size and arrangements are frequently encountered. The apical extension of the septomarginal trabeculation, “the moderator band” usually traverses the ventricular cavity. The muscle, containing a subdivision of the right bundle branch of the conduction system is prominent in most dogs, pigs and ruminants, but a thin, tendon-like band, apparently containing no muscles is also frequently noted in these and in other animals (Fig. 1.4). Double muscular or tendon-like bands with connecting bridges has been noted in pigs and horses (Fig. 1.4). Coarse and abundant trabeculations were observed in dolphins, seals, brown bears, a beaver and an elephant. In adult horses, elks and roe deers, the trabeculations and the papillary muscles are usually shallow. In the human heart, the apex is apparently more trabeculated than in most other mammals.

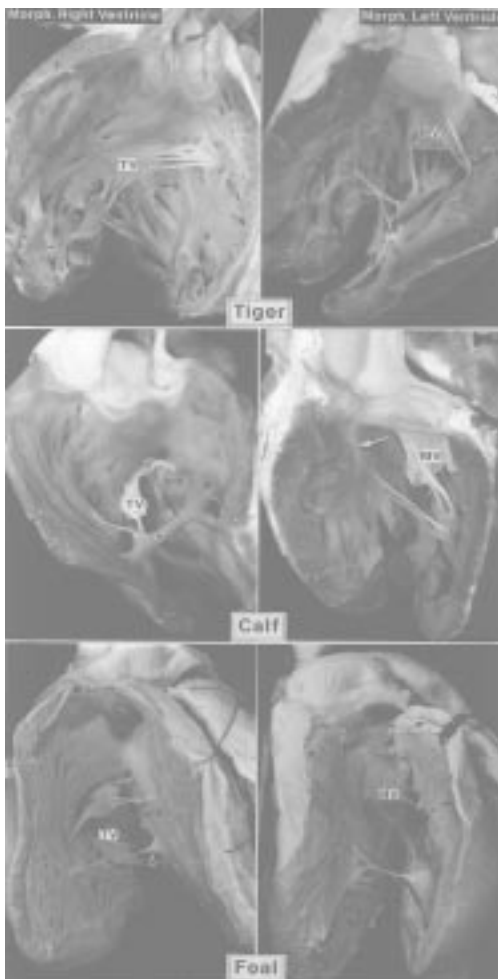


Fig. 1.4 Morphological differences between right and left ventricles in the tiger, calf and foal. The patterns of the apical trabeculations are less distinctive than in man. The atrioventricular valves are good markers for ventricular morphology. The septal leaflet(s) of the tricuspid valve is characteristic of the morphologic right ventricle. In contrast, the upper part of the septal surface in the left ventricle is smooth. The moderator band (arrowhead) is also distinctive of the morphologic right ventricle but in horses, for instance, can be reduced to thin strands and appear similar to the false tendons seen in the left ventricle. Note the greyish area (arrow) marking the site of the main fascicle of the left bundle branch in the calf.

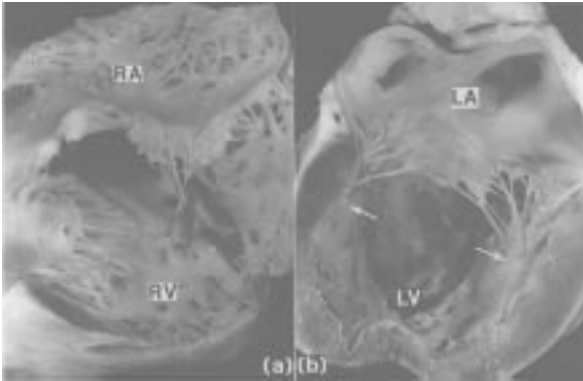


Fig. 1.5 The tricuspid (a) and mitral (b) valves in a four-year-old flat-coated Retriever dog. Note the thickening of the edges of the leaflets, the insertion of the anterior papillary muscle (★) to the septum, and the attachments of the mitral valve virtually directly to the ventricular wall (arrows). The septal leaflet(s) of the tricuspid valve has cordal attachments to the septum.

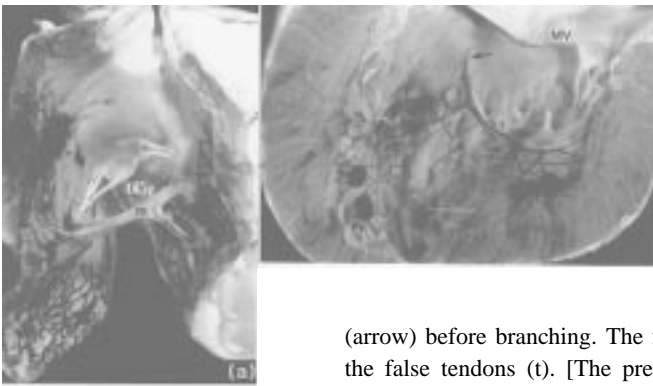


Fig. 1.6 The subendocardial network of Purkinje fibres revealed in the right (a) and left (b) ventricles of a sheep heart. The fibres were marked by injection of India ink into the fibrous sheaths. The dark blotches are artefacts. The Purkinje fibres traverse from the septum to the parietal wall of the right ventricle through the moderator band (m). In the left ventricle the left bundle branch descends as a solitary bundle

(arrow) before branching. The fibres cross the cavity to the papillary muscles via the false tendons (t). [The preparation was made by Mr. Aneel Ansari.]

A fine greyish network of the distal ramifications of the ventricular conduction system (the Purkinje fibers) (Fig. 1.6) is often found in the trabecular zone of the cavity, especially in cats. The right ventricular free wall is surprisingly thin in many cats. In five non-related Abyssinian cats, the right ventricular wall was translucent with a sparse muscular network and areas of fibrous tissue reminiscent of the parchment right ventricle known as Uhl's syndrome in human (Fig. 1.7). This disease has been described once in a cat and a mink. The seemingly trait-specific finding in the five Abyssinian cats could be worthy of further studies. A similar shape of the right ventricular free wall was seen in a Burmese cat. Bicuspid or quadricuspid pulmonary valves are rarely found. The finding is of no pathological significance.

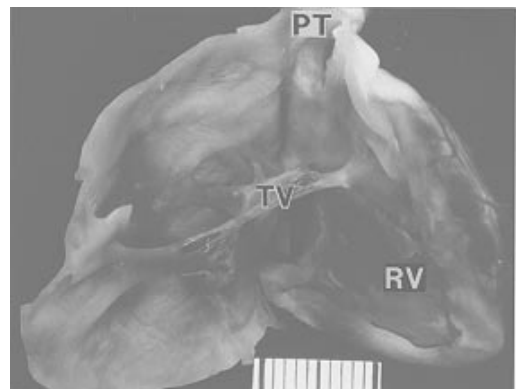


Fig. 1.7 Abyssinian cat. The right ventricular wall is very thin.

Pulmonary arteries and arterial duct (ductus arteriosus)

The shape and the course of the proximal pulmonary artery is similar in all mammals. The arterial duct or the ductal ligament connects the proximal part of the left pulmonary artery with the aorta distal to the brachio-cephalic trunk in horses and ruminants and distal to the left subclavian artery in other animals. The arterial branches are leaving the ascending aorta early and the ligament connects to the lesser curve of the arch early in its course. In man, the duct connects the pulmonary artery to the lesser curve of the arch of the aorta at the point of transition from arch to descending aorta. The length of the ligament is 2–4 cm in the adult horse and the ox. A small thin-walled diverticulum at the aortic end of the ductal ligament was observed in a pig. The anomaly could be looked upon as a “forme fruste” of persistent *ductus arteriosus* in accordance with the observations in dogs.²⁴

In full-term healthy terrestrial mammals, the functional closure of the arterial duct is usually a matter of minutes or hours. A functional patency after the age of five days should be considered abnormal. Complete anatomical closure with reduction of the ductal tissue to a ligament is a gradual process which, at least in larger animals, is said to last weeks or even longer. Ductal closure is delayed in the Common Seal, the Common Porpoise and other delphinids, in Baleen whales and possibly in elephants (see Chapter 11).

A small crescent-like fold on the luminal surface of the aortic wall immediately proximal to the aortic end of the ligament is frequently found in animals of varying species. This remnant from the patency period is probably due to the fact that, in most animals, the duct runs almost parallel to the aorta (Fig. 1.8). The fold has also been considered as a mechanism of ductal closure in the older literature. From the practical viewpoint, it should not be mistaken for a coarctation lesion.

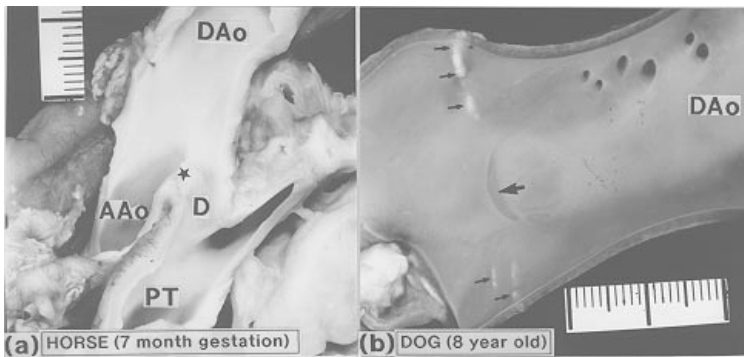


Fig. 1.8 (a) The arterial duct runs parallel to the aorta. The sharp angle between the duct and the aorta results in a flap-like wall (★). (b) The duct is closed and a crescent-like fold of the “flap” (arrow) remains. The ridges of calcification (small arrows) mimic coarctation.

Pulmonary veins and left atrium

The right pulmonary veins are easily identified from the ventral aspect close to the interatrial groove. The number of pulmonary veins or venous confluences entering the left atrium varies between two and eight within species and between species. In man, there are usually four venous openings but variations are not uncommon and the right and left orifices are more distant from

each other compared to other mammals. The cavity of the left atrium is smooth with the exception of the appendage with its pectinate muscles. In contrast to the right atrium, the junction between the atrium and the appendage is narrow, a finding present in all animals studied (Figs. 1.1, 1.2 and 1.3). Varying degrees of crenellation of the appendage were found. The hook-shaped appendage with several constrictions as seen in man was noted in pigs and some ruminants but it was usually less pronounced in other mammals. There was no terminal crest or groove in the left atrium.

In large animals, the atrial myocardium was found to extend on the atrial side beyond the attachment of the aortic leaflet of the mitral valve. In the adult horse, the muscular layer is 2–4 mm thick immediately below the hinge (line of attachment), and becomes gradually thinner until it disappears 2–3 cm from the free edge of the leaflet (Fig. 1.9). We have not been able to find descriptions of this anatomical detail in the literature.

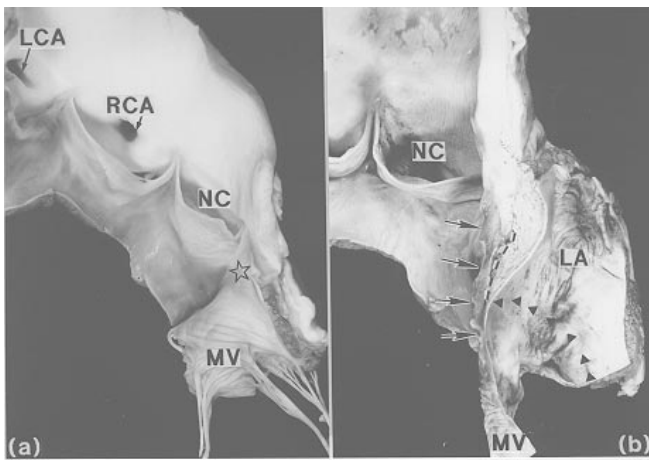


Fig. 1.9 (a) The aortic-mitral unit from a horse dissected to show the limited area of fibrous continuity (☆) between the two valves. (b) This longitudinal section shows extensive overlap of muscle (arrows) forming the subaortic infundibulum. The dotted line is the cleavage between atrial and ventricular myocardium. The triangles mark the hingeline of the mitral valve.

Left ventricle and mitral valve

An inlet component, the mitral valve complex, an apical zone with fine trabeculations and an outlet is present. With the exception of the horse, the donkey and the zebra, the arterial-atrioventricular valve fibrous continuity is similar to man, extending from the central fibrous body to the left fibrous trigone. The wide line of attachment at the hinge of the aortic (anterior) leaflet of the mitral valve is in continuity with the aorta corresponding to a major part of the left and the non-coronary leaflets. The line of attachment varies somewhat in man and other mammals, but in the equine species the zone of aorto-mitral continuity is diminished and can even be absent. In the horse, the left ventricular muscles are seen to converge bilaterally towards the commissure between the left and the non-coronary aortic cusps, thus forming an angle with its peak between 0 and 3 cm, varying from animal to animal (Fig. 1.9). Three zebra hearts showed slightly wider fibrous continuity (Fig. 1.10a), and in one donkey heart the discontinuity was complete. In 12 out of 86 horses studied, aorto-mitral discontinuity was present (Fig. 1.10b). The dividing muscular band was between 1 and 3 cm broad. It is reasonable to assume that the left ventricular contractile pattern is influenced by this different myocardial arrangement. Two-

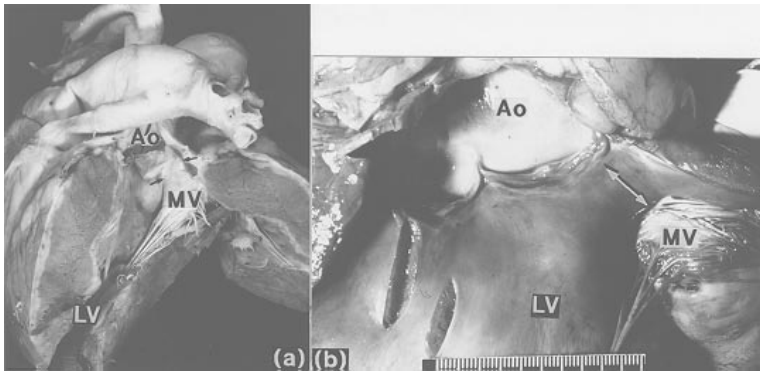


Fig. 1.10 (a) Heart from a zebra showing extensive fibrous continuity (arrows) between aortic and mitral valves. (b) In contrast, there is muscular discontinuity (double arrows) in this heart from a horse.

dimensional and M-mode echocardiographic studies with comparisons to man and to other mammals could give valuable information on the functional aspects of this prominent musculature.

Two leaflets of the mitral valve are always recognisable, the aortic (or anterior) and the mural (or posterior) leaflets. Like in man, variations in the number of scallops do exist and can be quite marked, giving the impression of extra leaflets. In the horse, the mitral valve is often described as quadricuspid, with two smaller lateral leaflets between the aortic and the mural leaflets²² (Fig. 1.11). The papillary muscles are mostly arranged in two groups but accessory muscles are frequently seen. The trabecular network seems to be more prominent in younger animals except in horses where the trabeculations are sparse and less prominent, even in foetal life. In the adult horse, the papillary muscles can often be difficult to identify and the tendinous cords then come out directly from an almost smooth myocardium.

Ramifications of the Purkinje network is often seen to be located freely as thin strands in the cavity or only partly hidden between the trabeculations (Fig. 1.6). The intracavitary network can be abundant in the cat and has been called “excessive moderator bands”. It was believed to have a restrictive effect on the ventricular function.²¹ Excessive intracavitary Purkinje fibers can be found in human hearts as well.¹⁹ A constant finding in all animals seems to be two or more transcavitary branches of conductive tissue passing from the middle of the ventricular septum to the two papillary muscles. In the European Hamster, a well-developed muscular band is described traversing the left ventricle from the upper interventricular septum to the papillary muscles. This muscle band was called left-sided septomarginal trabecula. Similarly, we found, in the heart of the Common Porpoise, two muscular trabeculations, probably containing ramifications of the left bundle branch passing from the

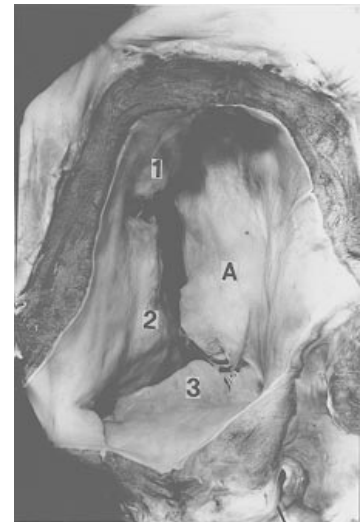


Fig. 1.11 The mitral valve of a horse viewed from the atrial aspect. The aortic or anterior (A) leaflet has a short span. The mural leaflet has three well-developed scallops (1, 2 and 3), giving the mitral valve a four-leaflet appearance.

septum to the papillary muscles. These animals have richly trabeculated ventricles and another thick transcavitary muscle was found near the apex of the left ventricle.

In cattle, the outlet is said to deviate to the right to such a degree that this morphology should explain the frequent occurrence of overriding aorta when a ventricular septal defect is present. Such a species difference can hardly be verified. The angulation between the trabecular and outlet part of the left ventricle seems to be of the same order in all mammals, man included.

Membranous septum

The membranous septum has an atrioventricular and an interventricular component owing to the attachment of the septal leaflet of the tricuspid valve. In man, as viewed from the left ventricular aspect, this oval-shaped part of the cardiac fibrous skeleton is situated above the crest of the muscular septum. It extends between the right and the non-coronary aortic leaflets and merges with the basal border of the aortic leaflet of the mitral valve. The septum is attached to the right fibrous trigone to form the central fibrous body. The interventricular membranous septum has the same location in animals. It is usually small and can sometimes be seen only by transillumination. The shape varies between crescent-like, triangular or oval and is usually seen in adult dogs, cats and pigs. In ruminants and especially the cow, it is difficult to identify the membranous septum even by transillumination. The difficulties could partly be explained by the existence of a well-developed right heart bone at the place of the membranous septum in the ox, rain deer, roe deer, red deer, sheep, goat and possibly in other ruminants as well (Figs. 1.12 and 1.13). In horses, difficulties in identification of the ventricular membranous septum could be explained by the unique arrangement of the muscular septum covering the right aspect of the anterior mitral leaflet. The membranous interventricular septum could not be identified in newborn or very young animals. In accordance with human heart studies,^{1,10} the explanation is probably the relatively late transformation of the membranous septum into atrioventricular and interventricular components. The transformation is associated with the undermining process of delamination in early cardiac development, which liberates the septal leaflet of the tricuspid valve from the muscular ventricular septum.

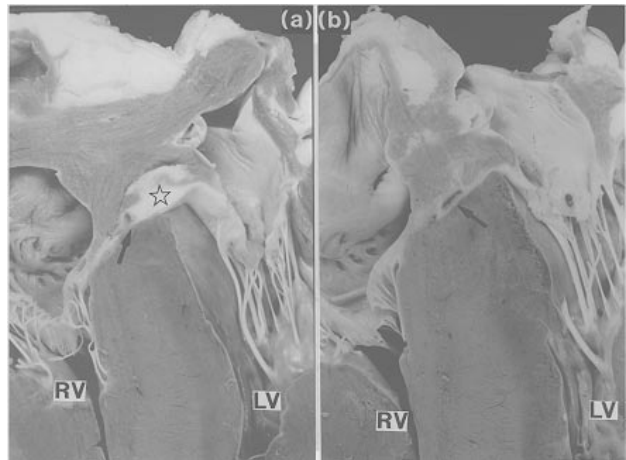


Fig. 1.12 A calf heart sectioned in four-chamber planes. Plane (a) is more ventral than (b). The right trigone between the aortic and mitral valves is an extensive area of cartilage (☆) with bone (arrow).

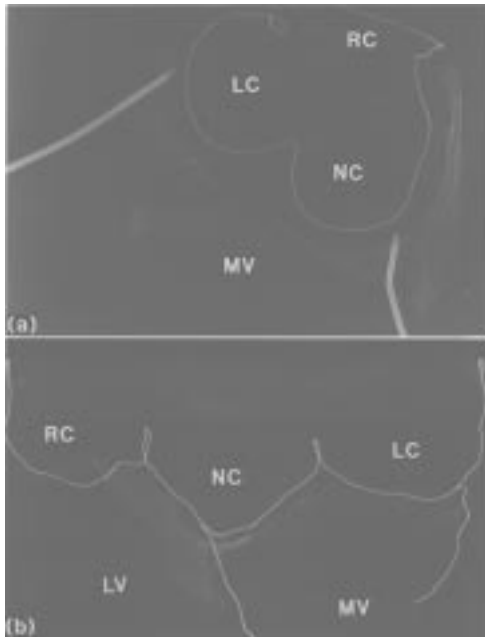


Fig. 1.13 Radiographs showing the heart bone in a seven-year-old cow. **(a)** is a view from the aortic aspect and **(b)** is a view of the left ventricular outflow tract. The looped wires mark the sites of the aortic sinuses and the straight wires indicate the aortic leaflet of the mitral valve.

Coronary arteries

All mammals have two coronary arteries, the right originating from the right sinus of Valsalva and the left from the left sinus of Valsalva (Fig. 1.14). The coronary arterial sinuses are also termed the facing aortic sinuses since they are closest to the pulmonary valve. Minimal accessory ostia are common, especially a separate orifice for the infundibular branch of the right artery, an almost constant finding in the sheep. Other than difference in the perfusion areas of the right and left coronary arteries between species, there are also differences within species, as described in man. Dogs, cats and ruminants usually have a left coronary type of supply, meaning that the dominant perfusion area, including the ventricular septum is through the left coronary artery. In these, the circumflex artery supplies the posterior interventricular artery. In the horse and the pig, both coronary arteries supply equal parts of the perfusion areas.

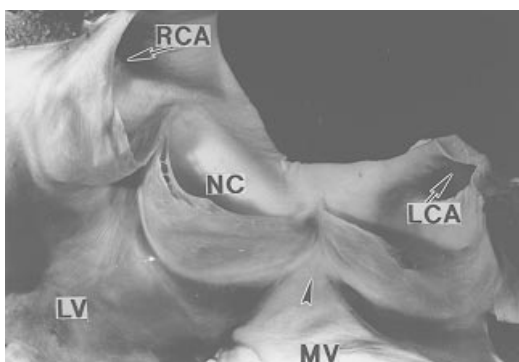


Fig. 1.14 Normal aortic valve in a horse displayed to show the origins of the right and left coronary arteries. These arise from the two sinuses that are nearest to the pulmonary valve. The third sinus is non-facing and non-coronary. The area of fibrous continuity (arrow head) between aortic and mitral valves is limited in the horse.

Aortic arch branches

Normally all mammals have a left-sided aortic arch. The equine species and ruminants have only one vessel leaving the arch, the brachiocephalic trunk (Fig. 1.15). The main vessels leaving the trunk are the right subclavian, the bicarotid trunk and the left subclavian, in this order. In dogs, cats, pigs, guinea pigs, rabbits and mice, there are two vessels leaving the arch (Fig. 1.15). These are the brachiocephalic trunk and the left subclavian artery. The European Hamster and the rat have the human three-vessel system with a brachiocephalic trunk branching into the right subclavian and the right common carotid, followed by separate origins of the left common carotid and the left subclavian arteries. Seals and the Common Porpoise seem to have the same arrangement but our observation is based on a few animals only. Liechty *et al.*²⁰ described the variations of the aortic arch and its branches based on a series of 1000 human autopsies. Only 65% of the cases had the usual arrangement and 27% had only two vessels, a common trunk and a separate left subclavian artery. In the remaining 13% of the cases there were twelve different branching variants.



Fig. 1.15 Branching patterns of the aortic arch in (a) guinea pig, (b) tiger, (c) calf, (d) zebra, and (e) foal.

Conduction system

The similarities to the human morphology in the distribution of the cardiac conduction system was remarkable in all animals studied. There is a sinus node, an atrioventricular node, a bundle of His (the penetrating bundle) with right and left branches and a distal system of Purkinje fibers. Interspecies variations are well-recognised, especially with regard to the finer details of arrangement of the transitional and compact components of the atrioventricular node.

The sinus node is situated cranial to the region of terminal groove of the right atrium at the lateral junction of the cranial caval vein. In larger adult animals, the node can be seen after dissection of the epicardium as a region of lighter colour as compared to the atrial musculature. The atrioventricular node is embedded in the base of the interatrial septum. The landmark of identification is the apex of the triangle of Koch where the tendon of Todaro approximates the attachment of the tricuspid valve (Fig. 1.16). The atrioventricular conduction bundle continues through the bundle of His that penetrates the central fibrous body and then branches. The central

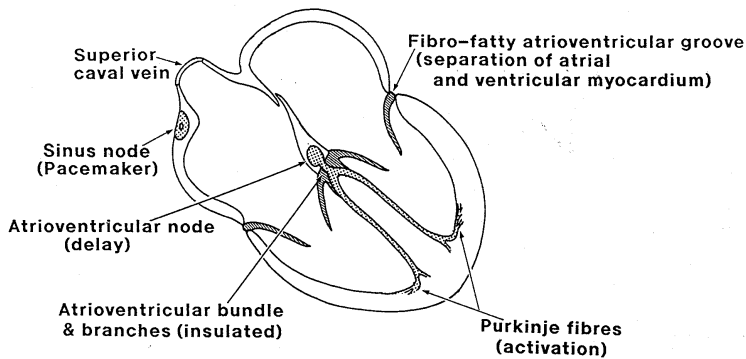


Fig. 1.16 Diagram showing the arrangement of the cardiac conduction system.

fibrous body is partly transformed into cartilage or bone in cattle, sheep, goats, reindeer, older horses and several other species. Having penetrated the fibrous body, the branching of the conduction bundle is astride the upper part of the muscular septum. The right bundle branch runs forward and toward the apex deep in the right part of the ventricular septum. Close to the junction of the septum with the anterior wall of the right ventricle, a fascicle of the branch leaves the septomarginal trabeculation and passes across the ventricular cavity through the “moderator band” to reach the anterior wall close to the origin of the anterior papillary muscle (Fig. 1.6). The left bundle branch of the bundle penetrates the septum in the transition between the membranous (cartilage or bone in some mammals) and the muscular ventricular septum beneath the commissure that is between the right and the non-coronary aortic leaflets. After reaching a subendocardial position, the left bundle with its fan-like branching is easily identified especially in large animals due to the greyish colour of its fibrous sheath (Fig. 1.4). The septal branches can be traced, even on gross examination, to the apex of the heart. Two or more branches cross the ventricular cavity to the papillary muscles giving the appearance of telegraph wires. Other intracavitary Purkinje fibers are frequently seen in the apical part of the ventricle (Fig. 1.6).

In a cow with extensive melanosis of the liver, the marrow of the suprarenal glands, the pleura and the heart, the melanotic pigments were seen to depict the subendocardial Purkinje network in numerous areas of both ventricles (Fig. 1.17). Microscopically, the pigment was accumulated along and around the Purkinje cells. The cause of this predilection is obscure. Visualisation of the superficial part of the peripheral conduction system is possible by swabbing the endocardial surface with aqueous Lugol’s iodine solution. The staining depends upon the glycogen present in the conduction system. The drawback with this technique is that glycogen disappears at a very rapid

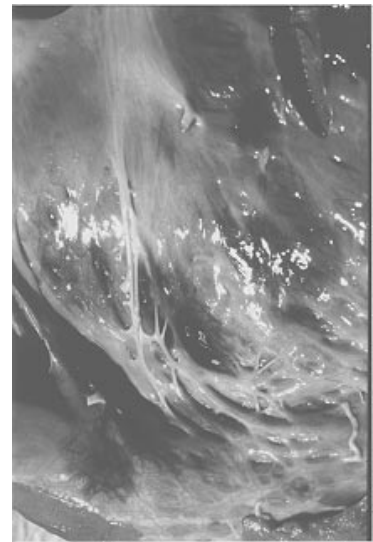


Fig. 1.17 The endocardial surface of the left ventricle of a cow with melanosis of the liver. Note the accumulation of pigment in the Purkinje network (compare with Fig. 1.6).

rate after death. The examination should therefore be done within 1 1/2 hours after death. Injection of India ink into the Purkinje network of sheep (Fig. 1.6) and calf is possible in unfixed tissue but has not been achieved in the human heart. The human anatomy of accessory muscular atrioventricular connections responsible for pre-excitation was recently reviewed and clarified.³ The arrangements are probably similar in animals, and a study of this paper is recommended if and when catheter ablation is planned, for instance in dogs or horses.

The cardiac skeleton

A system of interconnected fibrous structures helps the cardiac muscle to support the cardiac valves and to anchor the valves to the myocardium. The conjoined valvar rings are often depicted in textbooks as firm structures which separate the atrial muscles from the ventricular muscles. In this way, the atria are disjoined from the ventricles with the exception of muscular continuity between the atrioventricular nodal tissue with the ventricular conduction bundles through the penetrating bundle (of His). The skeleton includes the so-called aortic ring but the pulmonary valve is supported by the musculature of the right ventricular infundibulum forming the outflow tract. The “rings” supporting the mitral and aortic valves are united in the area of aortic-mitral fibrous continuity. This area extends from a point of condensed fibrous tissue, the right fibrous trigone which, in turn, is continuous with the annulus of the tricuspid valve. The tricuspid valve in man, however, does not have a firm fibrous annulus. Instead, the so-called ring is seldom completely formed. The right fibrous trigone together with the membranous septum constitute the central fibrous body. The area of aortic-mitral continuity extends to the left to another condensation of fibrous tissue — the left fibrous trigone. In some mammals, bones or cartilage reinforce both fibrous trigones. The right bone extends almost completely from the right to the left trigone in the elderly ox. Of the animals studied, the equine species is unique in the arrangement of the aortic-mitral continuity being narrow and sometimes even non-existing. The literature does not give any information about this special arrangement in the equine species. This statement is relevant also to an otherwise detailed study on the cardiac skeleton in horses, cattle and dogs,²⁶ and a special study on structure and function of the equine mitral valve.²² The identification of fibrous continuity, or discontinuity, between mitral and semilunar valves is a widely used feature in assessing some forms of congenital cardiovascular anomalies, such as double outlet right ventricle although this is by no means a pathognomonic feature. The development of aortic and mitral valve continuity has been studied in the human embryonic heart³⁰ but not in animals. Studies in animal models could clarify the process by which the normal fibrous continuity is acquired and possibly explain why the equine morphology is different.

The central fibrous body is not present in the sperm whale.¹⁸ The lack of a firm central part of the heart is thought to result in inadequate mechanical support should the sperm whale find itself beached, leading to severe consequences on cardiac function.¹⁸

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