# EVOLUTION OFCIRCULATORY SYSTEM

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- The circulatory system of vertebrates consists of a heart, arteries, veins, capillaries and blood (the blood vascular system) and of lymph channels and lymph (lymphatic system).
- Blood carries oxygen collected in respiratory organs, nutrients from extra embryonic membranes of embryos and from the adult digestive tract.
- It also carries hormones from endocrine tissues, substances associated with maintaining, immunity and disease.
- While flowing, it removes waste products of metabolism from the excretory organs.
- Lymph channels collect interstitial tissue fluids not taken up by the blood stream and emulsified fats absorbed in the small intestine.
- These lymph channels terminate in one or more of the large venous channels of the blood vascular system.
- Pressure differences that drive this flow of blood through the circulatory system are created by the pumping action of the heart.

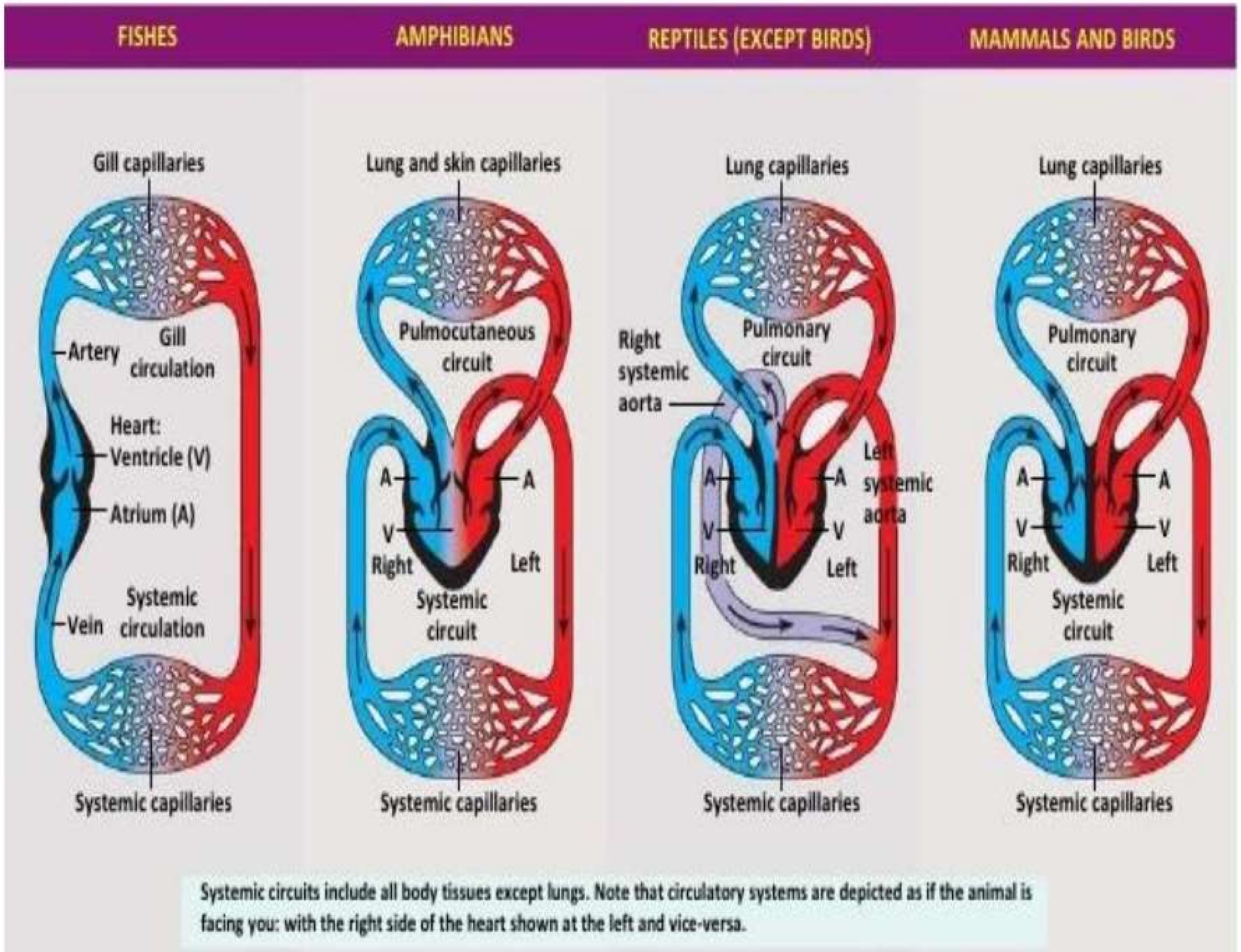
- Arteries carry blood away from heart.
- They have muscular elastic and fibrous walls capable of swelling with each intrusion of blood and of active constriction and dilation in response to nerve impulses.
- Arteries, thereby assist in regulating blood pressure.
- They terminate in capillary beds.
- Veins have proportionately less muscle and elastic tissue and more fibrous tissue and are therefore, capable of less dilation or constriction.
- They carry blood towards heart from capillary beds. Capillaries consist of endothelium only, with a lumen just large enough to accommodate red blood cells. In fact, the red cells must squeeze through and in so doing, become deformed. In vertebrates respiring by gills, blood is pumped from the heart to the gills, where external respiration takes place. From the gills it typically flows via arteries to capillaries throughout the body.

**venules** which combine to form **veins.** But some veins (portal
veins, renal veins, and hepatic vein) have capillaries which are just
like those of arteries. Veins are those blood vessels which carry
blood towards the heart. But all blood does not pass through
capillaries into venules, there are also some **through channels**
between arterioles and venules lying in some organs, such as the
skin, there are also **arterio-venous anastomoses** between arterioles
and venules. The function of such connections is not clearly known
though it is claimed that they regulate blood pressure and circula-
tion. At some places exchange of material between tissues and
blood takes place in thin-walled spaces or **sinusoids.** In certain
organs a blood vessel may form a coiled network of tiny blood vessels
called **rete mirabile** (kidneys, air bladder). The arteries and their
branches form an arterial system, while the veins and their tributa-
ries constitute a venous system.

The arterial ...

The arterial system is divisible into pulmonary and systemic divisions, the former takes blood to the lungs, and the latter to all other parts of the body.. The venous system also has pulmonary and systemic divisions, but in addition it has two or three portal systems. In a **portal system** the blood is not returned directly to the heart, but there is an interposing organ (liver or kidney) in the course of the returning blood, the vein bringing blood starts in capillaries and ends in capillaries, the vein concerned acting both as afferent and efferent vessel, the afferent vessels end in capillaries just like arteries, then the blood is collected into systemic veins. All vertebrates have a hepatic portal system in which blood passes into two sets of capillaries in the liver. Lower vertebrates and embryos of higher vertebrates have a renal portal system also in which blood passes through two sets of capillaries in the kidney before reaching the heart. The capillaries in the pituitary gland form a pituitary portal system which is a small but an important system.

## General pattern of circulation in vertebrates



... but an important system.

**Blood vessels.** In a vertebrate embryo small clusters of mesenchyme cells appear and are called **blood islands**. The blood islands are at first solid but soon become hollow to form small endothelial tubes, the blood island cells secrete plasma within the tubes. Some loose mesenchyme cells floating in the plasma become corpuscles. The endothelial tubes grow and join each other to form a network of blood vessels. But some blood vessels appear as clefts in the mesenchyme. By growth and branching of these primitive blood vessels new and larger blood vessels are formed. The mesenchyme surrounding the endothelium of blood vessels forms the coating layers of arteries and veins.

... cells become arranged

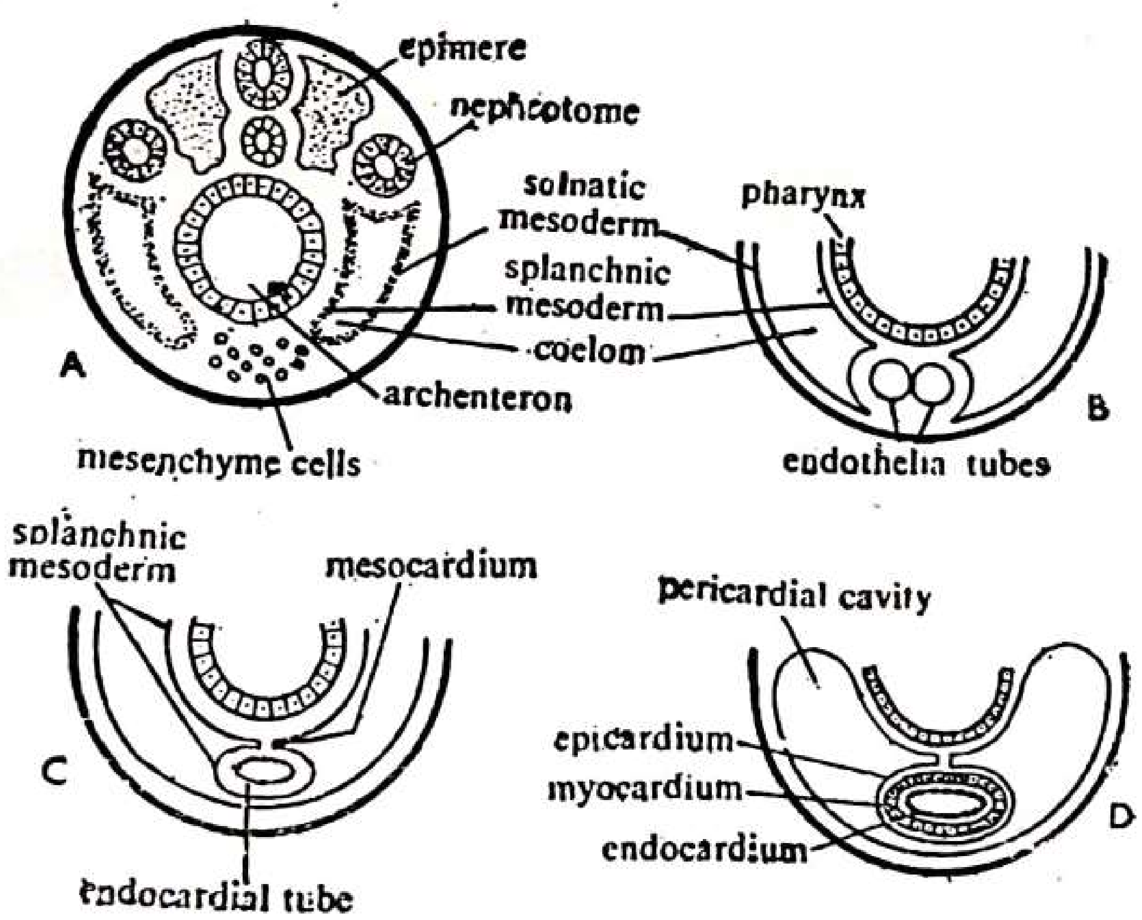



Fig. 256. T.S. of embryo showing stages in the development of heart.

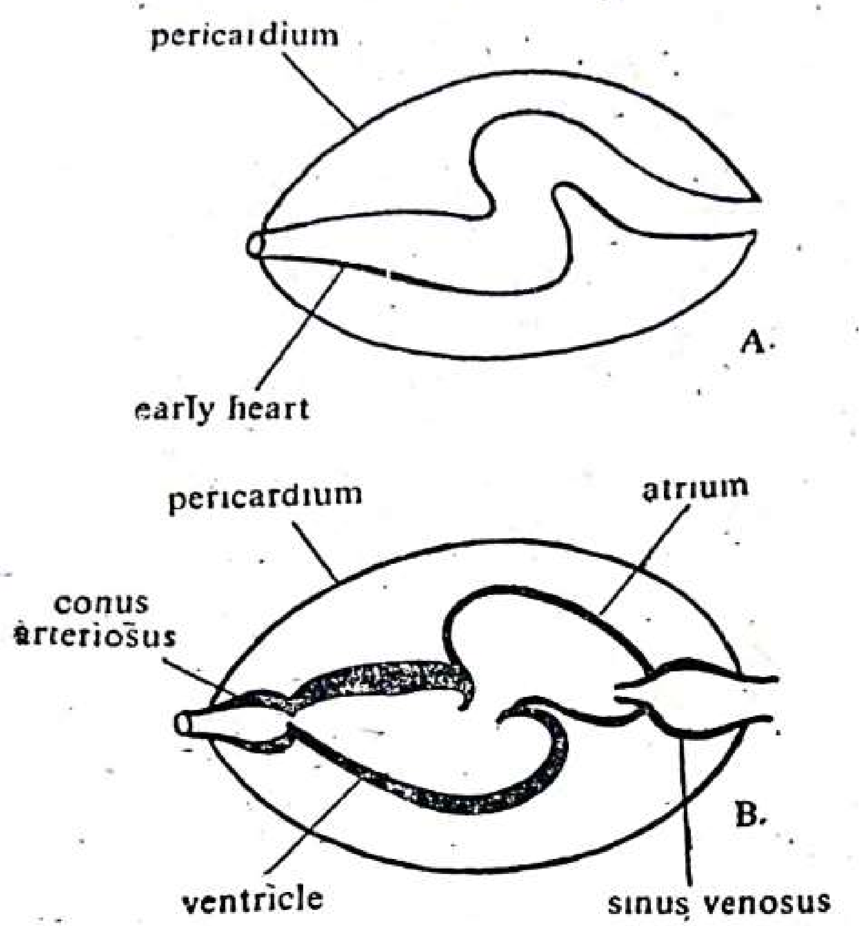



Fig. 267. Stages in the formation of heart.

# Protochordate Heart

- Protochordates (tunicates and Amphioxus) possess a simple, tubular heart that beats by peristaltic waves.
- Since arteries are more muscularised than veins, they may be taken as the primitive heart.
- Therefore, extensive muscularization of arteries has its functional significance in forcing blood into the smaller vessels (capillaries) from which blood may return back without special means of propulsion since it is passing from smaller into larger vessels.
- The protochordate stage does not need, a more specialized heart, this can be explained on the basis of lack of proper respiratory function of the pharyngeal clefts.
- The pharyngeal clefts in protochordates primarily serve as a sieve to aid in capturing the food.

# Early Vertebrate Heart

- When pharynx is provided with capillary network, then in order to facilitate the gaseous exchange, a more efficient and specialized pump is required to force blood through to the dorsal aorta.
- The most primitive vertebrate heart is seen in agnathans. They have a circulatory system consisting of a main systemic heart and 3 accessory hearts.
- The portal heart pumps blood from the intestines to the liver, the cardinal heart pumps blood from the head to the body, caudal heart pumps blood from the trunk and kidneys to the rest of the body.
- The agnathans have a different sinus venosus that is attached to the left side of the atrium.
- The circulatory system of hagfish has not changed in millions of years and since they are bottom feeders and dwellers they have adapted to a low arterial blood pressure and low cardiac output is sufficient.

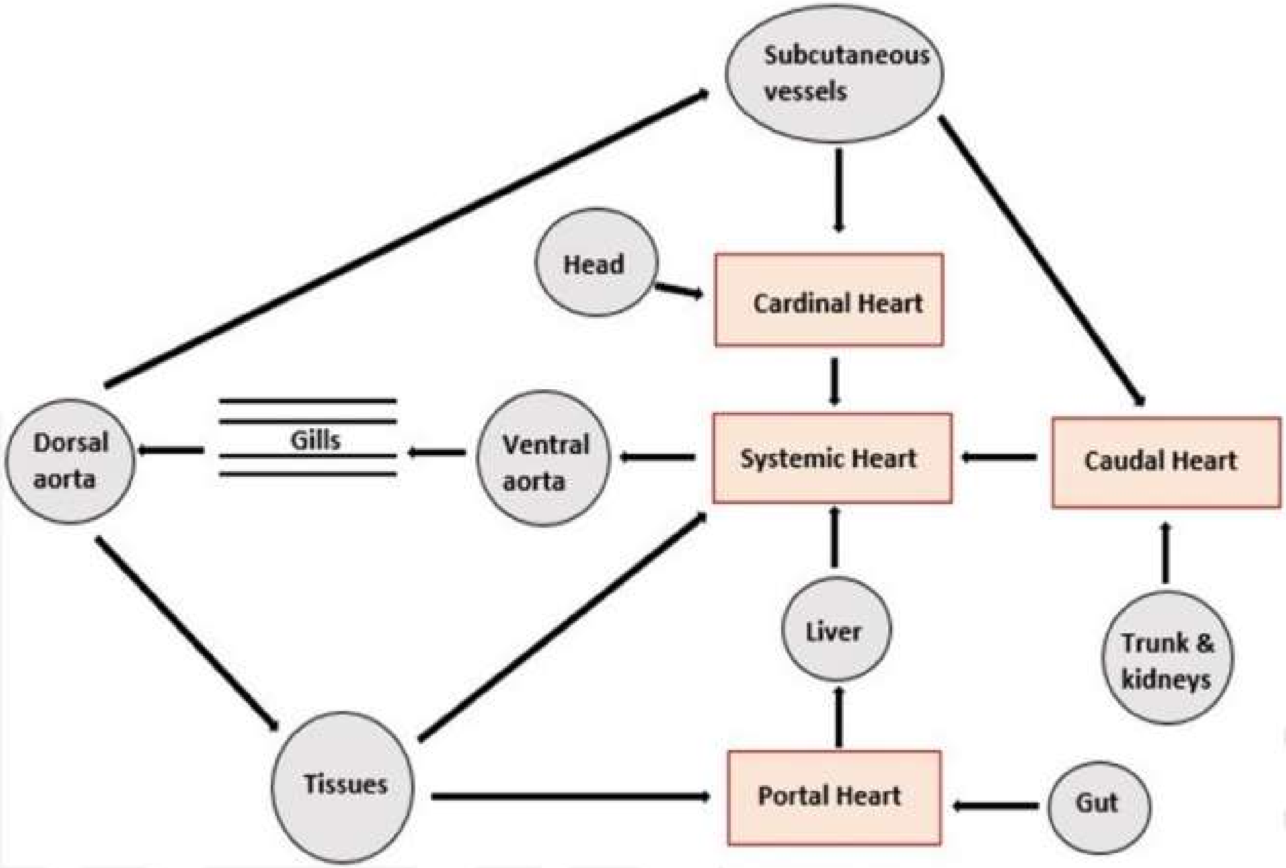



**Fig. 5.1: Simplified view of the relationship between the main 'systemic (or brachial)' heart and the three accessory hearts of the hagfish (adapted from Jensen, 1965 and Jorgensen et al. 1998).**

- Thus a true heart is seen for the first time in fishes; a heart consisting of a series of specialized chambers to which the function of forcible propulsion of blood in arterial channels is restricted.
- The heart of fishes is known as the branchial heart as its main function is to provide deoxygenated blood through the ventral aorta into the gills.
- Basically there are two main chambers : the atrium and the ventricle; two other chambers the sinus venosus (SA) and conus arteriosus (CA) in lamprey, elasmobranchs and holosteans .
- The same chamber in teleosts is known as bulbous arteriosus which is elastic and continues to form the ventral aorta

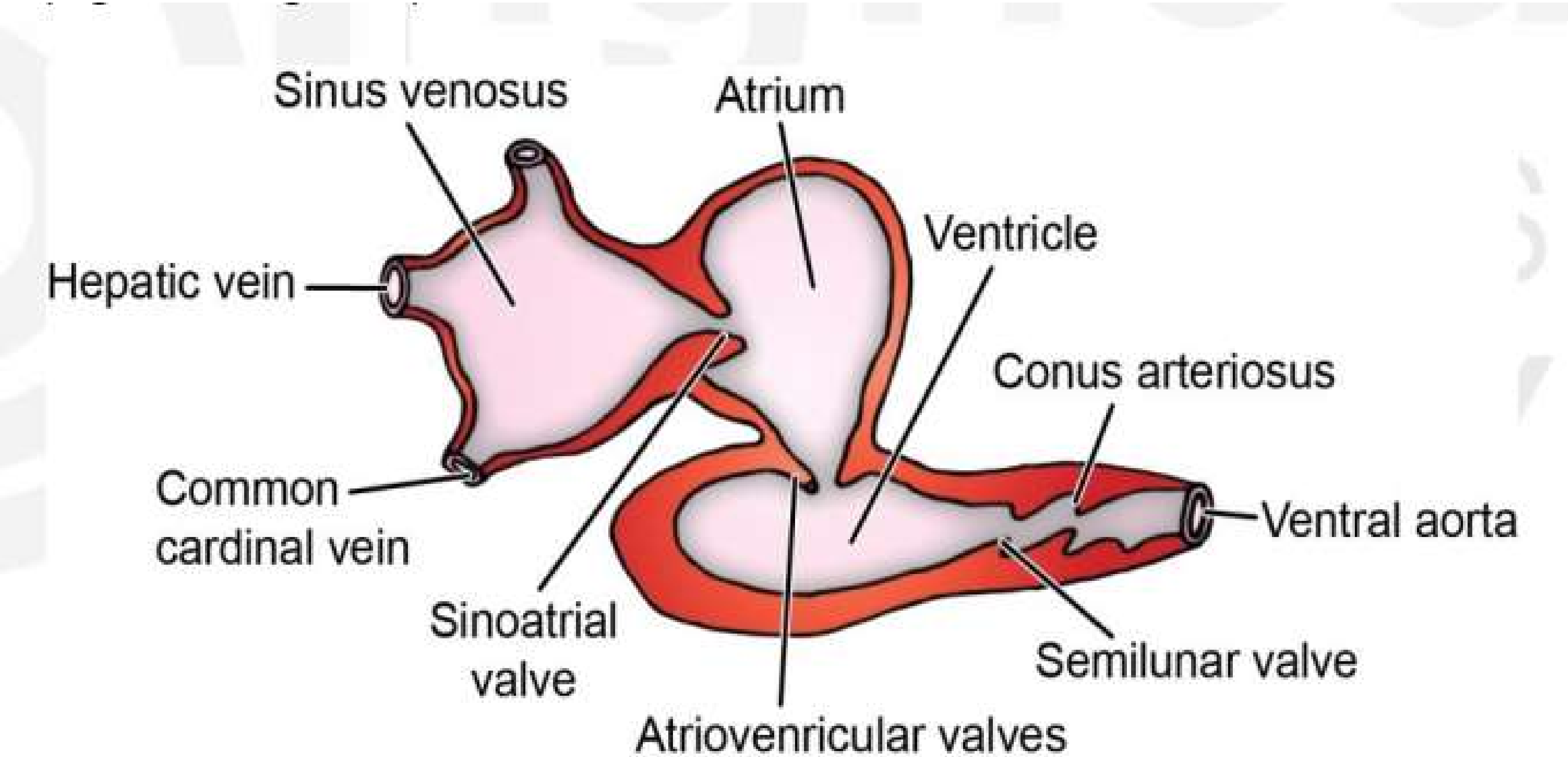
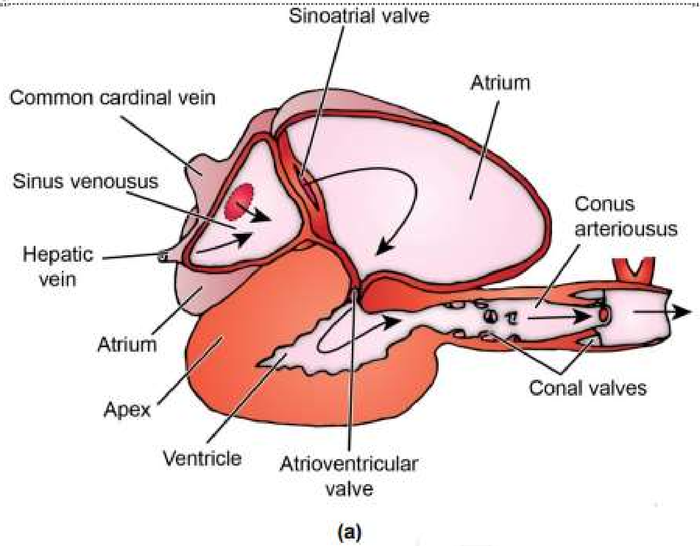



**Fig. 5.2: Lamprey heart showing the chambers characteristic of most fishes.**

- Actually two operations must be performed to carry out the cardiac function efficiently in a gill-respiring vertebrate.
- The blood must be first collected and then pushed along. Collecting chambers thus appear at the rear and propulsive chambers at the front.
- Fishes are provided with a posterior sinus venosus, followed by an atrium, then a ventricle, and finally a conus arteriosus in the anterior arranged in series.
- The sequence of beat is the peristaltic sequence; from the rear towards the front so the blood flows from posterior chambers to anterior chambers.

- The sinus venosus is little more than an expansion of the junction of the primary somatic (common cardinal) and visceral (hepatic) veins.
- The walls are very thin and contain the pacemaker cells that initiate contraction.
- A slight negative pressure actually exists in this chamber, resulting from the integration of atrial contraction and action of the sinoatrial valve.
- The venous blood from the body fills the sinus venosus and through the sinoatrial valve blood passes with minimum cardiac assistance into the atrium.
- Because the S-shaped arrangement of the chambers in the fish heart places the thin-walled sinus venosus and atrium dorsal to the ventricle, the blood is forced by gravity and atrial contraction through the atrioventricular valve into the ventricle.
- The sinoatrial and atrioventricular valves prevent the back flow of the blood.
- The thickened walls of ventricle with cardiac muscle provide energy to move blood into the ventral aorta and gills.

- Once received in the ventricle, blood passes through one or more series of semilunar valves (conal valves) in reaching the fairly rigid conus arteriosus, which adds still further push to the blood and smooths its flow on its way to the ventral aorta.
- The entrance into the latter is guarded by several rows of other semilunar valves.
- The semilunar valves are folds in the wall which prevent the back flow of blood and possibly help in distributing blood to the aortic arches.
- In teleosts the blood flows from the ventricle into the bulbous arteriosus which is a unique structure, it is thin walled and elastic and expands each time the blood is pumped from the ventricle and connects to the ventral aorta.
- The blood pressure for this is generated in the ventricle which is much higher than what is required in the thin walled gills so the bulbous arteriosus regulates the pressure as it enters the gills.
- In fact the teleosts synchronize the opercular movement with the pulsation of the heart so that a steady flow of blood is maintained.



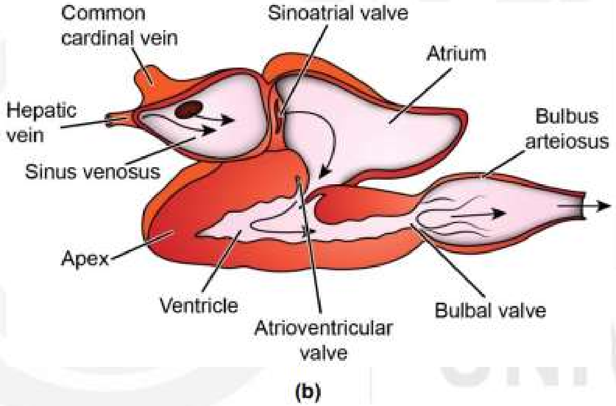




**Fig. 5.3: Fish hearts, (a) Shark (b) Teleost. Blood leaves the shark heart through the muscular conus arteriosus, a chamber that is absent in teleost fishes. In the teleost heart, the base of the ventral aorta is swollen, creating the elastic, non contractile bulbus arteriosus. A single pair of bulbus valves prevent the back flow of blood into the ventricle.**

# Early Tetrapod Heart

- This stage was initiated by the development of air bladder in pretetrapod ancestors for the perfection of aerial respiratory function in tetrapods. .
- Gradually, the air bladder became specialised to serve the role in external respiration as seen in the present day lung fishes, the sarcopterygians.
- Lungfishes primarily use their gills for respiration but when they are outside water they adopt a vascularized lung supplied by two pulmonary arteries to assist in breathing air.
- The aerated blood does not supply the body directly but returns to the heart via a single pulmonary vein which opens on the left side of the atrium from where it is pumped into systemic circulation.
- The blood returning after circulation in the body comes back via the sinus venosus which has shifted to the right side of the heart.
- This modification forms the basis for dual circulation first seen in vertebrates which chiefly involved changes in the heart.
- First the atrium was subdivided into two chambers; a systemic chamber (right), receiving non-aerated blood from the sinus venosus, and a pulmonary chamber (left), receiving aerated blood from the pulmonary veins

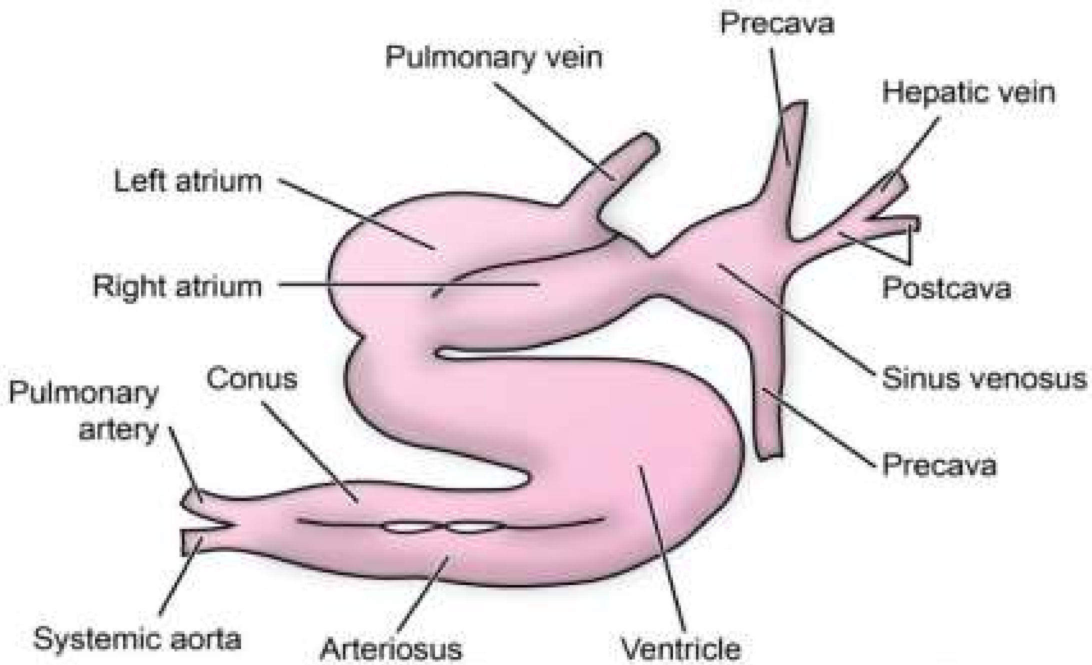



**Fig. 5.4: The early tetrapod heart, ventral view with parts drawn to side instead of superimposed as in life.**

- A second related alteration involved a partial separation of two chambers in the conus arteriosus, serving apparently to direct the aerated blood (from the left side) chiefly into the anterior vessels of the ventral aorta, whereas the nonaerated blood (from the right side) was directed chiefly into the posterior pair of vessels bearing the pulmonary arteries.
- Thus we can recognize a pulmonary and a systemic chamber in the conus arteriosus.
- In amphibians that have functional lungs; the heart consists of 3 chambers:, atrium completely divided into right and left atria, a ventricle and a sinus venosus and conus arteriosus which is partially divided with the help of a spiral valve.
- In frogs, whose cardiovascular system is best studied, the conus arteriosus arises from the single trabeculate ventricle.
- Trabeculae are the projecting cones of the muscles that arise from the inner wall of myocardium of the ventricle creating deep recesses or compartments in the wall.
- Semilunar valves lie at the base of conus arteriosus and prevent the backflow of the blood into the ventricle.
- A spiral valve twisting almost through a complete rotation establishes chambers within the conus arteriosus that target blood to the systemic and pulmocutaneous arches, both of which arise from truncus arteriosus, a remnant of ventral aorta.
- The sources of oxygenated blood vary in amphibians; as for respiration they depend on the skin, on gills, on lungs or on all the three modes.
- It is for this reason the heart structure varies in different amphibians.

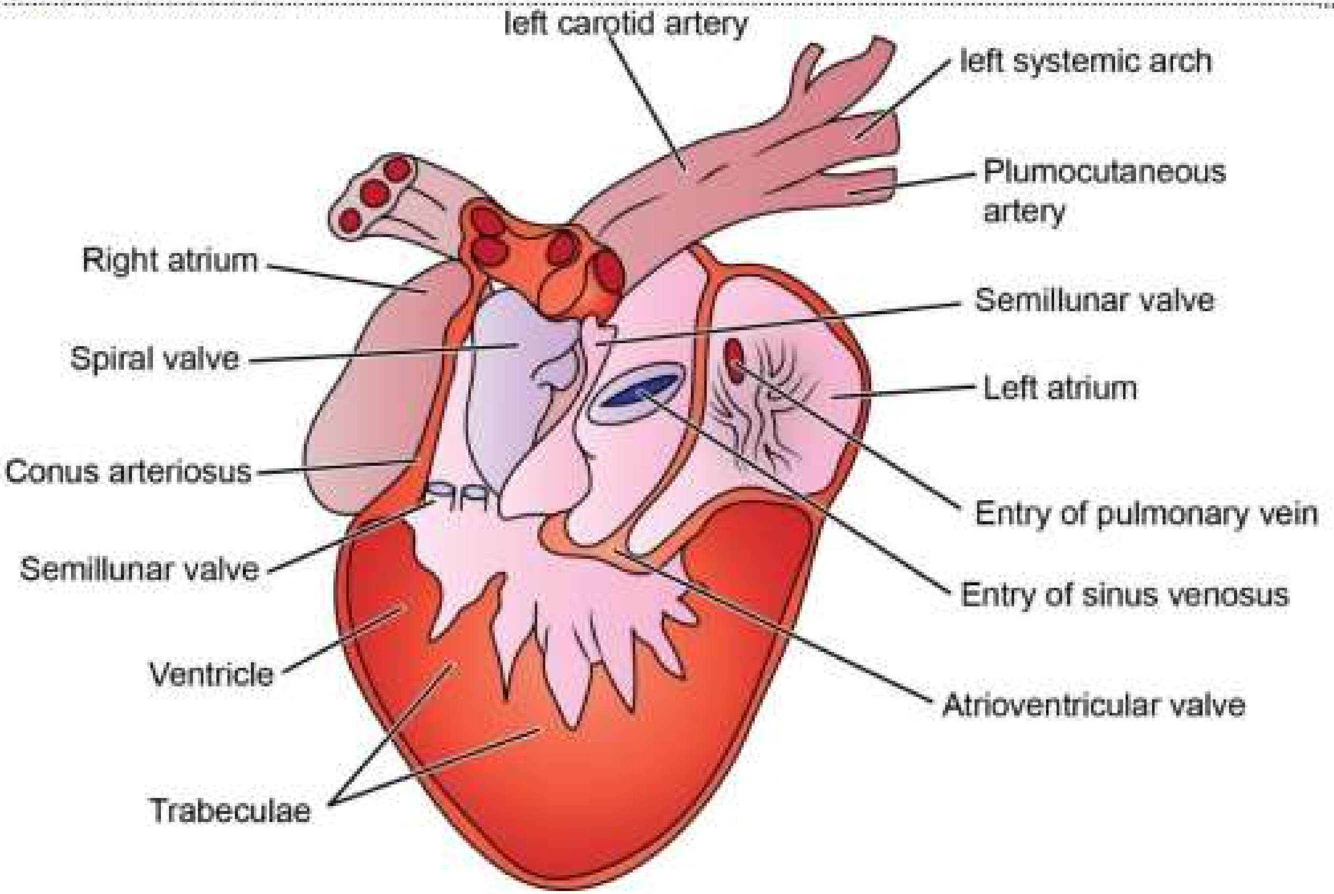



**Fig. 5.5: Structure of the heart of a bull frog.**

- In lungless salamanders or the ones with reduced lung function the septum dividing the atrium as well as the spiral valve may be much reduced or entirely absent.
- In amphibians such as Necturus where gills dominate lungs as respiratory organs, the interatrial septum is reduced or perforated. The atrium is completely divided in modern anurans and in all living reptiles, birds and mammals.
- Another alteration in amphibian heart is the reduction of sinus venosus both in size and importance as a blood-gathering chamber.
- A large thin-walled heart chamber (sinus venosus), into which the blood can flow against an absolute minimum of resistance is essential for fishes.
- In land-dwelling vertebrates, subjected to the markedly lesser atmospheric pressure, such an elaborate collecting device is not essential; in later stages it is discarded completely.

- In amphibians the deoxygenated and oxygenated blood streams returning from systemic and pulmonary circuits are kept separate as they pass through the heart.
- The deoxygenated blood is selectively directed to the lung via pulmonary artery and the oxygenated blood is directed to the systemic tissue via aortic arches.
- In frogs during the time of air breathing, the trabeculae in the ventricle separate the two different streams of blood in the heart.
- It is thought that as one stream enters the ventricle, it fills the compartments between the trabeculae, and then the second stream occupies the centre of the ventricle.
- Because of their different positions, the oxygenated and deoxygenated streams depart by different exits to reach appropriate set of arteries.
- Whenever a frog dives in the water, the lung collapses from the water pressure on the body wall.
- The blood flow is reduced in the lungs and increased in the skin. Thus, the loss of pulmonary respiration is somewhat compensated by increased cutaneous respiration in submerged frogs.

# Late Ectotherm Heart

- Living reptiles varied in cardiac structure though they exhibit uniformly a number of improvements over the early tetrapod heart .
- Since most reptiles are adapted to a fully terrestrial environment and have more active lifestyle, their cardiovascular system supports the accompanying higher metabolic rates and elevated levels of oxygen and carbon-dioxide transport.
- It is also capable of generating higher cardiac out-put, elevated blood pressures and more efficient separation of oxygenated and deoxygenated blood streams as compared to amphibians. Basically two types of reptilian hearts (one in chelonians and squamates and other in crocodiles) have been recognized.

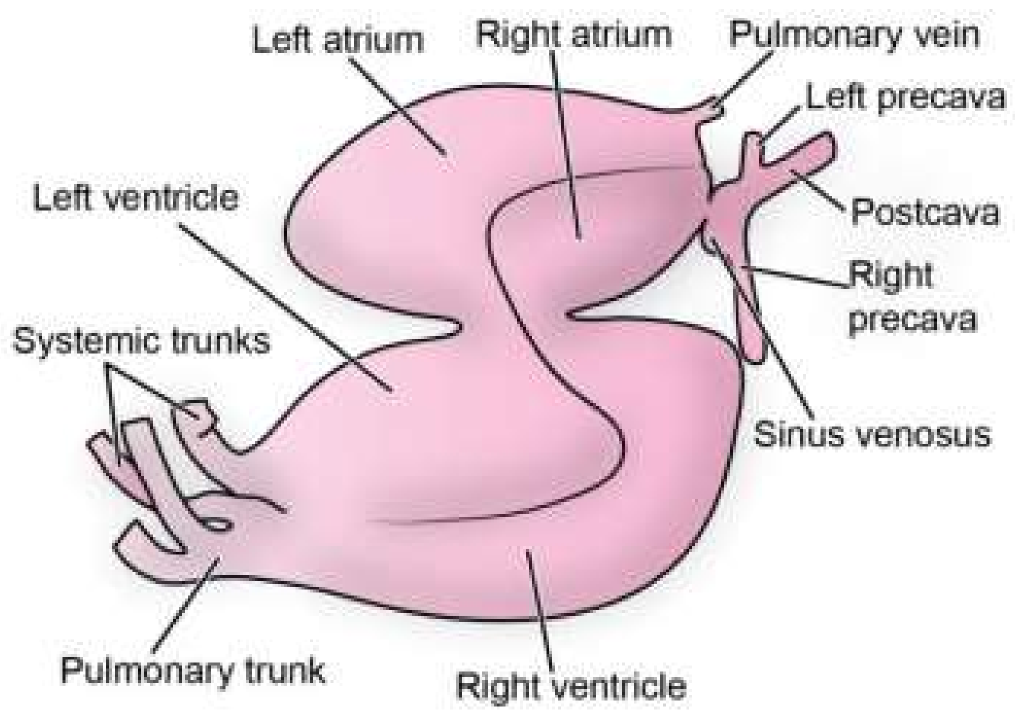



**Fig. 5.6: Late ectothermic heart, ventral view with parts drawn to side instead of superimposed as in actual structure.**

- In chelonian/squamate heart, the sinus venosus is reduced in size as compared to that in amphibians and in advanced types ancestral to mammals, it has disappeared completely as a chamber, although it is present in all living reptiles.
- From the very first vertebrates, however, the sinus venosus served a function not only as a collecting chamber but also as a site of origin of heartbeat.
- Although its identity as a chamber may have been lost in at least some reptiles and certainly in birds and mammals, the function it formerly performed for initiation of heart beat still remains.
- The excitatory tissue remained embedded in the wall of the right atrium near the point of the entry of veins, that now with the loss of the sinus as a chamber, empty directly into the atrium.
- This myogenic center is the sinoatrial node, which serves in all amniotes lacking sinus venosus as the originator of each heartbeat.
- The conus arteriosus also disappeared, though it appears during early embryonic development, in adults it was subdivided to form the bases (trunks) of the three large arteries leaving the ventricle: the pulmonary trunk and the right and left aortic trunks (systemic trunks).

- This pairing of systemic trunk is seen in many reptiles, the right trunk connected with the left side of the heart, the left with the right side.
- Despite the loss of the role of the conus arteriosus as a cardiac chamber in reptiles, the semilunar valves that conus formerly possessed remained intact and unchanged.
- These persist at the bases of the pulmonary and systemic trunks in all amniotes, but are reduced into three valves in each vessel. Atrium is divided into right and left atria.
- Entry to the ventricle is guarded by the atrioventricular valves. Ventricle is partially divided internally resulting in a rather effective separation of venous and arterial blood.
- It has three interconnected compartments: cavum venosum, cavum pulmonale, cavum arteriosum.
- Cavum venosum and cavum pulmonale are separated from each other by a muscular ridge and cavum arteriosum is connected to the cavum venosum through an interventricular canal.

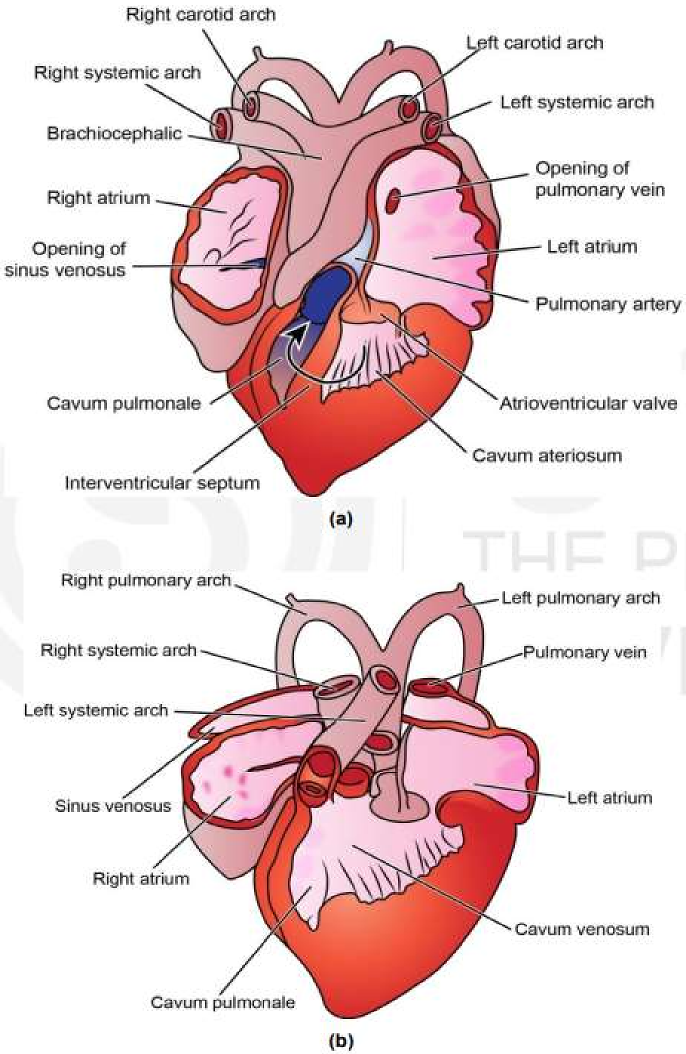



**Fig. 5.7: Ventral view of the lizard heart. (a) Small part of the ventral wall has been removed. The arrow shows the direction of blood flow from cavum arteriosum to cavum venosum through interventricular canal. The blood goes to systemic arches from cavum venosum. (b) Structure of the heart after some more part of the ventral wall has been removed.**

The pattern of blood flow through the hearts of chelonian and squamates varies depending on whether they breathe air or hold their breath (a condition called apnea).

. For example, when turtle is air breathing on the land most of the deoxygenated blood returning from systemic tissues is directed to the lungs and most of the oxygenated blood from the lungs is directed to the systemic tissues via the aortic trunk.

When the turtle dives in the water, the heart responds with a right to left cardiac shunt. Blood flowing in the cavum venosum is directed to the aortae rather than the pulmonary circuit.

This shunting is controlled by the differences in the resistance of systemic and pulmonary circuits.

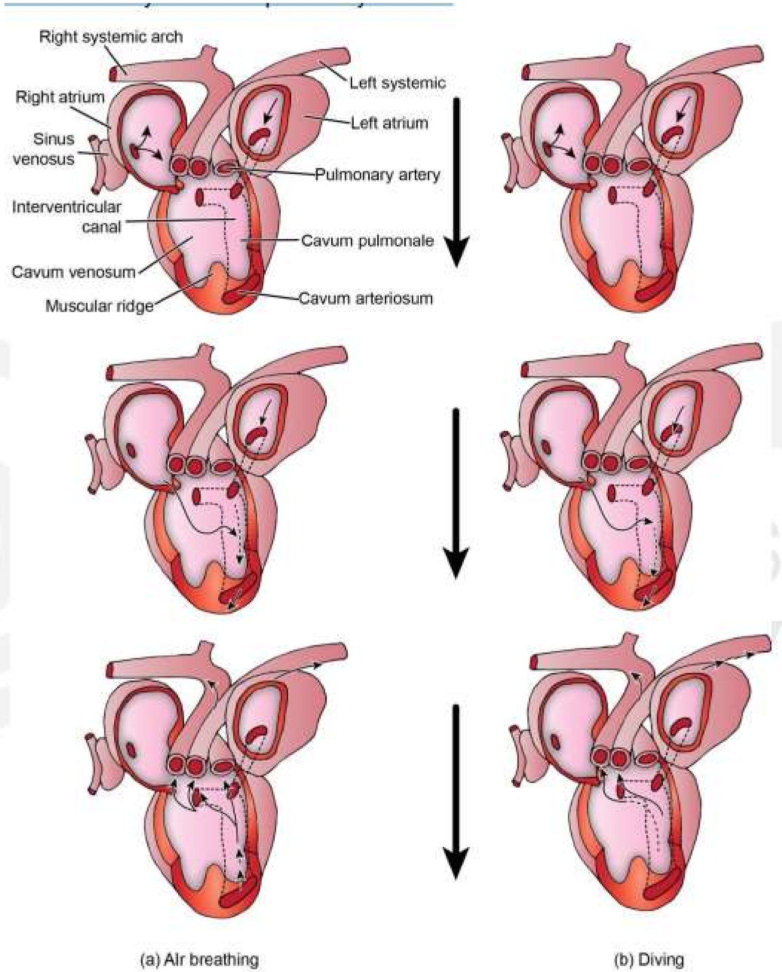



**Fig. 5.8: The path of blood flow in the squamate heart. (a) In the squamates breathing air, venous blood from the right atrium enters the cavum venosum, crosses the muscular ridge and fills the cavum pulmonale. When ventricle contracts, most of this blood flows in the pulmonary artery. Simultaneously, blood from the left atrium enters the deep cavum arteriosum. Upon contraction of the ventricle this blood passes through the interventricular canal to the left and right aortic arches. (b) On diving, due to the resistance to the pulmonary blood flow, the blood moves across the muscular ridge and departs mainly through the left aortic arch.**

- The heart of crocodiles shows structural variations in certain aspects.
- The ventricle is completely divided into right and left chambers by a complete interventricular septum.
- The pulmonary trunk and the left aortic arch opens off the right ventricle and the right aortic arch opens off the left ventricle.
- Curiously, the left arch does not receive blood directly from its own (right) ventricle, since the semilunar valves actually prevent flow from ventricle to aorta except under unusual stress situation.
- The left arch receives blood, through the foramen of Panizza that connects the right and left arches where they cross a short distance from the heart

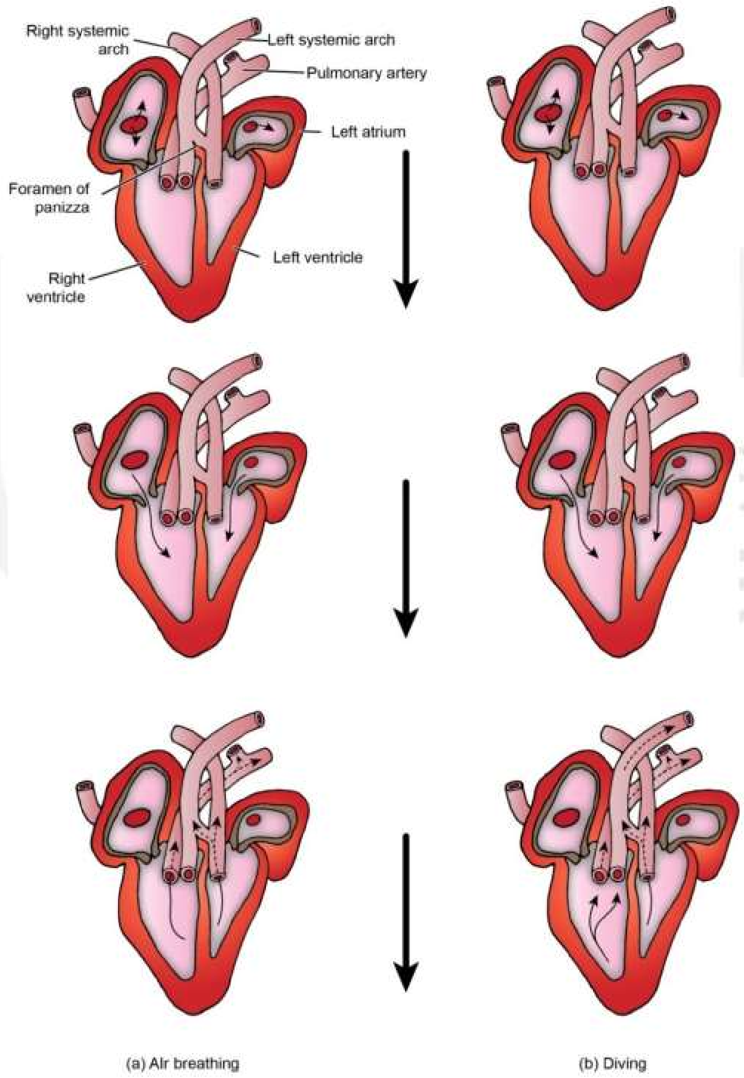



**Fig. 5.9: Blood flow through the crocodile heart. (a) Systemic and pulmonary blood flow during air breathing period. (b) Internal changes that result in decreased pulmonary flow when the crocodile dives.**

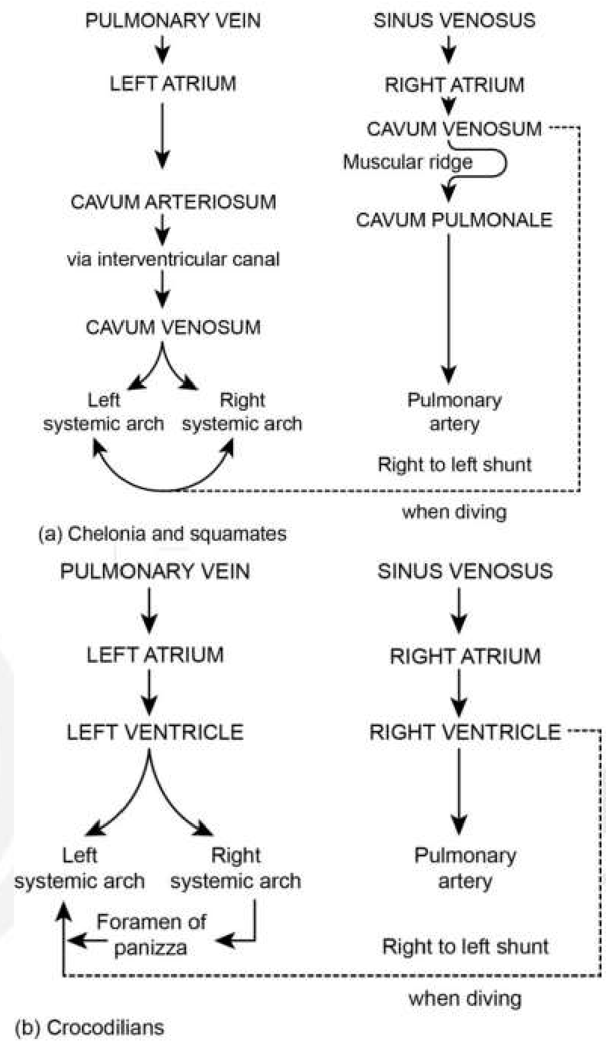



**Fig. 5.10: The flowchart comparing the blood flow patterns in the hearts of (a) chelonian and squamate, and (b) crocodiles. Dashed lines indicate the cardiac shunts that divert blood flow from pulmonary circuit to systemic circuit while diving. During this cardiac shunt resistance to pulmonary flow increases due to contraction of the sphincter at the base of pulmonary artery. In crocodiles the vasoconstriction of the vascular supply to the lungs also aids in this resistance.**

# Endotherm Heart

- Only a few, relatively slight alterations have occurred in endotherms to effect the maximum efficiency of the heart
- Most important is the complete closure of the ventricular wall, rendering absolutely impossible any mixture of aerated and non-aerated blood.
- The trend towards double circulation in the heart was initiated certainly in the sarcopterygians. It attained perfection in endotherms.
- Closure of the ventricles along with simplification of the systemic aorta is the last step in reaching the greatest possible perfection in the cardiac link of the "forced draft" respiratory mechanism unique to birds and mammals and chiefly responsible for their endothermic condition.

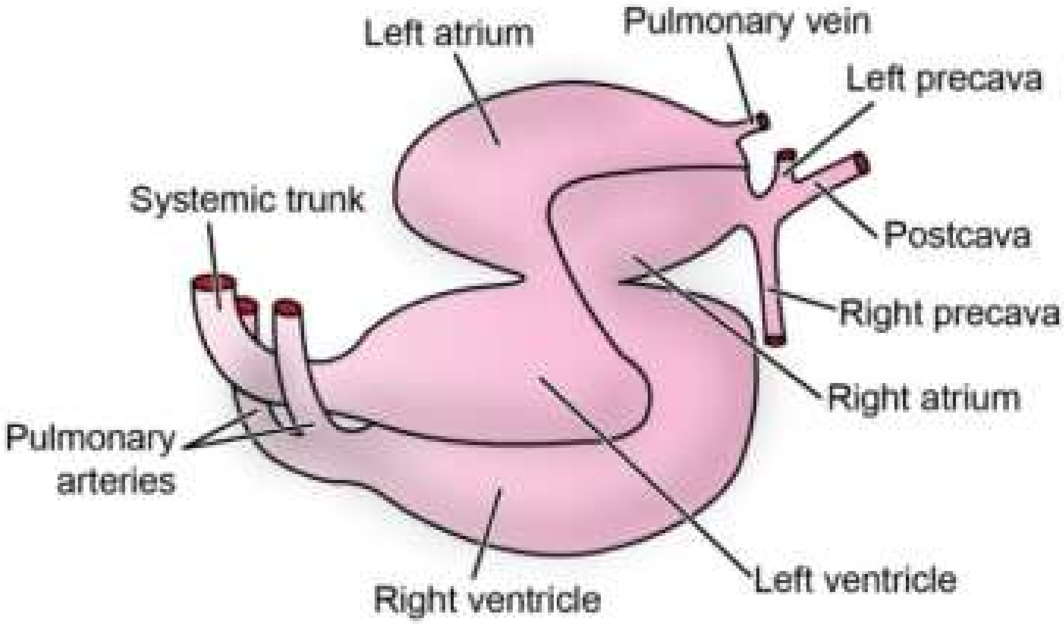



**Fig. 5.11: Endothermic heart, ventral view with parts drawn to side.**

- In birds, though the sinus venosus is reduced, it still remains a small discrete area.
- The conus arteriosus is only transiently present in embryonic condition, that gives rise to the pulmonary trunk and a single aortic trunk.

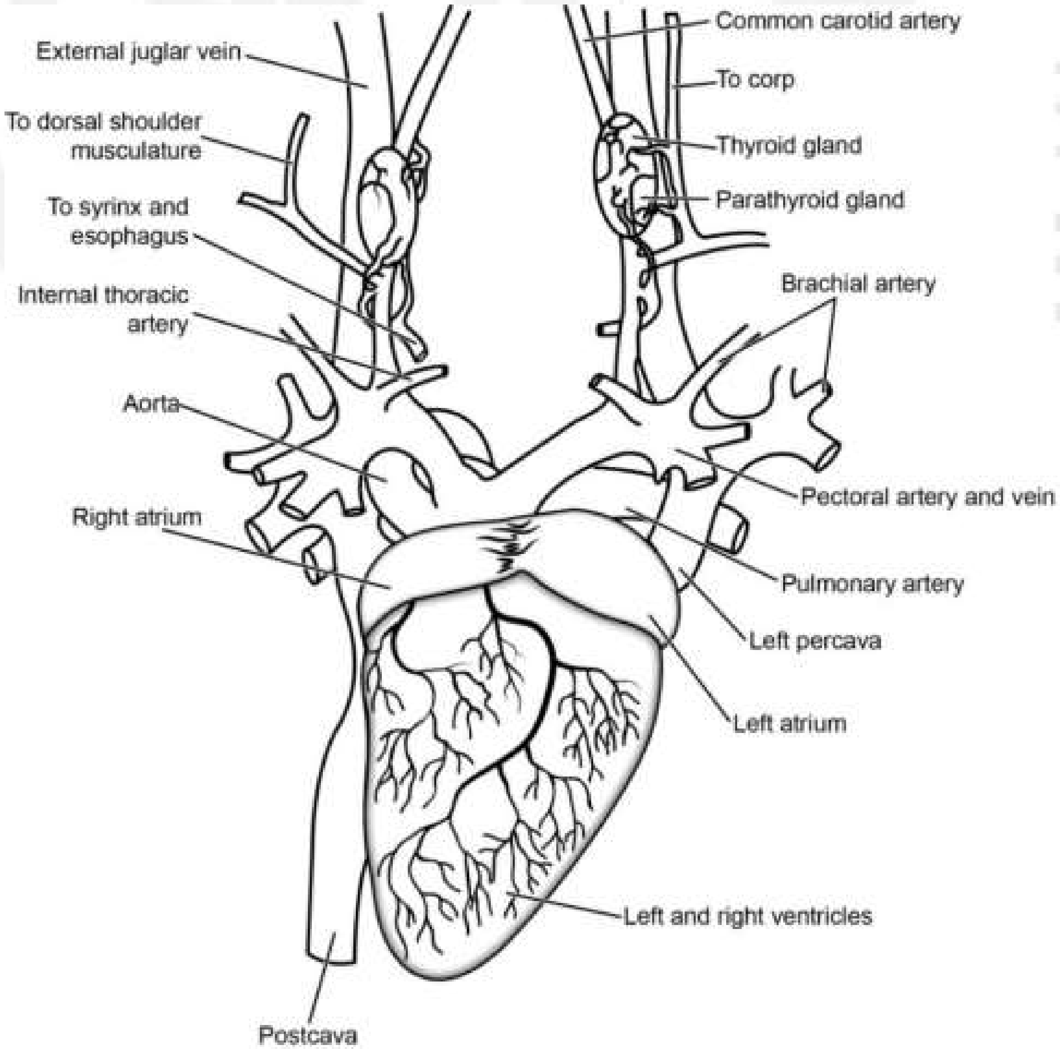



**Fig. 5.12: The heart of a bird (ventral view).**

- In mammals the sinus venosus is reduced to a patch of Purkinje fibers (also called sinoatrial node) in the wall of right atrium.
- This node acts as a pacemaker, initiating the wave of contraction i.e. rhythmic heart beat that spreads across the heart like in all other vertebrates.
- Another mass of typical muscle fibers called as the atrioventricular node in the wall of right atrium in the four chambered heart, also acts as pacemaker under experimental conditions when the sinoatrial node is destroyed or prevented from functioning.
- Similar to that in birds the conus arteriosus during embryonic development splits to produce the pulmonary trunk and single aortic trunk of the adult.
- The mammalian heart possesses only two of the three sets of valves present in piscine ancestors; the semilunar valves and the atrioventricular valves.
- The latter set is now divided into two, to which the names tricuspid valve and bicuspid or mitral valve are applied in mammals.

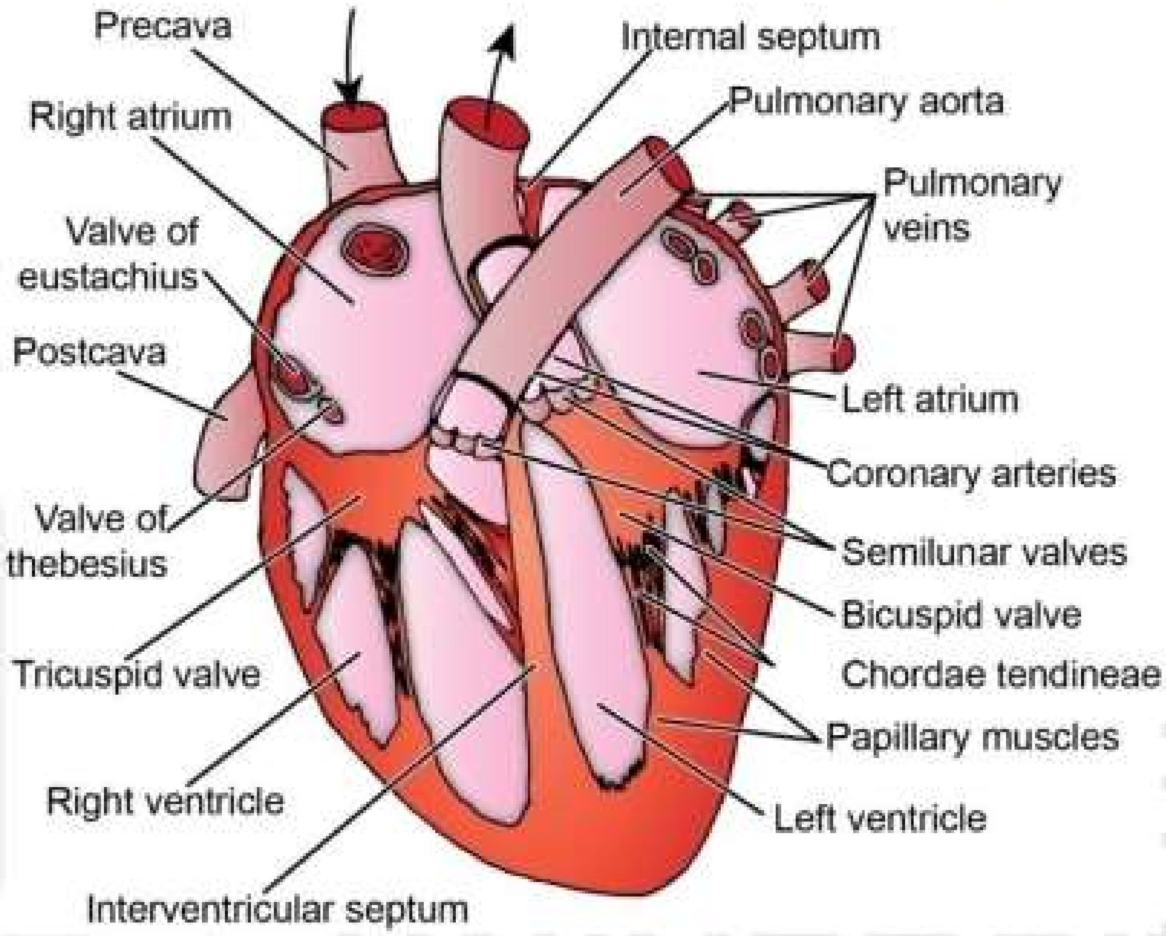



**Fig. 5.13: Ventral view of the mammalian heart.**

- Although the structure of avian and mammalian heart is similar they both have evolved from different reptilian groups.
- This difference is reflected in their embryonic development. Both these hearts also function similarly as both consist of parallel pumps with double circulation circuits.
- The right side of the heart gathers deoxygenated blood from the systemic tissues and pumps it in pulmonary circuit.
- The left side of the heart pumps oxygenated blood from the lungs through the systemic circuit.
- There is no cardiac shunting as hearts of birds and mammals are divided into right and left chambers.

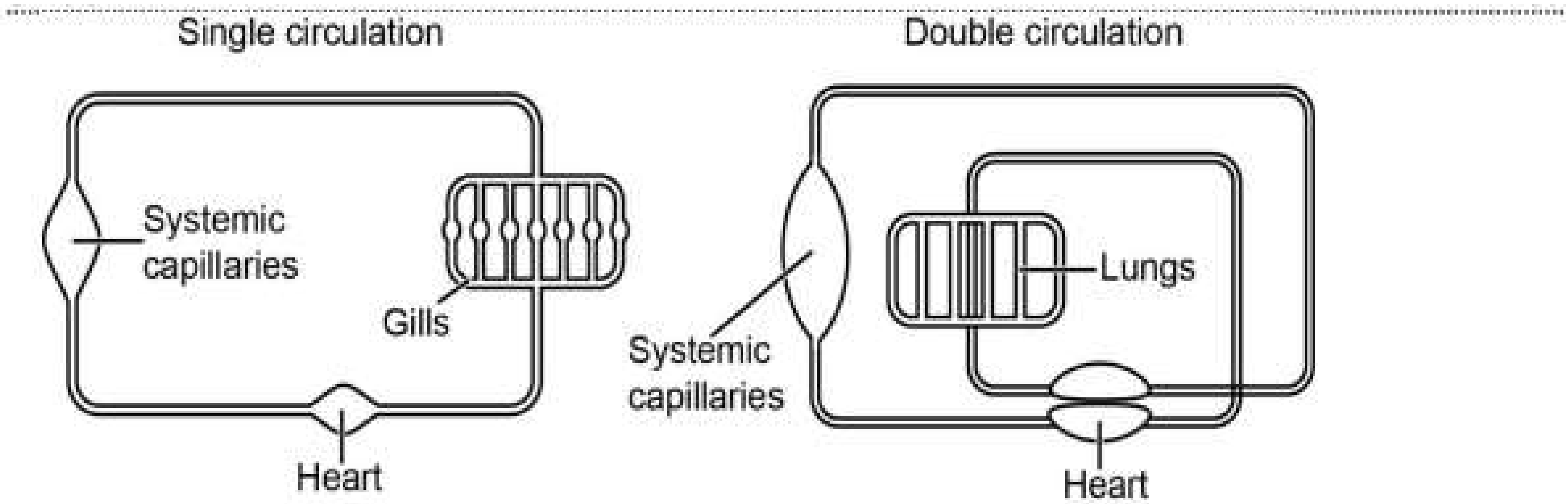



**Fig. 5.14: Diagrammatical representation of single circulation (a) and double circulation (b).**

- In single circulation pattern the blood passes only once through the heart during each complete circle as seen in most of the fishes .
- Amniotes have double circulation pattern in which blood passes twice through the heart in every circuit.
- From the heart the blood goes to the lungs, back to heart out to systemic tissues and again back to the heart.
- The major evolutionary event was addition of pulmonary circuit in the circulatory pattern.
- The intermediates that have characteristics of both the conditions include lung fishes, amphibians and reptiles.
- The evolution of this type of circulatory system design is the adaptive advantage of the transitional forms that came onto land.