Circulatory System in Vertebrates

Circulatory system evolved with increasing complexity in the grades of organization among animals. In lower invertebrates, diffusion served the cause of transporting nutrients, wastes and gases. However, in higher invertebrates and vertebrates, their complex grades of organization made diffusion useless for rapid transport. Thus, circulatory system evolved to perform three basic functions in vertebrates:

- Transport of nutrients and O_2 to all parts of body.
- Collection and transport of metabolic waste from all parts of body to excretory organs.
- Transport of signaling molecules for better integration of organ system. This helps to maintain homoeostasis.

The evolution of circulatory system in the vertebrates can be studied through evolution of heart and aortic arches. We discuss evolution of heart first and aortic arches later.

Evolution of heart in vertebrates:

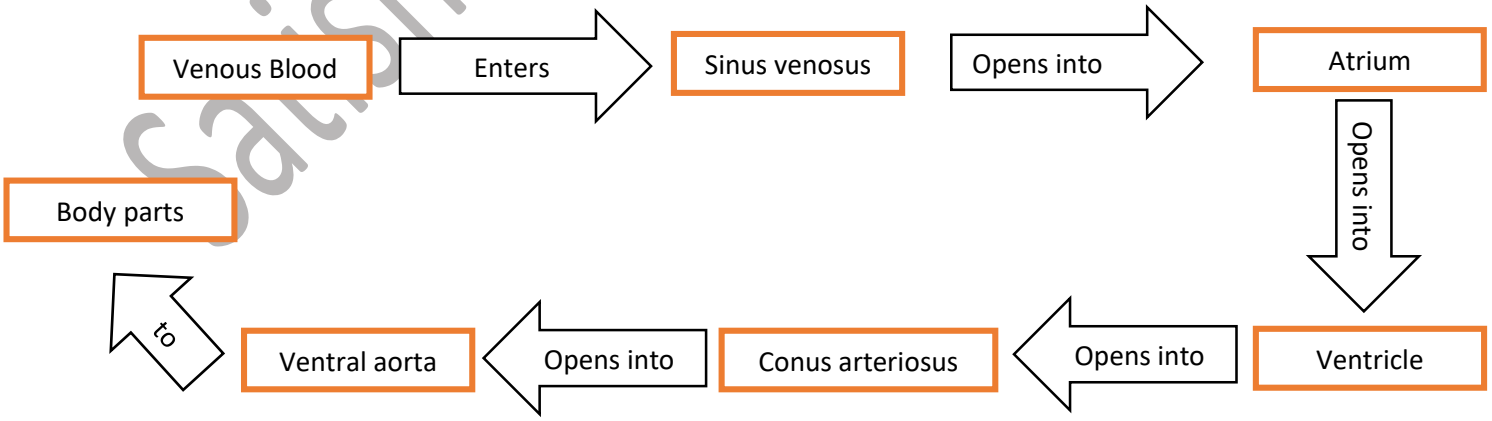
The vertebrate heart is made on a basic architectural plan. It is a sac – like muscular organ having a series of chambers that receive blood from veins and pump it through arteries.

1. **Single chambered heart:** In primitive chordates such as *Branchiostoma*, a true heart is lacking. In these Cephalochordates, a part of ventral aorta below pharynx is muscular and contractile and some Zoologists consider it as a single chambered heart.

As we proceed from primitive to higher chordates, heart modifications occur on following lines:

- Cardiac tube forms chambers due to looping and constrictions.
- Each chamber divides into two separate chambers due to formation of partitions.
- Heart shift from just behind head near gills (fishes and amphibians) position into the thoracic cavity (amniotes) with elongation of neck and development of lungs.

2. **Two chambered, single circuit venous heart:** It is found in fishes. The heart of dogfish is typical and generalized for most fishes. It is muscular, dorso – ventrally bent, S-shaped tube consisting of 4 chambers arranged in a linear sequence.
   The chambers are sinus venosus, auricle, ventricle and conus arteriosus. The sinus venosus and conus arteriosus are accessory chambers while auricle and ventricle are true chambers. Thus, we say that fish heart is 2 chambered.
   The route of blood flow in fish heart is as under:



   Sinus venosus opens into atrium across sino-atrial valve and atrium opens into ventricle across atrio-ventricular valve.
   The blood that enters fish heart is deoxygenated or venous and blood that exits the fish heart is venous too. Such heart that pumps only venous or deoxygenated blood is called as venous or branchial heart.

Heart pumps it to gills for aeration and from there blood is distributed to body. Since the received blood flows only once through heart, it is said to have single circuit of blood circulation.
The heart of fish and other vertebrates are enclosed in a pericardial cavity.

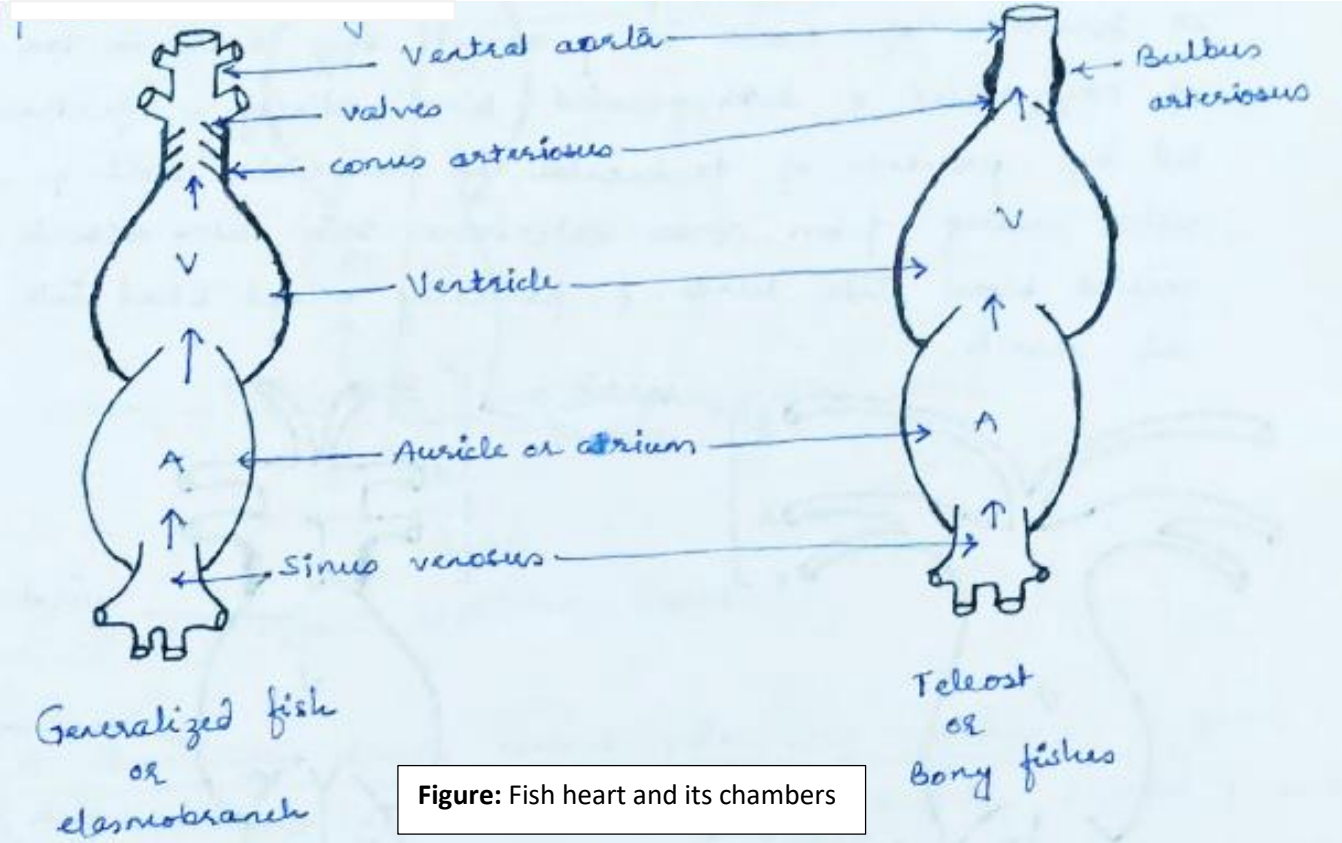


Figure: Fish heart and its chambers

3. **3-chambered transitional heart:** This condition is found in lung fishes, amphibians and reptiles. It is discussed below for amphibians and reptiles.

Amphibian heart: The shift to terrestrial living led to development of pulmonary circulation alongside systemic circulation. Pulmonary circulation ensures that oxygenated blood from lungs first returns to heart and is then pumped to whole body by ventricle.

Its development also necessitated evolution of heart, so as to be able to separate deoxygenated blood from oxygenated blood. Thus, heart evolved in 4 chambered one from a 2 chambered one.

In urodele amphibians, atrium is divided into right and left auricles by inter – auricular septum. This septum is incomplete and perforated by foramen of ovale. This septum leads to mixing of oxygenated blood in left auricle with deoxygenated blood in right auricle.

In anuran amphibians, the interauricular septum is complete so foramen of ovale is absent. This reduces the mixing of oxygenated and deoxygenated blood. Mixing is further reduced by presence of trabeculae in ventricle wall and spiral valve arising from the conus arteriosus. This valve directs deoxygenated blood into lungs and partially mixed blood into systemic vessels.

Reptilian heart: With auricular partition complete in amphibia, ventricular partition began in reptiles. In most reptiles, ventricle is divided into right and left ventricle by interventricular septum. However, this septum is incomplete in most reptiles and allows partial mixing of oxygenated and deoxygenated blood.

In crocodilian, the septum is complete and heart becomes 4 chambered. But separation of blood is not achieved because systemic aortae right (arterial blood) and left (venous blood) join to form dorsal aorta. Thus, two bloods are mixed before distribution.

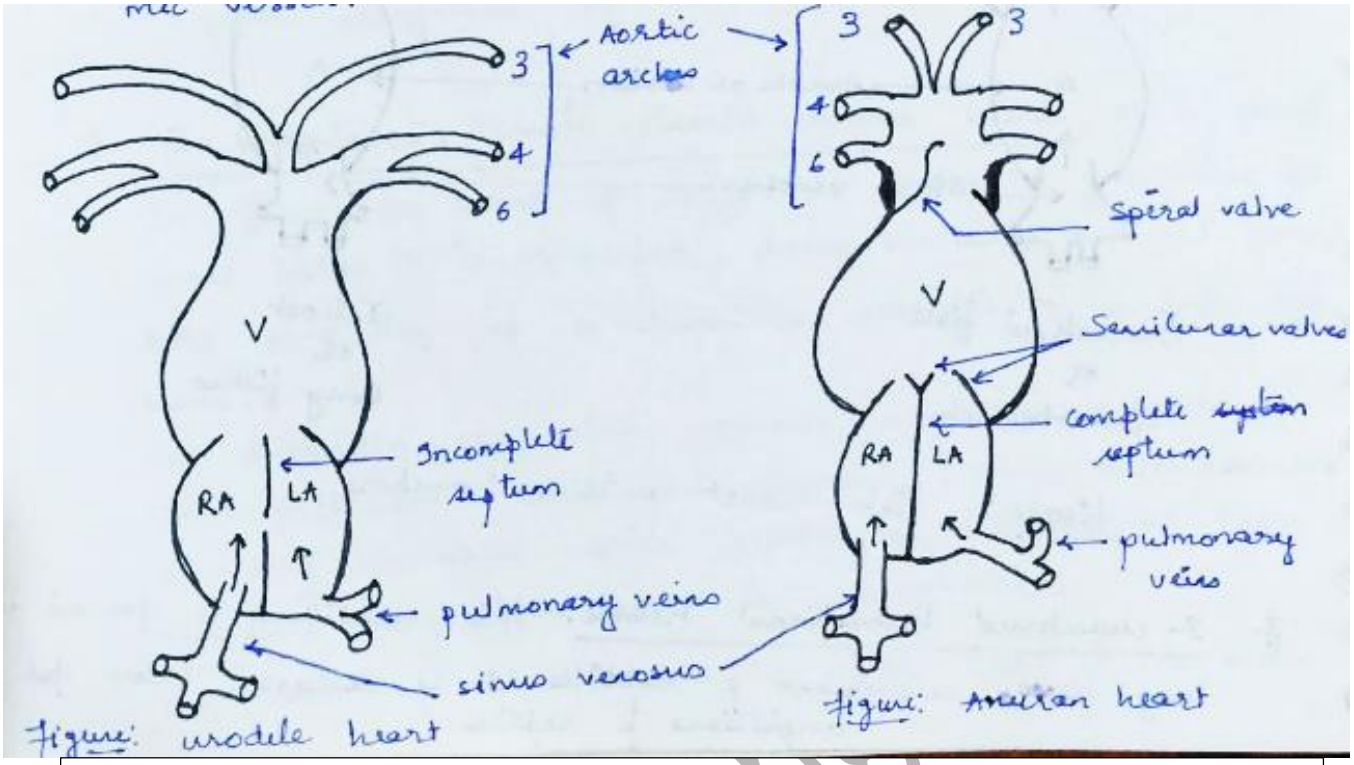


Figure: Urodele heart **Figure: Anuran heart**

Examples of the Amphibian hearts

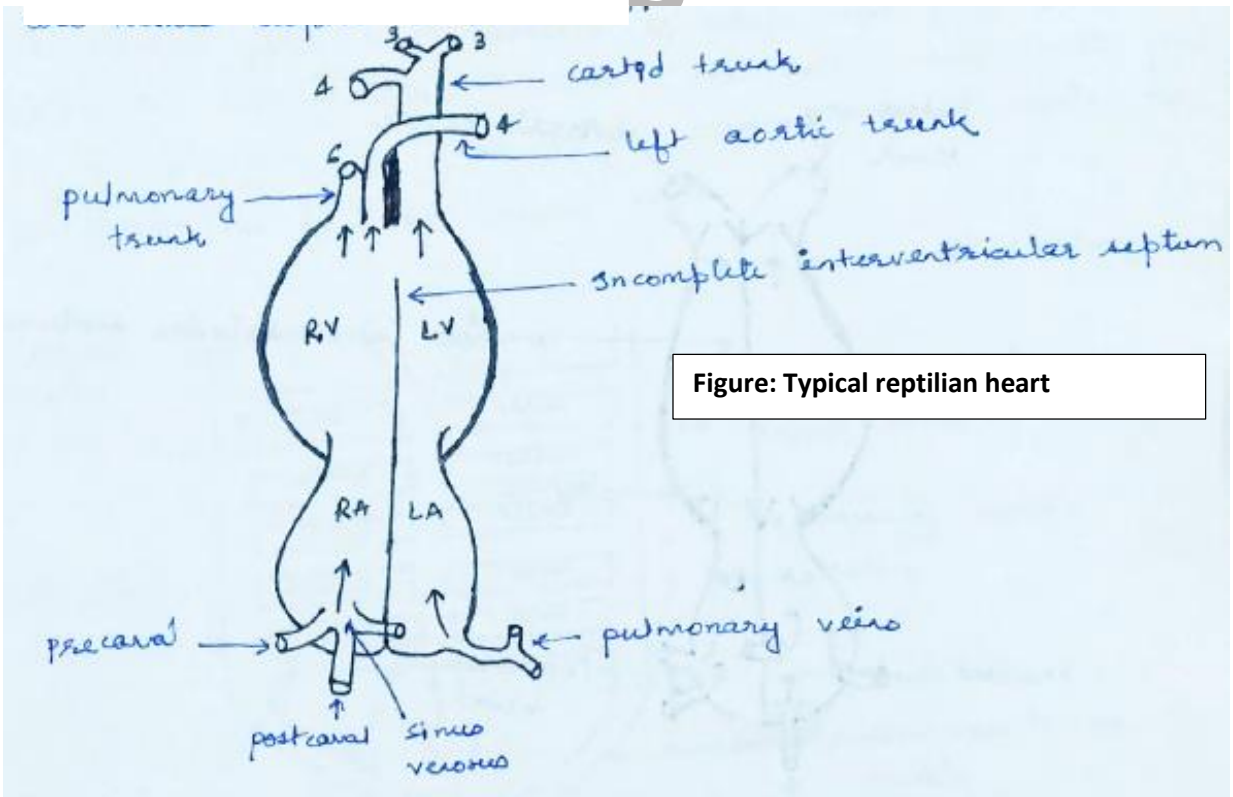


Figure: Typical reptilian heart

4. **4-chambered double circuit pulmonary heart:** It is found in birds and mammals. In them, ventricle is completely divided and so is auricle. Thus, the heart is 4 – chambered having 2 – auricles and 2 - ventricles.
   There are two circuits of blood circulation.
   Pulmonary circulation: The pattern in exact order is given below:
   a. Deoxygenated blood enters right auricle.
   b. Then it goes to right ventricle when right atrioventricular valve opens.
   c. Deoxygenated blood then enters pulmonary artery and reaches lungs for oxygenation.
   d. After oxygenation the blood enters pulmonary veins
   e. Pulmonary veins drain into the left ventricle.

   Systemic circulation: The pattern in exact order is given below:

   a. Oxygenated blood enters the left ventricle when left atrioventricular valve opens.
   b. On contraction of the left ventricle the oxygenated blood enters aorta and is distributed in the arteries for distribution to body parts, cells and tissues.
   c. The deoxygenated blood from cells, tissues and other body parts is collected via veins.
   d. Veins open in the vena cava and drain the deoxygenated blood to the right atrium.

This pattern of double circulation does not allow any mixing of oxygenated and deoxygenated blood and such hearts are called as pulmonary heart.

The sinus venosus is completely absent as it is absorbed into right auricle. The conus arteriosus is replaced by pulmonary aorta leaving the right ventricle for lungs and systemic aorta leaving the left ventricle for body.

Modifications of aortic arches in vertebrates:

Basic embryonic plan: In a typical vertebrate embryo, major arterial channels include a ventral aorta, a dorsal aorta and 6 pairs of aortic arches connecting ventral aorta with dorsal aorta. Blood leaves heart through ventral aorta, which runs forward, mid-ventrally beneath pharynx and branches anteriorly into a pair of external carotid arteries into head.

At intervals, ventral aorta gives off 6 pairs of aortic arches. Each aortic arch has a ventral afferent branchial artery entering a gill and dorsal efferent branchial artery draining a gill.

All efferent branchial arteries of each side join to form radix or lateral dorsal aorta. The two radix unite just behind pharynx to form single median dorsal aorta. It continues into tail as caudal region.

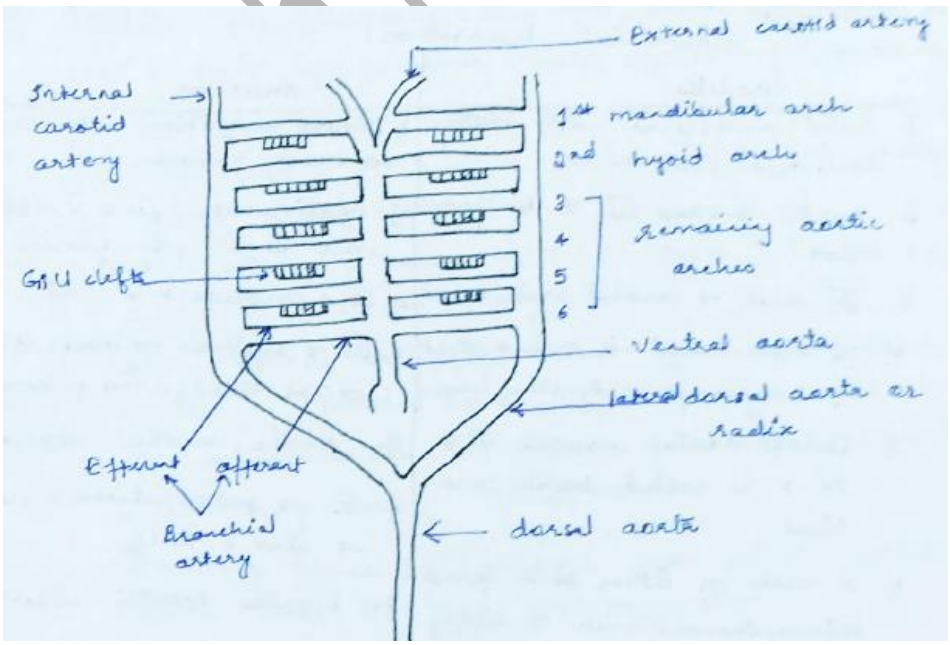


Figure: Embryonic plan of aortic arches

The basic plan has undergone many changes during evolution from fishes to mammals. It is mainly due to shift to terrestrial habitat and circulatory changes needed to adapt it.

1. **Superclass Fishes:** In elasmobranchs, pair I is non-functional and pairs II to VI are functional.
   In teleosts, pair I and II are absent while pair III to VI are present and functional. In these two cases relationship of the aortic arches is similar to basic embryonic plan.
   In dipnoi, pair I and II are absent while pair III to VI are functional. The dipnoi have poorly developed gills, a pulmonary artery arises from efferent part of VI arch on each side and supplies blood to developing air bladder or lung for oxygenation.

2. **Superclass Tetrapoda:** Aortic arches I and II are absent in all tetrapods. Their other modifications are discussed below.

Amphibia: Aortic arches show modification over fishes due to terrestrial transition. These differences for urodeles and anurans are compared below:

Urodeles	Anurans
• Tailed amphibians with water dominant habitat. • Aortic arches III to VI are present. • III arch is carotid arch and supplies head. • IV arch is systemic arch and supplies most of body except head, skin and lungs. • Dorsal aorta connects III and IV, it is called as ductus caroticus. • VI arch on either side forms pulmocutaneous arch to supply lungs and skin. • VI arch retains connection with radix called ductus Botalli.	• Tailless amphibians with land dominant habitats. • Aortic arch I, II and V are absent and III, IV and VI are present. • III arch is carotid and supplies head. • IV arch is systemic and supplies most of the body except head, skin and lungs. • Ductus caroticus is absent. • VI is pulmocutaneous arch and supplies skin and lungs. • Ductus Botalli is absent.

Thus, we see that later amphibians have 3 arches. These are also retained by amniotes i.e. reptiles, birds and mammals.

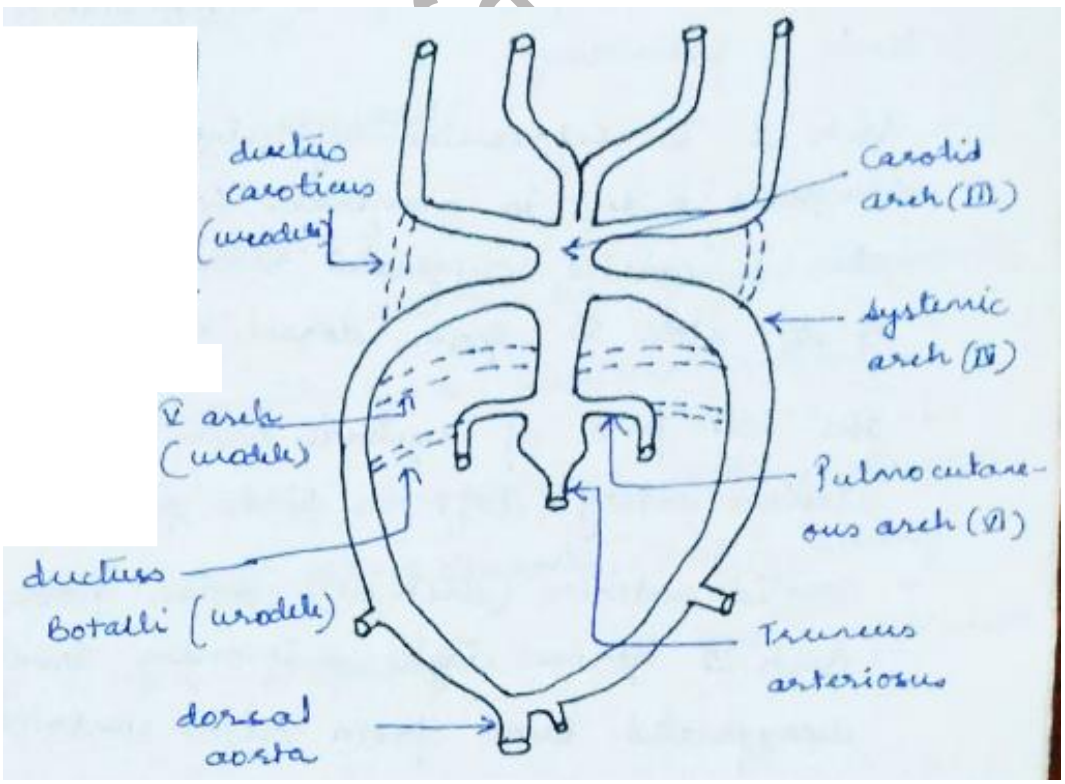


Figure: Modification of aortic arches in amphibia.

Reptiles: They are fully terrestrial and have only 3 pairs of functional aortic arches viz. III, IV and VI. The modifications they show are due to elongation of neck, posterior shifting of heart and partial division of ventricles.

The major modifications are:

- Ventral aorta and conus split to form 3 trunks i.e. 2 systemic and 1 pulmonary.
- Right systemic arch (IV) arises from left ventricle and supplies to carotid arch (III) to supply to head.
- Left systemic arch (IV) arises from right ventricle and supplies body through dorsal aorta.
- Pulmonary trunk (VI) emerges from right ventricle and supplies blood to lungs for oxygenation.
- Ductus caroticus and ductus Botalli are absent.

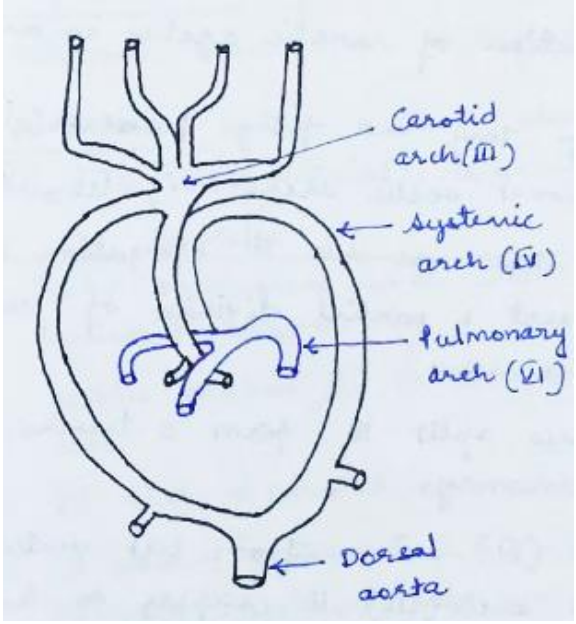


Figure: Typical aortic arch modification in reptiles

Bird and Mammals: These have 4 chambered, double circuit pulmonary heart. They have functional arches as III, IV and VI. The modifications are-

- Ventral aorta replaced by 2 independent aortae viz. systemic and pulmonary.
- Arch IV is represented by single systemic aorta. Right in birds and left in mammals. It emerges from left ventricle and carries oxygenated blood. It unites with radix of its side to form dorsal aorta.
- The lost part of systemic arch is represented by subclavian artery, left in birds and right in mammals.
- Carotid arteries (arch III) arise from systemic aorta.
- Arch VI forms single pulmonary trunk to supply deoxygenated blood from right ventricle to lungs.

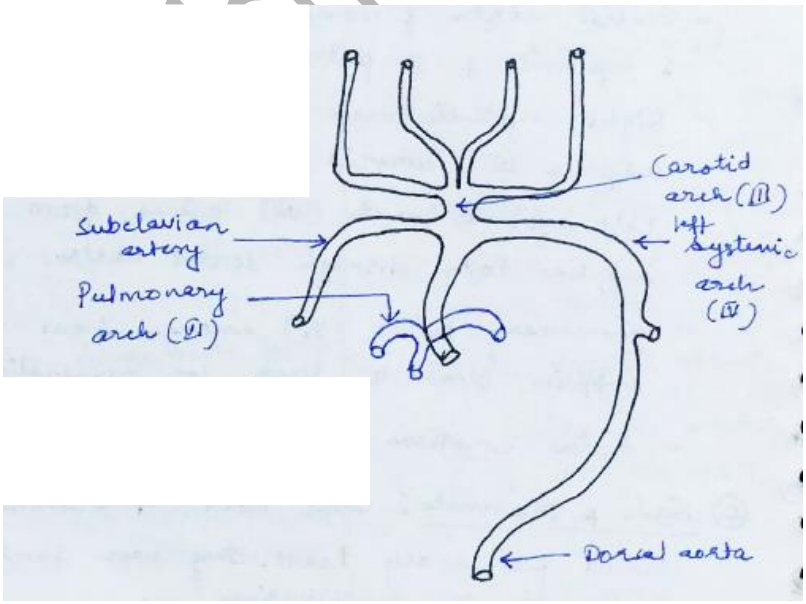


Figure: Aortic arch modification in mammals.