8 Transport in mammals

As animals become larger, more complex and more active, transport systems become essential to supply nutrients to, and remove waste from, individual cells. Mammals are far more active than plants and require much greater supplies of oxygen. This is transported by haemoglobin inside red blood cells.

8.1 The circulatory system

The mammalian circulatory system consists of a pump, many blood vessels and blood, which is a suspension of red blood cells and white blood cells in plasma.

By the end of this section you should be able to:

a) state that the mammalian circulatory system is a closed double circulation consisting of a heart, blood vessels and blood
b) observe and make plan diagrams of the structure of arteries, veins and capillaries using prepared slides and be able to recognise these vessels using the light microscope
c) explain the relationship between the structure and function of arteries, veins and capillaries
d) observe and draw the structure of red blood cells, monocytes, neutrophils and lymphocytes using prepared slides and photomicrographs
e) state and explain the differences between blood, tissue fluid and lymph
f) describe the role of haemoglobin in carrying oxygen and carbon dioxide with reference to the role of carbonic anhydrase, the formation of haemoglobinic acid and carbaminohaemoglobin
g) describe and explain the significance of the oxygen dissociation curves of adult oxyhaemoglobin at different carbon dioxide concentrations (the Bohr effect)
h) describe and explain the significance of the increase in the red blood cell count of humans at high altitude

Efficient internal transport in animals

The cells of organisms need a constant supply of water and organic nutrients such as glucose and amino acids; most need oxygen, and the waste products of cellular metabolism have to be removed. Larger animals have evolved a blood circulatory system for efficient internal transport. This links the parts of the body and makes these resources available where they are required.

Mammals have a closed circulation in which blood is pumped by a powerful, muscular heart and circulated in a continuous system of tubes – the arteries, veins and capillaries – under pressure. The heart has four chambers and is divided into right and left sides. Blood flows from the right side of the heart to the lungs, then back to the left side of the heart. From here it is pumped around the rest of the body and back to the right side of the heart. As the blood passes twice through the heart in every single circulation of the body this is called a double circulation. The circulatory system of mammals is shown in Figure 8.1, alongside alternative systems.

Look at these systems carefully.

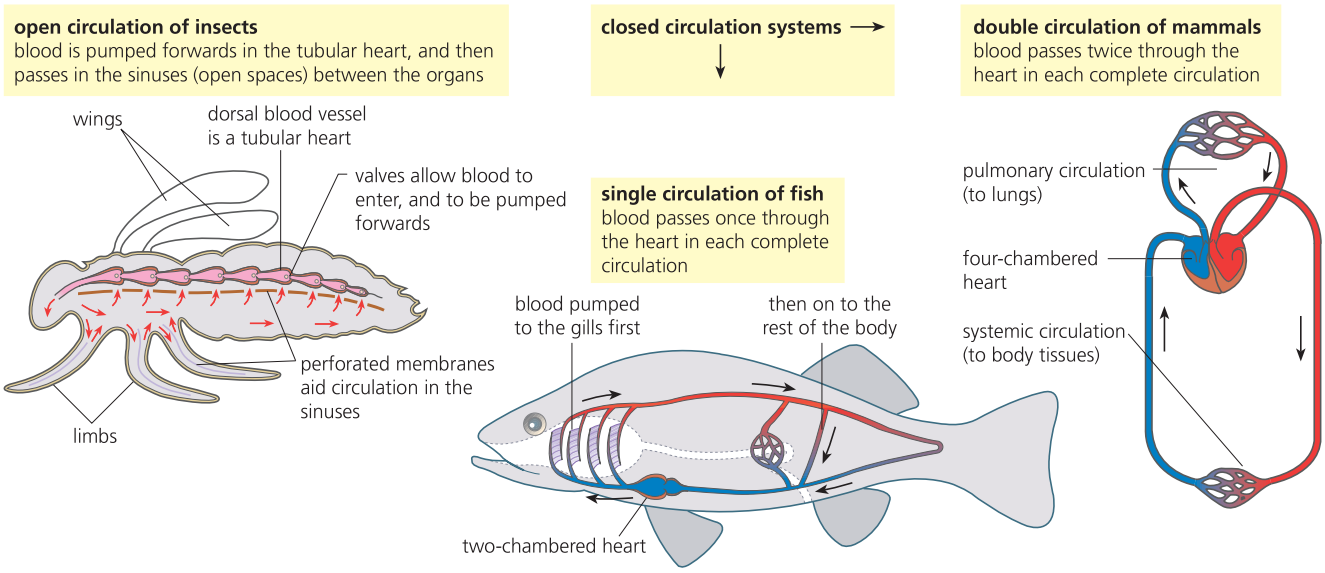


Figure 8.1 Open and closed circulations

Question

1 In an open circulation there is 'little control over circulation'. Suggest what this means?

Looking at these other systems helps us to understand the features of the mammalian circulation. It becomes clear that the major advantages of the mammalian circulation are:

- simultaneous high pressure delivery of oxygenated blood to all regions of the body
- oxygenated blood reaches the respiring tissues, undiluted by deoxygenated blood.

Blood – the transport medium

Blood is a special tissue of several different types of cell suspended in a liquid medium called plasma (Figure 8.2).

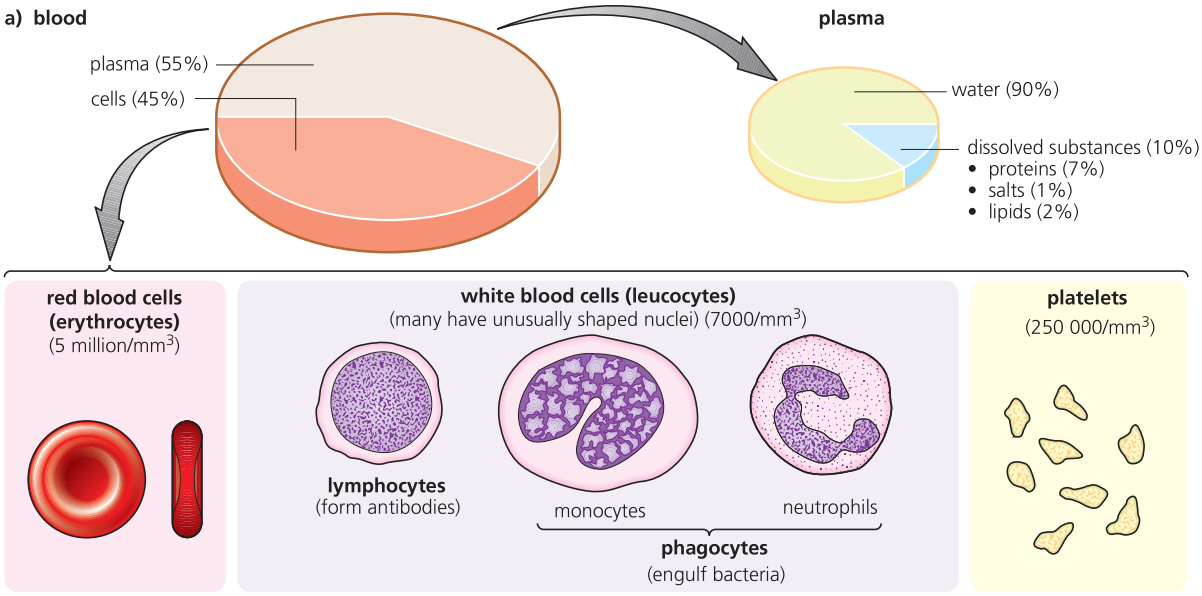
Plasma is a straw-coloured, very slightly alkaline liquid consisting mainly of **water**. It is the medium for the continual exchange of substances by cells and tissues throughout the body. Dissolved in the plasma are **nutrients** in transit from the gut or liver to all the cells. Excretory products are also transported in solution, mainly **urea** from the liver to the kidneys. So too are **hormones**, from the ductless (endocrine glands), where they are formed and released, to the tissues and organs.

The plasma also contains **dissolved proteins**. The principle blood protein is **albumin**, which has the role of regulating the water potential of the blood. The presence of dissolved albumin stops too much water leaving at the capillaries by osmosis and also helps in the return of fluids (Figure 8.8, page 159). Albumin and other proteins also assist in the transport of lipids and iron in the plasma. Other blood proteins present are **antibodies** (page 222) and components of the **blood clotting mechanism**.

Question

2 Assuming the body contains 5 litres of blood, that there are 5 million (5×10^6) red blood cells per mm^3 and that a red blood cell lasts for 120 days, how many red blood cells must be replaced per day?

Suspended in the plasma are the **blood cells**. The majority of these are **red blood cells** (erythrocytes) – about 5 million in every cubic millimetre of blood. The red blood cells are formed in the bone marrow tissue. Initially each red blood cell has a nucleus but early in development the nucleus is lost and these tiny cells (7 µm in diameter) adopt the shape of a biconcave disc. Mitochondria and endoplasmic reticulum are also lost and a great deal of a protein, **haemoglobin**, takes their place, together with the enzyme **carbonic anhydrase**. The role of mature red blood cells is exclusively the transport of respiratory gases in the blood. The lifespan of a working red blood cell is only about 120 days, after which they are broken down and replaced. Most of their components are retrieved and reused.



b)

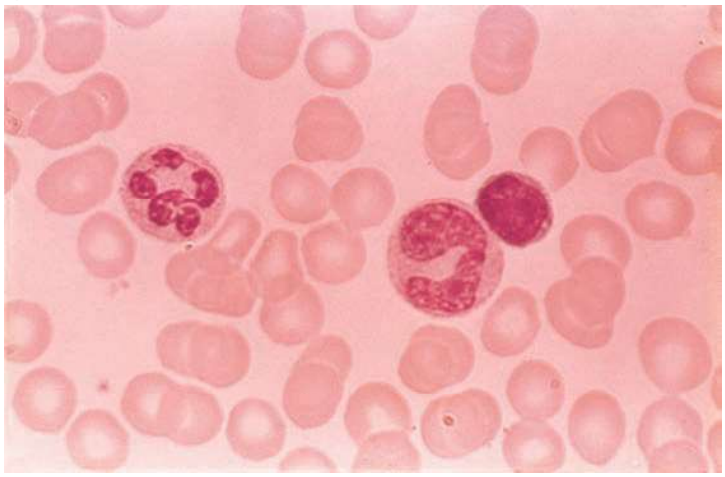


Figure 8.2 **a)** The composition of the blood; **b)** Blood smear stained to show the few white blood cells present

Also present are some **white blood cells** (leucocytes) – about 7000 per cubic millimetre of blood. These also originate in the bone marrow but they retain their nucleus. In the growth and development stage, white blood cells may migrate to the thymus gland, lymph nodes or the skin. The white blood cells do not necessarily function in the blood stream but all use the blood circulation as a means of reaching specific body organs or tissues. Many leave the bloodstream by migrating between the cells of the capillary wall. There are several different types of white blood cells, all of which play a part in the body's defences (Topic 11) and are mostly relatively short-lived cells. The white blood cells that are particularly important are:

- **lymphocytes** – these form antibodies
- **phagocytes** – these ingest bacteria or cell fragments.

Finally the blood contains **platelets**, best described as cell fragments. These are tiny packages of cytoplasm containing vesicles of substances that, when released, have a role in the blood clotting mechanism.

Observing and drawing the structure of red blood cells, monocytes, neutrophyls and lymphocytes

You need to observe and draw the structure of red cells, monocytes, neutrophyls and lymphocytes, using photomicrographs and prepared slides and a light microscope under medium and high power magnification, so that you will be able to recognise them.

Table 8.1 A summary of the roles of blood components

Component	Role
Plasma	Transport of: • **nutrients** from the gut or liver to all the cells • excretory products such as **urea** from the liver to the kidneys • **hormones** from the endocrine glands to all tissues and organs • **dissolved proteins** which have roles including regulating the osmotic concentration (water potential) of the blood • dissolved proteins that are **antibodies** **Heat** distribution to all tissues
Red blood cells (erythrocytes)	Transport of: • **oxygen** from the lungs to respiring cells • **carbon dioxide** from respiring cells to the lungs (also carried in plasma)
White blood cells (leucocytes)	**Lymphocytes**: major roles in the **immune system**, including forming antibodies (Topic 7) **Phagocytes: ingest bacteria** and cell fragments
Platelets	Part of the **blood clotting mechanism**

The blood circulation in mammals

Mammals have a closed circulation system in which blood is pumped by a powerful, muscular **heart** and circulated under pressure in a continuous system of tubes – the **arteries**, **veins** and **capillaries**. The heart has four chambers, and is divided into right and left sides. This is shown in Figure 8.3, in the diagram of the layout of the human blood circulation.

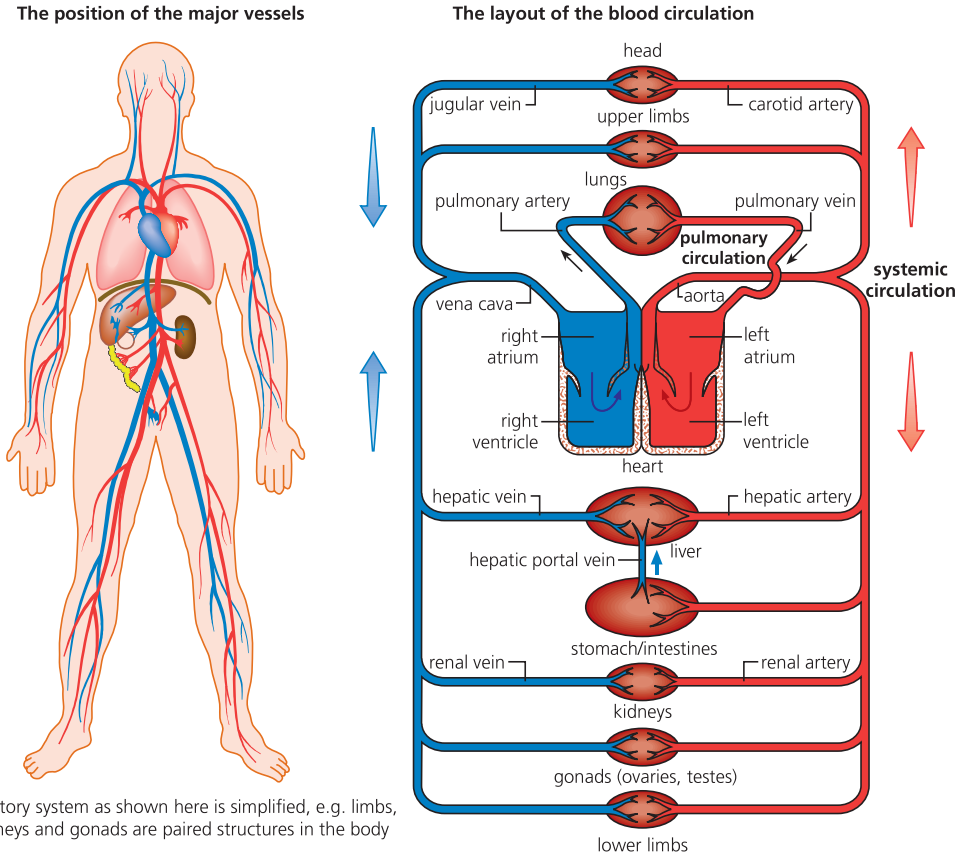


Figure 8.3 The human blood circulation

Notice that blood is pumped from the right side of the heart to the **lungs**. From the lungs, blood returns to the left side of the heart. This part of the system is called the **pulmonary circulation**.

From the left side of the heart, blood is pumped around the **rest of the body** before returning to the right side of the heart. This is called the **systemic circulation**.

Extension

The hepatic portal vein

The blood supply to the liver is via the hepatic artery but the liver also receives blood directly from the small intestine, via a vein called the **hepatic portal vein**. This brings much of the products of digestion, after they have been absorbed into the capillaries of the villi in the small intestine.

So you can see that blood passes *twice* through the heart in every single circulation of the body. This arrangement is a called a **double circulation**. This means there is no mixing of oxygenated and deoxygenated blood in the heart, so the blood circulating around the body has a higher concentration of oxygen than would otherwise be possible.

Arteries, veins and capillaries

There are three types of vessel in the circulation system, each with different roles.

- **Arteries** carry blood away from the heart.
- **Veins** carry blood back to the heart.
- **Capillaries** are fine networks of tiny tubes linking arteries and veins.

In Figure 8.3 you can see how the main arteries and veins serve the organs of the body. (Notice that arteries and veins are often named after the organs they serve.)

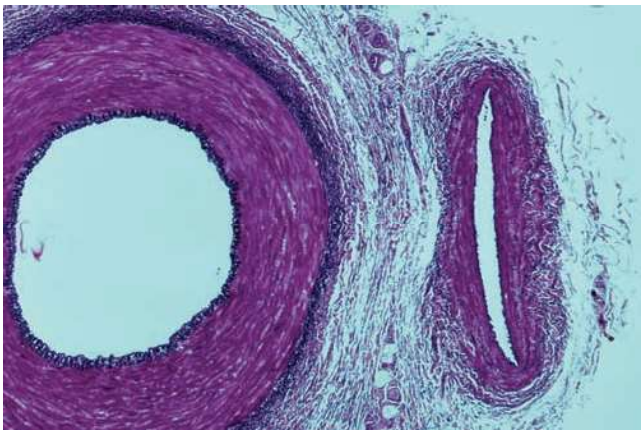
For example, in the systemic circulation, each organ is supplied with blood by a separate **artery** that branches from the main **aorta**. Inside organs, the artery branches into numerous **arterioles** (smaller arteries). The smallest of these arterioles supply numerous and very extensive **capillary networks**. These capillaries then drain into **venules** (smaller veins) and these venules join to form **veins**. Finally, the veins join the **vena cava** carrying blood back to the right side of the heart. The branching sequence of blood vessels that make up the systemic circulation is, therefore:
aorta → artery → arteriole → capillary → venule → vein → vena cava

The structure of arteries, capillaries and veins

Blood leaving the heart is under very high pressure and travels in waves or pulses following each heart beat. By the time the blood has reached the capillaries it is under very much lower pressure, without a pulse. These differences in blood pressure account for the differences in the wall structure of arteries and veins. There are many subtle changes on the way between a main artery and the corresponding vein.

Arteries and veins have three distinct layers to their walls (Figure 8.4 and Table 8.2). Both arteries and veins have strong, elastic walls but the walls of the arteries are very much thicker and stronger than those of the veins. The strength of the walls comes from a combination of collagen and elastic fibres. Their elasticity is due to the elastic fibres and to the involuntary (smooth) muscle fibres.

Capillaries have an altogether different structure – they consist of a single layer of cells and they are tiny in cross-section when compared with the main arteries and veins.



TS artery and vein, LP (×20) – in sectioned material (as here), veins are more likely to appear squashed, whereas arteries are circular in section

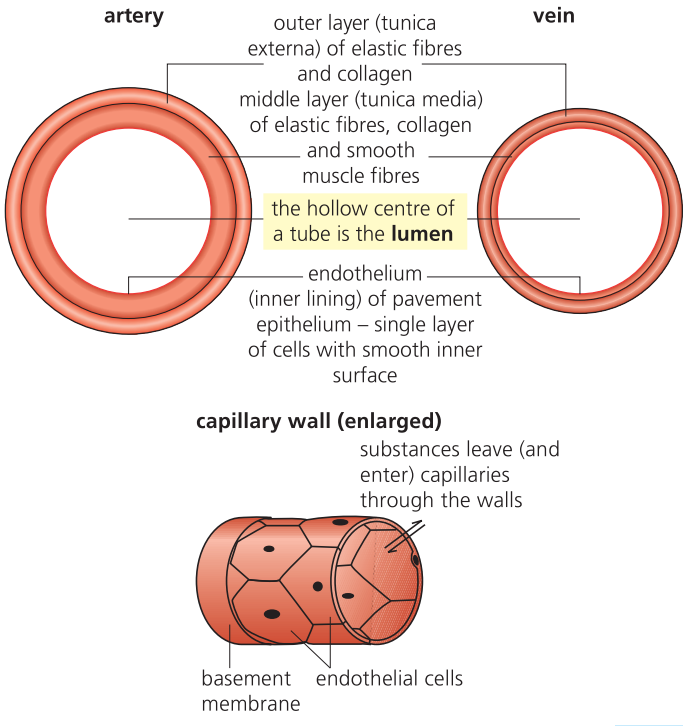


Figure 8.4 The structure of the wall of arteries, veins and capillaries

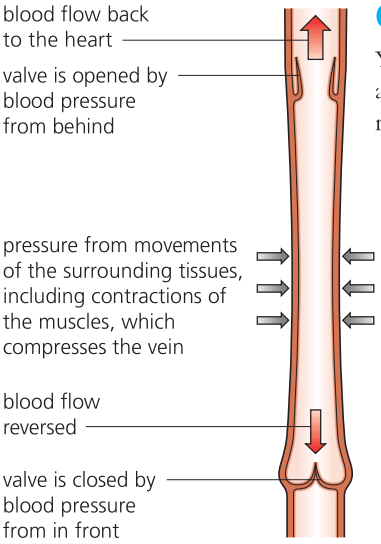


Figure 8.5 The valves in veins

Observing and drawing the structure of arteries, veins and capillaries

You need to observe and draw the structure of arteries, veins and capillaries, using prepared slides and a light microscope under medium and high power magnification, so that you will be able to recognise them.

Table 8.2 Differences between arteries, capillaries and veins

	Artery	Capillary	Vein
Outer layer (tunica externa) of elastic fibres and collagen	Present – thick layer	Absent	Present – thin layer
Middle layer (tunica media) of elastic fibres, collagen and involuntary (smooth) muscle fibres	Present – thick layer	Absent	Present – thin layer
Endothelium (inner lining) of pavement epithelium – a single layer of cells fitting together like jigsaw pieces, with a smooth inner surface that minimises friction	Present	Present	Present
Valves	Absent	Absent	Present

Now look carefully at the photomicrograph of an artery and vein in section and the details the wall structure of these three vessels (Figure 8.4).

If you examine a prepared slide of an artery and vein under the high power of a microscope you may see the layers of the walls in detail and you may be able to make out the muscle fibres. Because of the low pressure in veins there is a possibility of back-flow here. Veins have **valves** at intervals that prevent this (Figure 8.5).

We have noted that, as blood is transported around the body the pressure of blood progressively falls. This fact and the roles of the arteries, capillaries and veins are reflected in specific changes in their structure (Table 8.3).

Table 8.3 The changing structure of blood vessels in relation to function

Component and role	Structure in relation to function
Arteries: have the thickest and strongest walls; the tunica media is the thickest layer.	
Aorta: receives blood pumped from the heart in a 'pulse' (pressure about 120 mmHg).	• The walls stretch to accommodate the huge surge of blood when the ventricles contract. The elastic and collagen fibres of the tunica externa prevent rupture as blood surges from the heart. • The high proportion of elastic fibres are first stretched and then recoil, keeping the blood flowing and propelling it forwards after each pulse passes. • With increasing distance from the heart the tunica media progressively contains more smooth muscle fibres and fewer elastic fibres. By varying the constriction and dilation of the arteries, blood flow is maintained. Muscle fibres stretch and recoil, tending to even out the pressure but a pulse can still be detected.
Main arteries: distribute blood under high pressure to regions of the body. • Arteries become wider, so lowering the pressure. • Supply the smaller **branch arteries** that distribute blood to the main organs.	
Arterioles: deliver blood to the tissues.	• The walls have a high proportion of smooth muscle fibres and so are able to regulate blood flow from the arteries into the capillaries.
Capillaries	
Capillaries: serve the tissues and cells of the body. The blood is under lower pressure (about 35 mmHg).	• Narrow tubes, about the diameter of a single red blood cell (about 7 µm), reduce the flow rate to increase exchange between blood and tissue. • Thin walls of a single layer of endothelial cells. • The walls have gaps between cells sufficient to allow some components of the blood to escape and contribute to tissue fluid (page 146).
Veins: have thin walls; the tunica externa is the thickest layer.	
Venules: collect blood from the tissues. They are formed by the union of several capillaries (pressure about 15 mmHg).	• The walls consist of endothelium and a very thin tunica media of a few scattered smooth muscle fibres.
Veins: receive blood from the tissues under low pressure (pressure about 5 mmHg). • The veins become wider, so lowering pressure and increasing the flow rate.	• The tunica externa, containing elastic and collagen fibres, is present. • The tunica media contains a few elastic fibres and muscle fibres. • The presence of valves prevents the back-flow of blood.

Pressure: the **pascal (Pa)** and its multiple the **kilopascal (kPa)** are generally used by scientists to measure pressure. However, in medicine the older unit, **millimetres of mercury (mmHg)** is still used (1 mmHg = 0.13 kPa).

Questions

3 List the differences between the pulmonary circulation and the systemic circulation of blood.

4 The graph in Figure 8.6 shows the changing blood velocity, blood pressure and cross-sectional area of the vessels as blood circulates in the body. Use the information in the graph and in Table 8.2 where appropriate to answer the questions below.

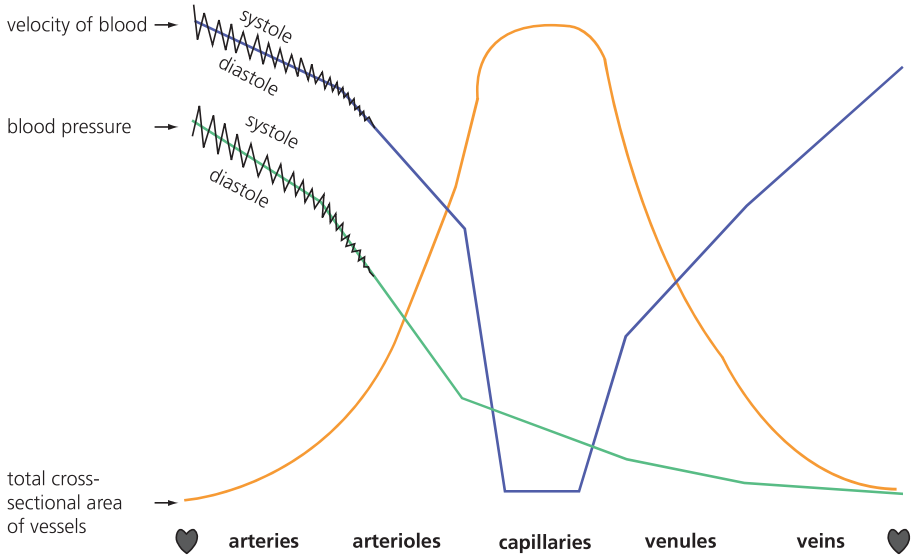


Figure 8.6 The changing blood velocity, blood pressure and cross-sectional area of the vessels as blood circulates in the body

a Comment on the velocity and pressure of the blood as it enters the aorta compared with when it is about to re-enter the heart.

b What aspects of the structure of the walls of arteries may be said to be in response to the condition of blood flow through them?

c What factors may cause the velocity of blood flow to be at the level it is in the capillaries and why is this advantageous?

The roles of the blood circulation system

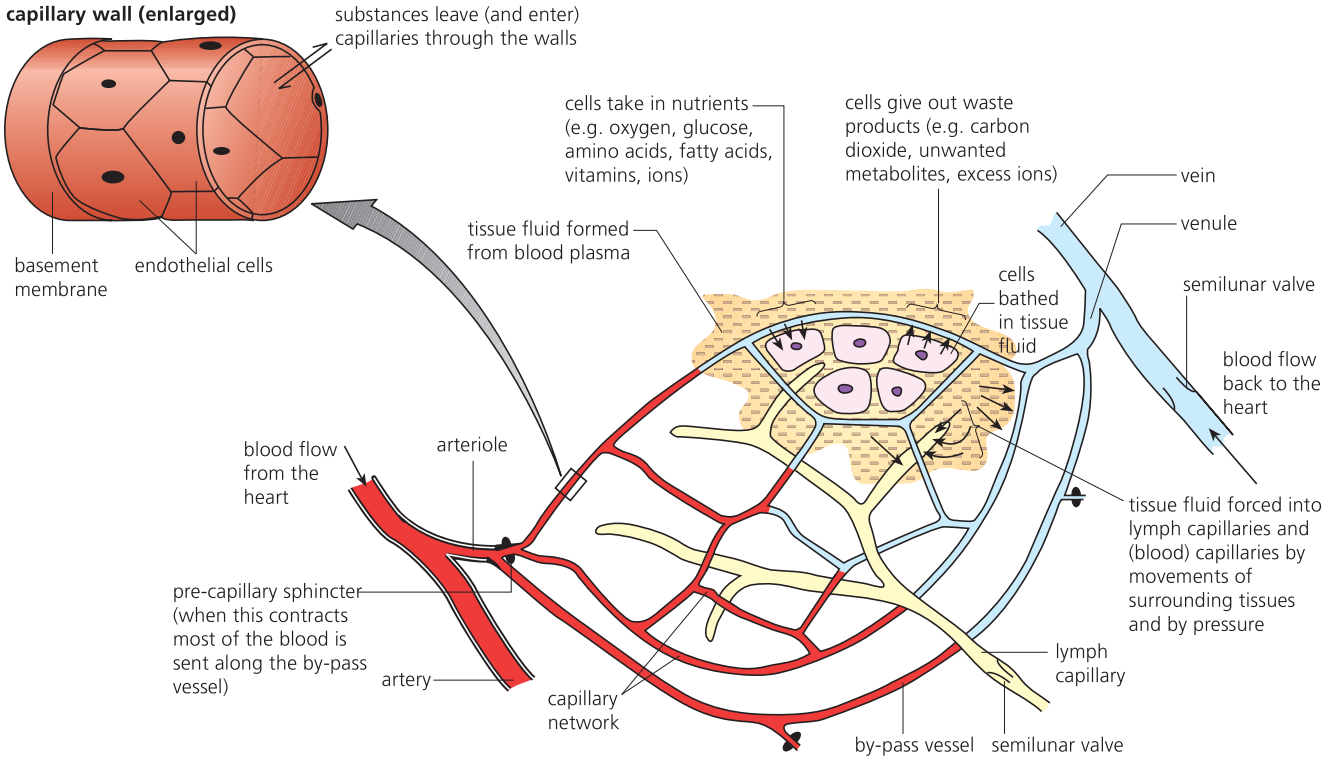
The blood circulation has a role in the body's defence against diseases (Topic 11), in internal communications and in the maintenance of a constant internal environment (Topic 14), as well as being the transport system of the body. It is the transport roles of the blood circulation (Table 8.4), a key feature of which is the formation and fate of **tissue fluid**, that we consider next.

Table 8.4 Transport roles of the blood circulation

Function in organism	Transport role of circulation
Tissue respiration	Transport of oxygen to all tissues and carbon dioxide back to the lungs
Hydration	Transport of water to all the tissues
Nutrition	Transport of nutrients (sugars, amino acids, lipids, vitamins) and inorganic ions to all cells
Excretion	Transport of waste products of metabolism to kidneys, lungs and sweat glands
Temperature regulation	Distribution of heat
Development and co-ordination	Transport of hormones from endocrine glands to target organs

Exchange in the tissues and the formation of tissue fluid

The blood circulation delivers essential resources (nutrients and oxygen, for example) to the tissues of the body. This occurs as the blood flows through the capillaries, between the cells of the body (Figure 8.7). There are tiny gaps in the capillary walls, found to vary in size in different parts of the body. Through these gaps passes a watery liquid, very similar in composition to plasma. This is **tissue fluid**. However, red blood cells, platelets and most blood proteins are not present in tissue fluid, instead these are retained in the capillaries. Tissue fluid bathes the living cells of the body. Nutrients are supplied from this fluid and carbon dioxide and waste products of metabolism are carried away by it.



The role of the by-pass vessel
Which tissues of the body are being served by the blood circulation is regulated. When tiny pre-capillary sphincter muscles are contracted, blood flow to that capillary bed is restricted to a minimum. Most blood is then diverted through by-pass vessels – it is shunted to other tissues and organs in the body.

Figure 8.7 Exchange between blood and cells via tissue fluid

Given the quantity of dissolved solutes in the plasma (including and especially all the blood plasma proteins), we would expect the water potential of the blood to limit the loss of water by osmosis. In fact, we might expect water to be passing back into the capillaries from the tissue fluid, due to osmosis. However, the force applied to the blood by the heart creates enough hydrostatic pressure to overcome osmotic water uptake, at least at the arteriole end of the capillary bed. Here the blood pressure is significantly higher than at the venule ends. Then, as the blood flows through the capillary bed there is progressive loss of water and of hydrostatic pressure, too. As a result, much of the tissue fluid is able to eventually return to the plasma – about 90 per cent returns by this route (Figure 8.8).

So, further along the capillary bed there is a net inflow of tissue fluid to the capillary. However, not all tissue fluid is returned to the blood circulation by this route – some enters the **lymph capillaries** (Figure 8.9). **Lymph** is the tissue fluid that drains into the lymphatic vessels, rather than directly back into a blood capillary.

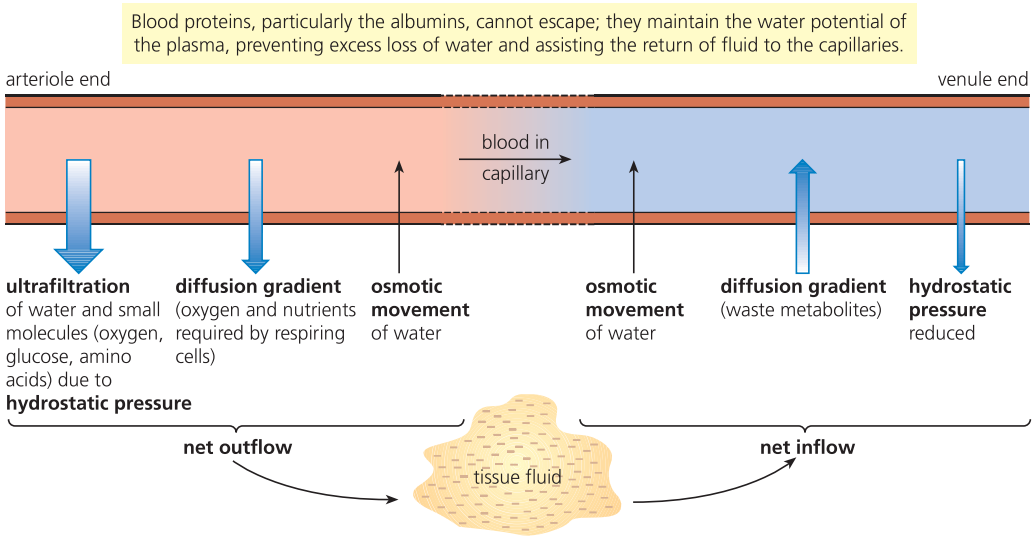


Figure 8.8 Forces for exchange in capillaries

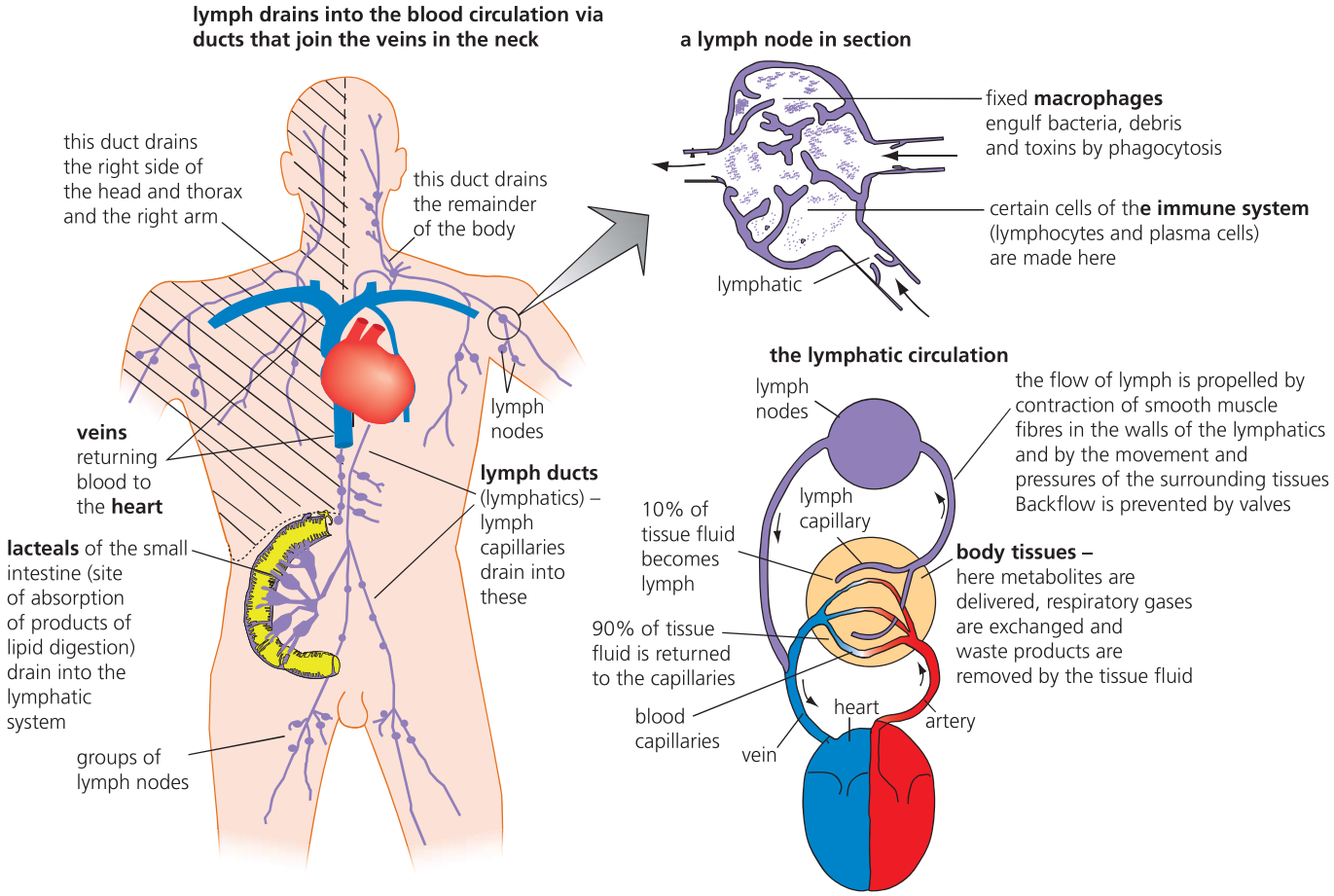


Figure 8.9 The layout and role of the lymphatic system

Question

5 **a** What components of the blood are not found in tissue fluid?
b Construct a table to summarise the differences between tissue fluid and lymph.

Molecules too large to enter capillaries are removed from the tissues via the lymph system. There are tiny valves in the walls of the lymph capillaries that permit this. The network of lymph capillaries drains into larger lymph ducts (known as **lymphatics**). Then, lymph is moved along the lymphatics by contractions of smooth muscles in their walls and by compression from body movements. Back-flow is prevented by valves, as it is in the veins.

Lymph finally drains back into the blood circulation in veins close to the heart. At intervals along the way there are **lymph nodes** present in the lymphatics. Lymph passes through these nodes before it is returned to the blood circulation. In the nodes phagocytic macrophages engulf bacteria and any cell detritus present. Also the nodes are a site where certain cells of the immune system are found. We return to this issue in Topic 11.

Extension

Oedema – fluid retention in the body

If the volume of fluid that filters out exceeds that which is re-absorbed, the result is a greatly increased volume of tissue fluid. The result is swelling of the tissues (**oedema**). This condition normally arises due either to increased blood pressure or increased permeability of capillary walls. However, a diet that is chronically deficient in protein may trigger the disease of kwashiorkor, a symptom of which includes oedema.

Can you see why? The answer lies in the importance of blood proteins in maintaining the osmotic potential of the blood (see Figure 8.8).

Transport of respiratory gases between the lungs and respiring tissues

Oxygen

A single red blood cell contains about 280 million molecules of **haemoglobin**. We have seen that each haemoglobin molecule is built of four, interlocking subunits composed of a large, globular protein with a non-protein haem group, containing iron, attached (Figure 2.28, page 53). At the concentration of oxygen that occurs in our lungs, one molecule of oxygen will combine with each haem group. This means each haemoglobin molecule is able to transport four molecules of oxygen.

$$\text{haemoglobin} + \text{oxygen} \rightarrow \text{oxyhaemoglobin}$$
$$\text{Hb} \qquad 4O_2 \qquad HbO_8$$

Figure 8.10 shows the relationship between haemoglobin and oxygen as the concentration of oxygen around the haemoglobin molecule changes. (Oxygen concentration is expressed as its partial pressure, in kPa.) This is called an **oxygen dissociation curve**. The curve is S-shaped. This tells us that the first oxygen molecule attaches with difficulty. This is because the addition of the first oxygen molecule has to slightly distort the shape of the haemoglobin molecule. However, once this has occurred, the second oxygen molecule combines slightly more easily and then the third and forth combine progressively more easily. This sequence of changes accounts for the S-shape of the curve.

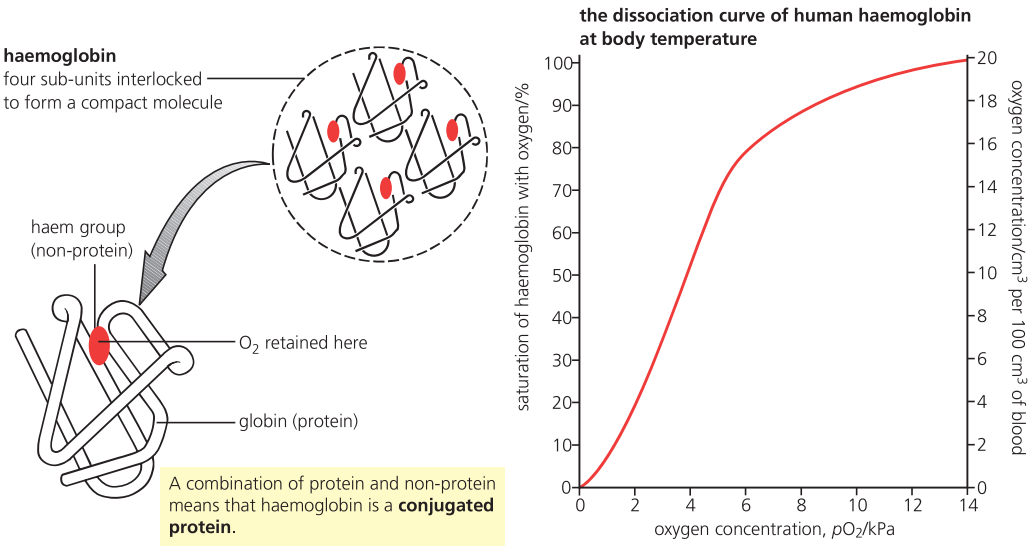


Figure 8.10 The structure of haemoglobin and its affinity for oxygen

Extension

A note on partial pressure

We live at the bottom of a 'sea of air' – hence air pressure. The air we breathe is a mixture of gases and, in a gas mixture, each gas exerts a pressure. In fact, the pressure of a mixture of gases is the sum of the pressure of the component gases. Consequently, the pressure of a specific gas in a mixture of gases is called its **partial pressure**. The symbol for partial pressure is *p* and for the partial pressure of a gas X is *p***X** (so, for example, $p\mathbf{O}_2$ denotes the partial pressure of oxygen). The unit of pressure is the **Pascal** (**Pa**) and its multiple the **kilopascal** (**kPa**).

Atmospheric pressure at sea level is approximately 100 kPa and oxygen makes up about 21 per cent of the air. *What is pO_2 at sea level?*

Extension

Carbon monoxide poisoning

Carbon monoxide is found in vehicle exhaust gas, **cigarette smoke**, and as a product of incomplete combustion of natural gas where there is restricted access for air.

Carbon monoxide combines irreversibly with the iron of haemoglobin at the site that oxygen would otherwise occupy, forming **carboxyhaemoglobin**. The affinity of carbon monoxide for haemoglobin is about 300 times greater than oxygen's and at low partial pressures of this poison the blood's ability to transport oxygen may be fatally reduced.

(Incidentally, a catalytic converter, when fitted to a vehicle's exhaust, can significantly reduce the quantity of the gas by oxidising it to carbon dioxide.)

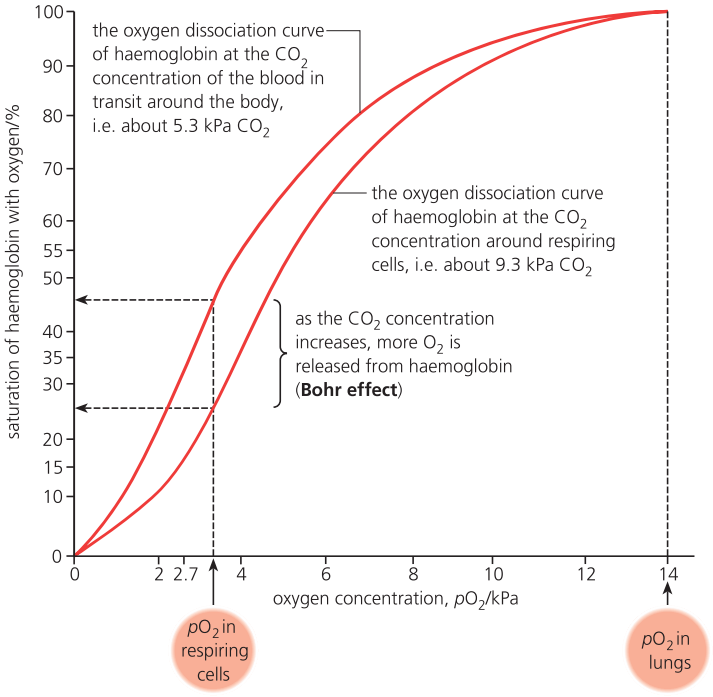


Figure 8.11 How carbon dioxide favours the release of oxygen in respiring tissues

To return to haemoglobin, most haemoglobin molecules are fully saturated at a partial pressure of oxygen of only 8kPa so oxygen is efficiently loaded under the conditions in our ventilated lungs. However, in respiring tissue the situation is quite different. Here the partial pressure of oxygen is much lower because oxygen is used in aerobic respiration. Oxyhaemoglobin will dissociate if the partial pressure is less than 8kPa, making oxygen molecules readily available for use in the cells of respiring tissues.

So oxygen is scarce in respiring cells. On the other hand, the concentration of carbon dioxide is high. In this environment it is interesting to see what effect the concentration of carbon dioxide has on the loading and unloading of oxygen by haemoglobin.

In fact, carbon dioxide has a marked effect. An increased carbon dioxide concentration shifts the oxygen dissociation curve to the right. That is, where the carbon dioxide concentration is high (obviously in the actively respiring cells), oxygen is released from oxyhaemoglobin even more readily. This very useful outcome is known as the **Bohr effect**.

Question

6 Use Figure 8.11 to deduce the change in the percentage saturation of haemoglobin if the partial pressure of oxygen drops from 4 to 2.7 kPa when the partial pressure of carbon dioxide is 5.3 kPa.

Carbon dioxide

Carbon dioxide is transported in the blood, in both the plasma and in red blood cells, mainly as hydrogencarbonate ions.

$$CO_2 + H_2O \xrightarrow{\text{carbonic anhydrase}} HCO_3^{2} + H^+$$

The enzyme **carbonic anhydrase**, which catalyses this reaction, is present in the red blood cells. You can see that hydrogen ions are one of the products. The hydrogen ions released become associated with haemoglobin to form **haemoglobinic acid**. In effect, the haemoglobin molecules act as a buffer for hydrogen ions, preventing the blood from becoming acidic (Figure 8.12).

In addition, about 5 per cent of the carbon dioxide remains as carbon dioxide in the blood, dissolved in the plasma. A further 10 per cent combines with haemoglobin, reacting with amine groups ($-NH_2$) to form **carbaminohaemoglobin**. In the lungs, the partial pressure of carbon dioxide (pCO_2) there allows these forms of carbon dioxide to be released, also.

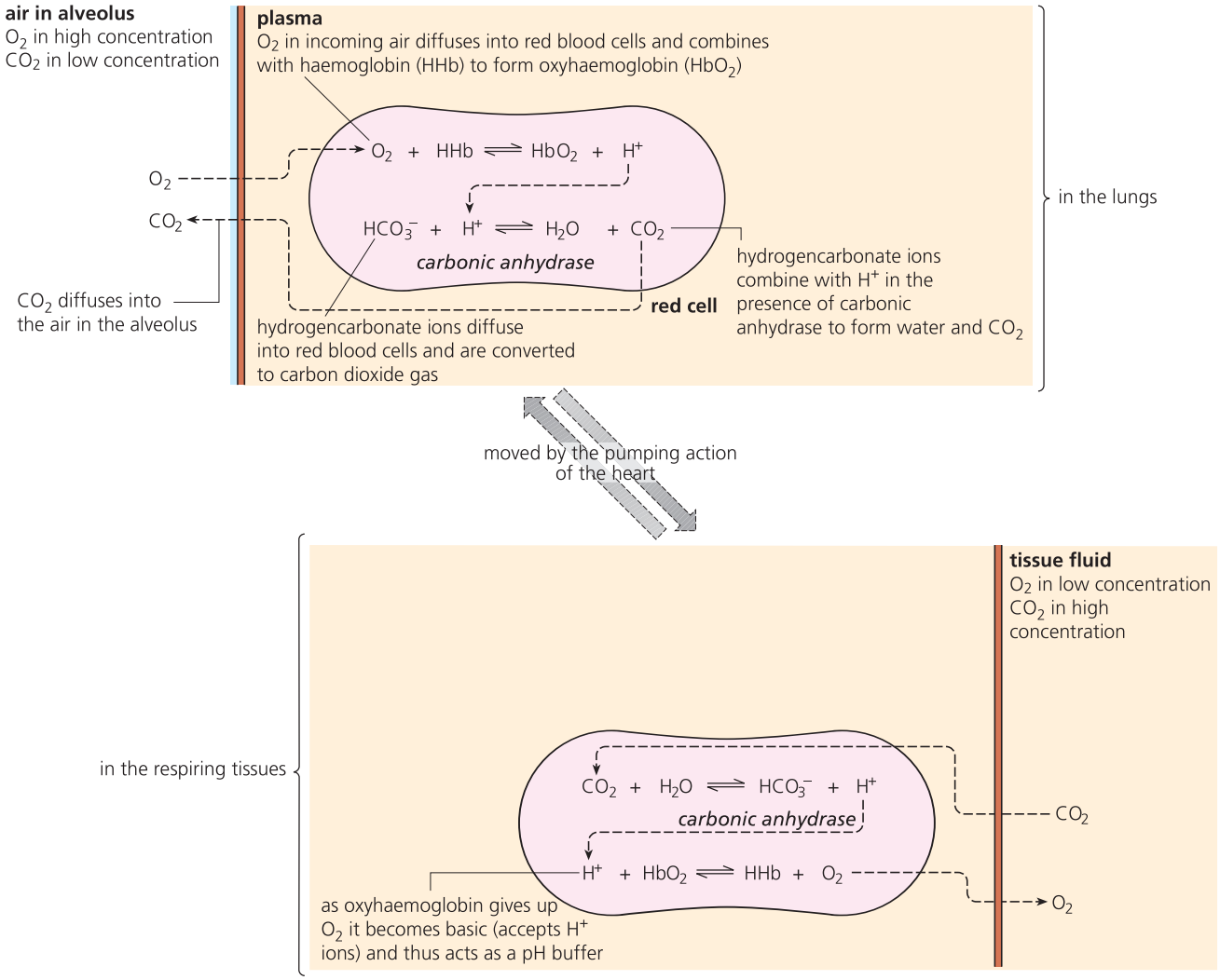


Figure 8.12 The transport of oxygen and carbon dioxide between the lungs and respiring tissues

Humans at high altitude

It is estimated that more than 40 million people live and work at altitudes between 3000 and 5500 m, for example in the Andes and Himalayas. The problems of gaseous exchange at high altitude do not arise because the percentage of oxygen is lower up there – it isn't. The percentage of oxygen does not vary significantly between sea level and high altitudes. However, with increasing altitude it is the atmospheric pressure that falls, and so the partial pressure of oxygen falls also (Table 8.5).

Table 8.5 Change in the partial pressure of oxygen with altitude

Altitude/m above sea level	Atmospheric pressure/kPa	Oxygen content/%	Partial pressure of oxygen/kPa
0	101.3	20.9	21.2
2500	74.7	20.9	15.7
5000	54.0	20.9	11.3
7000	38.5	20.9	8.1
10000	26.4	20.9	5.5

The result of these changes is that as altitude increases it becomes increasingly hard for haemoglobin in red cells in the lungs to load oxygen. Once the percentage saturation with oxygen is lowered, this is detected by chemoreceptors. The response of the respiratory centre is to cause the taking of extra deep breathes. As a result, more carbon dioxide is lost from the body, which causes a small but significant rise in the pH of the blood. Now the chemoreceptors become ineffective. Ventilation regulation is hampered.

The body cannot adapt to high altitude immediately; sudden, prolonged exposure at very high altitudes by people without prior experience of these conditions can be fatal. However, progressively the following changes take place:

- A more alkaline urine is secreted by the kidney tubules via the collecting ducts, and the pH of the blood returns to normal. As a result, the carbon dioxide chemoreceptors become sensitive again, and normal ventilation is maintained.
- Bone marrow tissue, the site of red cell formation, produces and releases more red cells, thereby enhancing the oxygen-carrying capacity of the blood (Table 8.6).

Table 8.6 The change in red blood cell count in humans at different altitudes

Altitude/m above sea level	Red cell count/$\times 10^{12} d^3$
0 (sea level)	5.0
5000^+ as a temporary visitor	5.95
5000^+ as a resident	7.37

These changes are called 'acclimatisation'. Other mammal species have evolved at high altitudes, such as the llama of the mountains of South America. In this case the mammal has a form of haemoglobin that loads more readily at lower partial pressures of oxygen.

8.2 The heart

The mammalian heart is a double pump: the right side pumps blood at low pressure to the lungs and the left side pumps blood at high pressure to the rest of the body.

By the end of this section you should be able to:

a) describe the external and internal structure of the mammalian heart
b) explain the differences in the thickness of the walls of the different chambers in terms of their functions with reference to resistance to flow
c) describe the cardiac cycle (including blood pressure changes during systole and diastole)
d) explain how heart action is initiated and controlled

The heart as a pump

The human heart is the size of a clenched fist. It lies in the thorax between the lungs and below the breast bone (sternum). The heart is a hollow organ with a muscular wall. It is contained in a tightly fitting membrane, the **pericardium** – a strong, non-elastic sac which anchors the heart within the thorax and prevents the overfilling of the heart with blood. Within the pericardium is fluid which reduces friction between the beating heart muscle and the surrounding tissues.

The wall of the heart is supplied with oxygenated blood from the aorta via **coronary arteries**. All muscle tissue consists of cells called fibres that are able to shorten by a half to a third of their length. **Cardiac muscle** consists of cylindrical branching columns of fibres, uniquely forming a three-dimensional network and allowing contractions in three dimensions. The fibres have a single nucleus, are striped or striated and are surrounded by **sarcolemma** (muscle cell surface membrane) (Figure 8.13). They are very well supplied by mitochondria and capillaries. The fibres are connected by special junctions called **intercalated discs**. These discs transmit the impulse to

contract to all cells simultaneously. The impulse to contract is generated within the heart muscle itself (known as a **myogenic origin**), not by nervous stimulation (a **neurogenic origin**). Heart muscle fibres contract rhythmically from their formation until they die.

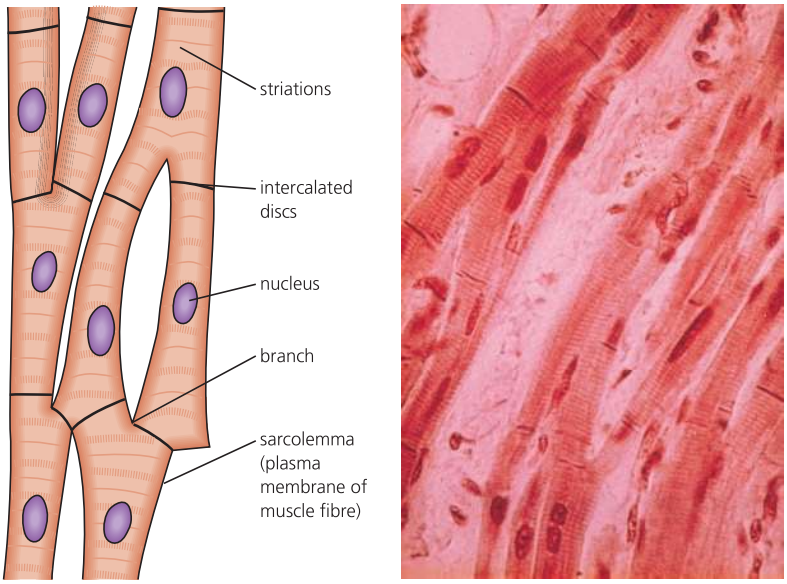


Figure 8.13 Cardiac muscle

Structure of the heart chamber walls in relation to function

The cavity of the heart is divided into four **chambers**. The chambers of the right side of the heart are separated from those of the left side by a wall of muscle called the **septum**.

The upper chambers are thin-walled and are called **atria** (singular: **atrium**). These chambers receive blood into the heart under relatively low pressure. Later, when the walls of the atria contract, the blood they now contain is pumped into the ventricles. At this stage the ventricles are in a relaxed condition – there is little resistance to this inward flow of blood.

The two lower chambers are thick-walled and called **ventricles**. They eventually pump the blood out of the heart – the left ventricle pumps blood through the entire systemic circulation, whereas the right ventricle pumps blood through the pulmonary circulation. Consequently, the muscular wall of the left ventricle is much thicker than that of the right ventricle, for it has to overcome the greater resistance of the capillaries throughout the body tissues in comparison with a lower resistance in the lungs. However, the volumes of the right and left sides (the quantities of blood they contain) are identical.

The functions of the heart valves

The direction of blood flow through the heart is maintained by valves, because it is the valves that prevent back-flow of the blood when the muscles of the chamber walls contract. Figure 8.15 shows the action of all the valves of the heart.

The **atrioventricular valves** are large valves that separate the upper and lower chambers. The edges of these valves are supported by tendons anchored to the muscle walls of the ventricles below and which prevent the valves from folding back due to pressure from the ventricles. The valves separating the right and left sides of the heart are individually named – on the right side, the **tricuspid valve** and on the left, the **bicuspid** or mitral valve.

Valves of a different type separate the ventricles from pulmonary artery (right side) and aorta (left side). These are pocket-like structures called **semilunar valves**, rather similar to the valves seen in veins.

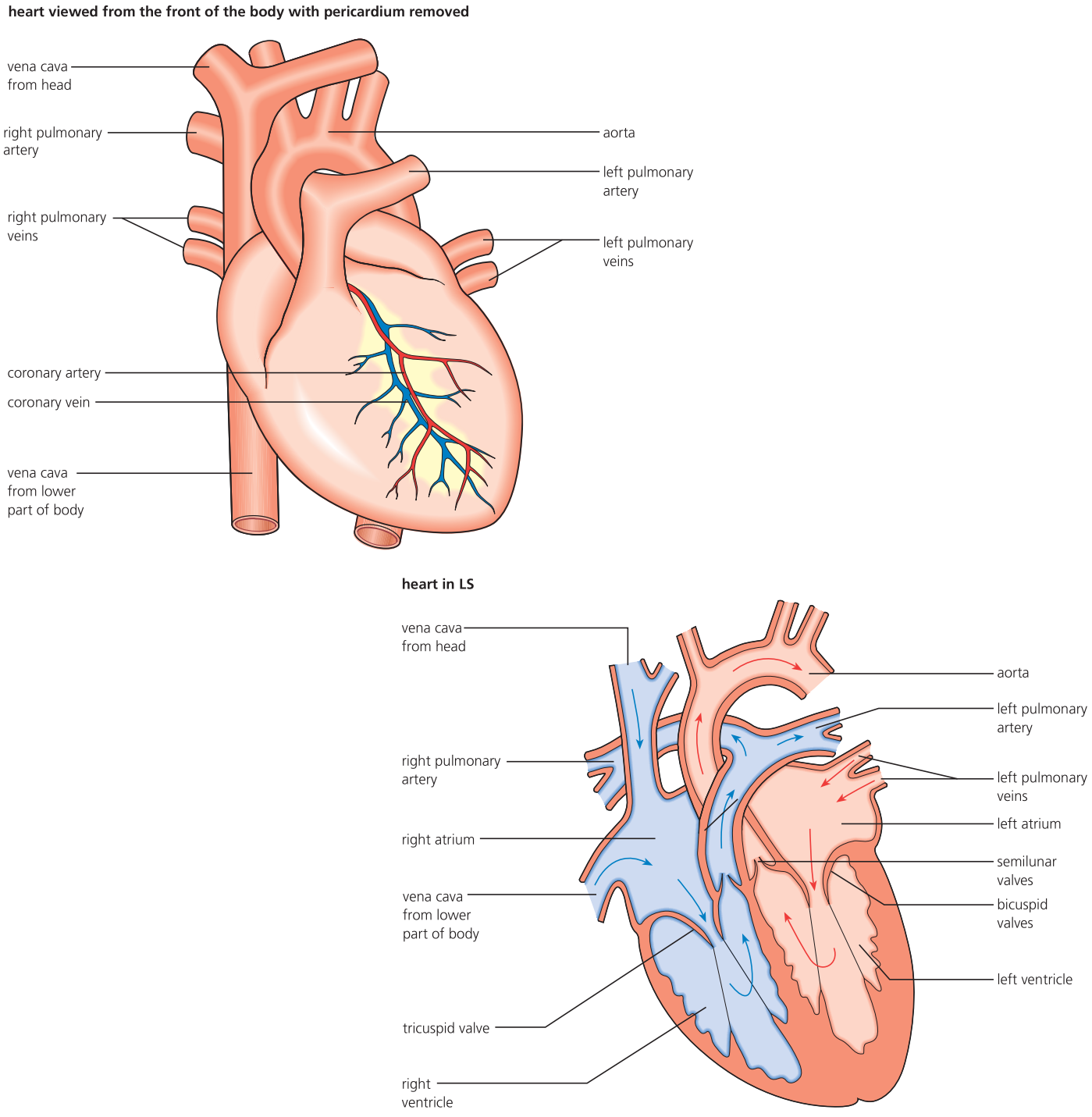


Figure 8.14 The structure of the heart

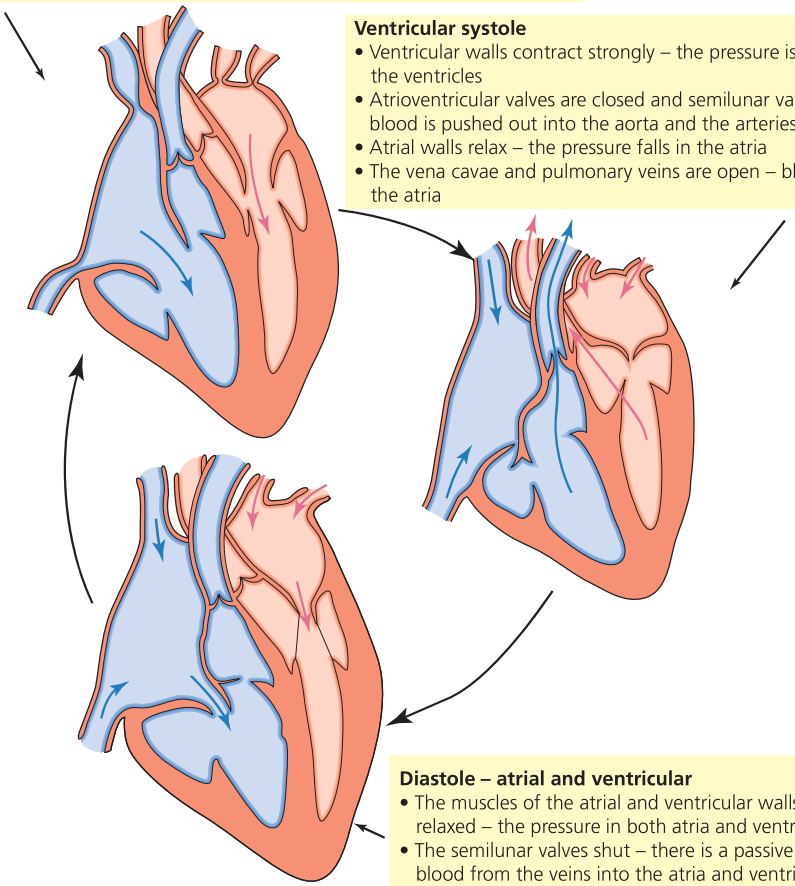
What causes the valves of the heart to open and close?

The heart valves are opened and closed by differences in the blood pressure caused by alternating contraction of heart muscle, first in the atrial walls (atrial systole), then in the ventricles (ventricular systole).

- Valves open when pressure on the input side (caused by muscle contraction) exceeds that on the output side.
- Valves close when pressure on the output side (caused by muscle contraction) exceeds that on the input side – typically caused by relaxation of the muscles on the input side.

Heart valves allow blood flow in one direction only. They are opened and closed by differences in blood pressure.
- They are opened when the pressure on the input side (caused by muscle contraction) exceeds that on the output side.
- They are closed when the pressure on the output side exceeds that on the input side. Typically caused by the relaxation of muscle on the input side.

Atrial systole
- Atrial walls contract – the pressure is raised in the atria
- Vena cavae and pulmonary veins are closed
- Atrioventricular valves pushed open – blood flows into the ventricles
- Ventricular walls relaxed – the pressure is low in the ventricles
- High pressure in the aorta and pulmonary arteries (due to the elastic and muscle fibres in their walls) – the semilunar valves are shut



Ventricular systole
- Ventricular walls contract strongly – the pressure is raised in the ventricles
- Atrioventricular valves are closed and semilunar valves are opened – blood is pushed out into the aorta and the arteries are stretched
- Atrial walls relax – the pressure falls in the atria
- The vena cavae and pulmonary veins are open – blood flows into the atria

Diastole – atrial and ventricular
- The muscles of the atrial and ventricular walls are relaxed – the pressure in both atria and ventricles is low
- The semilunar valves shut – there is a passive flow of blood from the veins into the atria and ventricles

Figure 8.15 The action of the heart valves

Question

7 The edges of the atrioventricular valves have non-elastic strands attached which are anchored to the ventricle walls (Figure 8.14). What is the role of these strands?

The cardiac cycle

The cardiac cycle is the sequence of events of a heart beat, by which blood is pumped all over the body. The heart beats at a rate of about 75 times per minute, so each cardiac cycle is about 0.8 seconds long. This period of 'heart beat' is divided into two stages which are called **systole** and **diastole**. In the systole stage heart muscle contracts and during the diastole stage heart muscle relaxes. When the muscular walls of the chambers of the heart contract, the volume of the chambers decreases. This increases the pressure on the blood contained there. This forces the blood to a region where pressure is lower. Valves prevent blood flowing backwards to a region of low pressure, so blood always flows on through the heart.

Look at the steps in Figures 8.15 and 8.16. You will see that Figure 8.16 illustrates the cycle on the left side of the heart only, but both sides function together, in exactly the same way, as Figure 8.15 makes clear.

We can start with contraction of the atrium (**atrial systole**, about 0.1 second). As the walls of the atrium contract, blood pushes past the atrioventricular valve, into the ventricles where the contents are under low pressure. At this time, any back-flow of blood from the aorta back into the ventricle chamber is prevented by the semilunar valves. Notice that back-flow from the atria into the vena cavae and the pulmonary veins is prevented because contraction of the atrial walls seals off these veins. Veins also contain semilunar valves which prevent back-flow here, too.

The atrium then relaxes for the remainder of the cycle (**atrial diastole**, about 0.7 seconds).

Next the ventricle contracts (**ventricular systole**, about 0.3 seconds). The high pressure this generates slams shut the atrioventricular valve and opens the semilunar valves, forcing blood into the aorta. A 'pulse', detectable in arteries all over the body, is generated (see below).

This is followed by relaxation of the ventricles (**ventricular diastole**, about 0.5 seconds) until the next contraction of the ventricles.

Each contraction of cardiac muscle is followed by relaxation and elastic recoil. The changing pressure of the blood in the atria, ventricles, pulmonary artery and aorta (shown in the graph in Figure 8.16) automatically opens and closes the valves.

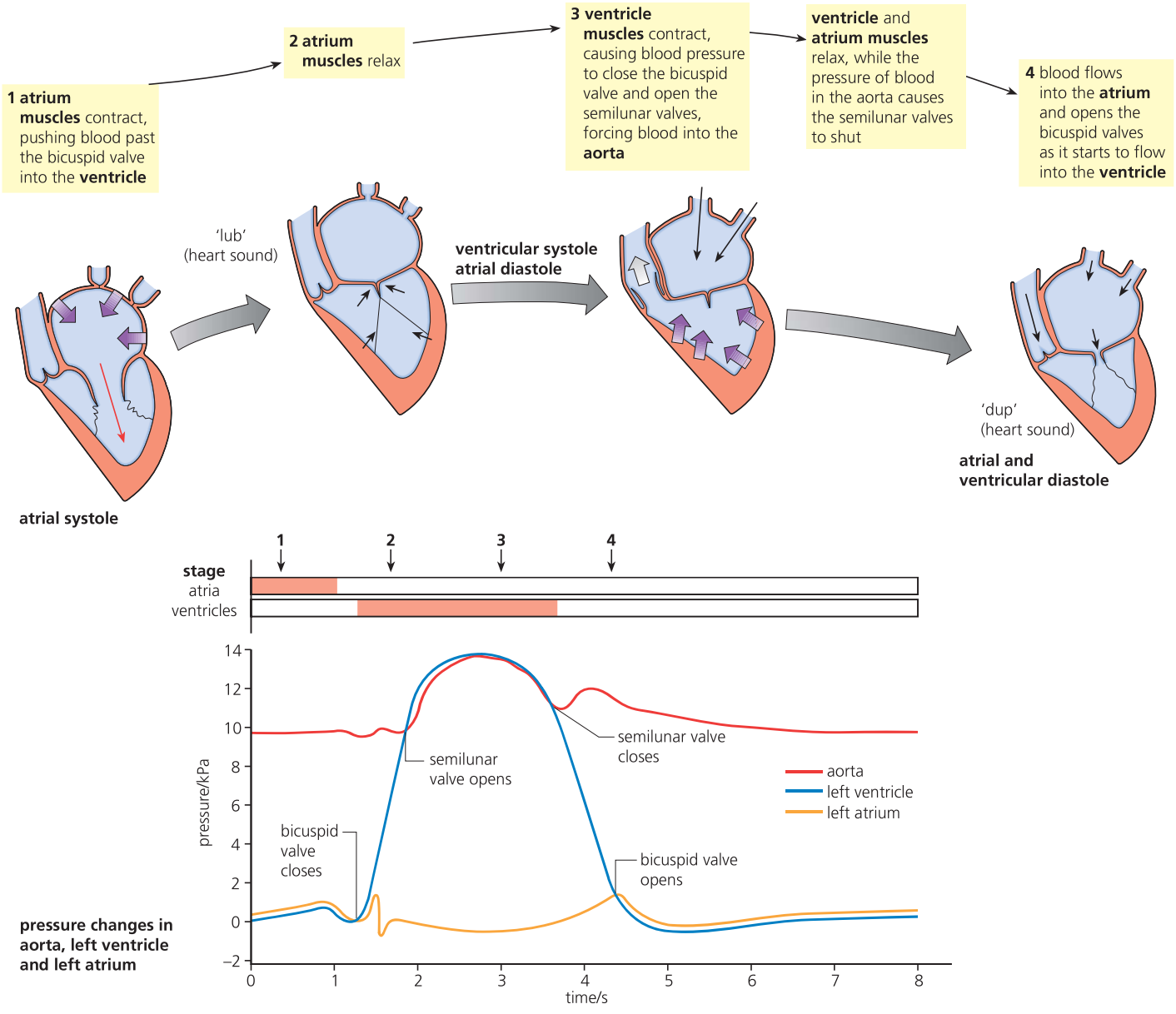


Figure 8.16 The cardiac cycle

Question

8 Examine the data on pressure change during the cardiac cycle in Figure 8.15. Determine or suggest why:

- **a** pressure in the aorta is always significantly higher than that in the atria
- **b** pressure falls *most* abruptly in the atrium once ventricular systole is underway
- **c** the semilunar valve in the aorta does not open immediately that ventricular systole commences
- **d** when ventricular diastole commences, there is a significant delay before the bicuspid valve opens, despite rising pressure in the atrium
- **e** it is significant that about 50 per cent of the cardiac cycle is given over to diastole.

Heart rate and the pulse

The contraction of the ventricle walls forces a surge of blood into the aorta and the pulmonary arteries come under great pressure. This volume of blood is called the **stroke volume**. Each surge stretches the elastic fibres in the artery walls (Table 8.3, page 156). The artery walls are distended as the surge passes, before the subsequent elastic recoil occurs. This is known as the **pulse**. Each contraction of the ventricles generates a pulse, so when we measure our pulse rate we are measuring our heart rate. We can measure heart rate in the carotid artery in the neck or at the wrist, where an artery passes over a bone. Incidentally, the amount of blood flowing from the heart is known as the **cardiac output**. At rest, our cardiac output is typically about 5 litres of blood per minute.

$$\text{cardiac output} = \text{stroke volume} \times \text{pulse rate}$$

Pulsation of the blood flow has entirely disappeared by the time it reaches the capillaries. This is due to the extensive nature of the capillary networks and to the resistance the blood experiences as it flows through the capillary networks.

Origin and control of the heart beat

The heart beats rhythmically throughout life, without rest, apart from the momentary relaxation that occurs between each beat. Even more remarkably, heart beats occur naturally, without the cardiac muscle needing to be stimulated by an external nerve. Since the origin of each beat is within the heart itself, we say that heart beat is '**myogenic**' in origin. However, the alternating contractions of the cardiac muscle of the atria and ventricles are controlled and co-ordinated precisely. Only in this way can the heart act as an efficient pump. The positions of the structures within the heart that bring this about are shown in Figure 8.17.

The steps in the control of the cardiac cycle are as follows.

- The heart beat originates in a tiny part of the muscle of the wall of the right atrium, called the **sinoatrial node (SA node)** or **pacemaker**.
- From here a wave of excitation (electrical impulses) spreads out across both atria.
- In response, the muscle of both atrial walls contracts simultaneously (**atrial systole**).
- This stimulus does not spread to the ventricles immediately because of the presence of a narrow band of non-conducting fibres at the base of the atria. These block the excitation wave, preventing its conduction across to the ventricles. Instead, the stimulus is picked up by the **atrioventricular node (AV node)**, situated at the base of the right atrium.
- After a delay of 0.1–0.2 seconds, the excitation is passed from the atrioventricular node to the base of both ventricles by tiny bundles of conducting fibres known as the **Purkyne tissue**. These are collectively called the **bundles of His**.
- On receiving this stimulation from the bundles of His, the ventricle muscles start to contract from the base of the heart upwards (**ventricular systole**).
- The delay that occurs before the atrioventricular node acts as a 'relay station' for the impulse permits the emptying of the atria into the ventricles to go to completion and prevents the atria and ventricles from contracting simultaneously.
- After every contraction, cardiac muscle has a period of insensitivity to stimulation, the **refractory period** (a period of enforced non-contraction – **diastole**). In this phase, the heart begins to refill with blood passively. This period is a relatively long one in heart muscle and enables the heart to beat throughout life.

The heart's own rhythm, set by the sinoatrial node, is about 50–60 beats per minute. Conditions in the body can and do override this basic rate and increase heart performance. The action of the pacemaker is modified according to the needs of the body. For example, it may be increased during physical activity. This occurs because increased muscle contraction causes an increased volume of blood passing back to the heart. The response may be more powerful contractions without an increase in the rate of contractions. Alternatively, the rate of 75 beats per minute of the heart 'at rest' may be increased to up to 200 beats a minute during very strenuous exercise.

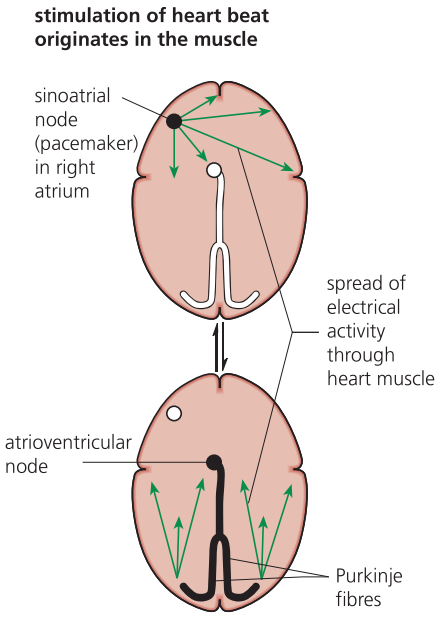


Figure 8.17 Myogenic origin of the heart beat

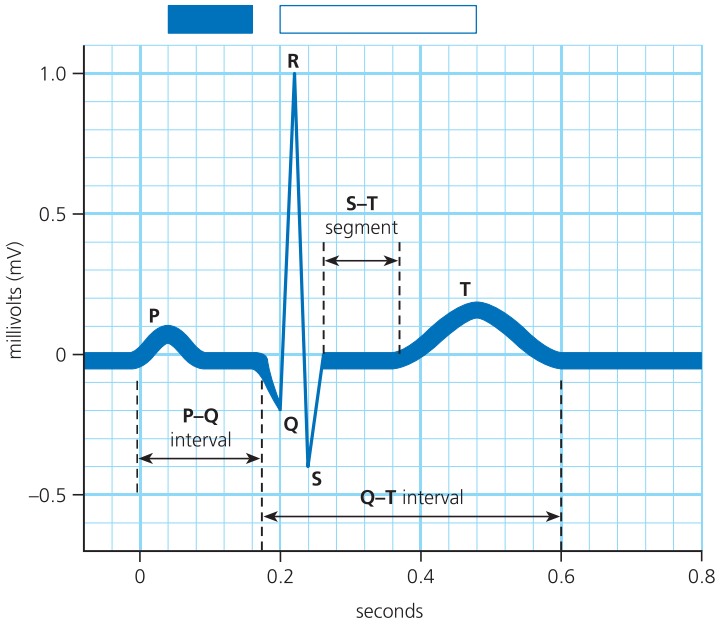
Extension

Electrocardiography

The impulses (action potentials) that originate in the sinoatrial node (pacemaker) of the heart during the cardiac cycle produce electrical currents that are also conducted through the fluids of the body as a whole and can be detected at the body surface by electrocardiography. Here, electrodes are attached to the patient's chest and the electrical activity detected is displayed as an electrocardiogram (ECG) by means of a chart recorder (Figure 8.18).

Electrocardiography has clinical applications; it is an aid in the diagnosis of **cardiovascular disease** (**CVD**, page 198). Some heart conditions that can be detected by the analysis of electrocardiograms are listed in Table 8.7.

normal electrocardiogram (ECG), analysed



Key

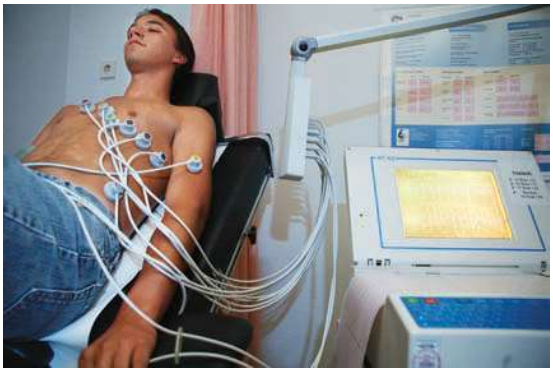
	atrial contraction (atrial systole)
	ventricular contraction (systole)
P wave	atrial depolarisation – leads to atrial contraction
P–R interval	time for impulse to be conducted from SA node to ventricles, via AV node
QRS complex	onset of ventricular depolarisation – leads to ventricular contraction
T wave	ventricular repolarisation – relaxation phase

abnormal traces showing

1 tachycardia
heart rate is over 100 beats/minute

2 ventricular fibrillation
uncontrolled contraction of the ventricles – little blood is pumped

3 heart block
ventricles not always stimulated



electrical activity detected through electrodes attached to the patient's chest is displayed on the chart recorder as an electrocardiogram

Figure 8.18 Electrocardiography

(Continued)

Extension (Continued)

Table 8.7 Heart conditions detected by ECG analysis

Heart conditions detected by abnormal ECG traces	
Tachycardia	A normal adult heart beats between 60 and 100 times a minute; a heart rate over 100 beats a minute is called tachycardia. Tachycardia may be relatively harmless and need no treatment but some forms can be life-threatening.
Ventricular fibrillation	Asynchronous contraction of the ventricle muscle fibres results in a failure of the heart to pump sufficient blood because some muscle fibres are contracting whilst others are relaxing.
Heart block	The most common site of blockage is at the atrioventricular node.
Arrhythmia	Arrhythmia is a condition of irregularity in heart rhythm due to a defect in the conduction system of the heart. It may be due to: • drugs, such as nicotine or alcohol • anxiety, hypothyroidism or potassium deficiency.

Summary

- Mammals have a **closed circulation** in which blood is pumped by a muscular **heart** through a continuous series of tubes – the **arteries**, **veins** and **capillaries**. It is a **double circulation** in that blood goes twice through the heart in every complete circulation. The **pulmonary circulation** is to the lungs, supplied by the right side of the heart. The **systemic circulation** is to the rest of the body, supplied by the left side of the heart.
- **Blood** consists of a straw-coloured fluid, the **plasma**, and **blood cells**. In humans, **red blood cells (erythrocytes)** are without a nucleus, contain **haemoglobin** and transport oxygen. **White blood cells (leucocytes)** combat disease. They are circulated by the blood to locations in the body where they act.
- **Tissue fluid** is the liquid that bathes all the body cells, formed from the blood plasma that has escaped from the capillaries. This fluid differs from plasma in that blood cells and plasma proteins are absent. **Lymph** is the tissue fluid that drains back into the blood circulation via the lymphatic system (lymph vessels and nodes).
- The main **role of the blood circulation** is the **transport** of respiratory gases, water, nutrients, waste products, heat and hormones. The transfer of substances in solution or suspension is essential since diffusion is insufficient.
- **Haemoglobin**, a conjugated protein, and the enzyme **carbonic anhydrase** occur in red blood cells and together affect the transport of **respiratory gases**. Oxygen is transported as **oxyhaemoglobin**. Haemoglobin buffers the H^+ ions from the reaction of carbon dioxide and water in which carbon dioxide is converted to **hydrogencarbonate ions**. These are transported mainly in the plasma.
- The **heart** is a hollow, muscular organ of **four chambers**. The right and left halves of the heart are completely separate. The upper chambers, the **atria**, have relatively thin walls. The lower chambers, the **ventricles**, have thick walls. The thickness of the wall of the left ventricle is much greater than the right because the left ventricle has to pump blood all around the rest of the body whereas the right ventricle pumps blood only to the lungs which are very close to the heart. Direction of blood flow through the heart is maintained by **valves**.
- The cycle of changes during a heart beat, known as the **cardiac cycle**, lasts about 0.8 seconds when the body is at rest. It consists of alternate contraction (**systole**) and relaxation (**diastole**). Atrial systole precedes ventricular systole and both are followed by periods of diastole that partly overlap. Then atrial systole commences again.
- The heart beat originates in the heart itself (**myogenic**), at the **sinoatrial node** (SAN or pacemaker) in the upper wall of the right atrium. This activates the atrial muscle to contract and triggers the atrioventricular node (AVN), which carries the signal to contract on to the ventricles. The excitation passes from the atrioventricular node to the base of both ventricles by tiny bundles of conducting fibres, known as the **Purkyne tissue**. These are collectively called the **bundles of His**. Impulses from the cerebral hemispheres or involuntary reflexes from stretch receptors in arteries outside the heart, or hormone action can all alter the rate at which the heart beats.

Examination style questions

1 Fig. 1.1 shows the changes in blood pressure in the left atrium, left ventricle and aorta during one complete contraction of the heart. It also shows a recording of the electrical activity of the heart.

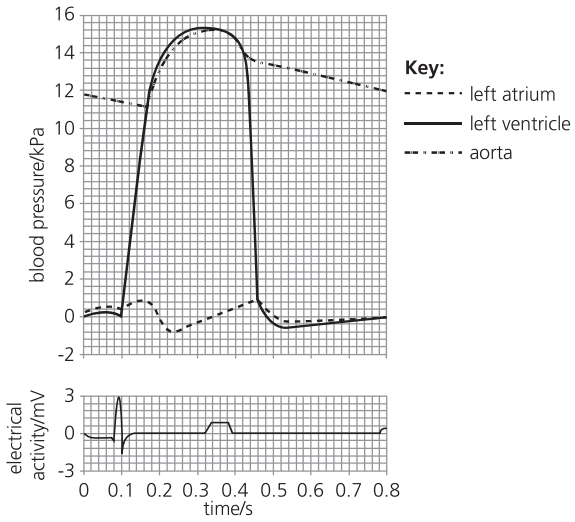


Fig. 1.1

a) Name the source of the electrical activity in the heart. [1]

b) Explain how the heart is co-ordinated so that the ventricle contracts after the atrium has contracted. [4]

c) With reference to Fig. 1.1, calculate the heart rate in beats per minute. Show your working and express your answer to the nearest whole number. [2]

d) The pressure in the **right ventricle** is rarely higher than 4.0 kPa.

Explain why the pressure in the right ventricle is much lower than that in the left ventricle. [2]

[Total: 9]

(Cambridge International AS and A Level Biology 9700, Paper 02 Q4 November 2007)

2 **a)** What tissue is found in all types of blood vessel? How it is adapted to its functions? [4]

b) In a table, give the differences between the structure of an artery and a vein as seen in transverse section. [4]

c) Explain the difference between a single and a double circulation, and the benefits gained by respiring tissues served by the latter. [2]

d) In a table, give the differences in composition between plasma and tissue fluid. [4]

e) List in order the pathway of vessels and chambers taken by a red blood cell, from leaving the liver until it reaches cells of the muscles of the arm. [6]

[Total: 20]

3 Both red blood cells in mammals and companion cells in flowering plants play a part in internal transport. Describe the mature structure of both these cells, and how those structures are adapted to deliver their precise roles.