WHY DO WE NEED A CARDIOVASCULAR SYSTEM?

The cardiovascular system serves to provide rapid transport of nutrients to the tissues in the body and allow rapid removal of waste products. In smaller, less complex organisms than the human body there is no such system because their needs can be met by simple diffusion. Evolution of the cardiovascular system provided a means of aiding the diffusion process, allowing the development of larger organisms. The cardiovascular system allows nutrients:

- To diffuse into the system at their source (e.g., oxygen from the alveoli).
- To travel long distances quickly.
- To diffuse into tissues where they are needed (e.g., oxygen to working muscle).

This is an active process requiring a pump: the heart. The functions of the cardiovascular system rely on a transport medium: blood. Blood is made up of cells (mainly red and white blood cells) and plasma (water, proteins, electrolytes, etc.).

Functions of the cardiovascular system

The main functions of the cardiovascular system are:

1. Rapid transport of nutrients (oxygen, amino acids, glucose, fatty acids, water, etc.).
2. Removal of waste products of metabolism (carbon dioxide, urea, creatinine, etc.).
3. Hormonal control, by transporting hormones to their target organs and by secreting its own hormones (e.g., atrial natriuretic peptide).
4. Temperature regulation, by controlling heat distribution between the body core and the skin.
5. Reproduction, by producing penis erection and providing nutrition to the foetus via a complex system of placental blood flow.
6. Host defence, by transporting immune cells, antigens and other mediators (e.g., antibodies).

ANATOMY OF THE HEART AND GREAT VESSELS

Overview of the heart and circulation

The heart consists of two muscular pumps (the left and right ventricles). Each pump has its own reservoir (the left and right atria). The two pumps each serve a different circulation.

The right ventricle is the pump for the pulmonary circulation. It receives blood from the right atrium, which is then pumped through the pulmonary artery into the lungs. Here it is oxygenated and gives up carbon dioxide; it then returns via the pulmonary veins into the left atrium of the heart, and then enters the left ventricle.

The left ventricle is the pump for the systemic circulation. Blood is pumped from the left ventricle via the aorta to the rest of the body. In the tissues of the body, nutrients and waste products are exchanged. Blood returns to the right atrium via the superior and inferior vena cavae.

The two circulations operate simultaneously and are arranged in series. Unidirectional flow is ensured by valves in the heart, pressure differences in the arterial tree and valves in the veins (Fig. 1.1).

CLINICAL NOTE

As the heart consists of two separate pumps, failure of an individual pump is possible, e.g., right heart failure as a result of severe lung disease (cor pulmonale).

The circulatory system is made up of arteries, veins, capillaries and lymphatic vessels:

1. Arteries transport blood from the heart to the tissues.
2. Capillaries are where diffusion of nutrients and waste products takes place.
3. Veins return blood from the tissues to the heart. (The hepatic portal vein is an exception. This transports blood from the intestines to the liver.)
4. Lymphatic vessels return to the blood any excess water and nutrients that have diffused out of the capillaries.

HINTS AND TIPS

Arteries carry oxygenated blood and veins carry deoxygenated blood. The two exceptions to this rule are the umbilical vessels (supplying the foetus) and pulmonary vessels where this is reversed.

The volume of blood ejected from one ventricle during 1 minute is called the cardiac output. The cardiac output of each ventricle is equal overall, but there may be occasional
Cardiac anatomy, physiology and development

Beat-by-beat variation. The entire cardiac output of the right ventricle passes through the lungs and into the left side of the heart. The cardiac output of the left ventricle passes into the aorta, and it is distributed to various organs and tissues according to their metabolic requirements or particular functions (e.g., the kidney receives 20% of cardiac output so that its excretory function can be maintained). This distribution can be changed to meet changes in demand (e.g., during exercise, the flow to the skeletal muscle is increased considerably).

Blood is driven along the vessels by pressure. This pressure, which is produced by the ejection of blood from the ventricles, is highest in the aorta (about 120 mmHg above atmospheric pressure) and lowest in the great veins (almost atmospheric). It is this pressure difference that moves blood through the arterial tree, through the capillaries, and into the veins.

The mediastinum

This is the space between the two pleural cavities. It contains all the structures of the chest except the lungs and pleura. The mediastinum extends from the superior thoracic aperture to the diaphragm and from the sternum to the vertebrae and is divided into superior and inferior parts by the plane passing from the sternal angle to the T4/T5 intervertebral disc. The inferior mediastinum is then further subdivided into anterior, middle and posterior parts (Fig. 1.2). The contents of each part are shown in Table 1.1. The structures in the mediastinum are surrounded by loose connective tissue, nerves, blood vessels, and lymph vessels. It can accommodate movement and volume changes.

The heart is in the middle mediastinum, and it has the following relations:
1. Superiorly, the great vessels and bronchi.
2. Inferiorly, the diaphragm.
3. Laterally, the pleurae and lungs.
4. Anteriorly, the thymus.
5. Posteriorly, the oesophagus.

The structures visible on a normal chest X-ray are shown in Fig. 1.3.

---

**Table 1.1 Contents of the mediastinum**

<table>
<thead>
<tr>
<th>Mediastinal compartment</th>
<th>Contents</th>
</tr>
</thead>
</table>
| Superior                | Great vessels  
Thymus  
Trachea  
Oesophagus                |
| Anterior                | Internal thoracic arteries  
Thymus               |
| Middle                  | Heart and pericardium  
Origins of the great vessels |
| Posterior               | Descending aorta  
Oesophagus  
Sympathetic chain          |

---

**Fig. 1.1** Systemic and pulmonary circulations.

**Fig. 1.2** Lateral view of the mediastinum.
Anatomy of the heart and great vessels

Pericardium

This is the fibroserous sac that surrounds the heart. It consists of two layers, between which there is a small amount of pericardial fluid. The pericardium is fused with the central tendon of the diaphragm at its base, the sternum by the sternopericardial ligament anteriorly and with the tunica adventitia of the great vessels.

**Clinical Note**

When fluid accumulates within the pericardial sac this is called a pericardial effusion. If it builds up quickly and begins to affect cardiac function this is called cardiac tamponade. (Both are described in Chapter 17.)

External structure of the heart

The heart lies obliquely about two-thirds to the left and one-third to the right of the median plane (Figs 1.4–1.6). It has the following surfaces:

1. The base of the heart is located posteriorly and formed mainly by the left atrium.
2. The apex of the heart is formed by the left ventricle and is posterior to the fifth intercostal space.
Cardiac anatomy, physiology and development

Internal structure of the heart

The internal structure of the heart is shown in Fig. 1.7. The right atrium contains the orifices of the superior and inferior venae cavae and coronary sinus. The right ventricle is separated from the right atrium by the tricuspid (three cusps) valve. The right ventricle is separated from its outflow tract (the pulmonary trunk) by the pulmonary valve. This has three semilunar valve cusps.

The left atrium has the orifices of four pulmonary veins in its posterior wall and is separated from the left ventricle by the mitral (sometimes referred to as bicuspid, i.e., two cusps) valve. The left ventricle is separated from its outflow tract (the pulmonary trunk) by the pulmonary valve. This has three semilunar valve cusps.

Coronary arteries

The coronary arteries are shown in Figs 1.8 and 1.9. The left coronary artery arises just distal to the left anterior cusp of the aortic valve. The right coronary artery arises from the right anterior aortic sinus just above the right anterior cusp of the aortic valve. The coronary arteries are the first branches of the aorta; the heart supplies itself with a blood supply before any other organ.

Coronary veins

The coronary veins drain mainly into the coronary sinus, which drains directly into the right atrium (Figs 1.10 and 1.11). There are some small veins that drain directly into the heart chambers. Generally, these drain into the right side of the heart.

Great vessels

‘Great vessels’ is the term used to denote the large arteries and veins that are directly related to the heart. The great arteries include the pulmonary trunk and the aorta (and sometimes its three main branches: the brachiocephalic, the left common carotid, and the left subclavian). The great veins include the pulmonary veins and the superior and inferior venae cavae. The great vessels and their thoracic branches are illustrated in Figs 1.12–1.14.

Tissue layers of the heart and pericardium

Figure 1.15 shows the tissue layers of the heart and pericardium.

Pericardium

The pericardium consists of an outer fibrous pericardial sac, enclosing the whole heart, and an inner double layer of flat mesothelial cells, called the serous pericardium. The two layers of the serous pericardium are:

1. The parietal pericardium, which is attached to the fibrous sac.
2. The visceral pericardium, which forms part of the epicardium and which covers the heart’s outer surface.

Clinical note

In approximately 1% of the population, the aortic valve is bicuspid (has only two cusps). This usually goes unnoticed, but puts a person at increased risk of developing aortic stenosis at an earlier age.
Anatomy of the heart and great vessels

Fig. 1.7 Internal structure of the four chambers of the heart. (A) Right atrium. (B) Left atrium. (C) Right ventricle. (D) Left ventricle.
Fig. 1.8 Anterior surface of the heart showing coronary arteries. The left coronary artery has two terminal branches: the anterior interventricular branch (also called the left anterior descending artery, or ‘widow’s artery’) and the circumflex branch. The anterior interventricular branch supplies both ventricles and the interventricular septum. The circumflex branch supplies the left atrium and the inferior part of the left ventricle. The right coronary artery supplies the sinoatrial node via the right atrial branch.

Fig. 1.9 Posteroinferior surface of the heart showing coronary arteries. The right coronary artery gives off a right marginal branch and a large posterior interventricular branch. Near the apex, the posterior interventricular branch may anastomose with the anterior interventricular branch of the left coronary artery. The right coronary artery mainly supplies the right atrium, right ventricle, and interventricular septum. It may also supply part of the left atrium and left ventricle. The nodal branch supplies the atrioventricular node.

Fig. 1.10 Anterior view of the heart showing coronary veins.

Fig. 1.11 Posteroinferior view of the heart showing coronary veins.

Fig. 1.12 The thoracic aorta and its branches.
The serous pericardium produces approximately 50 mL of pericardial fluid, which sits in the pericardial cavity formed by the parietal and visceral layers. The primary function of this fluid is to provide lubrication so that the heart can move within the pericardium during the cardiac cycle.

**Heart**
The heart itself contains three layers:
- Epicardium.
- Myocardium.
- Endocardium.

**Epicardium**
The epicardium is a thin layer of connective tissue that contains adipose tissue, nerves and the coronary arteries and veins.

**Myocardium**
The myocardium is the thickest layer of the heart, and it is made up of cardiac muscle cells. The myocardium is thickest in the left ventricle and thinnest in the atria.

All the muscle layers attach to the fibrocollagenous heart skeleton, which provides a stable base for contraction. The atrial myocardium secretes atrial natriuretic peptide (ANP) when stretched, promoting salt and water excretion. The ventricular myocardium secretes brain natriuretic peptide (BNP) when stretched, which seems rather a misnomer. BNP is sometimes used to monitor left ventricular dysfunction in heart failure.
Cardiac anatomy, physiology and development

Endocardium
The endocardium has three layers: an outermost connective tissue layer (which contains nerves, veins and Purkinje fibres) a middle layer of connective tissue and an endothelium of flat endothelial cells.

Heart valves
The heart valves are avascular (i.e., they have no blood supply) (Fig. 1.16). This is important if bacteria invade the valves because there is little immune reaction and infective endocarditis may result. Their avascular nature also means that they can be replaced with a porcine (pig) or bovine (cow) tissue valve without generating a rejection-like immune response.

Cardiac myocytes
There are three types of myocytes – work myocytes, nodal cells and conduction fibres:
1. Work myocytes are the main contractile cells.
2. Nodal cells make up the SA node and AV node, and generate cardiac electrical impulses.
3. Conduction (Purkinje) fibres have a greater diameter than work myocytes (70–80 μm) and allow fast conduction of action potentials around the heart.

Ultrastructure of the typical cardiomyocyte
The typical cardiac myocyte (Fig. 1.17) has the following features:
1. Length of 50–100 μm (shorter than skeletal muscle fibres).
4. Branched structure.
5. Attached to neighbouring cells via intercalated disks at the branch points. These cell junctions consist of desmosomes (which hold the cells together via proteoglycan bridges) and gap junctions (which allow electrical conductivity).
6. Many mitochondria arranged in rows between the intracellular myofibrils.

Fig. 1.16 Structure of a heart valve.

Fig. 1.17 Cardiac myocyte arrangement. Myocytes are branched, and they attach to each other through desmosomes to form muscle fibres. Gap junctions enable rapid electrical conductivity between cells. There is an extensive sarcoplasmic reticulum, which is the internal Ca\(^{2+}\) store. The contractile elements within each cell produce characteristic bands and lines. In between each myofibril unit there are rows of mitochondria. Accompanying blood vessels and connective tissue lie alongside each muscle fibre. (Redrawn with permission from Tortora, G.J., Grabowski, S.R., 2000. Principles of anatomy and physiology, ninth ed. John Wiley & Sons, New York.)
7. T (transverse) tubules organized in diads with cisternae of sarcoplasmic reticulum (Fig. 1.18), which enable rapid electrical conduction deep into the cell, activating the whole contractile apparatus.
8. Extensive sarcoplasmic reticulum, which stores Ca\(^{2+}\) ions necessary for electrical activity and contraction. Each myocyte contains many myofibril-like units (similar to the myofibrils of skeletal muscle) (see Fig. 1.18). These units are made up of sarcomeres attached end-to-end and collected into a bundle. A sarcomere is the basic contractile unit. It is composed of two bands, the A band and the I band, between two Z lines.
1. The A (anisotropic) band is made up of thick myosin filaments and some interdigitating actin filaments.
2. The I (isotropic) band is made up of thin actin filaments that do not overlap with myosin filaments. Troponin and tropomyosin are also contained in the thin filaments.
3. The Z line is a dark-staining structure containing α-actinin protein that provides attachment for the thin filaments.

![Diagram of cardiac muscle](image-url)
The heart develops in the cardiogenic region of the mesoderm from week 3. This region is at the cranial end of the embryonic disc. Angioblastic cords (aggregates of endothelial cell precursors) develop and here they coalesce to form two lateral endocardial tubes. During week 4, these tubes fuse together to form the primitive heart tube and the heart begins to pump (Fig. 1.19).

From weeks 5 to 8, the primitive heart tube folds and remolds to form the four-chambered heart. Initially, the primitive heart tube develops a series of expansions separated by shallow sulci (infoldings) (Fig. 1.20).

The primitive atrium will give rise to parts of both future atria. The primitive ventricle will make up most of the left ventricle. The bulbus cordis will form the right ventricle. The truncus arteriosus will form the ascending aorta and the pulmonary trunk.

Venous blood initially enters the sinus horns of the sinus venosus from the cardinal veins (a branch of the umbilical vein). Within the next few weeks, the whole systemic venous return is shifted to the right sinus horn through the newly formed superior and inferior venae cavae. The left sinus horn becomes the coronary sinus, which drains the myocardium.

**HINTS AND TIPS**

Embryology terms can be understood by considering what process the term describes. For example, the septum primum is the first septum to form (primus means first in Latin), and septum secundum is the second septum to form.

In weeks 5–6, the septum primum and the septum secundum grow to separate the right and left atria (Fig.1.21). These septa are incomplete and leave two openings (foramina or ostia) that allow blood to move between the atria. The septum primum grows downwards from the superior posterior wall. The foramen (ostium primum) it creates narrows as the septum grows.

While the septum primum is growing, the thicker septum secundum also starts to form. This septum secundum does not meet the septum intermediate, leaving an opening called the foramen ovale near the floor of the right atrium.

Blood now has to shunt from the right to the left atrium through the two staggered openings in the septum, the foramen ovale and the ostium secundum (Fig. 1.22). At
Development of the heart and great vessels

Fig. 1.22 Completed septation of the atria. The septum primum is deficient superiorly at the ostium secundum. The septum secundum is deficient inferiorly at the foramen ovale. Blood shunts from the right atrium through these two holes in the septa to the left atrium. In this way, blood bypasses the lungs in the foetal circulation. As these two openings are staggered, fusion of the septum primum and secundum will abolish any shunt between the atria. (Redrawn with permission from Larsen, W.J., 1997. Human embryology, second ed. Churchill Livingstone, Edinburgh.)

Development of the vasculature

The vasculature develops from the angioblastic cords of mesoderm. The aortic ends of the primitive heart tube become the aortic arches and dorsal aortae. The aortic arches develop into the great arteries of the neck and thorax, and the dorsal aortae develop branches which supply the rest of the body. The paired dorsal aortae connect to the umbilical arteries, which carry blood to the placenta.

The umbilical veins carry oxygenated and nutrient-rich blood from the placenta to the foetus. The venous system (from the foetus, yolk sac and umbilical veins) drains into the sinus horns, and subsequently into the venae cavae and right atrium.

The ductus venosus shunts a portion of blood from the umbilical vein directly into the inferior vena cava during gestation. This is vital as it allows oxygenated blood to enter the right atrium of the heart, to be pumped around the foetus.

The lungs are not functional during gestation, negating the need for a large pulmonary circulation. The pulmonary circulation is largely bypassed by two mechanisms. The foramen ovale enables most of the oxygenated blood in the right atrium to pass into the left atrium and reach the systemic circulation. The ductus arteriosus develops from the sixth aortic arch, and connects the pulmonary arteries to the descending aorta. This allows oxygenated blood not shunted through the foramen ovale to enter the systemic circulation directly. The duct is kept open during foetal life by circulating prostaglandins, and this stimulation may be continued artificially early in the neonatal period.

Circulatory adaptations at birth

A series of changes convert the single system of blood flow around the foetus into dual systems at birth (Figs 1.23 and 1.24). Blood flow in the umbilical vessels drastically declines in the first few minutes after birth because of:

- Compression of the cord.
- Vasoconstriction in response to cold, mechanical stimuli and circulating foetal catecholamines as a result of the stress of descending through the birth canal.

At birth, the pulmonary vascular resistance falls rapidly because:

- The thorax of the foetus is compressed on descent, emptying the amniotic fluid from the lungs.
- The mechanical effort of ventilation opens the constricted alveolar vessels.
- Raising $P_O_2$ and lowering $P_C_O_2$ cause vasodilatation of the pulmonary vessels.

This produces an increase in the pulmonary blood flow.

The sudden cessation of umbilical blood flow and the opening of the pulmonary system cause a change in the pressure balance in the atria. There is a pressure drop in the right atrium and a pressure rise in the left atrium (caused by an increased pulmonary venous return to the left atrium). This changes the pressure gradient across the atrial septum and forces the flexible septum primum against the rigid septum secundum, closing the foramen ovale. These two septa fuse together about 3 months.
The ductus arteriosus closes 1–8 days after birth. It is thought that as the pulmonary vascular resistance falls, the pressure drop in the pulmonary trunk causes blood to flow from the aorta into the pulmonary trunk through the ductus arteriosus. This blood is oxygenated and the increase in PO$_2$ causes the smooth muscle in the wall of the ductus to constrict due to decreased prostaglandin production, obstructing the flow in the ductus arteriosus. Eventually, the intima of the ductus arteriosus thickens – complete obliteration of the ductus results in the formation of the ligamentum arteriosum, which attaches the pulmonary trunk to the aorta.

The ductus venosus closes soon after birth and becomes a remnant known as the ligamentum venosus. The mechanism is unclear, but it is thought to involve prostaglandin inhibition. The closure is not vital to life as the umbilical vein no longer carries any blood.

**Chapter Summary**

- The cardiovascular system is vital to the survival of all other tissues in the human body.
- The right ventricle pumps blood to the pulmonary circulation, and the left ventricle pumps blood to the rest of the body.
- Knowledge of the coronary arterial anatomy is important when considering which region of the myocardium is affected in ischaemic heart disease, and allows prediction of clinical sequelae.
- Appreciation of the development of the foetal circulation and its changes after birth are essential to understanding congenital heart abnormalities and their effects.