Cambridge AS level Biology

CODE: (9700)

Chapter 08

Transport in mammals

Transport systems in animals

Animals, especially large mammals, are more active than plants and rely on locomotion for food and a nervous system for coordination. They also require oxygen for respiration, leading to the evolution of transport systems for oxygen. As animals become more complex, their demands on transport systems increase. Small organisms like Paramecium can meet their needs through diffusion, but larger, more active organisms like insects, fish, and mammals require well-organized transport systems with pumps to keep fluid moving through their bodies.

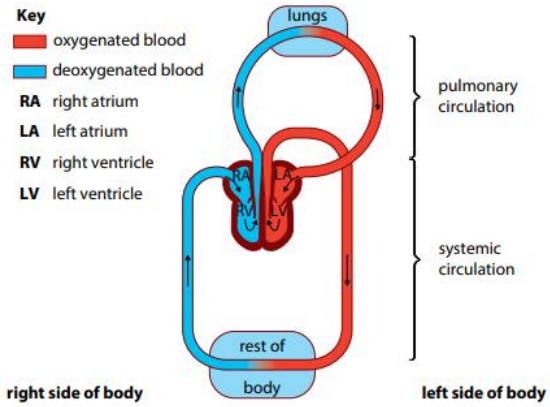


Figure 8.2 The general plan of the mammalian transport system, viewed as though looking at someone facing you. It is a closed double circulatory system.

The mammalian cardiovascular system

Figure 8.2 shows the general layout of the main transport system of mammals – the blood system or **cardiovascular system**. It is made up of a pump, the heart, and a system of interconnecting tubes, the **blood vessels**.

The blood always remains within these vessels, and so the system is known as a **closed** blood system.

The blood is then pumped out of the right ventricle into the **pulmonary arteries,** which carry it to the lungs. The final part of the journey is along the **pulmonary veins**, which return it to the left side of the heart. This is called the **pulmonary circulation.**

This combination of pulmonary circulation and systemic circulation makes a **double circulatory system**. The mammalian circulatory system is therefore a closed double circulation.

Blood vessels

The vessels making up the blood system are of three main types. Figure 8.5 shows these vessels in transverse section. Vessels carrying blood away from the heart are known as arteries, while those carrying blood towards the heart are veins. Linking arteries and veins, taking blood close to almost every cell in the body, are tiny vessels called capillaries.

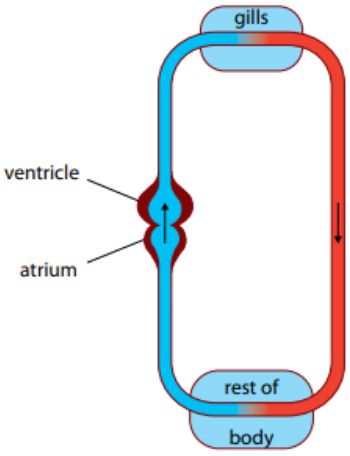


Figure 8.4 The general plan of the transport system of a fish.

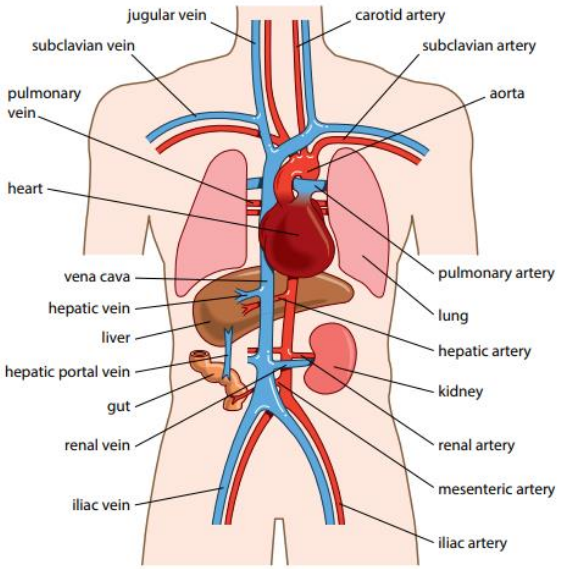


Figure 8.3 The positions of some of the main blood vessels in the human body.

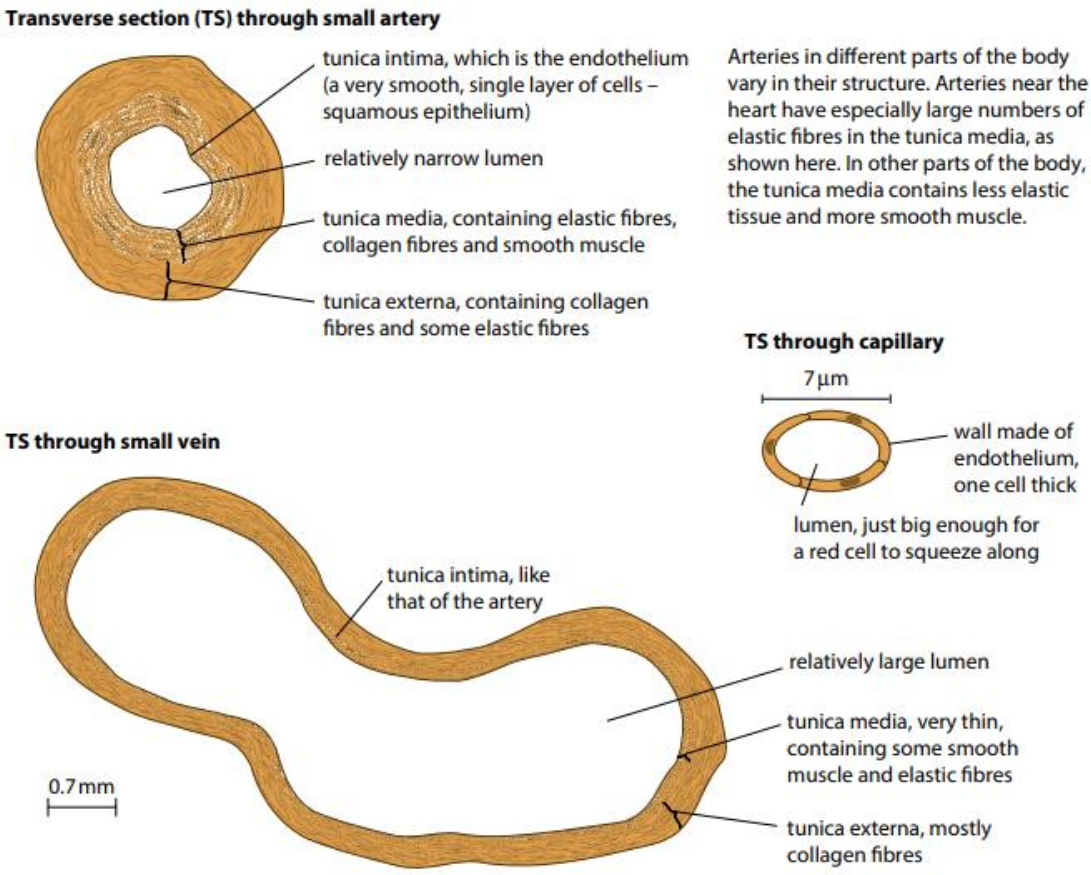


Figure 8.5 The tissues making up the walls of arteries, capillaries and veins.

Arteries

The function of arteries is to transport blood, swiftly and at high pressure, to the tissues. The structure of the wall of an artery enables it to perform this function efficiently. Arteries and veins both have walls made up of three layers:

■ An inner endothelium (lining tissue), called the tunica intima, made up of a layer of flat cells (squamous epithelium) fitting together like jigsaw pieces; this layer is very smooth, minimising friction with the moving blood

■ A middle layer called the tunica media ('middle coat'), containing smooth muscle, collagen and elastic fibres

■ An outer layer called the tunica externa ('outer coat'), containing elastic fibres and collagen fibres.

As arteries reach the tissue to which they are transporting blood, they branch into smaller and smaller vessels, called **arterioles**.

Capillaries

The arterioles themselves continue to branch, eventually forming the tiniest of all blood vessels, **capillaries**.

Capillaries form a network throughout every tissue in the body except the cornea and cartilage. Such networks are sometimes called **capillary beds.**

Veins

As blood leaves a capillary bed, the capillaries gradually join with one another, forming larger vessels called **venules**. These join to form veins. The function of veins is **to return blood to the heart.**

This squeezing would not help to push the blood back towards the heart; blood would just squidge up and down as you walked. To keep the blood flowing in the right direction, veins contain half-moon valves, or **semilunar valves,** formed from their endothelium.

Thus, when you contract your leg muscles, the blood in the veins is squeezed **up** through these valves but cannot pass **down** through them.

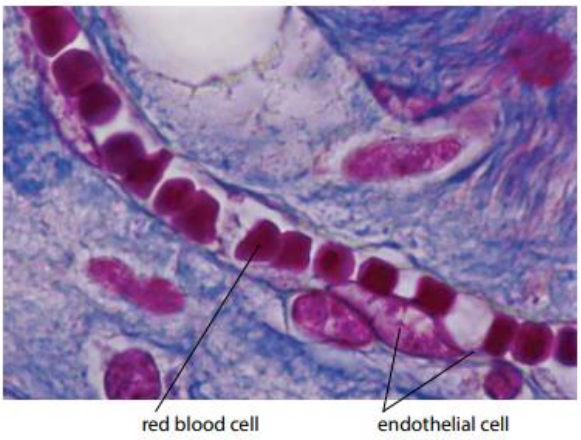


Figure 8.7 Photomicrograph of a blood capillary containing red blood cells (dark red) (×900). The cells of the endothelium are very thin, except where there is a nucleus (red).

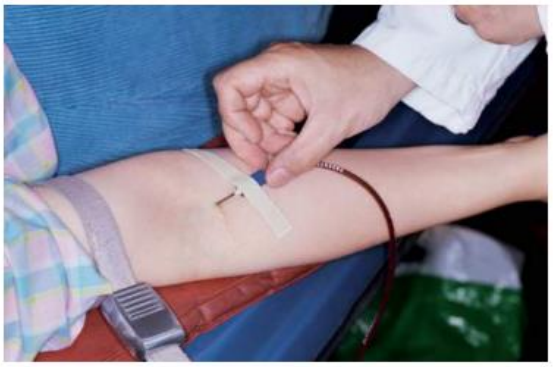


Figure 8.9 Veins are closer to the skin surface than arteries, and blood flows more gently and smoothly in them. They are therefore used when a blood sample is being taken, or to donate blood for transfusions.

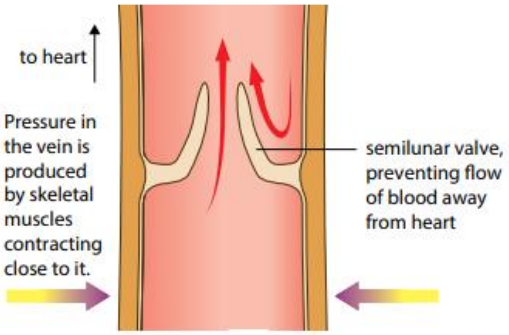


Figure 8.8 Longitudinal section through a small vein and a valve.

Figure 8.10 shows how blood pressure changes as the blood travels on one complete journey from the heart, through the systemic circulatory system, back to the heart and then through the pulmonary circulatory system.

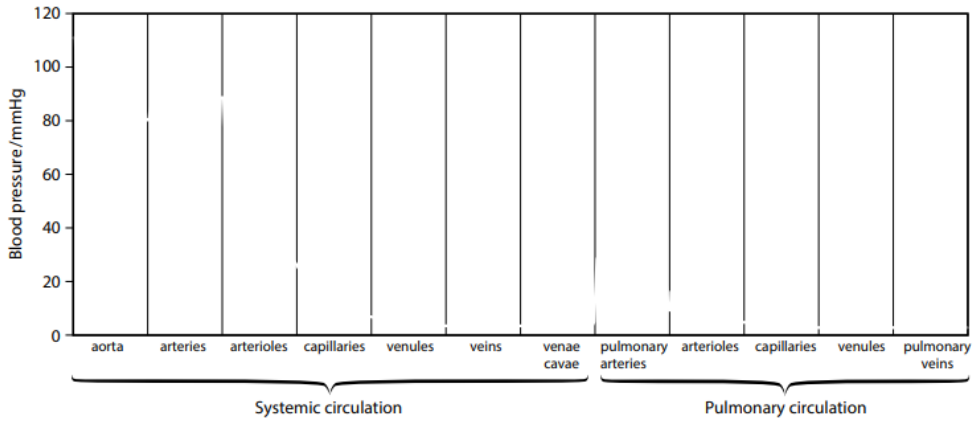


Figure 8.10 Blood pressure in different regions of the human circulatory system.

Blood plasma and tissue fluid

Blood is composed of cells floating in a pale-yellow liquid called **plasma**. Blood plasma is mostly water, with a variety of substances dissolved in it. These solutes include nutrients such

as glucose and waste products such as urea that are being transported from one place to another in the body. Solutes also include protein molecules, called **plasma proteins**, that remain in the blood all the time.

The volume of fluid leaving the capillary to form tissue fluid is determined by two opposing pressures. Blood pressure at the arterial end pushes fluid into tissue, while water moves through osmosis from low solute concentration to high solute concentration.

The net result of these competing processes is that fluid tends to flow **out** of capillaries into tissue fluid at the **arterial** end of a capillary bed and **into** capillaries from tissue fluid near the **venous** end of a capillary bed.

If blood pressure is too high, too much fluid is forced out of the capillaries, and may accumulate in the tissues. This build-up of fluid is called **oedema**.

Lymph

About 90% of the fluid that leaks from capillaries eventually seeps back into them. The remaining 10% is collected up and returned to the blood system by means of a series of tubes known as **lymph vessels** or **lymphatics.**

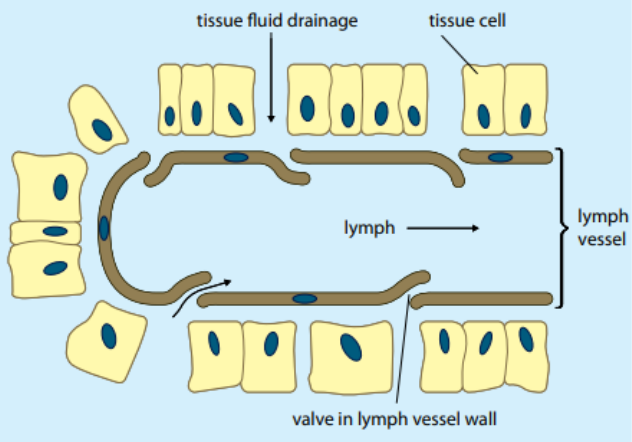


Figure 8.11 Drainage of tissue fluid into a lymph vessel.

Substance	Relative molecular mass	Permeability of capillary walls
water	18	1.00
sodium ions	23	0.96
urea	60	0.8
glucose	180	0.6
haemoglobin	68 000	0.01
albumin	69 000	0.000 01

Table 8.1 Relative permeability of capillaries in a muscle to different substances. The permeability to water is given a value of 1. The other values are given in proportion to that of water.

Lymphatics join up to form larger lymph vessels, that gradually transport the lymph back to the large veins that run just beneath the collarbone, the **subclavian veins** (Figure 8.12).

As in veins, the movement of fluid along the lymphatics is largely caused by the contraction of muscles around the vessels and kept going in the right direction by valves. Lymph vessels also have smooth muscle in their walls, which can contract to push the lymph along

At intervals along lymph vessels, there are **lymph nodes.** These are involved in protection against disease. Bacteria and other unwanted particles are removed from lymph by some types of white blood cells as the lymph passes through a node, while other white blood cells within the nodes secrete **antibodies**.

Blood

You have about 5dm3 of blood in your body, with a mass of about 5 kg. Suspended in the blood plasma, you have around 2.5×1013 red blood cells, 5×1011 white blood cells and 6×1012 platelets (small cell fragments with no nucleus) (Figures 8.13 and 8.14).

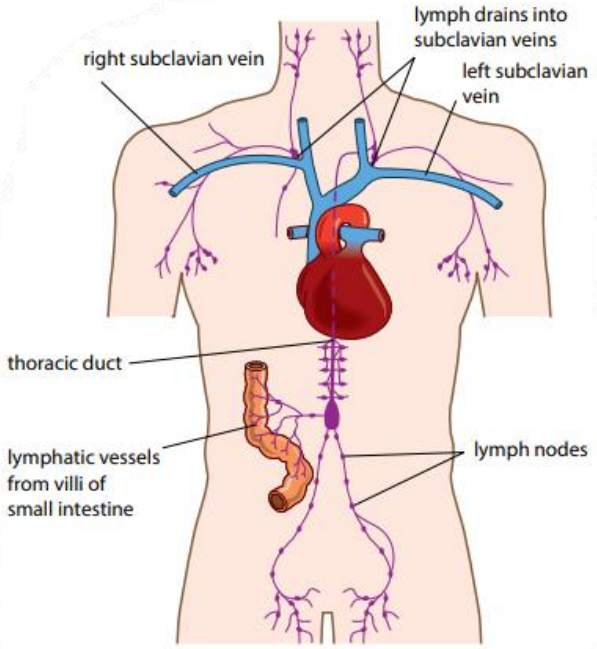


Figure 8.12 Outline of the human lymphatic system.

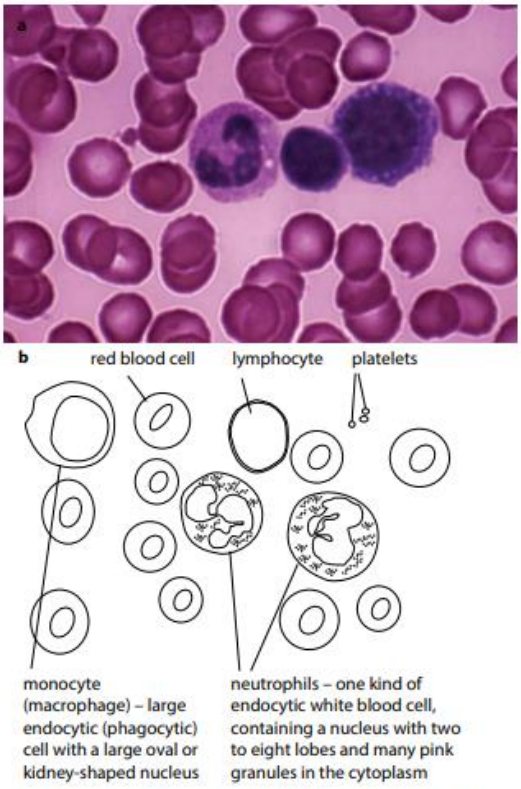


Figure 8.13 **a** Photomicrograph of human blood. It has been stained so that the nuclei of the cells are dark purple (× 1600). **b** Diagram of the types of cells seen in a stained blood film.

Red blood cells

Red blood cells (Figures 8.14 and 8.15) are also called erythrocytes, which simply means 'red cells. Their red colour is caused by the pigment haemoglobin, a globular protein (page 43). The main function of haemoglobin is to transport oxygen from lungs to respiring tissues.

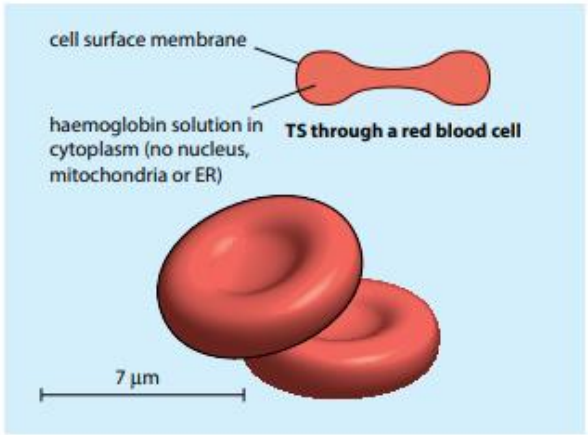


Figure 8.15 Red blood cells.

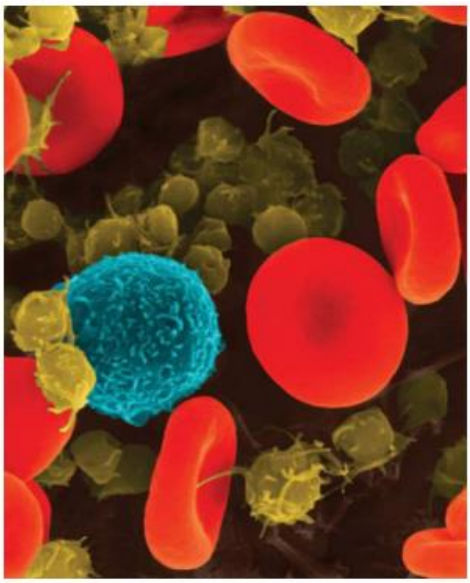


Figure 8.14 False-colour scanning electron micrograph of human blood. Red blood cells are coloured red. The blue sphere is a white blood cell. Platelets are coloured yellow (× 4000).

The structure of a red blood cell is unusual in several ways.

■ Red blood cells are shaped like a biconcave disc. The dent in each side of a red blood cell increases the amount of surface area in relation to the volume of the cell, giving it a large surface area: volume ratio.

■ Red blood cells are very small. The diameter of a human red blood cell is about 7µm, compared with the diameter of an average liver cell of 40µm. This small size means that no haemoglobin molecule within the cell is very far from the cell surface membrane, and the haemoglobin molecule can therefore quickly exchange oxygen with the fluid outside the cell.

■ Red blood cells are very flexible. Some capillaries are even narrower than the diameter of a red blood cell. The cells can deform so that they can pass through these vessels. This is possible because the cells have a specialised cytoskeleton made up of a mesh-like network of protein fibres that allows them to be squashed into different shapes, but then springs back to produce the normal biconcave shape.

■ Red blood cells have no nucleus, no mitochondria and no endoplasmic reticulum. The lack of these organelles means that there is more room for haemoglobin, so maximising the amount of oxygen which can be carried by each red blood cell.

White blood cells

White blood cells are sometimes known as leucocytes, which just means 'white cells. They, too, are made in the bone marrow, but are easy to distinguish from red blood cells in a blood sample because:

■ white blood cells all have a nucleus, although the shape of this varies in different types of white cell

■ most white blood cells are larger than red blood cells, although one type, lymphocytes, may be slightly smaller

■ white blood cells are either spherical or irregular in shape, never looking like a biconcave disc (Figures 8.14 and 8.16).

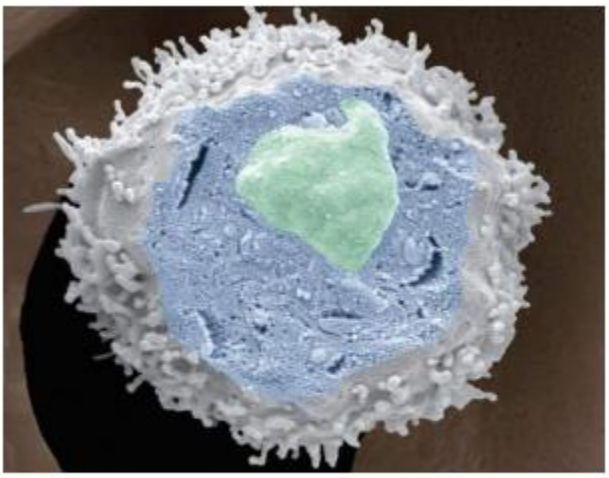


Figure 8.16 False-colour scanning electron micrograph of a section through a white blood cell (×6000). This is a lymphocyte.

Phagocytes are cells that destroy invading microorganisms by phagocytosis (page 87). The commonest type of phagocyte (neutrophils) can be recognised by the lobed nuclei and granular cytoplasm. Monocytes (Figure 8.13) are also phagocytes.

Lymphocytes also destroy microorganisms, but not by phagocytosis. Some of them secrete chemicals called **antibodies**, which attach to and destroy the invading cells.

Hemoglobin

The cardiovascular system transports oxygen from lungs to tissues, enabling aerobic respiration. Oxygen is transported in red blood cells with haemoglobin protein.

$$\underset{\text{haemoglobin}}{Hb} + \underset{\text{oxygen}}{4O_2} \rightleftharpoons \underset{\text{oxyhaemoglobin}}{HbO_8}$$

The hemoglobin dissociation curve

A molecule whose function is to transport oxygen from one part of the body to another must be able not only to pick up oxygen at the lungs, but also to release oxygen within respiring tissues. Haemoglobin performs this task superbly

To investigate how haemoglobin behaves, samples are extracted from blood and exposed to different concentrations, or **partial pressures,** of oxygen.

A sample of haemoglobin which has combined with this maximum amount of oxygen is said to be **saturated**.

The percentage saturation of each sample can be plotted against the partial pressure of oxygen to obtain the curve shown in Figure 8.17. This is known as a **dissociation curve.**

Partial pressure of oxygen / kPa	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Percentage saturation of haemoglobin	8.5	24.0	43.0	57.5	71.5	80.0	85.5	88.0	92.0	94.0	95.5	96.5	97.5	98.0

Table 8.2 The varying ability of haemoglobin to carry oxygen.

This means that haemoglobin coming from the lungs carries a lot of oxygen; as it reaches a muscle, it releases around three-quarters of it. This released oxygen diffuses out of the red blood cell and into the muscle where it can be used in respiration.

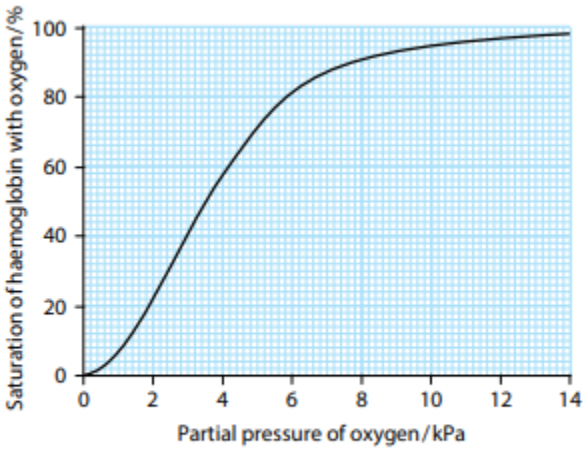


Figure 8.17 The haemoglobin dissociation curve.

The S-shaped curve

The haemoglobin dissociation curve's shape is determined by a haemoglobin molecule's behavior as it combines with or loses oxygen molecules. Oxygen molecules combine with iron atoms in haem groups, causing slight distortion. This distortion facilitates the combination of oxygen molecules with other haem groups.

Over this part of the curve, a **small** change in the partial pressure of oxygen causes a **very large** change in the amount of oxygen which is carried by the haemoglobin.

The Bohr shift

The behaviour of haemoglobin in picking up oxygen at the lungs, and readily releasing it when in conditions of low oxygen partial pressure, is exactly what is needed. But, in fact, it is even better at this than is shown by the dissociation curve in Figure 8.17. This is because the amount of oxygen the haemoglobin carries is affected not only by the partial pressure of **oxygen**, but also by the partial pressure of **carbon dioxide.**

In the cytoplasm of red blood cells there is an enzyme, **carbonic anhydrase**, that catalyses the following reaction:

$$CO_2 + H_2O \xrightleftharpoons{\text{carbonic anhydrase}} H_2CO_3$$

carbon dioxide + water ⇌ carbonic acid

The carbonic acid dissociates:

$$H_2CO_3 \rightleftharpoons H^+ + HCO_3^-$$

carbonic acid ⇌ hydrogen ion + hydrogencarbonate ion

Haemoglobin readily combines with the hydrogen ions, forming **haemoglobinic** acid, **HHb**. In so doing, it releases the oxygen which it is carrying. The net result of this reaction is two-fold.

■ The haemoglobin 'mops up' the hydrogen ions which are formed when carbon dioxide dissolves and dissociates. A high concentration of hydrogen ions means a low pH;

■ The presence of a high partial pressure of carbon dioxide causes haemoglobin to release oxygen. This is called the Bohr effect, after Christian Bohr who discovered it in 1904. It is exactly what is needed.

The Bohr effect explains how carbon dioxide is carried in the blood. Dissolved carbon dioxide forms hydrogencarbonate ions, which are formed in red blood cell cytoplasm. Most of these ions diffuse into blood plasma, carrying 85% of carbon dioxide. Some carbon dioxide molecules remain in the blood plasma, forming 5% of the total.

The compound formed is called **carbaminohaemoglobin**. About 10% of the carbon dioxide is carried in this way (Figure 8.19)

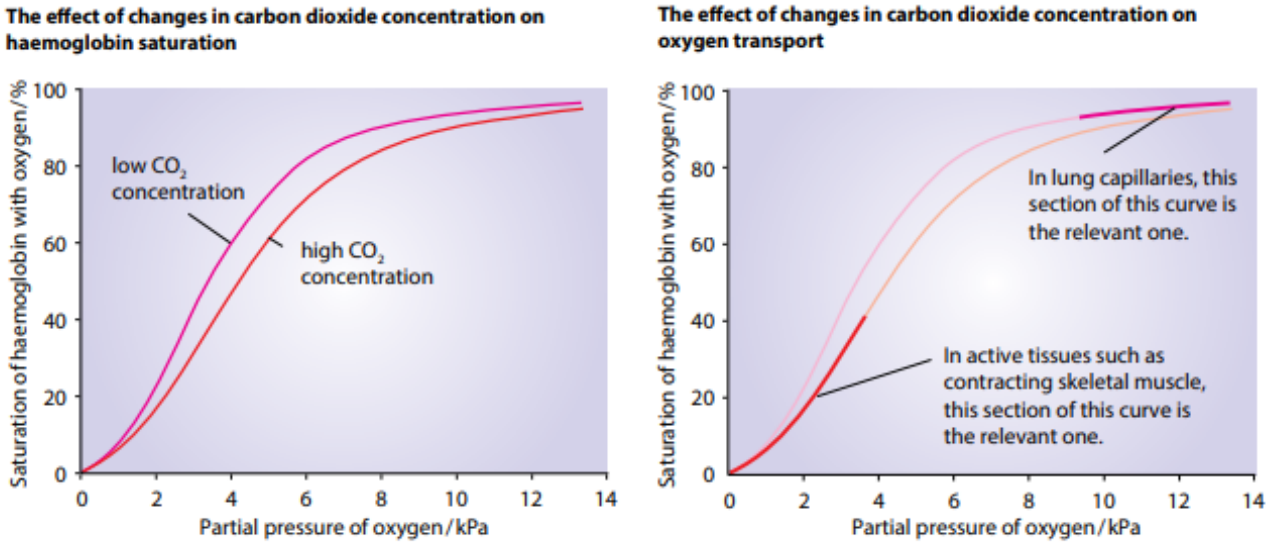


Figure 8.18 Dissociation curves for haemoglobin at two different partial pressures of carbon dioxide. The shift of the curve to the right when the haemoglobin is exposed to higher carbon dioxide concentration is called the Bohr effect.

When blood reaches the lungs, the reactions described above go into reverse. The relatively low concentration of carbon dioxide in the alveoli compared with that in the blood causes carbon dioxide to diffuse from the blood into the air in the alveoli, stimulating the carbon dioxide of carbaminohaemoglobin to leave the red blood cell, and hydrogencarbonate and hydrogen ions to recombine to form carbon dioxide molecules once more. This leaves the haemoglobin molecules free to combine with oxygen, ready to begin another circuit of the body.

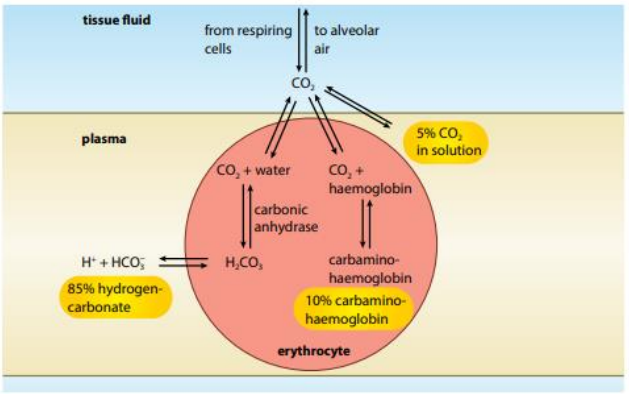


Figure 8.19 Carbon dioxide transport in the blood. The blood carries carbon dioxide partly as undissociated carbon dioxide in solution in the plasma, partly as hydrogencarbonate ions in solution in the plasma, and partly combined with haemoglobin in the red blood cells.

Problems with oxygen transport

The efficient transport of oxygen around the body can be impaired by many different factors.

Carbon monoxide

Haemoglobin, a perfect oxygen-transporting molecule, can be dangerous due to its ability to easily and irreversibly combine with carbon monoxide, which is formed when carbon-containing compounds burn incompletely.

Here it combines with the haem groups in the haemoglobin molecules, forming **carboxyhaemoglobin**.

High altitude

Oxygen is obtained from the air around us, with partial pressures of over 20kPa in the atmosphere and 13kPa in the lungs. At sea level, haemoglobin is almost saturated with oxygen. However, climbing a mountain to 6500 meters results in less oxygen, leading to breathing issues and illness. Rapid travel from sea level to high altitudes can cause **altitude sickness**, as the body doesn't have time to adjust.

Figure 8.20 A climber rests on the summit of Mount Everest. He is breathing oxygen through a mask.

The heart

The heart of an adult human, around 300 g, is a bag of muscle filled with blood, made of cardiac muscle. Its structure consists of interconnecting cells with tightly joined membranes, allowing waves of electrical excitation to pass easily between them. This close contact is a crucial feature of cardiac muscle.

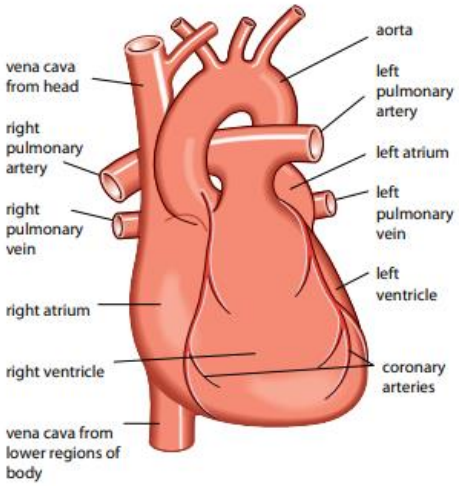


Figure 8.22 Diagram of the external structure of a human heart, seen from the front.

Figure 8.21 A human heart. The blood vessels in the photograph lie immediately below the surface of the heart and have been injected with gelatine containing a dye. The cardiac muscle was treated to make it transparent to a depth of 2 millimetres to allow the blood vessels to seen.

The large, arching blood vessel is the largest artery, the **aorta**, with branches leading upwards towards the head, and the main flow doubling back downwards to the rest of the body.

The other blood vessel leaving the heart is the **pulmonary** artery. This, too, branches very quickly after leaving the heart, into two arteries taking blood to the right and left lungs. Running vertically on the right-hand side of the heart are the two large veins, the **venae cavae,** one bringing blood downwards from the head and the other bringing it upwards from the rest of the body. The **pulmonary veins** bring blood back to the heart from the left and right lungs.

The two chambers on the left of the heart are completely separated from those on the right by a wall of muscle called the **septum**.

The upper chamber on each side of the heart is called an **atrium** (plural: **atria**), or sometimes an **auricle**.

The lower chambers are **ventricles**. Blood flows into the ventricles from the atria, and is then squeezed out into the arteries

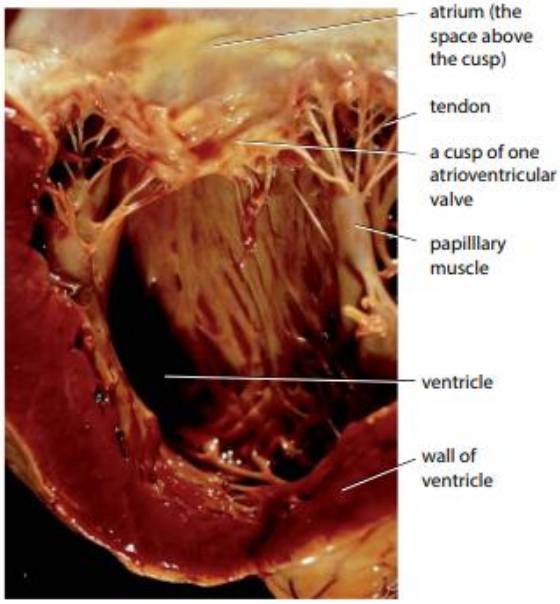


Figure 8.24 Section through part of the left side of the heart.

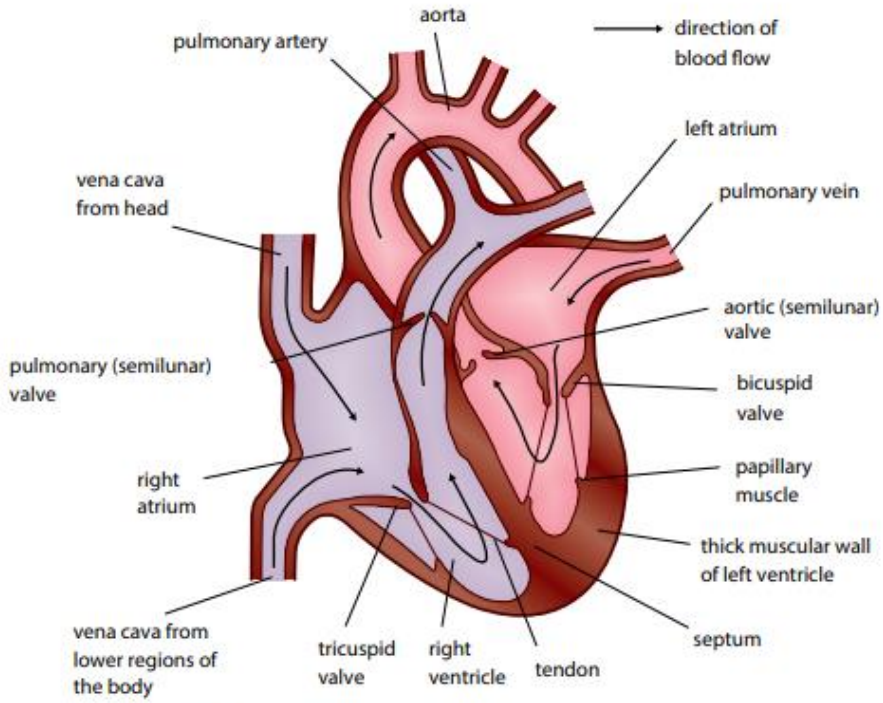


Figure 8.25 Diagrammatic section through a heart.

The atria and ventricles have valves between them, which are known as the **atrioventricular valves.** The one on the left is the **mitral** or **bicuspid** valve, and the one on the right is the **tricuspid valve.**

The cardiac cycle

Your heart beats around 70 times a minute. The **cardiac cycle** is the sequence of events which makes up one heartbeat.

We will begin with the time when the heart is filled with blood and the muscle in the atrial walls contracts. This stage is called **atrial systole.**

About 0.1 seconds after the atria contract, the ventricles contract. This is called **ventricular systole.**

Ventricular systole lasts for about 0.3 seconds. The muscle then relaxes, and the stage called **ventricular diastole begins.**

The heart muscle relaxes, causing the pressure in the ventricles to drop. The semilunar valves snap shut as blood fills their cusps, allowing high-pressure blood to flow back into the ventricles. During diastole, blood flows into the atria, which have thin walls and little resistance to blood flow. Some blood tricks downwards into the ventricles through the atrioventricular valves, and the atrial muscle contracts to force blood down.

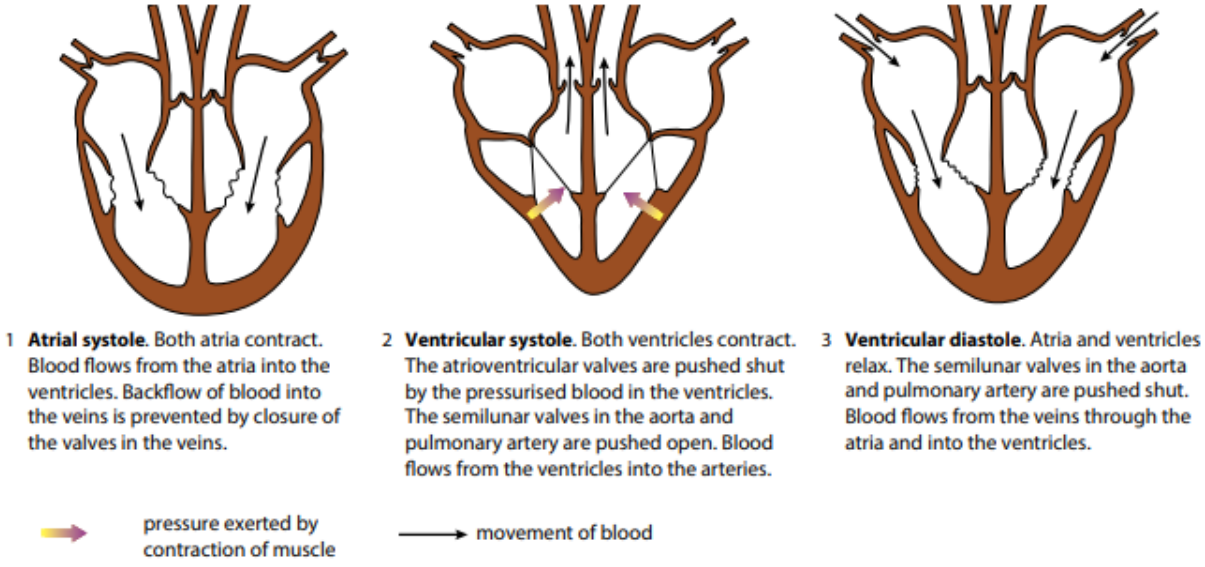


Figure 8.26 The cardiac cycle. Only three stages in this continuous process are shown.

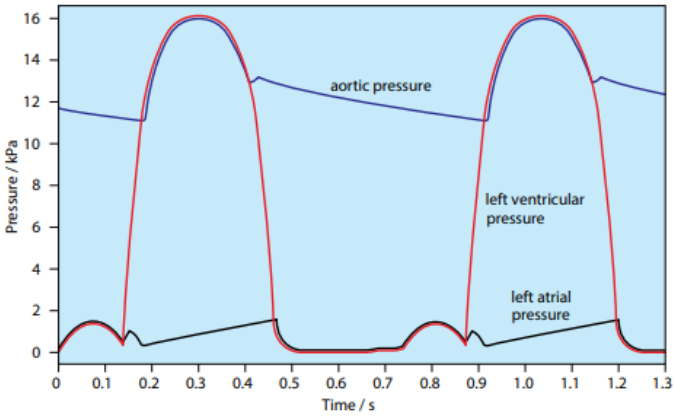


Figure 8.28 Pressure changes in the left side of the heart during the cardiac cycle.

the blood is higher in the atrium than in the ventricle, and so forces the atrioventricular valve open.
During **ventricular systole**, the pressure of the blood is higher in the ventricle than in the atrium. The pressure of the blood pushes up against the cusps of the atrioventricular valve, pushing it shut. Contraction of the papillary muscles, attached to the valve by tendons, prevents the atrioventricular valve from being forced inside-out.

During **ventricular systole**, the pressure of the blood forces the semilunar valves open.
During **ventricular diastole**, the pressure of the blood in the arteries is higher than in the ventricles. The pressure of the blood pushes into the cusps of the semilunar valves, squeezing them shut.

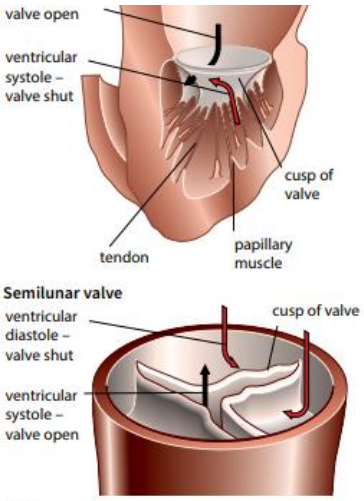


Figure 8.27 How the heart valves function.

Control of heartbeat

Cardiac muscle differs from the muscle in all other areas of the body in that it is **myogenic**. This means that it **naturally** contracts and relaxes.

The cardiac cycle is initiated in a specialised patch of muscle in the wall of the right atrium, called the **sinoatrial node**. It is often called the **SAN** for short, or **pacemaker**.

As we have seen, the muscles of the ventricles do not contract until **after** the muscles of the atria.

The only route through is via a patch of conducting fibres, situated in the septum, known as the **atrioventricular node,** or AVN (Figure 8.29). The **AVN** picks up the excitation wave as it spreads across the atria and, after a delay of about 0.1 seconds, passes it on to a bunch of conducting fibres called the **Purkyne tissue**, which runs down the septum between the ventricles.

Small sections of the cardiac muscle contract while other sections are relaxing. The result is **fibrillation**, in which the heart wall simply flutters rather than contracting as a whole and then relaxing.

Electrocardiograms (ECGs)

Electrocardiogram (ECG) is a method to detect and record electrical potentials in the heart muscle, providing a graph of voltage against time.

The part labelled **P** represents the wave of excitation sweeping over the atrial walls. The parts labelled **Q**, **R** and **S** represent the wave of excitation in the ventricle walls. The **T** section indicates the recovery of the ventricle walls.

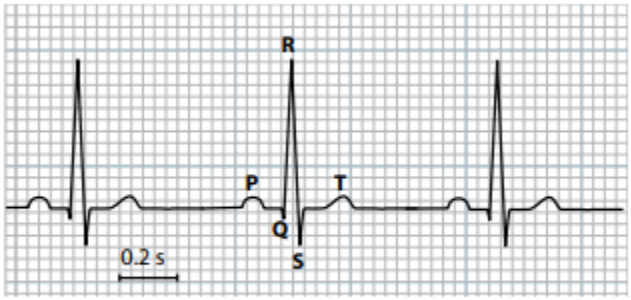
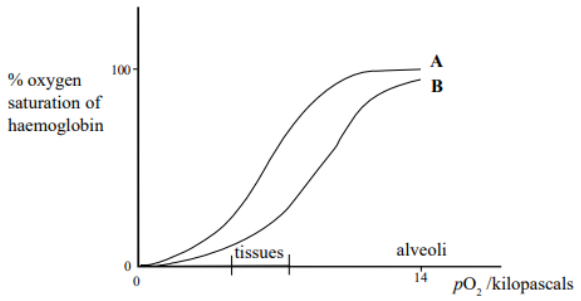


Figure 8.30 A normal ECG.

Revision questions

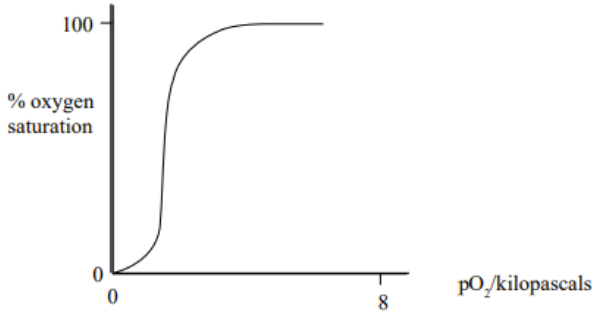
(1) The figure shows the oxygen saturation curves for haemoglobin under different conditions. Curve A represents normal resting conditions.



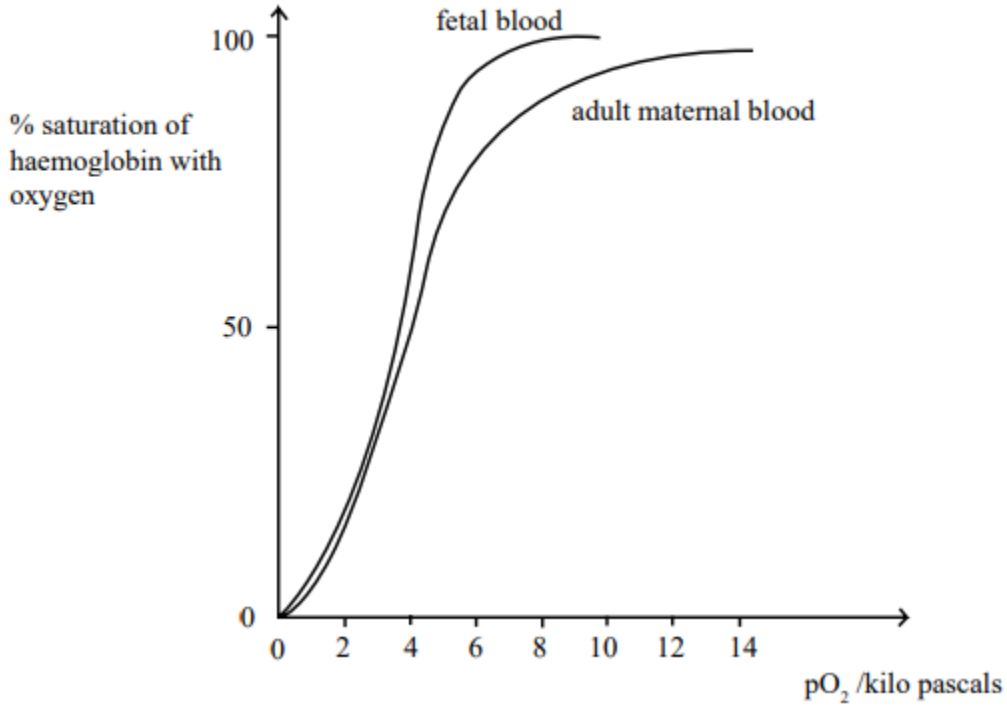
(a) Suggest two factors which could be responsible for the shift of the curve from A to B.

(b) Explain the physiological significance of the shift from A to B on the behaviour of haemoglobin in the tissues and alveoli.

(c) The figure below shows the oxygen dissociation curve of the haemoglobin of a mud dwelling worm. Explain the physiological advantage of this curve



(2)The figure below shows the oxygen dissociation curves of fetal and adult maternal human blood.

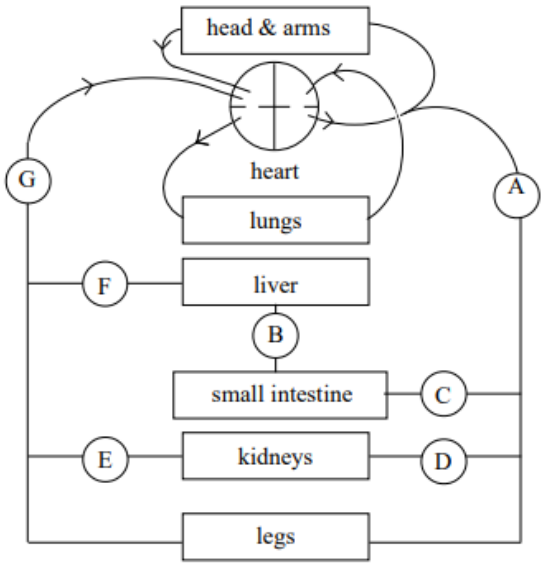


(a) Explain why the fetal oxygen dissociation curve lies to the left of the adult curve

(b)(i) Describe two other adaptations that enable oxygen to be transported rapidly from maternal blood into the fetal tissues.

(ii) Shortly after birth fetal haemoglobin is broken down and replaced by adult haemoglobin. Why is fetal haemoglobin unsuitable for use after birth?

(3) The diagram represents the human circulatory system



(a) Name vessels A to G.

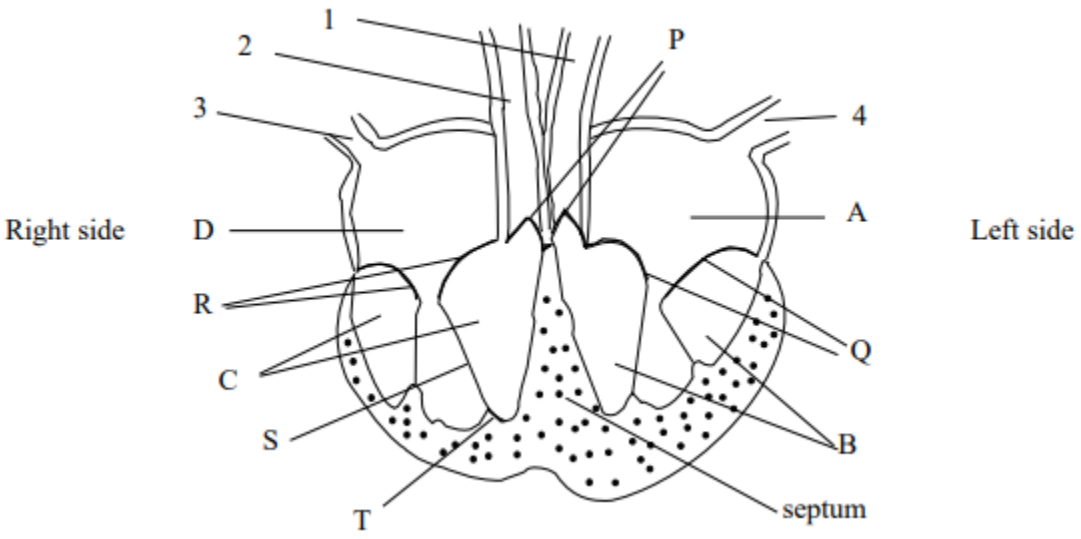
(b)What important differences, other than oxygen or carbon dioxide content, would be present in the composition of the blood in the following pairs of vessels?

(i) B and C after a meal

(ii) B and F after a meal

(iii) D and E:

(4)The diagram below shows a human heart in ventral view, in a simplified form



(a) Name chambers A, B, C and D.

(b)Name vessels 1 to 4 and state whether each one is carrying blood to or from the heart

(c) (i) State the functions of valves R and Q.

(ii) State the functions of valves P.

(iii) What do S and T do?

(5) The diagram below shows the conducting system of the heart in a simplified form

a) (i) The heart muscle is said to be 'myogenic'. What does this mean?

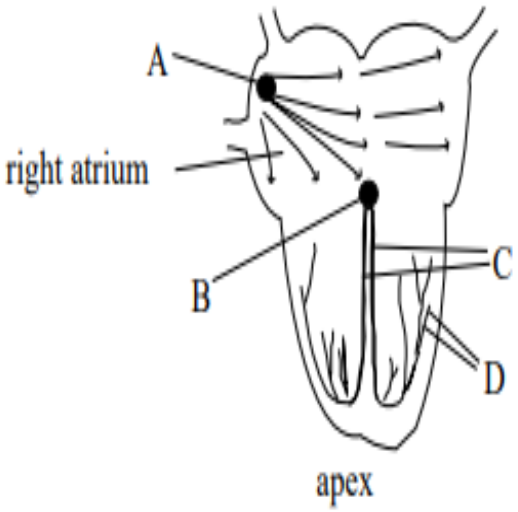
(ii) Name components A to D of the conducting system.

(b)With reference to the parts of the conducting system of the heart, explain why:
(i) the right atrium contracts before the left atrium.

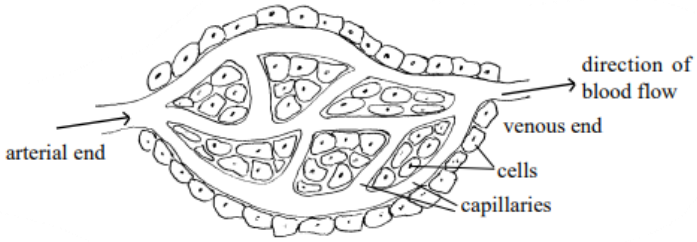
(ii) the ventricles contract after the atria

(iii) the ventricles contract from the apex upwards

(c) How is the frequency and force of the heartbeat modified to meet the body's needs?



(6) The diagram shows a capillary bed



(a) Some components of the blood flowing through the capillaries move out into the spaces between the cells.

(i) Name two blood components that move out of the capillaries.

(ii) Name two components of the blood that do not move out through the capillary walls

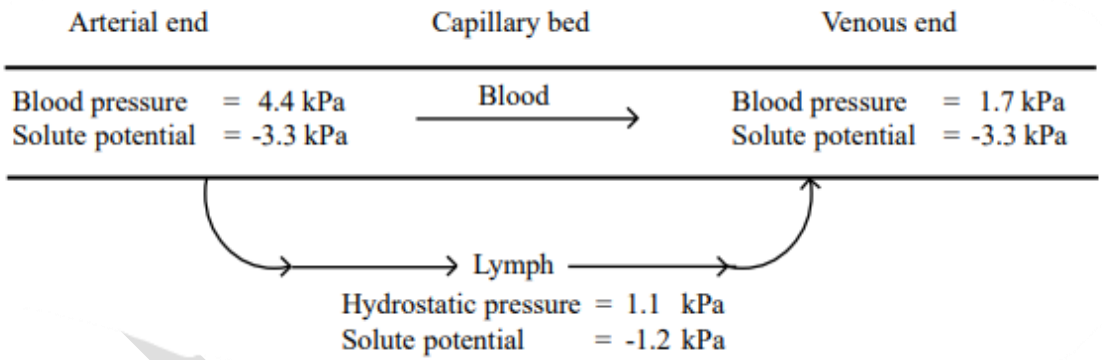
(iii) Name four transported substances that would move out of the blood into the tissues.

(b)(i) Distinguish lymph from tissue fluid

(ii) Outline the process by which lymph is formed

(iii) Outline the processes by which lymph is returned to the blood

(7) The diagram below shows some of the pressures which are important in the formation and uptake of lymph in a capillary bed.

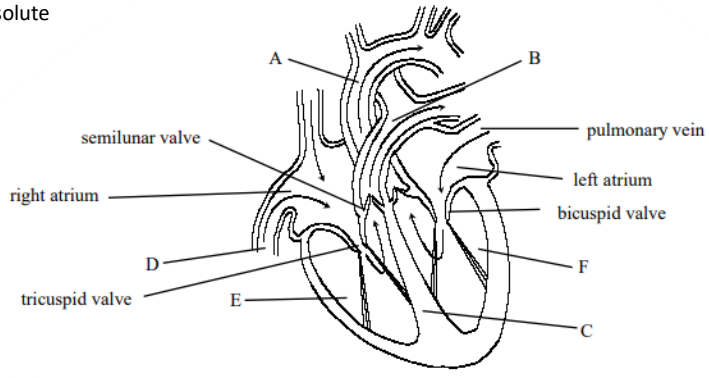


(a) (i) Explain how fluid leaves the capillary at the arterial end.

(ii) Explain how fluid is returned to the capillary at the venous end.

(iii) Why is the solute potential of the blood more negative than the solute potential of the lymph?

(b)In kidney disease (nephritis) plasma proteins are lost into the urine. How might this affect the circulation of lymph?



(8) The graph below shows the oxygen dissociation curves for normal haemoglobin, fetal haemoglobin and myoglobin

(a) Identify features A - F.

(a) Identify features A - F.

(b)Starting with the heart full of blood outline the stages of the cardiac cycle