

8.2.1 Circulatory systems

Circulatory systems are needed in multicellular animals to ensure that all cells receive the oxygen and nutrients they require and so that waste can be removed and disposed of. These circulatory systems are **mass flow** systems, which contain blood or other fluids that transport materials. They enable different sections of the body to communicate with one another, for example through hormones that travel in the blood. Blood flows down a pressure gradient with the highest blood pressure being produced as blood is expelled from the heart. Blood also carries cells and antibodies that defend the body from infection ([Chapter 10](#)) and it has an important role in homeostasis ([Section 8.5](#)).

KEY POINTS

circulatory system refers to an organ system that enables blood to flow round the body and transport nutrients, oxygen, carbon dioxide and hormones.

mass flow is the movement of fluids down a pressure gradient, in the case of the circulatory system, flow from the heart to other parts of the body.

Different sorts of circulatory system

Different organisms have circulatory systems that have evolved to suit to their needs. Unicellular organisms exchange materials through their cell surfaces but all multicellular organisms have some form of transport and circulatory system to deliver oxygen and food and to remove metabolic waste. Very simple organisms such as marine sponges use the seawater that is drawn in and out of their bodies for transport. The cnidarian *Hydra* exchanges

materials by diffusion through its body cells. But these simple systems cannot supply the needs of large animals and so the organisms that use them are limited in size.

More complex organisms such as arthropods and molluscs have open circulatory systems with no blood vessels. They have a simple heart that pumps a fluid known as hemolymph, which is similar to blood, around their bodies. Hemolymph enters blood spaces called hemocoels, which surround body tissues to exchange materials. From here hemolymph must diffuse back to the heart. Flow in these simple **open systems** is slow. Vertebrates have larger and more complex bodies and they have evolved **closed circulatory systems** with blood that is kept inside blood vessels.

The heart

In the human circulatory system, blood is kept on the move by the pumping action of the powerful heart muscle. It has been estimated that a normal human heart beats more than 2.5×10^9 times in a lifetime, sending a total of more than 1.5 million dm³ of blood from each ventricle.

A human heart is about the size of a clenched fist. It is a double pump with two separate sides (Figure 8.2.1). The right-hand side receives deoxygenated blood from all over the body and pumps it to the lungs via the pulmonary artery to pick up more oxygen. The left-hand side receives oxygenated blood from the lungs via the pulmonary vein and pumps it to cells all over the body where the oxygen is unloaded. This arrangement means that humans, like all mammals, have a double circulation: a pulmonary circulation between the heart and lungs and a larger circulation that carries blood from the heart to the rest of the body and back

again (Figure 8.2.7). On any complete journey round the body, blood passes through the heart twice.

Type of organism	Internal body structure	Circulatory system	Organ that controls blood flow
cnidarians (<i>Hydra</i> , jellyfish and sea anemones) and unsegmented flatworms (e.g. <i>Planaria</i>)	one internal cavity that is used for both digestion and circulation	no blood system	none
molluscs and arthropods	digestive and circulatory systems are separate	most have open systems containing hemolymph that is in direct contact with the cells of the body	simple heart
annelid (segmented) worms (e.g. earthworms) and vertebrates	digestive and circulatory systems are separate	closed system; blood is always enclosed inside vessels	annelids: specialised blood vessels that can contract vertebrates: heart with more than

			one chamber
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Table 8.2.7: As organisms have evolved increasing complexity in their body structure, the need for an efficient circulatory system has increased. Simple organisms have no circulatory system, small multicellular organisms have open systems and larger more complex organisms have evolved an enclosed circulatory system.

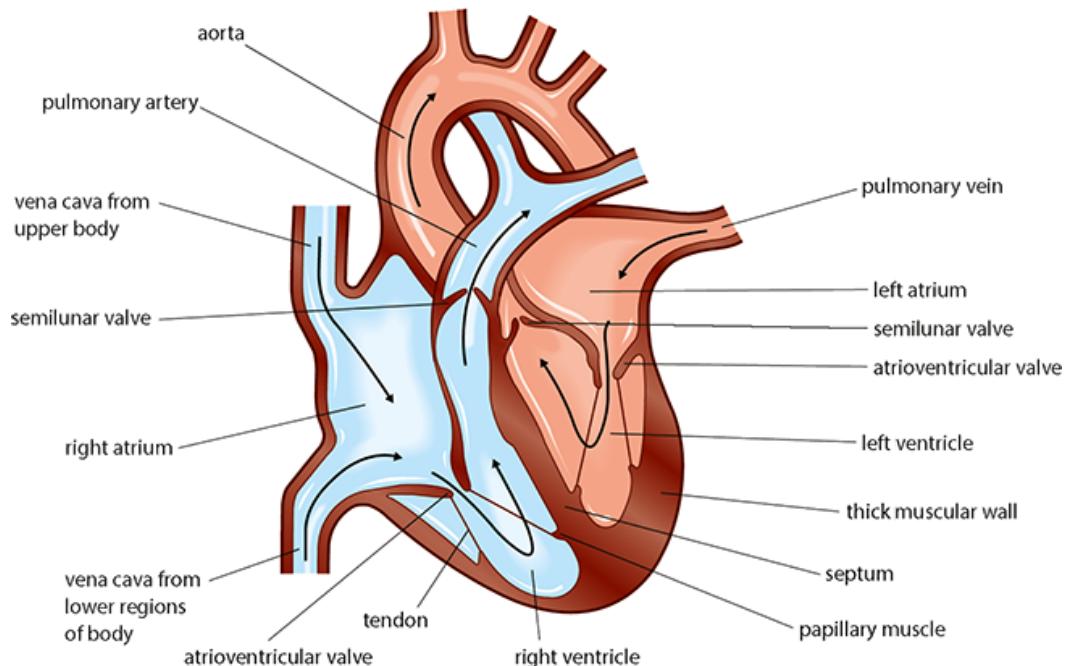


Figure 8.2.1: Diagram of the human heart, in longitudinal section, showing the direction of blood flow.

The heart has four chambers: two smaller atria (singular **atrium**) at the top and two larger ventricles below. The right-hand and left-hand sides are completely separated from one another. Atria have thin walls as the blood they receive from the veins is under relatively low pressure. Ventricles are stronger and more muscular as their job is to pump blood out of the heart. Both

ventricles hold the same volume of blood, but the left ventricle wall is thicker than the right as it must generate enough pressure to pump blood all round the body. The right ventricle pumps blood a much shorter distance to the lungs.

Atria are separated from ventricles by atrioventricular valves, which prevent the blood flowing backwards into the atria. A second set of valves in the aorta and pulmonary arteries – the semilunar valves – prevent backflow into the ventricles as they relax after a contraction.

KEY POINT

blood pressure the pressure of circulating blood against the walls of blood vessels.

Heart muscle works continuously, beating about 75 times per minute when a person is resting, and so it has a large demand for oxygen. Coronary arteries extend over the surface of the heart and penetrate deep into the muscle fibres to supply oxygen and nutrients for this constant activity (Figure 8.2.2).

The pulse rate, measured at the wrist or neck, can give an indication of heart rate in beats per minute (Figure 8.2.3). Electronic devices that measure blood pressure (Figure 8.2.4) also provide a pulse rate reading.

Blood pressure

As the heart pumps harder and faster, blood pressure also rises. Blood pressure is the pressure of circulating blood against the walls of blood vessels, which is produced by the heart pumping. In medicine ‘blood pressure’ usually refers to blood pressure in the large arteries and it is measured using a sphygmomanometer.

Older devices to measure blood pressure contained mercury and blood pressure is still recorded in millimetres of mercury (mmHg) even though modern devices do not contain mercury (Figure 8.2.4).



Figure 8.2.2: A human heart. Clearly visible are the coronary arteries, which supply oxygen to the heart muscle.

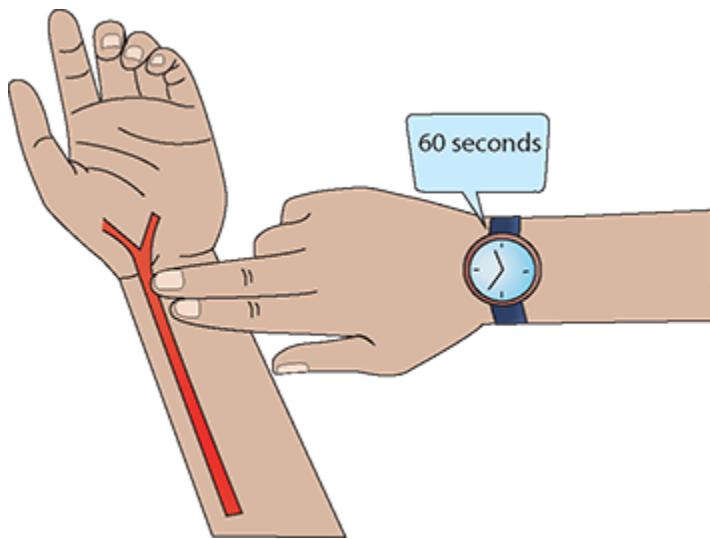


Figure 8.2.3: Pulse measurements are taken at small arteries in the wrist or neck.

A blood pressure reading consists of two parts. **Diastolic pressure** is the pressure on the blood vessels when the heart muscle relaxes. The diastolic pressure is always lower than the systolic pressure, which is recorded as the ventricles contract.



Figure 8.2.4: Taking a pulse and blood pressure reading.

Normal blood pressure for a healthy adult at rest should be under 140 mmHg for systolic pressure and under 90 mmHg for diastolic pressure.

KEY POINT

systolic pressure pressure generated in the arteries as the heart contracts.

EXAM TIP

You should be able to interpret measurements of pulse and blood pressure readings.

Blood vessels

Arteries are blood vessels that carry blood away from the ventricles of the heart. They branch and divide many times, forming small arteries called **arterioles** and eventually the tiny **capillaries** that reach all our tissues. Arteries have thick outer walls of collagen and elastic fibres (Figure 8.2.5), which withstand high blood pressure and prevent vessels becoming overstretched or bursting. Just beneath the outer covering is a ring of circular smooth muscle that contracts with each heart beat to maintain blood pressure and keep blood moving along. The central space inside an artery, called the lumen, is narrow to keep blood pressure high. The lumen's lining of smooth epithelial cells reduces friction and keeps blood flowing smoothly. Each heartbeat sends a pulse of blood through the arteries, which expand slightly and then recoil. This produces the pulse that we can monitor at the wrist or neck.

NATURE OF SCIENCE

'Margin of error' is a term that is used to describe the likelihood and extent of error in quantities that we measure in experiments. Every time we repeat a reading with an instrument such as a thermometer or timing device such as a stopwatch, we may get a slightly different result. To reduce errors like this, it is important to take a series of readings and calculate an average.

If we use statistics in calculations, errors are said to be of two types:

- Systematic error or bias always occurs with the same value when we use an instrument in the same way. This can be minimised by using the correct measuring instrument and the same technique each time we take a reading. Examples include using a stopwatch not an alarm clock for timing something, and holding a thermometer in a liquid for exactly the same period of time in an experiment.
- Random errors may vary from reading to reading and are due to factors that we cannot control.

When you carry out practical work you will be expected to show the margin of error in your readings, using either error bars on a graph or \pm in your table of data. This shows you understand the degree of error that your data may contain.

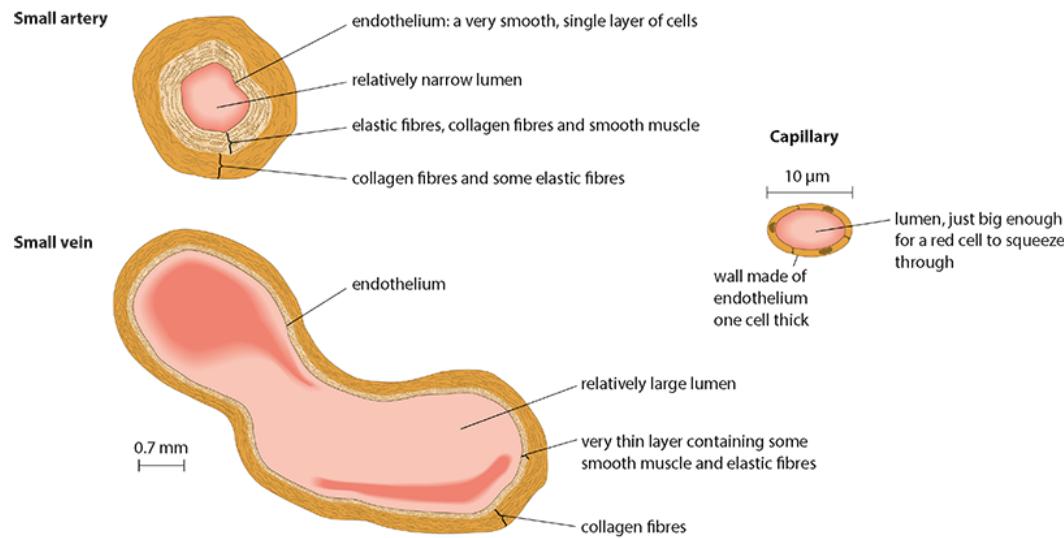


Figure 8.2.5: Diagrams of transverse sections of an artery, a vein and a capillary.

Capillaries are the smallest vessels. The lumen of a capillary is only about $10\text{ }\mu\text{m}$ in diameter and some are so small that red blood cells must fold up in order to pass along. Networks of these tiny capillaries reach almost every cell in the body. Blood flow here is very slow, at less than 1 mm per second, and capillary walls are only one cell thick so the distance for diffusion of materials in and out of them is as small as possible. Some capillary walls have spaces between their cells, enabling plasma and phagocytes (white blood cells) to leak out into the tissues.

Veins carry blood back towards the atria of the heart from body tissues. Small veins called **venules** join up to form large veins, which can be distinguished from arteries by their much thinner walls, which contain few elastic and muscle fibres. Blood inside a vein is not under high pressure and does not pulse along and the lumen is large to hold the slow-moving flow. The relatively thin walls can be compressed by adjacent muscles and this helps to squeeze blood along and keep it moving. Many veins contain

valves to prevent blood flowing backwards, a problem that can arise if flow is sluggish.

Table 8.2.1 summarises some differences and similarities between the three types of blood vessel.

Artery	Vein	Capillary
thick walls	thin walls	walls one cell thick
no valves (except in aorta and pulmonary artery)	valves sometimes present	no valves
blood pressure high	blood pressure low	blood pressure low
carries blood from the heart	carries blood to the heart	links small arteries to small veins

Table 8.2.1: Comparing arteries, veins and capillaries.

Coronary heart disease

Three large coronary arteries branch from the aorta and supply heart muscle with oxygen-rich blood (Figure 8.2.2). If any of these arteries is blocked, an area of the heart will receive less oxygen and cells in that region may stop contracting or even die. A blockage in a coronary artery is known as an **occlusion** and can lead to a heart attack.

One serious cause of coronary heart disease (CHD) is **atherosclerosis**, a slow degeneration of the arteries caused by a build-up of material known as **plaque** inside them. Plaque becomes attached to the smooth endothelium lining where it can

accumulate. Over time, the diameter of the artery becomes restricted so that blood cannot flow along it properly, and it loses elasticity (Figure 8.2.6). As the rate of flow slows down, blood may clot in the artery, further restricting the movement of blood along it. Clots may also break free and travel to block another smaller artery elsewhere in the body. If this artery is in the brain, the clot may cause a stroke.

Feedback control of heart rate

Heart rate, the number of contractions per minute, must be controlled to ensure the body receives the appropriate amounts of nutrients and oxygen. The amount of blood that leaves the left ventricle per minute is called the **cardiac output**. It is determined by the heart rate, number of beats per minute and the stroke volume, the volume of blood that is pumped out with each contraction. Heart rate is regulated by the cardiovascular control centre in the medulla oblongata in the brain stem and is controlled by the sino atrial node (SAN) or pacemaker in the left atrium. Two types of receptors, **baroreceptors** (pressure receptors) and **chemoreceptors** (chemical receptors) are responsible for detecting stimuli in the blood and signalling to the medulla oblongata to adjust our heart rate. Baroreceptors detect changes in blood pressure and are found in the **aortic** and **carotid bodies**. Aortic bodies are located in the aortic arch and carotid bodies in the carotid arteries in the neck. Chemoreceptors detect the concentration of oxygen in the blood and are also sensitive to changes in pH caused by the carbon dioxide dissolved in the blood. Chemoreceptors are also located in the aortic and carotid bodies.

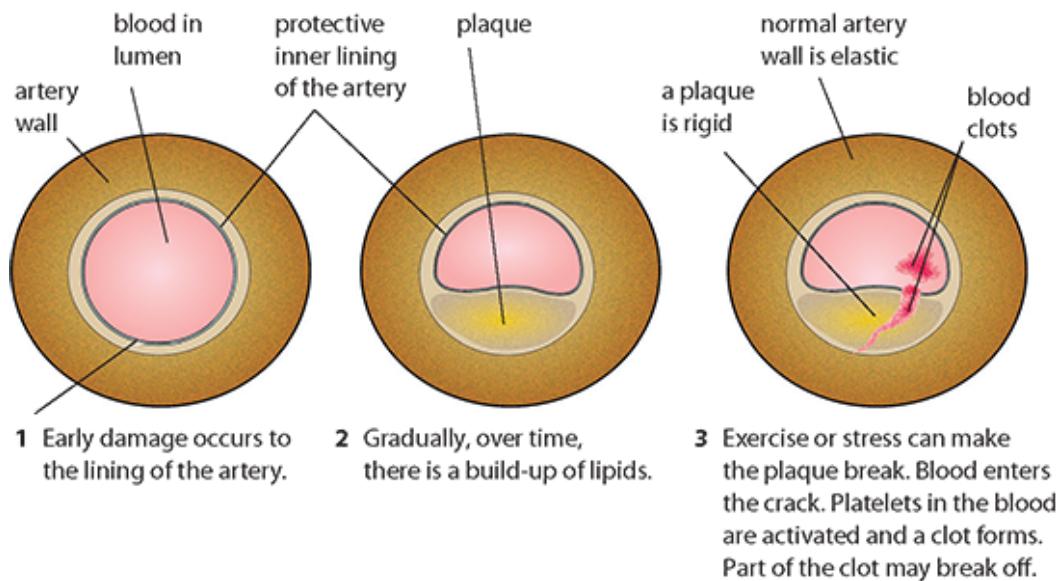


Figure 8.2.6: The development of atherosclerosis.

The medulla sends impulses via the sympathetic or parasympathetic neurons which stimulate the heart pacemaker (SAN) to slow down or speed up the heart rate. If blood pressure or oxygen levels are low the sympathetic nervous system increases heart rate by releasing noradrenaline which binds to the pacemaker and increases heart rate. If blood pressure or oxygen levels are high, the parasympathetic nervous system releases acetylcholine which slows down the heart rate.

You can read more about how blood pressure and heart rate are controlled in [Section 8.5](#).

8.2.2 Single and double circulations

Bony fish are vertebrates that have a single circulation. This means that blood flows through the heart only once on a complete journey around the fish's body. Humans and all mammals, have a double circulation so that blood passes through the heart twice on any journey around the body (Figure 8.2.7).

Fish have a lower metabolic rate than mammals. So, in fish a single circulation is able to deliver sufficient oxygen to their tissues at a fairly low blood pressure. Mammals have a high metabolic rate and, unlike fish, are able to maintain body temperatures at the optimum rate for enzyme activity. This is only possible because of their double circulation that keeps their blood pressure high enough to deliver oxygen to the tissues that need it.

The main function of a circulatory system is to link exchange surfaces such as the alveoli in the lungs, where oxygen enters the body, with the muscles that need the oxygen to work. You can read more about exchange surfaces in [Section 8.3](#). Figure 8.2.7 shows how the gills of a fish and lungs of a human are linked to the body cells by the circulatory system. Oxygen and other substances transported in the blood move across exchange surfaces by diffusion. Oxygen diffuses into the blood in the gills and lungs and diffuses out in the body tissues that require it. Blood must keep flowing past the different surfaces to maintain a concentration gradient. As blood carries oxygen away and more deoxygenated blood arrives, the difference in oxygen concentration between the alveoli or gills and the blood is kept at a suitable level to ensure that diffusion is efficient (you can read more about concentration gradients in [Section 6.2](#)). The movement of blood is maintained by the heart, which pumps to

keep blood moving in a continual one-way flow through the body. The three essential components of a closed circulatory system are:

- 1 blood, a transport fluid
- 2 the heart, a pump to maintain flow and pressure gradient
- 3 vessels to contain the blood.

Adaptations of the human heart to deliver pressurised blood to the arteries

The heart has four chambers – two smaller **atria** (singular **atrium**) at the top and two larger **ventricles** below. The right- and left-hand sides are completely separated from one another. Atria have thin walls as the blood they receive from the veins is under relatively low pressure. Ventricles are stronger and more muscular as their job is to pump blood out of the heart. Both ventricles hold the same volume of blood but the left ventricle wall is thicker than the right as it must generate enough pressure to pump blood all round the body. The right ventricle pumps blood a much shorter distance to the lungs.

Humans have a double circulation: a pulmonary circulation between the heart and lungs and a circulation which carried blood from the heart to the rest of the body and back again. The pulmonary artery carries deoxygenated blood from the right ventricle of the heart to the lungs and the pulmonary vein returns oxygenated blood to the left atrium.

Atria are separated from ventricles by **atrioventricular valves**, which prevent the blood flowing backwards into the atria. A second set of valves in the aorta and pulmonary arteries – the

semilunar valves – prevent backflow into the ventricles as they relax after a contraction.

Heart muscle works continuously, so it has a large demand for oxygen. Coronary arteries extend over the surface of the heart and penetrate deep into the muscle fibres to supply oxygen and nutrients for this unremitting activity (Figure 8.2.8).

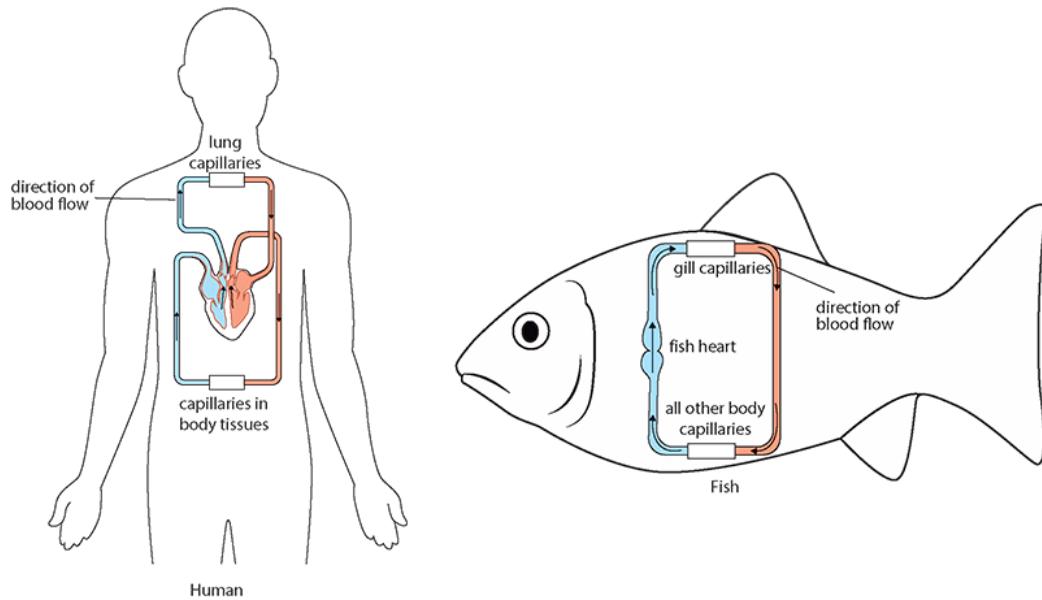


Figure 8.2.7: Single and double circulations in a fish and a human.

Control of blood flow and heart beat

Heart tissue is made of a special type of muscle that is different from other muscles in our bodies. **Cardiac muscle** is unique because it contracts and relaxes without stimulation from the nervous system. It is said to be myogenic. Natural **myogenic** contractions are initiated at an inbuilt pacemaker, which keeps cardiac muscle working in a coordinated, controlled sequence. The pacemaker, or **sinoatrial node** (SAN) is a special region of muscle cells in the right atrium that sets the basic pace of the

heart. The rate set by the SAN is also influenced by stimulation from the nervous system and by hormones.

The natural rhythm of the pacemaker is modulated by the nervous system so that the heart rate is adjusted to our activity levels. It speeds up when we are exercising and need extra oxygen and nutrients and slows down as we sleep. Changes to our heart rate are not under our conscious control but result from impulses sent from a control centre in the part of the brain stem known as the medulla. Impulses to speed up the heart pass along the sympathetic nerve, which stimulates the pacemaker to increase its rate. Impulses sent along the parasympathetic (vagus) nerve cause the heart rate to slow down. The medulla monitors blood pressure and carbon dioxide levels using information it receives from receptors in arteries ([Section 8.5](#)).

Emotions such as stress, as well as increases in activity level, can cause an increase in heart rate. During periods of excitement, fear or stress the adrenal glands release the hormone **epinephrine** (adrenaline), which travels in the blood to the pacemaker and stimulates it to increase the heart rate.

The cardiac cycle and circulation

In the human circulatory system, blood is kept on the move by the pumping action of the powerful heart muscle. It has been estimated that a normal human heart beats more than 2.5×10^9 times in a lifetime, sending a total of more than 1.5 million litres of blood from each ventricle.

The **cardiac cycle** is the sequence of events that takes place during one heart beat (Figure 8.2.9). As the heart's chambers contract, blood inside them is forced on its way. Valves in the heart and arteries stop the blood flowing backwards.

The pressure and volume of blood in each of the chambers of the heart change during the cardiac cycle. Fig 8.2.10 shows these changes for one complete cycle.

Control of the heart beat

At the start of every heart beat, the SAN produces an impulse that stimulates both atria to contract. A second structure, the **atrioventricular node** (AVN) at the base of the right atrium, is also stimulated. It delays the impulse briefly until the atrial contraction finishes and then transmits it on down a bundle of modified muscle fibres – the bundle of His and Purkinje fibres – to the base of the ventricles. Impulses radiate up through the ventricles, which contract simultaneously about 0.1 seconds after the atria. (Fig 8.2.9)

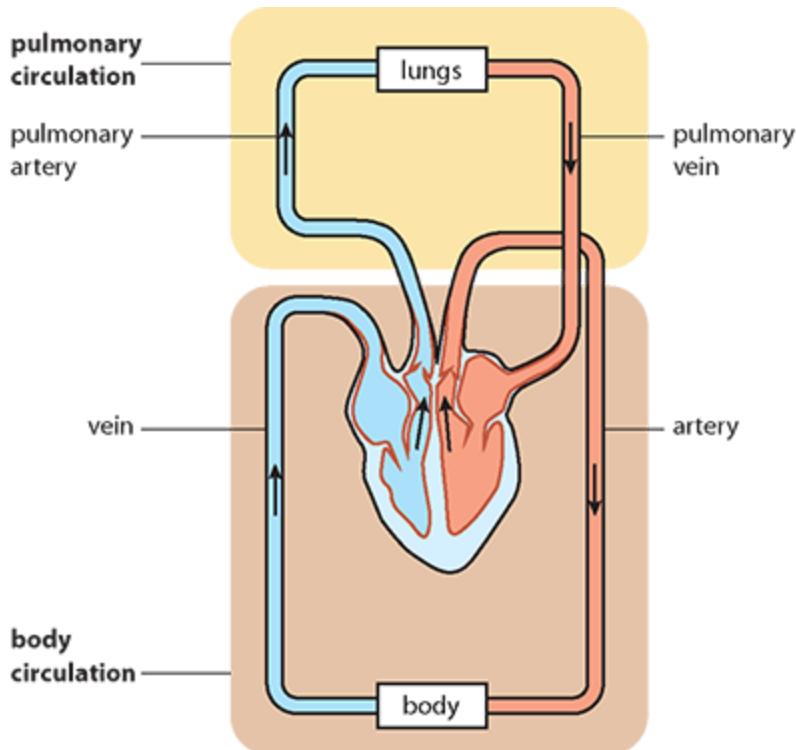


Figure 8.2.8: Diagram to show the double circulation of blood through the heart.

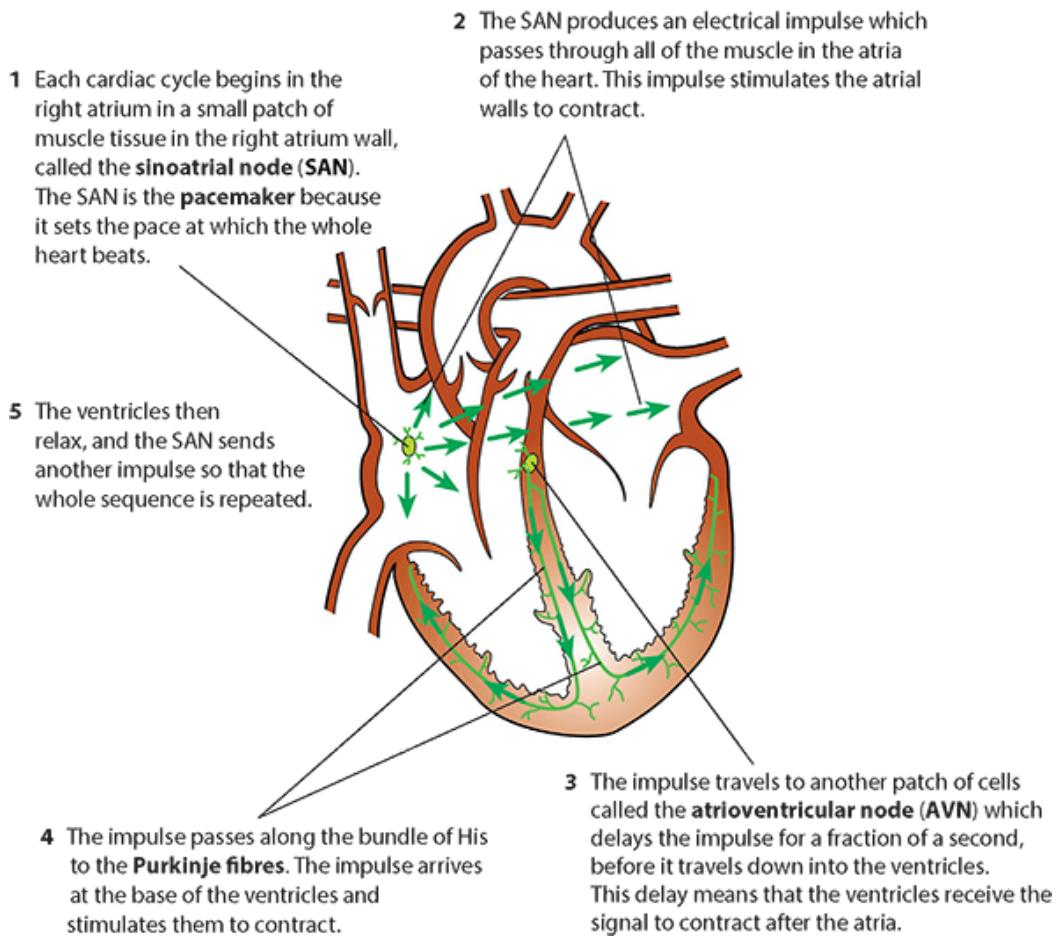


Figure 8.2.9: How electrical impulses move through the heart.

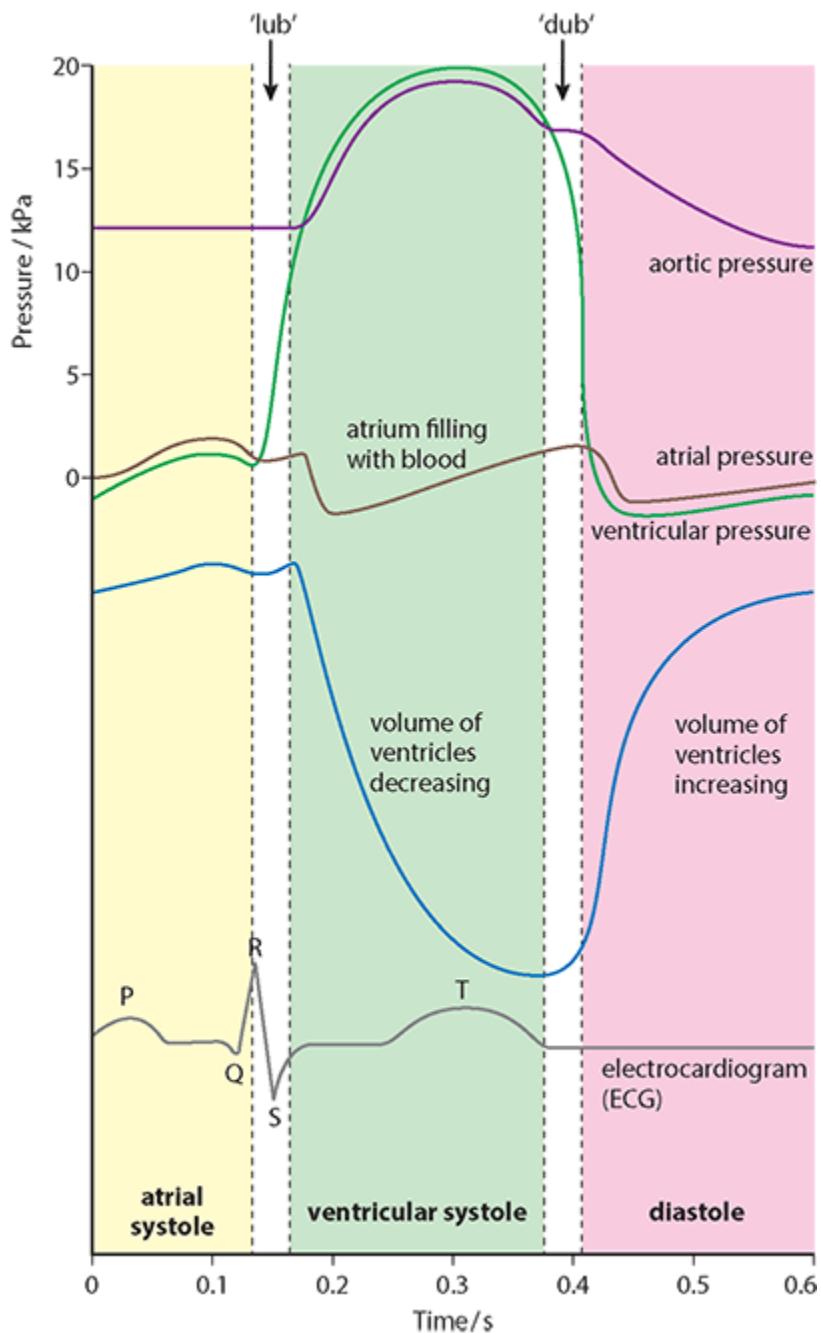


Figure 8.2.10: Pressure and volume changes in the heart during the cardiac cycle.

SCIENCE IN CONTEXT

The maximum heart rate that an individual can achieve is estimated from a simple calculation:

$$\text{Maximum heart rate} = \frac{220 \text{ beats}}{\text{min}} - \text{age in years}$$

A 20-year-old person will have a maximum heart rate of about 200 beats per minute but for a 50-year-old this will decrease to about 170 beats per minute. This rate cannot be modified by exercise, training or other factors because it is genetically determined for each individual.

8.2.3 Blood distribution

When we are resting about 25% of the output of blood from the heart travels to the muscles and the heart itself. If we exercise vigorously this will change to about 95%. Cardiac output is the volume of blood pumped out of the heart per minute. At rest it is about 5 litres per minute but this will increase five fold to about 25 litres per minute during heavy exercise.

Table 8.2.3 shows how blood is distributed to the organs of the body depending on their needs and how the distribution changes in response to activity.

Blood flow to the brain seldom changes as its function is vital but blood flow to the heart, muscles and skin increases with exercise to supply more oxygen and allow heat to be lost from the skin. Blood flow to the digestive system, liver and kidneys decreases during activity so food absorption and excretion also decrease.

Organ	Blood flow % when body is at rest	% blood flow during strenuous activity
brain	15%	12%
skin	5%	7%
heart	5%	8%
muscles	20%	70%
kidney	20%	1%
Liver and intestines	30%	1%
Other parts	5%	1%

of the body

Table 8.2.3: Distribution of blood to different parts of the body at rest and during activity.

8.2.4 Lymphatic system

Blood that acts as the means of transport for nutrients, oxygen and many other materials is composed of cells and a liquid called plasma. Blood plasma is a pale yellow watery liquid that makes up 50–60% of our blood volume. Plasma contains dissolved proteins, nutrients, gases and waste substances. Suspended in plasma are three important groups of cells: erythrocytes (red blood cells), whose job is to carry oxygen, leucocytes (white blood cells), which fight disease, and platelets (cell fragments), which are needed for blood clotting.

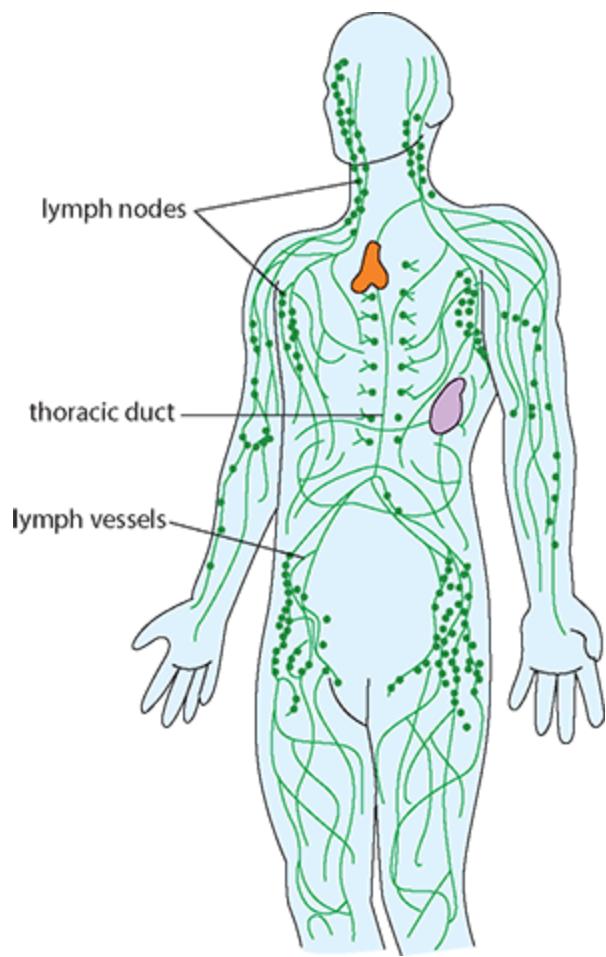


Figure 8.2.11: The lymph system. Lymph nodes are distributed throughout the body. The lymphatic system is an organ system that is part of both the circulatory system and immune systems. It is made up of a large network of lymphatic vessels that contain the clear fluid called lymph.

As blood is pumped around the body, plasma leaks out of the many tiny capillaries and bathes the nearby tissues to supply oxygen and nutrients to the cells. Once outside the capillary, the fluid is known as tissue fluid. This fluid must be collected up and returned to the circulation and this is done by the lymphatic system (Figure 8.2.11 and Figure 8.3.1).

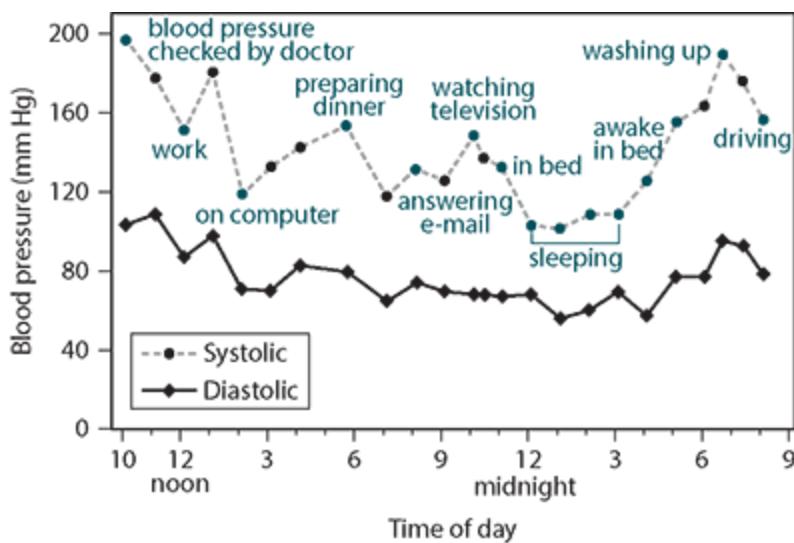
Much of the tissue fluid that leaves the capillaries is reabsorbed by the capillaries, but the remainder enters lymph vessels and is taken back to the subclavian vein close to the heart. Fluid in the lymph system contains waste products, bacteria and cell fragments. These are filtered out by the lymph nodes. Clusters of lymph nodes in the groin, neck and armpits are also responsible for releasing lymphocytes that are part of the body's immune response to infection. These help to fight bacteria, viruses and any other pathogens that cause infection.

SCIENCE IN CONTEXT

Many people call lymph nodes ‘glands’. Swollen lymph nodes are usually a sign of infection and tend to go down when you recover. Lymph nodes are usually the size of a pea but they can swell to a few centimetres in response to disease or infection. Many different infections, such as a cold, tonsillitis or glandular fever, cause swollen glands. The glands in the affected area may become tender or painful as the production of lymphocytes increases to fight the infection.

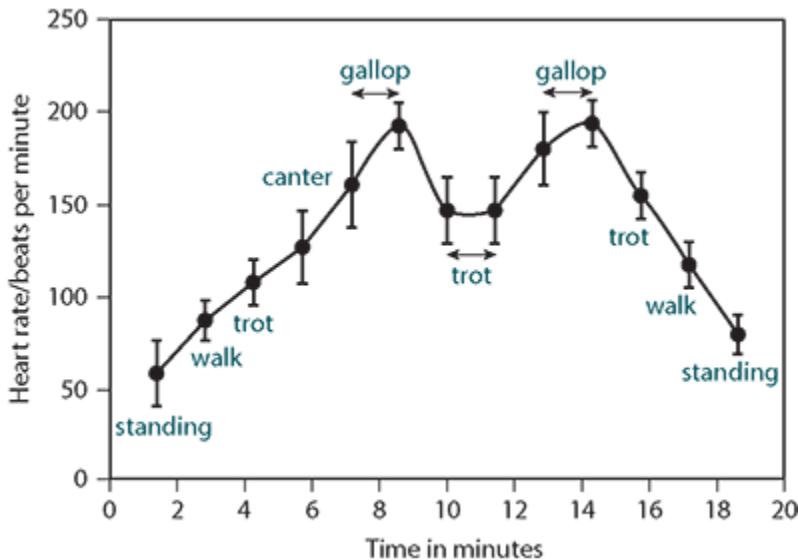
TEST YOUR UNDERSTANDING

Study the graph in the figure and answer the following questions.



- 5 Suggest a reason for the high systolic reading at 1 p.m.
- 6 Describe the effect of sleeping on blood pressure.
- 7 State whether the graph indicates that this person has blood pressure within the normal range.

Study the graph in the figure, which shows the heart rate of a horse.



- 8 What is the resting heart rate for this animal?
- 9 Suggest reasons for the different values for heart rate during the three periods of trotting shown on the graph.
- 10 Why is the final heart rate when the horse was standing higher than the original value?

8.2.5 Transport in plants

Transpiration is the loss of water vapour from the leaves and stems of plants. Water is absorbed into the roots, travels up the stem in the xylem vessels in the vascular bundles to the leaves, and is lost by evaporation through stomata, which open to allow the exchange of oxygen and carbon dioxide in the leaf (Figure 8.2.12).

Most plants grow in areas where the amount of water in the air, the humidity, is less than in the leaves. During the day, water vapour leaves the air spaces in the spongy mesophyll and evaporates through open stomata in the lower epidermis of the leaf and in the stem. The evaporating water is drawn from the xylem in the vascular bundles in the leaf and stem. The vascular bundles are continuous with those in the roots so a column of water is formed, connecting the roots, stem, leaves and air spaces. This is known as the transpiration stream. Water molecules form a continuous column due to the cohesive forces between water molecules and the adhesive forces between water molecules and the walls of the xylem ([Section 1.2](#)).

Transpiration also carries minerals through the plant, and serves to cool the plant.

Pairs of modified epidermis cells, known as **guard cells**, that surround each stoma regulate transpiration. Guard cells have unevenly shaped cell walls with more cellulose on the side next to the **stoma**. This inner part of the cell wall is less elastic, so that when guard cells take up water and become turgid, they take on a sausage-like shape and an opening – the stoma – is formed between the two guard cells (Figure 8.2.12). When the guard cells lose water, the cell walls relax and the stoma closes.

The opening and closing of stomata is controlled by the concentration of potassium ions in the plant's cells. In darkness, these ions move out of the guard cells into surrounding cells. In light conditions, potassium ions are actively pumped into the vacuoles of guard cells. This creates an increased solute concentration so that water enters by osmosis, making the cells turgid and opening the stomata. A plant growth factor (or plant hormone) called abscisic acid, produced in the roots during times of drought, affects potassium ion movement in guard cells. When abscisic acid is present, potassium ions leak out and water follows by osmosis. This means that the guard cells lose turgor and stomata close, thus conserving water.

Distribution of tissues in the stem and root

Water is absorbed by the roots of a plant and travels up the stem in the xylem vessels in the vascular bundles. Evaporating water is drawn from the vascular bundles in the leaf and stem. Vascular bundles are continuous from the roots, through the stem and into the leaves so a column of water is formed connecting the roots, stem, leaves and air spaces.

Vascular bundles in the roots, stems and leaves of plants are made up of both xylem and phloem. Cells in the xylem become long series of cells joined end to end in a continuous fine tube which forms once the cells have stopped growing and their end walls have been removed. The phloem on the other hand is composed of living cells with perforated end walls known as sieve plates. When viewed under a microscope xylem and phloem can easily be distinguished in both cross sections and longitudinal sections through stems. (Figure 8.2.14)

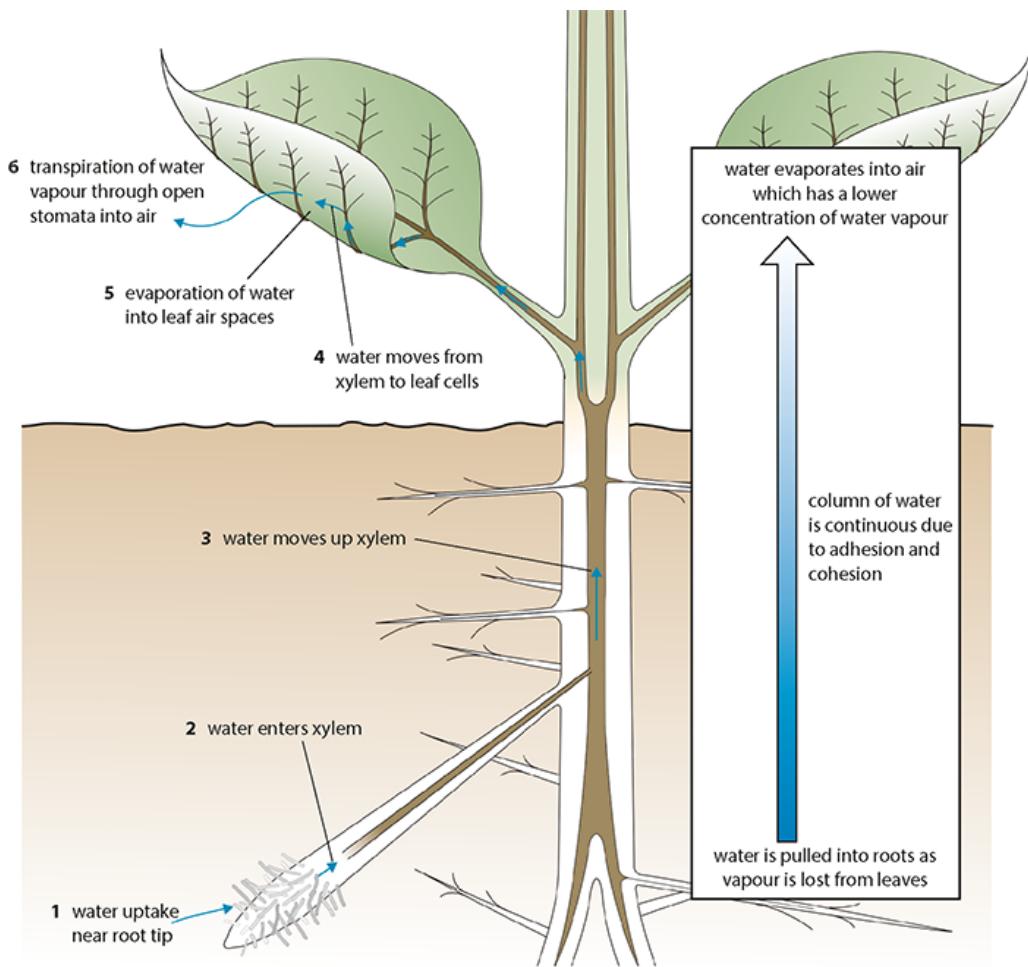


Figure 8.2.12: The movements of water through a plant: overall, water moves from the soil to the air (from where there is more water to where there is less water).

EXAM TIP

You should be able to draw diagrams of cross sections of stems and identify xylem phloem, cortex and epidermis

Adaptations of the xylem

The movement of water in the xylem can be explained by the cohesion– tension theory. A strong tension is produced in the

xylem as water is lost. The xylem is strengthened so that xylem vessels do not collapse.

- Loss of water vapour from the stomata in the leaves results in ‘tension’ or negative pressure in the xylem vessels.
- Water vapour re-enters the air spaces in the leaf from the xylem vessels.
- Continuous columns of water are drawn up the xylem due to cohesion between water molecules in the xylem and forces of adhesion between the water molecules and the xylem vessel walls. **Cohesion** is due to hydrogen bonding between water molecules and **adhesion** is caused by the hydrogen bonds between water molecules and molecules in the walls of the xylem vessels.

water enters guard cells by osmosis;
guard cells become turgid, opening stoma

water leaves guard cells by osmosis;
guard cells become flaccid, closing stoma

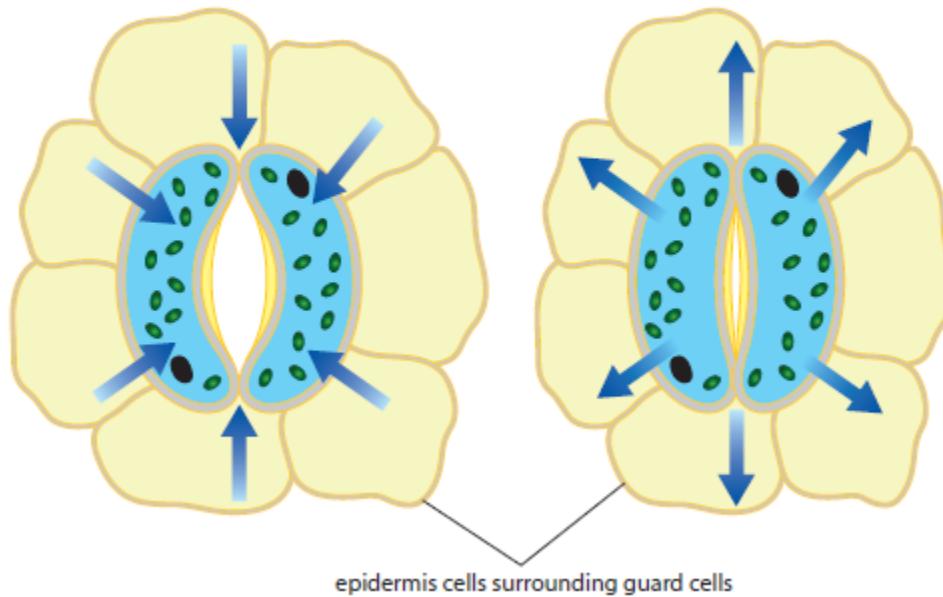
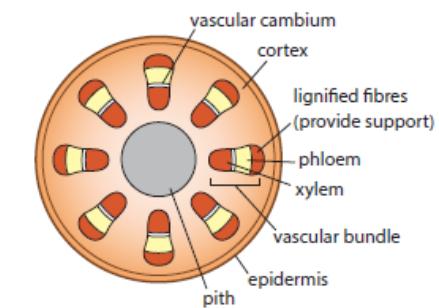
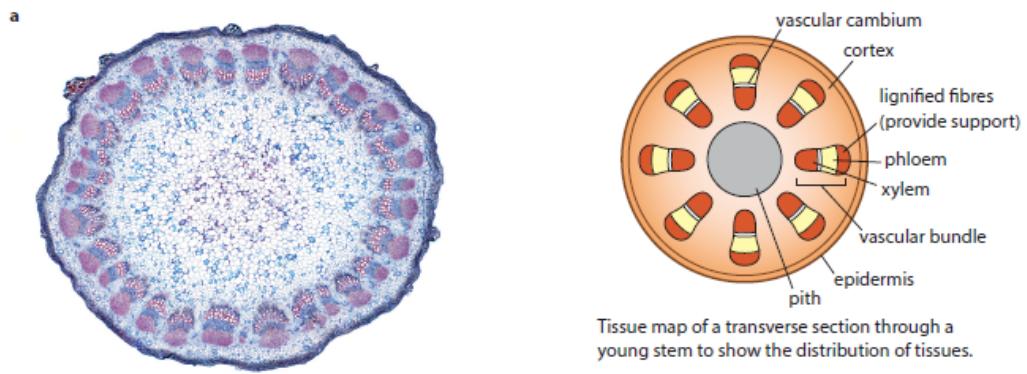
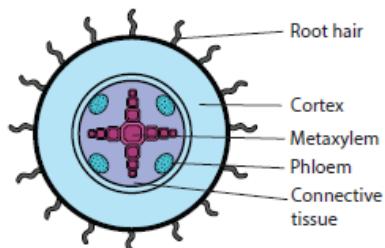
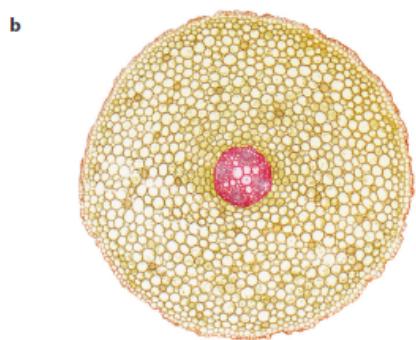


Figure 8.2.13: The opening and closing of stomata. Gases can diffuse in and out of open stomata. When stomata are closed, water loss is minimised.



Tissue map of a transverse section through a young stem to show the distribution of tissues.



Tissue map of transverse section through a root.
The epidermis protects the outer layer of the root.
The cortex carries water to the xylem, which transports it to the rest of the plant. The phloem carries nutrients and minerals around the plant.

Figure 8.2.14: **a** a transverse section through a stem **b** transverse section through a root.

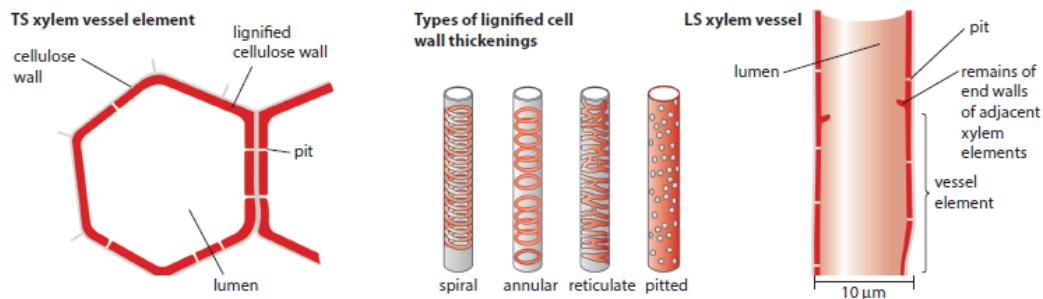


Figure 8.2.15: Xylem vessels are not alive and have no plasma membrane, so water can easily move in and out of them.

- The tension in the xylem is strong due to loss of water and there would be a tendency for xylem vessels to collapse

inwards. The thickening provided by lignin prevents this happening.

- Water is drawn in from the cortex in the roots to replace water that is lost in transpiration.
- The tension caused by transpiration also causes water to be drawn into the roots from the soil.

Factors affecting transpiration

Several abiotic environmental factors (notably light, temperature, humidity and wind speed) influence the rate of transpiration in plants.

- Light affects transpiration directly by controlling the opening and closing of stomata. As light intensity increases, stomata open, speeding up the rate of transpiration. In darkness, stomata close, thus restricting transpiration.
- Temperature affects transpiration because heat energy is needed for the evaporation of water. As the temperature rises, the rate of transpiration also rises as water evaporates from the air spaces in the spongy mesophyll and diffuses out of the stomata.
- An increase in atmospheric humidity reduces the rate of transpiration. Air in the mesophyll air spaces tends to be saturated with water vapour so if atmospheric air becomes more humid, the concentration gradient between the air space and the atmosphere is reduced and transpiration is slowed down.
- An increase in wind speed increases the rate of transpiration because it blows away the air just outside the stomata, which is saturated with water vapour. Reduced

humidity near the stomata enables water vapour to diffuse more readily from the spongy mesophyll, where the air is very humid, to the air just outside the leaf, which has lower humidity. The concentration gradient between the air space and the atmosphere is increased and transpiration speeds up.

Root pressure in the xylem

Roots are responsible for absorbing water and mineral ions from the soil. Many plants develop an extensive, branching root system in order to increase the surface area of root in contact with the soil. In addition, as new roots grow, numerous root hairs develop to increase the surface area even more (Figure 8.2.16). Root hairs are temporary and die away to be replaced by new ones near the growing tip.

Plants require a number of minerals to make a variety of substances necessary for growth. A few of these are listed in Table 8.2.4.

Minerals are present in the soil as salts – for example, calcium occurs in the form of carbonates. These dissolve in soil water and the dissolved ions can move into root cells in different ways.

KEY POINT

root pressure is a force that helps to drive water upwards in the xylem



Figure 8.2.16: A root of a young radish showing the root hairs.

Mineral ion	Importance
calcium	constituent of cell walls
magnesium	needed to make chlorophyll
iron	required as a cofactor for many enzymes

Table 8.2.4: How plants use some important mineral ions.

- Dissolved minerals may move into the root by **mass flow** of water carrying the ions, or by **facilitated diffusion** of ions from the soil water into root hairs, down their concentration gradient (Figure 8.2.17). Both these processes are passive – that is, they do not require energy in the form of ATP.
- Where the concentration of a mineral is lower in the soil water than in plant cells, **active transport** is needed to take it up. Potassium, nitrate and phosphate are usually absorbed by active transport. Root hair cells contain mitochondria to provide ATP and most roots can only take in minerals if oxygen is available for aerobic respiration, to provide sufficient ATP. Experiments have shown that potassium ions stop moving into root cells from the soil when potassium cyanide is added. Cyanide is a potent blocker of respiration as it inhibits enzyme action, and so it prevents active transport.

Active uptake of minerals into roots leads to an increase in the solute concentration inside root cells. This in turn causes the absorption of water by osmosis. The water then travels to the leaves in the transpiration stream. When transpiration is high, water in the xylem is usually under tension, not under pressure, as transpiration pulls water upward. But if transpiration is low, for example if the humidity is high or if soil moisture levels are high, water can enter the xylem and move up a plant as a result of **root pressure**.

KEY POINT

root pressure is osmotic pressure generated in the cells of a plant's root system that causes water and minerals to travel up the xylem

Root pressure can transport water and dissolved mineral nutrients from roots through the xylem to the tops of short plants even when transpiration is low or even zero. It occurs in trees in spring before the leaves of deciduous species have developed.

Root pressure is caused by the active transport of mineral ions into the root xylem. If there is no transpiration to carry the ions up the stem, they accumulate in the root xylem and lower the water potential. Water then diffuses from the soil into the root xylem due to osmosis. Root pressure is caused by this accumulated water in the xylem pushing on the rigid cells. Root pressure provides a force, which pushes water up the stem.

You can observe root pressure by cutting the stem of a plant close to the soil. Fluid will exude from the cut xylem for several hours due to root pressure.

Adaptations for translocation in the phloem

Translocation is the movement of organic molecules through the phloem tissue of plants. The phloem consists of two types of living cell: **sieve tube cells**, which are perforated to allow the movement of solutes through them, and **companion cells**, which are connected to the sieve tube cells as shown in Figure 8.2.18.

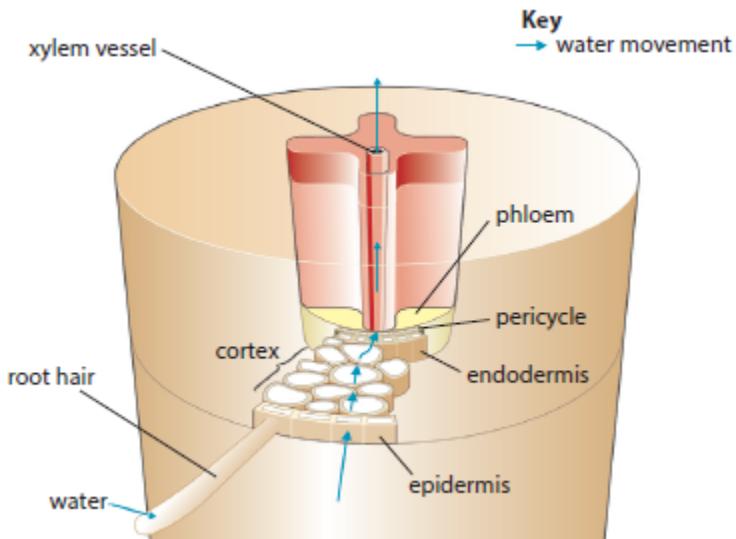


Figure 8.2.17: The pathway of water movement from root hair to xylem. The water may carry dissolved mineral ions.

Whereas the xylem carries water and mineral salts only in an upward direction, the phloem can transport materials either up or down the plant. Translocation moves materials from a **source**, where they are made or stored, to a **sink**, where they are used, as shown in Figure 8.2.19.

Storage structures such as seeds and bulbs are sinks during the growing season but may also act as sources when they begin to sprout.

The products of photosynthesis, including sugars and amino acids, move from leaf cells, which are a source, into the phloem. Once in the phloem, they are translocated to sink regions, such as growing tissue in the meristems of roots, buds and stems, or storage organs like fruits and seeds.

All the materials that are moved by translocation are dissolved in water to form a solution called ‘sap’ which also carries plant hormones. Sugar is usually carried as sucrose, which enters and

leaves the phloem by active transport using energy provided by the companion cells. High concentrations of solutes in the phloem, at sources, such as the leaves, leads to the uptake of water which enters by osmosis. Once materials have entered the phloem, they move passively throughout the plant towards ‘sinks’ as a result of raised hydrostatic pressure in the phloem.

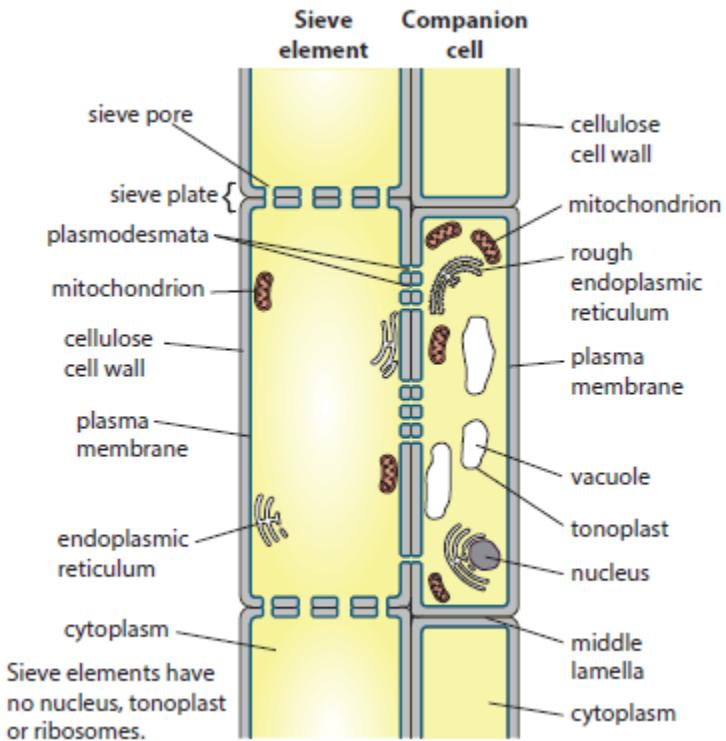


Figure 8.2.18: A phloem sieve tube element and its companion cell.

Hydrostatic pressure is defined as the pressure exerted by a liquid. It depends on the height of a column of liquid and gravity. In the case of plants, the contents of the phloem are at a hydrostatic pressure which increases lower down the plant because the hydrostatic pressure in a volume of liquid increases with depth as the fluid above exerts a downward force. This change in pressure with depth is known as the hydrostatic pressure gradient. In the leaves, a hydrostatic pressure gradient

is formed and water enters the phloem along with sugar and both will be moved down the phloem to other parts of the plant.

At the roots a negative pressure gradient is induced across the root cortex by transpiration. Soil has a higher solute concentration and water enters along with minerals and both are transported in the xylem as a result of the negative hydrostatic pressure gradient.

Table 8.2.5 Compares the structure and function of the xylem and phloem

Xylem	Phloem
Composed of a column of dead cells (when mature) – cell end walls removed	Composed of a column of living cells with perforated walls between them
Continuous tube of cells enables an unbroken column of water (held by cohesive forces) to move inside the xylem	Living cells enable substances to be loaded by active transport
Thickened with lignin to withstand negative pressure as water vapour is lost in transpiration	Associated with companion cells which carry out cell functions and supply energy for active transport into the phloem
Transports water and minerals passively from roots to leaves	Transports sugars, amino acids, hormones to all parts of the plant by mass flow

Table 8.2.5: Structure and function in the xylem and phloem.

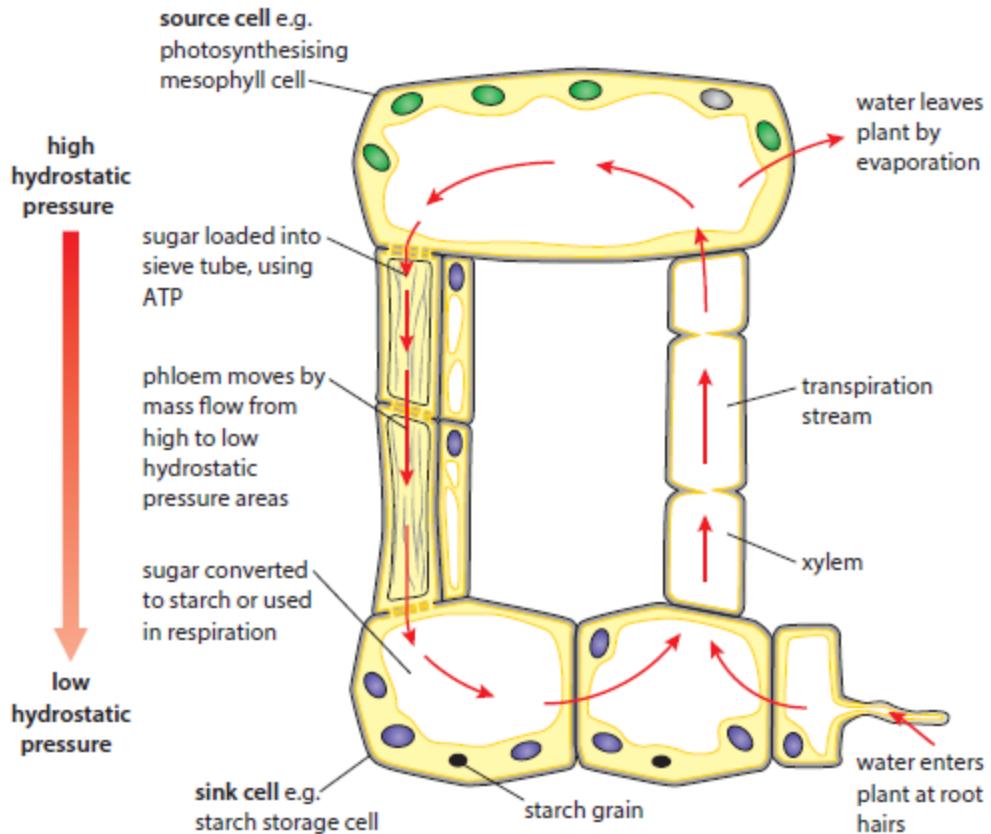


Figure 8.2.19: Sources, sinks and mass flow in phloem.

TEST YOUR UNDERSTANDING

- 11 Draw a plan of the structure of a typical stem to show the arrangement of tissue inside.
- 12 Compare the structure of xylem and phloem.
- 13 State the substances that are carried in the xylem
- 14 List the factors that affect the rate of transpiration.
- 15 Explain why hydrostatic pressure is important to translocation.

Links

- How does the circulatory system contribute to homeostasis? (Chapter 8.5)

8.3 Gas exchange

LEARNING OBJECTIVES

In this section you will:

- recognise that multicellular organisms need to exchange material within their bodies and with the external environment
- understand that exchange surfaces are permeable, moist and have a large surface area to allow materials to cross them easily
- recognise that circulatory surfaces maintain concentration gradients across exchange surfaces
- recall that materials are exchanged between blood and tissues via capillaries.
- learn that blood pressure influences the rate of exchange in capillaries
- understand that lungs contain alveoli that provide a large surface for the exchange of gases
- recognise that ventilation rate and depth influence the rate of exchange of gases in the lungs
- Recognise the adaptations of type I and type II pneumocytes in alveoli



understand that the affinity of hemoglobin for oxygen at different partial pressures of oxygen can be shown in

a graph called a dissociation curve

- learn that carbon dioxide is carried in the blood both in solution and bound to hemoglobin and that carbon dioxide is converted to hydrogen carbonate ions in the red blood cells
- learn that the increased release of oxygen by hemoglobin in respiring tissues can be explained by the Bohr shift
- recall that chemoreceptors are sensitive to pH changes in the blood
- learn that the respiratory centre in the medulla oblongata controls the ventilation rate
- understand that ventilation rate increases in response to the amount of carbon dioxide in the blood during exercise
- recognise that fetal hemoglobin differs from adult hemoglobin, which means that oxygen can be transferred across the placenta to the fetus
- understand that terrestrial plants have adaptations to their structure to enable them to survive on land
- recognise that hydrophytes and xerophytes have different leaf structures for gas exchange.

GUIDING QUESTIONS

- How are exchange surfaces adapted to carry out their roles?
- Why are these surfaces needed?
- Why are exchange surfaces closely linked to a circulatory system?

8.3.1 General features of exchange surfaces

Large organisms must supply nutrients and oxygen to all their cells and carry waste metabolic products away from them. To do this they need surfaces that enable them to exchange materials quickly and efficiently. Some materials enter from the environment outside the organism and are absorbed through a digestive system or respiratory surface. Others, such as hormones, are produced inside the body and must enter cells from the internal environment. All exchange surfaces have features in common that allow these processes to take place efficiently and speedily. Exchange surfaces must:

- be permeable to the substances that must pass across them.
- be thin, so that there is a short distance for exchange by diffusion or other means.
- be moist, so that materials can dissolve if necessary.
- have a large surface area so there is maximum area for exchange.
- have a means of maintaining a concentration gradient so that substances can flow down a gradient to where they are needed.

Maintaining a concentration gradient

In animals, a concentration gradient at exchange surfaces is usually maintained by blood flow through capillaries (Figure 8.3.1), which have all the features needed to make them good for efficient transfer of materials. Tiny capillaries have a very large

surface area and as blood enters a capillary network (also called a capillary bed) its flow slows down because the capillaries are so narrow. The slow flow means that materials can be exchanged with the nearby cells. The walls of the capillaries are only one cell thick so the diffusion distance across them is very small.

The concentration of substances, such as oxygen and glucose, in the cells around the capillary is lower than the concentration in the blood arriving from arterioles (small arteries) that branch into capillaries. At the arterial end of the capillary bed blood pressure is much higher and plasma (the liquid part of blood), containing dissolved glucose, oxygen, amino acids and salts, leaves the capillary through gaps between the cells of the capillary walls.

These substances move down the concentration gradient from the liquid (which is known as tissue fluid once it has left the capillary) into cells. Carbon dioxide and wastes diffuse into the fluid in the opposite direction down their concentration gradients. Oxygen, glucose and other materials can pass by diffusion into the cells. The narrow capillaries produce a drop in blood pressure at the venous end of the capillary bed so that water in tissue fluid re-enters by osmosis. With each pump of the heart, a fresh supply of blood arrives in the capillaries to maintain a high concentration gradient and pressure at the arterial end.

Blood pressure is responsible for the efficient exchange process and is maintained by:

- Pumping of the heart: keeps pressure high and supplies fresh materials in the blood
- Blood volume in the blood vessels: produces pressure on the capillaries
- Diameter of the blood vessels: narrow diameter increases blood pressure.

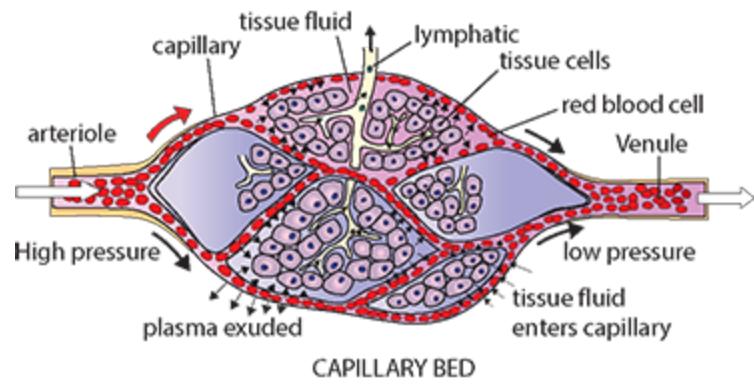


Figure 8.3.1: In a capillary network, blood pressure is higher at the arteriolar end and lower at the venous end where blood returns to the veins via venules.

8.3.2 Gas exchange in the lungs

Exchange and absorption of gases in the lungs

Oxygen enters an animal's body from the external environment, the water or air surrounding it. In simple animals, oxygen can be absorbed by the entire exposed body surface, but in more complex animals special respiratory surfaces such as gills or lungs are needed. Carbon dioxide is usually eliminated through the same surface.

An effective respiratory surface has a large surface area, a rich capillary network, a thin layer of cells separating air or water from the blood vessels and, in land animals, a moist surface. Animals also have a means of renewing the air or water in contact with the respiratory surface.

Gas exchange in land animals such as humans occurs in the **alveoli** of the lungs. Alveoli are tiny air sacs that form the exchange surface in the lungs. Oxygen from the air diffuses into blood capillaries, and carbon dioxide passes in the opposite direction through the walls of the alveoli. Gases are also exchanged in the tissues where oxygen diffuses into respiring cells and is exchanged for carbon dioxide.

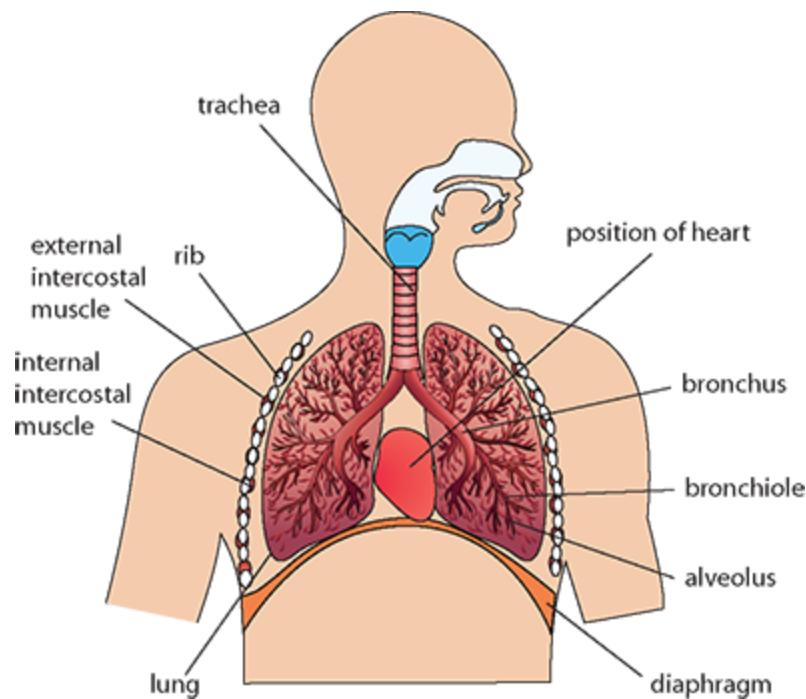


Figure 8.3.2: The human respiratory system.

Whenever diffusion occurs, there must always be a concentration gradient with a higher level of the diffusing substance in one area than in another. Air inside the alveoli contains a higher concentration of oxygen than the blood, so oxygen diffuses into the blood. Blood contains a higher level of carbon dioxide than inhaled air, so carbon dioxide diffuses into the alveoli.

For gas exchange to continue, these concentration gradients must be maintained. As oxygen diffuses out of the alveoli, the level of oxygen inside them gradually falls and the level of carbon dioxide rises. Stale air with high levels of carbon dioxide and low levels of oxygen must be expelled regularly and replaced with a fresh supply to restore the concentration gradients of the two gases. This is achieved by breathing in and out, a process known as **ventilation**.

The human respiratory system

The human respiratory system consists of two lungs protected inside an airtight cavity formed by the ribs and diaphragm. Air is drawn in through the nose, down the trachea to the two bronchi that connect to the two lungs. Bronchi divide into smaller tubes called bronchioles that end in tiny air sacs called alveoli where gas exchange occurs.

Importance of alveoli

Alveoli are the body's gas exchange surfaces. Formed in clusters at the ends of the smallest bronchioles, more than 300 million alveoli in each lung together provide a surface area of about 75 m². Alveoli are roughly spherical in shape and are made of cells less than 5 µm thick. The capillaries that wrap around them also have thin walls of single epithelial cells. These two thin layers make the distance for diffusion of gases as small as possible. Oxygen diffuses through the alveolus wall and capillary into the blood and carbon dioxide diffuses in the opposite direction (Figure 8.3.3). As long as the diffusion gradient is maintained by regular breathing, diffusion will continue.

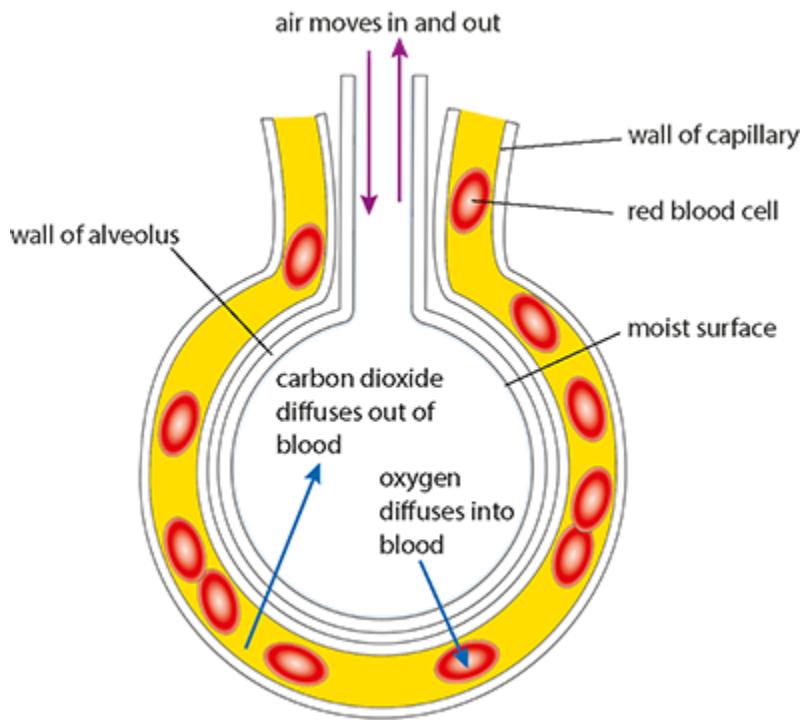


Figure 8.3.3: Gas exchange in the alveolus.

Two types of special cells called **pneumocytes** line the alveoli. Type I pneumocytes are very thin so that gases can diffuse easily while type II pneumocytes secrete a surfactant into the alveolus. The surfactant reduces surface tension and prevents the sides of the alveolus sticking to one another.

Table 8.3.1 summarises ways in which the alveoli are well adapted for their role in gas exchange.

Ventilation

Ventilation is essential to bring a fresh supply of oxygen-rich air into the alveoli and to remove carbon dioxide containing air from the alveoli.

Lungs have no muscles and cannot move by themselves. Breathing is brought about by two sets of intercostal muscles

between the ribs, and by the diaphragm, the sheet of muscle separating the thorax from the abdomen (Figure 8.3.4).

Feature of alveoli	Importance
many small, spherical alveoli	provide a large area for gas exchange
thin walls of flattened single cells type I pneumocytes	short diffusion distance
type II pneumocytes	secrete surfactant
rich blood supply from capillaries	maintains concentration gradient and carries absorbed gases away rapidly

Table 8.3.1: Adaptations of alveoli for gas exchange.

During **inhalation**, contraction of the external intercostal muscles raises the ribs and contraction of the diaphragm lowers the floor of the thorax. These movements increase the volume of the chest cavity. The pressure in the lungs becomes lower than that of the air outside. As a result, air is drawn down the trachea to fill the lungs.

Gentle **exhalation** occurs as the intercostal and diaphragm muscles relax, reducing the volume of the chest cavity. Elastic fibres around the alveoli return to their original length and pressure forces air out of the lungs.

Long or forced exhalations involve the internal intercostal muscles, which contract to lower the ribs. Muscles in the abdominal wall also contract and push the relaxed diaphragm

upward. Pressure inside the chest cavity increases and air is forced out of the lungs.

The volume and frequency of breathing are matched to a person's activities. During vigorous exercise the rate and depth of breathing increases, but as we sleep our breathing rate slows to only 12–20 breaths per minute.

Measuring changes in lung volume

A spirometer (Figure 8.3.5) is used to measure the amount of air that is exchanged during breathing. It can also measure the rate of breathing, for example, when a person is at rest or during or after exercise. A simple spirometer has a chamber filled with oxygen or air, which is inverted over a container of water. The subject is connected to the chamber via a tube and mouthpiece (the nostrils are closed with a nose clip). As the subject inhales and exhales, a trace is produced on a rotating drum or computer monitor. Inhalation causes the chamber to fall, producing a falling line on the trace. Exhalation causes the chamber to rise and produces a rising line. The trace is called a spirogram and various volume measurements can be made from it (Figure 8.3.6). Usually soda lime is used to absorb carbon dioxide that is exhaled.

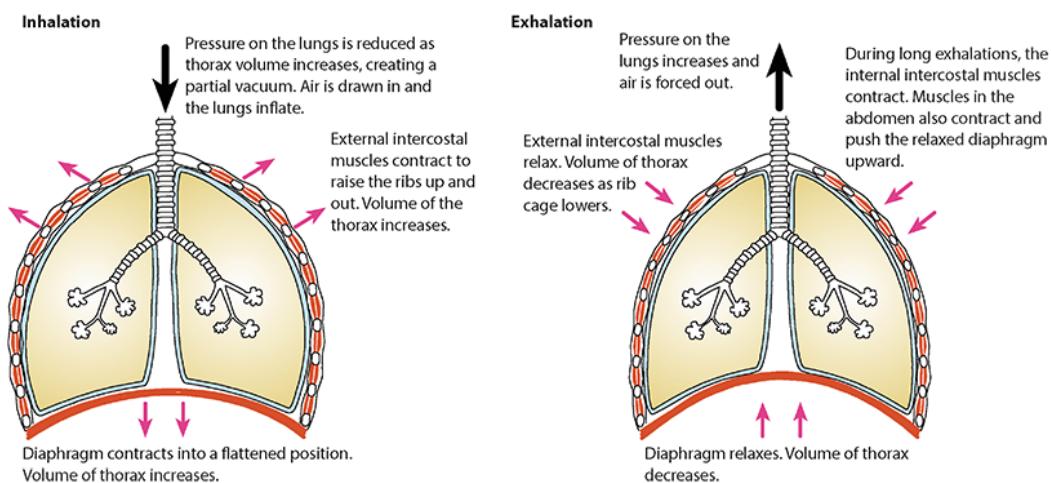


Figure 8.3.4: The mechanism of ventilation.

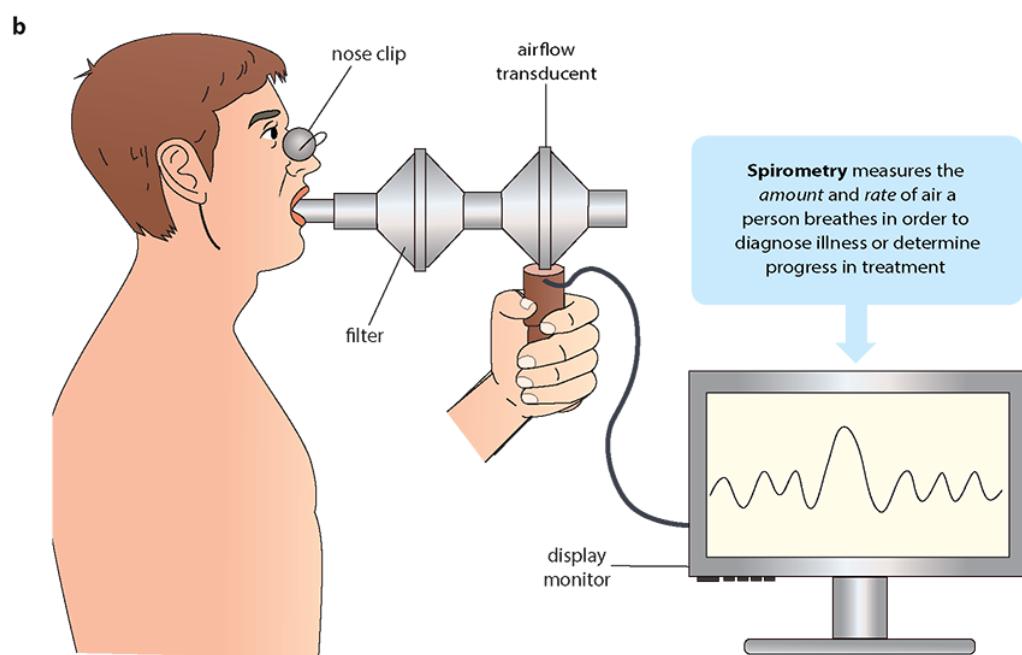
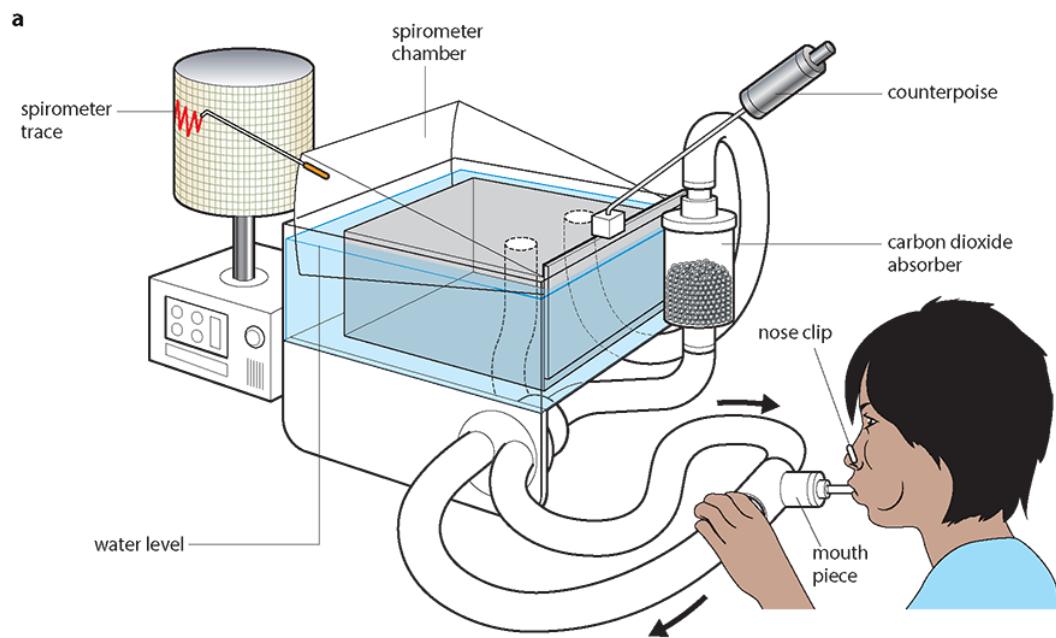


Figure 8.3.5: Simple spirometers can be connected to **a** a rotating drum or **b** a computer interface to record a trace.

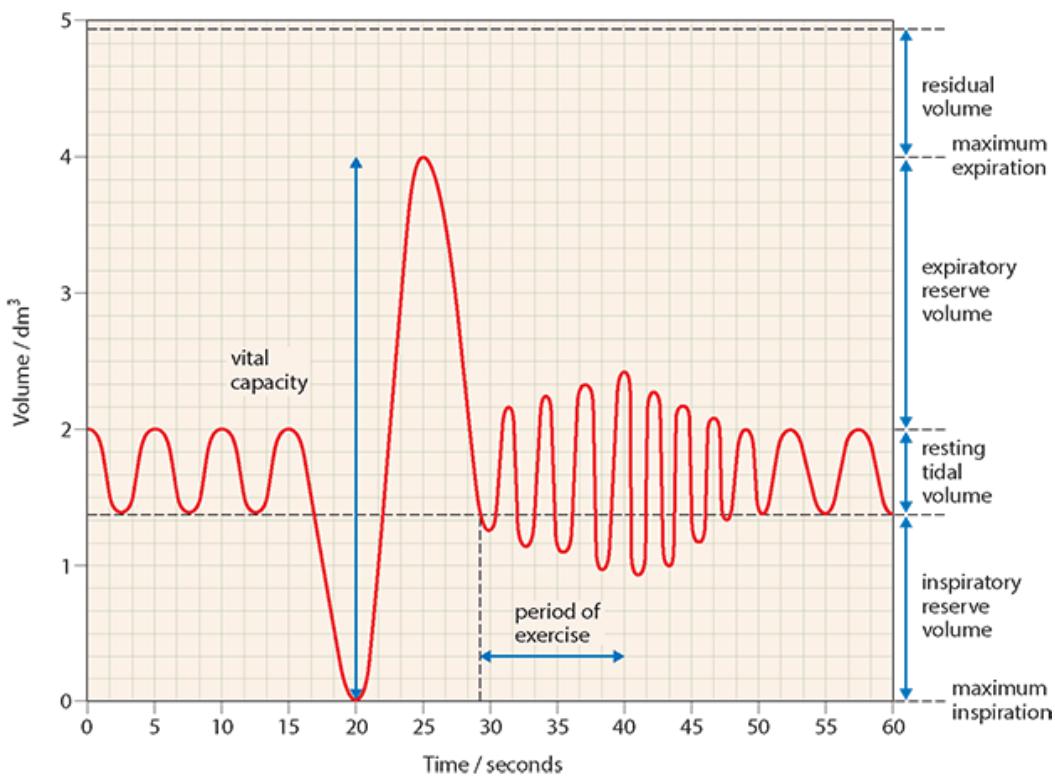


Figure 8.3.6: A spirometer produces a trace that can be used to measure various aspects of a person's breathing. Tidal volume is the volume of air breathed in and out in a single breath. Inspiratory reserve is the volume breathed in by a maximum inhalation at the end of a normal inhalation and expiratory reserve is the volume exhaled by a maximum effort after a normal exhalation. Residual volume is the volume of air remaining in the lungs at the end of a maximum exhalation.

EXAM TIP

You should be able to interpret spirometer traces like the one shown in Figure 8.3.6 and comment on the rate and depth of breathing that they show.

TEST YOUR UNDERSTANDING

- 16** State three features you would expect to find in an efficient exchange surface.
- 17** Outline how a concentration gradient is maintained in the alveoli.
- 18** What is the function of the surfactant in the lungs?

8.3.3 Transport of respiratory gases

Oxygen is transported from the lungs to respiring tissues bound to the hemoglobin molecules that are contained in all red blood cells. A hemoglobin molecule can bind four oxygen molecules via the iron in the heme groups at the centre of each molecule (Figure 8.3.7). When hemoglobin comes into contact with normal air, containing approximately 21% oxygen, it binds readily with oxygen molecules. It holds on to as many as it can so that it becomes almost 100% saturated.

Oxygen dissociation curves

The oxygen content of air is measured as a partial pressure. In a mixture of gases, each component gas exerts a pressure (the partial pressure) in proportion to its percentage in the mixture. It is calculated as follows. For normal dry air at sea level, atmospheric pressure is 101.3 kilopascals (kPa); a Pascal (Pa) is the SI unit of pressure. The partial pressure of oxygen, which makes up 21% of the air, is:

$$\frac{21}{100} \times 101.3 \text{ kPa} = 21.3 \text{ kPa}$$

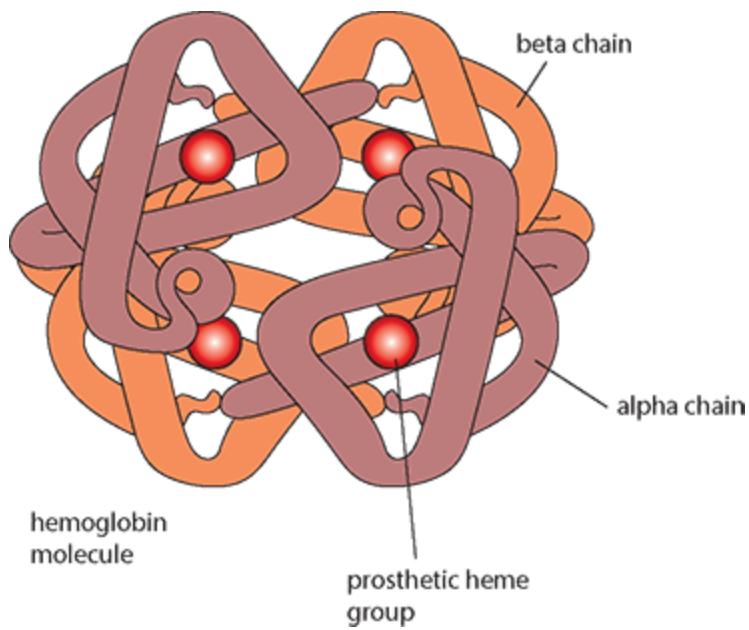


Figure 8.3.7: Hemoglobin is a protein that has quaternary structure. It consists of four subunits bound together. There are two alpha chains and two beta chains, and each of these includes an iron-containing heme group.

KEY POINTS

partial pressure the proportion of the total pressure that is due to one component of a mixture of gases.

Pascal (Pa) the SI unit of pressure; a measure of force per unit area, defined as 1 newton per square metre; $1000\text{ Pa} = 1\text{ kilopascal (kPa)}$.

The partial pressures of other gases in dry air at sea level are shown in Table 8.3.2.

In an area of the body where there is a lot of oxygen (a high partial pressure), such as the lungs, most hemoglobin molecules will be carrying the maximum amount of oxygen and will be fully saturated. However, in areas where the oxygen level is

lower, fewer hemoglobin molecules carry their maximum complement of oxygen and the hemoglobin may be only 50% saturated. As blood travels from the lungs to actively respiring tissues, the amount of oxygen bound to hemoglobin changes as the partial pressure of oxygen decreases. Hemoglobin readily releases oxygen where the partial pressure is lower, so it acts as an oxygen delivery service for respiring cells. Oxygen is said to dissociate from (meaning detach from) the hemoglobin molecules that carry it when partial pressure is lower. Figure 8.3.8 shows the percentage saturation of hemoglobin at different partial pressures of oxygen and is known as an oxygen dissociation curve. The steep S-shape of the dissociation curve shows how the affinity of adult hemoglobin changes at different partial pressures of oxygen. As each heme group accepts oxygen, it becomes easier for the next heme group of the molecule to pick up oxygen and hemoglobin is said to have a higher affinity for oxygen.

Gas	Approximate percentage composition / %	Partial pressure / kPa
oxygen	21	21.3
carbon dioxide	0.0035	negligible
nitrogen	79	80.0

Table 8.3.2: The partial pressures of gases in dry air at sea level. At high altitude, the pressure of air falls but the percentage of oxygen in the air remains approximately the same. At 5000 m, the partial pressure of oxygen is 11.5 kPa; at 10 000 m, it falls to just 5.5 kPa.

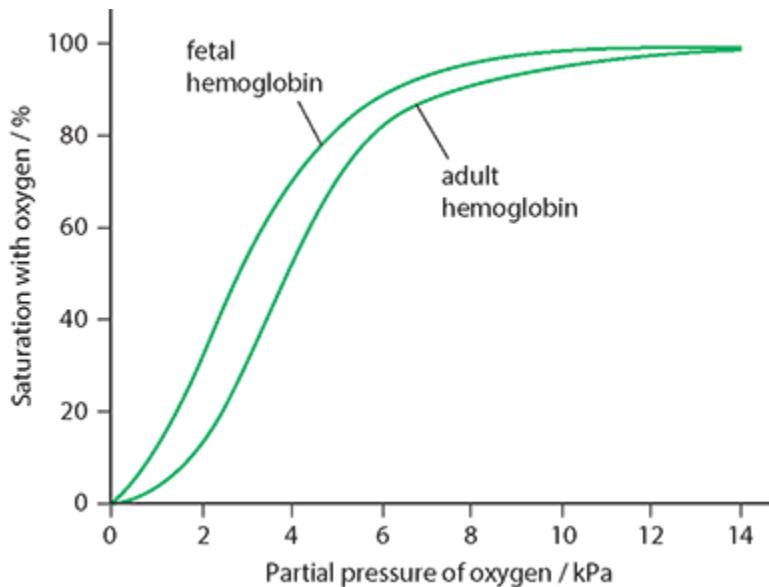


Figure 8.3.8: Dissociation curves for adult hemoglobin and fetal hemoglobin. The curves are constructed using the normal range (at sea level) of partial pressure of oxygen in the body. The partial pressure of oxygen in alveolar air is about 14 kPa due to the presence of water vapour, which forms about 6% of alveolar air.

KEY POINT

oxygen dissociation curve a graph showing the percentage saturation of hemoglobin with oxygen at different partial pressures.

At a partial pressure of 10 kPa, which might be found in the lungs, hemoglobin is 95% saturated. At a partial pressure of 4 kPa, found in the tissues, hemoglobin does not bind with oxygen and will release it, so saturation falls to only about 50%. About half of the oxygen collected by hemoglobin in the lungs is released at this low partial pressure to supply the needs of actively respiring cells.

Fetal hemoglobin

The molecular structure of hemoglobin in the blood of a fetus is different from that of an adult. The dissociation curve for fetal hemoglobin lies to the left of the adult curve for all partial pressures of oxygen (Figure 8.3.8). This tells us that fetal hemoglobin has a higher affinity for oxygen than maternal (adult) hemoglobin, whatever the concentration of oxygen. In the capillaries of the placenta, the partial pressure of oxygen is low. Here the mother's adult hemoglobin releases oxygen, which is easily picked up and bound to fetal hemoglobin. At a partial pressure of 4 kPa, the mother's hemoglobin is only 50% saturated, but fetal hemoglobin becomes approximately 70% saturated. The fetal hemoglobin carries the oxygen to the baby's body and releases it into the respiring fetal tissues.

Transport of carbon dioxide in the blood

Carbon dioxide produced during aerobic respiration is carried back to the lungs by the blood. It diffuses into capillaries close to respiring cells and is transported in one of three ways.

- 1 About 70% of carbon dioxide enters red blood cells and is converted to HCO_3^- (hydrogen carbonate) ions.
- 2 About 7% remains in the blood and is transported dissolved in plasma.
- 3 The remainder is bound to hemoglobin.

Carbon dioxide reacts with water to form carbonic acid, which dissociates to form hydrogen carbonate ions and hydrogen ions:



As carbon dioxide dissolves in the blood it lowers the pH, making the blood more acidic. As hydrogen ions and carbon dioxide bind to hemoglobin, they cause the Bohr shift, which is described next.

The Bohr shift

The affinity of hemoglobin for oxygen is not only affected by the partial pressure of oxygen, but it is also reduced in the presence of high carbon dioxide concentrations. As the partial pressure of carbon dioxide in the blood rises, the ability of hemoglobin to combine with oxygen falls and so the dissociation curve moves to the right. This effect is known as the **Bohr shift**. It is caused when hydrogen ions produced from carbonic acid combine with hemoglobin and the pH of the blood decreases.

Figure 8.3.9 shows the effect of two different partial pressures of carbon dioxide on the oxygen dissociation curve. In an environment where the partial pressure of carbon dioxide is high, such as in actively respiring tissue, the curve moves to the right. This means that, at any given oxygen partial pressure, oxygen is more likely to dissociate from hemoglobin if the partial pressure of carbon dioxide is high. This effect promotes the release of oxygen in active tissues where respiration is producing high levels of carbon dioxide, so cells receive the oxygen they need.

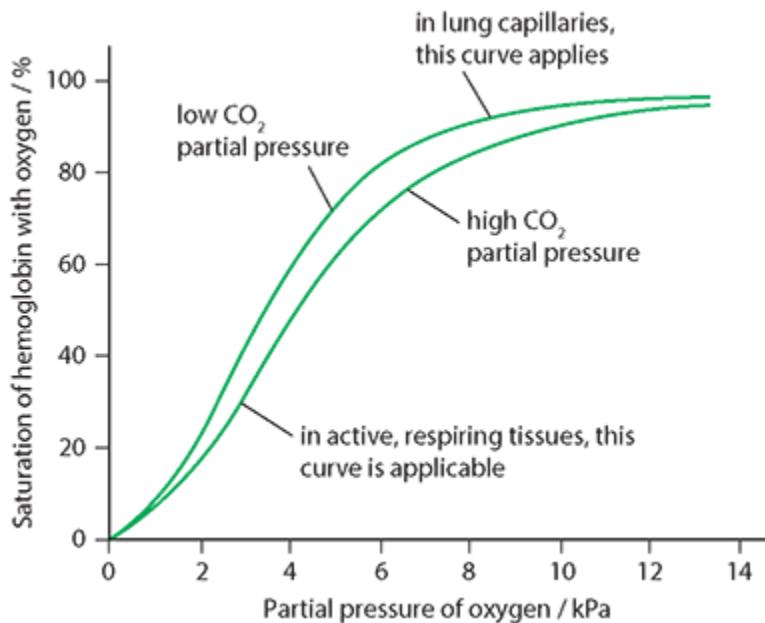


Figure 8.3.9: The effect of carbon dioxide concentration on hemoglobin saturation: the Bohr shift.

Ventilation rate and exercise

When a person exercises, their ventilation rate and tidal volume (depth of breathing) increase. Muscles need oxygen for aerobic respiration and so as the rate of exercise increases so does the rate of oxygen consumption. Blood returning to the lungs also has a higher level of carbon dioxide, produced as a result of the increased activity. An increase in ventilation rate and tidal volume draws in more fresh air to maintain the concentration gradient between the alveolar air and the blood. Thus oxygen can be absorbed at a faster rate and the body can get rid of the additional carbon dioxide produced. These changes in ventilation are adjusted to match the body's metabolic needs.

Ventilation rate is controlled by the breathing centre of the medulla oblongata in the brain stem, which receives nerve impulses from sensory cells in different parts of the body. The breathing centre responds to match ventilation rate to activity

levels (Figure 8.3.10). Chemoreceptors in the inner wall of the aorta and carotid arteries respond to an increase in carbon dioxide in the blood. This excess carbon dioxide forms carbonic acid and so the pH of the blood falls. Impulses are passed from the chemoreceptors to the medulla. The medulla increases the ventilation rate by sending motor impulses to the intercostal muscles and diaphragm to increase their rate of contraction. The breathing centre also contains similar chemoreceptors, which respond to deviations of blood pH from the normal level. An increase in ventilation rate causes carbon dioxide to be removed from the body at a faster rate and blood pH returns to its normal level of between 7.35 and 7.45. After exercise, as the level of carbon dioxide in the blood falls, ventilation rate decreases.

KEY POINT

medulla oblongata area of the brain stem that controls ventilation rate and heart rate.

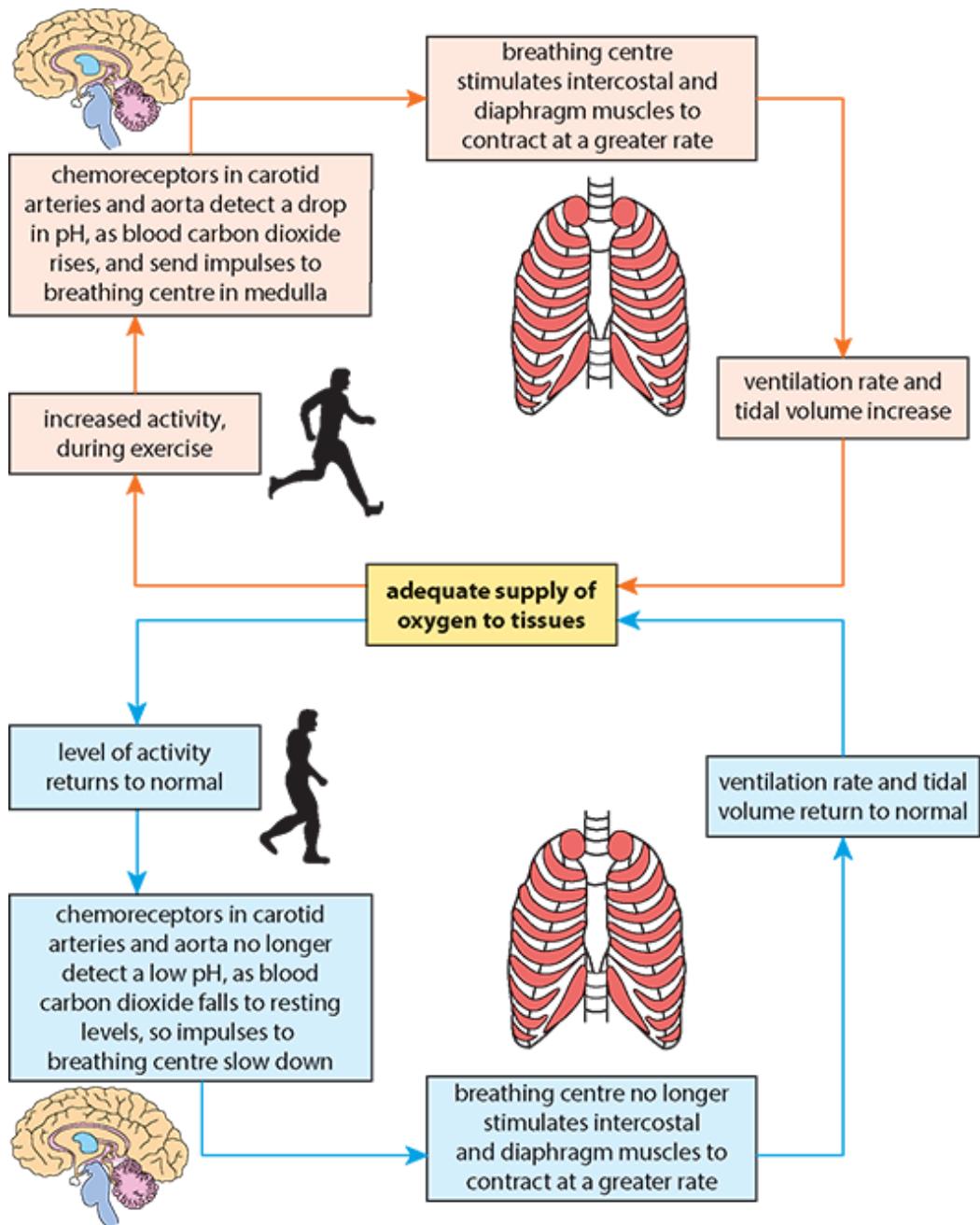


Figure 8.3.10: The control of breathing.

8.3.4 Gas exchange in plants

Terrestrial plants have many adaptations to their exchange surfaces, which enable them to take in the sunlight, gases, water and solutes that they need (Figure 8.3.11).

Leaves of flowering plants are adapted to capture light energy from the sun and exchange the carbon dioxide and oxygen needed for photosynthesis and respiration.

The stomata (pores) are openings in the epidermis that are more abundant on the underside of a leaf that is usually shaded and cooler. Stomata are formed between two guard cells that can open and close the stomata according to the environmental conditions. When there is sufficient light intensity for photosynthesis, the guard cells open the stomata to allow gases to enter and leave. But if water is scarce, the stomata close so that water is conserved in the plant cells (Figure 8.3.12).

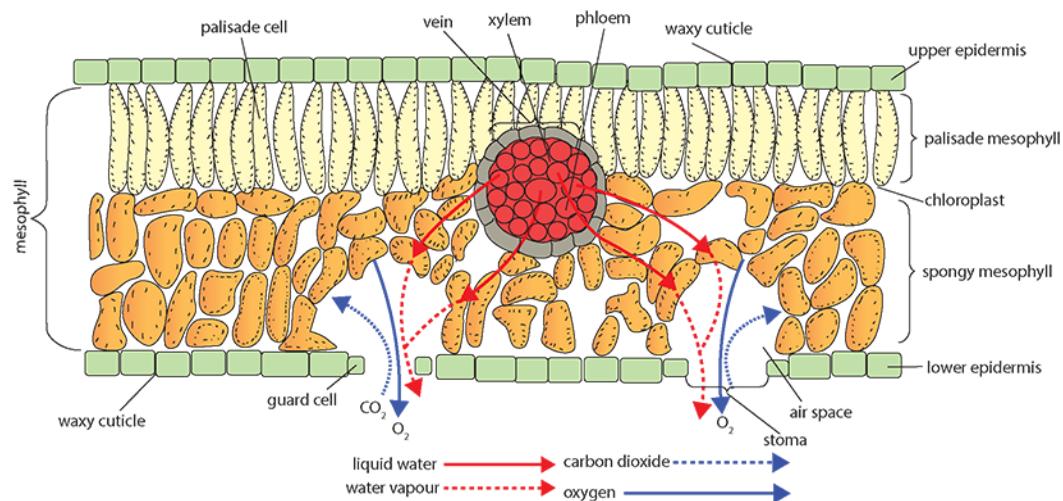


Figure 8.3.11: Cross-section showing the structure of a typical leaf of a terrestrial plant.

Part of leaf	Adaptation and functions
waxy cuticle covering epidermal cells	a waterproof layer that prevents evaporation of water from the leaf surfaces but allows light through
epidermis	single layer of transparent cells that allow light through but prevent the entry of pathogens
palisade mesophyll	elongated cells at the top of the leaf that contain many chloroplasts for photosynthesis
spongy mesophyll	cells with large air spaces to allow the diffusion of gases for photosynthesis and respiration
stomatal guard cells	can open and close pores to allow the passage of gases or to conserve water
veins (xylem and phloem)	contain xylem and phloem to bring water to the leaf and carry away products of photosynthesis

Table 8.3.3: Adaptations found in the leaf of a terrestrial plant.

water enters guard cells by osmosis;
guard cells become turgid, opening stoma

water leaves guard cells by osmosis;
guard cells become flaccid, closing stoma

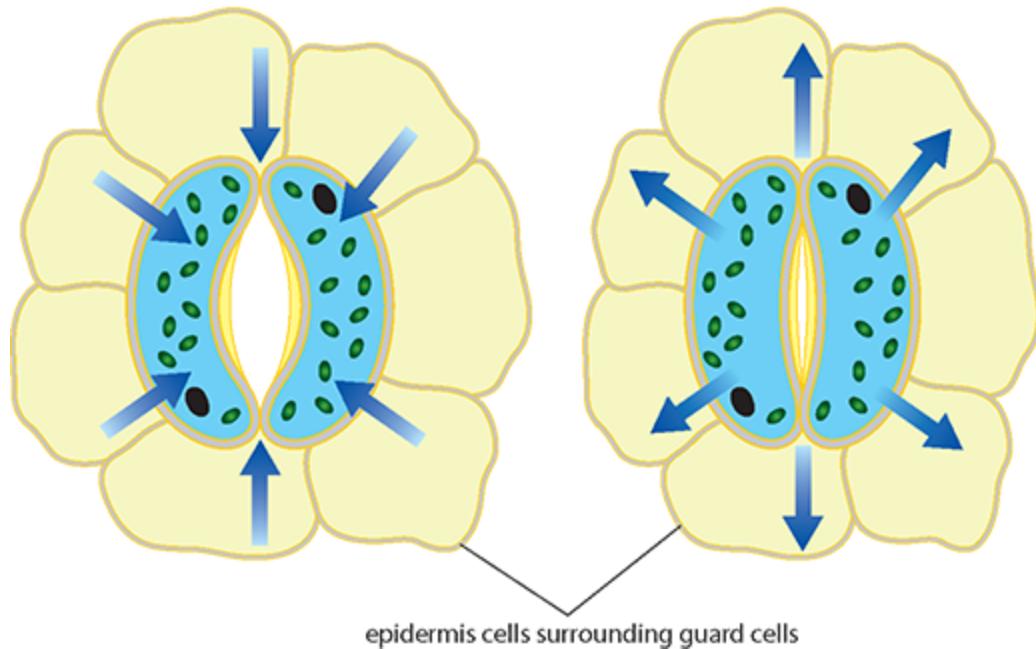


Figure 8.3.12: The opening and closing of stomata. Gases can diffuse in and out of open stomata. When stomata are closed, water loss is minimised.

EXAM TIP

Ensure that you can draw and label a plan (two-dimensional) diagram of a section through a leaf. Check that you can list the functions of each type of cell.

Stomatal density

The number of stomata in a given area of a leaf varies between plant species, and between the underside and upper surfaces of the leaves on an individual plant. The variation in size of stomata and their density is due to genetic factors and also environmental conditions. Stomatal density can vary due to factors such as light, humidity, water availability and concentration of carbon dioxide

in the atmosphere. Stomatal density gives a measure of the potential surface area for the movement of gases in and out of the leaf, but it is the opening and closing of the stomata that controls the final amount of gas exchange.

A simple way to estimate the number of stomata in a leaf surface is to use clear nail varnish to prepare an impression of the leaf. The leaf surface being investigated is coated with a thin layer of nail varnish and left to dry. A piece of clear sticky tape can be used to cover and peel off the layer of nail varnish that can be stuck onto a glass microscope slide. The number of stomata in a number of sample areas can be counted using an eyepiece graticule (Figure 8.3.13) and an average value can then be calculated.

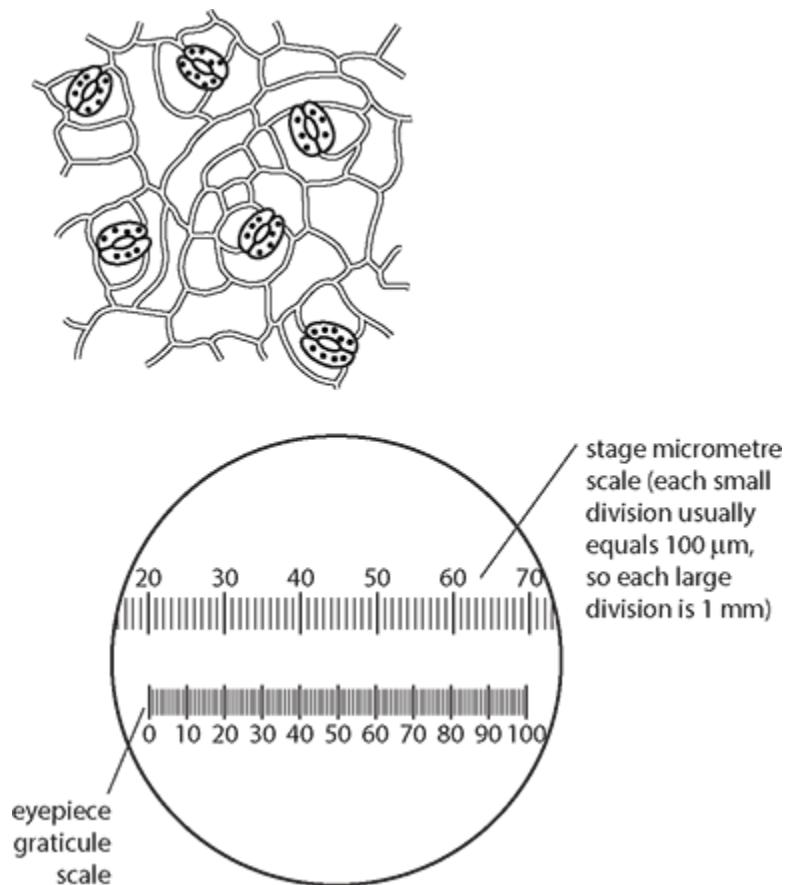


Figure 8.3.13: Stomata in an impression of the lower surface of a leaf and a graticule used with a microscope to observe and count stomata in a sample area.

INTERNATIONAL MINDEDNESS

Research from many parts of the world involving many species of trees and shrubs has shown that there has been a decrease in stomatal density over the last 100 years. This decrease is correlated with increased carbon dioxide levels in the atmosphere due to the use of fossil fuels.

To consider:

Why should an increase in carbon dioxide in the atmosphere lead to a reduction in stomatal density?

TEST YOUR UNDERSTANDING

- 19** Define ‘partial pressure’.
- 20** Explain what is meant by the term ‘Bohr shift’ and why it is important in supplying oxygen to respiring tissues.
- 21** Describe how fetal hemoglobin differs from adult hemoglobin in its affinity for oxygen.
- 22** Why is a waxy cuticle important to the leaves of terrestrial plants?
- 23** How could a scientist obtain an accurate measurement of stomatal density?

Links

- What strategies are used by cells and organs to increase surface area? (Chapter 6)
- What selection pressures in an environment may lead to differences in gas exchange systems in fish? (Chapter 11)

8.4 Reproduction

LEARNING OBJECTIVES

In this section you will:

- understand that sexual and asexual reproduction enables species to survive
- asexual reproduction is fast but unless mutations occur, it does not produce genetic variation
- recognise that sexual reproduction involves fusion of gametes and results in genetic variation
- learn that the human menstrual cycle is controlled by hormones
- recall that the menstrual cycle involves hormones from the ovaries and pituitary gland
- understand that both hormone therapy and IVF assist people to conceive
- learn that angiosperms produce seeds inside ovaries that develop into fruits
- recognise that pollination may be carried out by the wind or an animal pollinator
- discover that to increase variation many plants have self-incompatibility mechanisms
- recall that seeds of plants contain the embryo plant and energy stores

- recognise that the onset of puberty is controlled by GnRH and LH and FSH from the hypothalamus and pituitary glands
- recognise adaptations of sperm and ova and difference in spermatogenesis and oogenesis
- learn that fertilisation involves mechanisms to ensure that only one sperm fertilises an ovum
- learn that the human menstrual cycle involves negative and positive feedback
- understand that the blastocyst implants in the endometrium during early pregnancy
- recognise that human chorionic gonadotropin maintains the placenta early in pregnancy and is used in pregnancy tests
- understand the role of the placenta in fetal development
- understand that birth is controlled by positive feedback involving oxytocin and estrogen
- consider the risks and benefits of hormone replacement therapy.

GUIDING QUESTIONS

- What are the advantages of sexual reproduction compared with asexual reproduction?

- Why are hormones important in controlling sexual cycles in animals?
- How do external factors assist in plant reproduction?

8.4.1 Asexual reproduction

Asexual reproduction does not involve the combination of genetic material from different individuals. A single organism produces copies of itself that are almost identical and are said to be a clone of one another. All the offspring will be genetically identical unless a mutation occurs. Asexual reproduction can take place in a number of different ways in different species.

- Parthenogenesis is the development of new individuals from an unfertilised egg ([Section 6.5](#)).
- **Budding** is a method of reproduction in which an individual develops a bud from part of its body. The bud then detaches and develops separately. *Hydra* reproduces in this way (Figure 8.4.1).
- Binary fission occurs when one individual divides into two equal parts ([Section 6.5](#), Figure 6.5.1). Bacteria use this method of reproduction, and when conditions are favourable they may divide every 20 minutes. Fission can produce exponential growth and one bacterium dividing to produce 2 cells, and then 4, 8, 16, 32, and so on, could have the potential to produce 4×10^{21} cells in 24 hours, which explains how a pathogenic bacterium can cause illness in a very short time.

KEY POINTS

asexual reproduction reproduction that does not involve gametes or fertilisation; it involves only one organism in which there is no combination of genetic material from different individuals.

clone a population of genetically identical cells produced asexually produced by a single cell or organism.

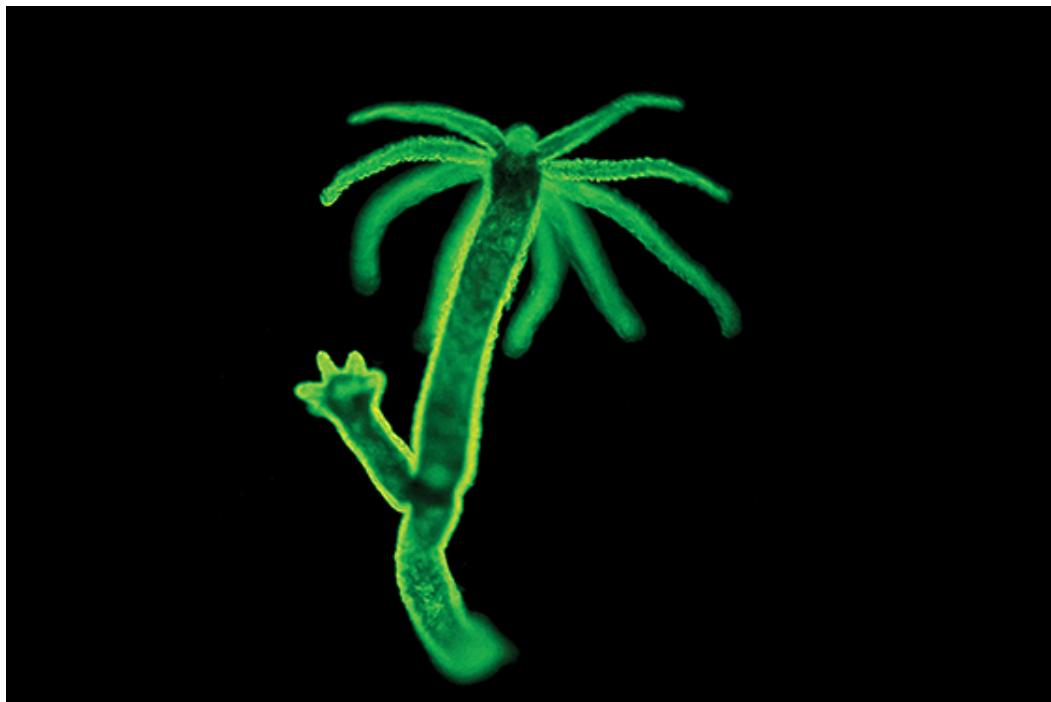


Figure 8.4.1: *Hydra* reproduces asexually by budding.



Figure 8.4.2: Bread mould (*Rhizopus nigricans*) produces spores in round, black structures called sporangia.

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- **Spores** are used by organisms, such as fungi, to reproduce asexually (Figure 8.4.2). Spores are small light structures that are produced in capsules called sporangia. They are dispersed easily to a new location where they germinate and start a new colony.

8.4.2 Sexual reproduction

Sexual reproduction involves the fusion of two **gametes** in a process called fertilisation. Gametes, which include sperm and eggs in animals, or pollen and ovules in plants, are haploid and contain the genetic material of only one parent. Sperm and eggs are found in many different animal species including corals, jellyfish, insects and vertebrates.

Gametes are produced by meiotic division. During the stages of meiosis, crossing over and the independent assortment of alleles increases genetic variation in the gametes. In addition, the combination of parental alleles during fertilisation ensures that sexual reproduction provides further genetic variation in the offspring. (These processes are discussed in Section 4.6 on inheritance and in [Section 6.5](#) on cell division.)

In humans, the gametes that must come together to begin a new life are produced in the ovaries and testes. The male and female reproductive systems enable the gametes to meet and the female reproductive system provides a suitable place for fertilisation to occur and an embryo to develop (Figures 8.4.3 and 8.4.4). The ovaries and testes also produce hormones that regulate sexual development and reproduction.

EXAM TIP

You must be able to label diagrams such as those of the male and female reproductive systems shown in Figures 8.4.3 and 8.4.4. You should be able to annotate the important parts with information about their functions. The functions are summarised in Tables 8.4.1 and 8.4.2.

Roles of testosterone

The hormone **testosterone**, which is produced by the testes, has important roles in the sexual development and reproductive behaviour in males.

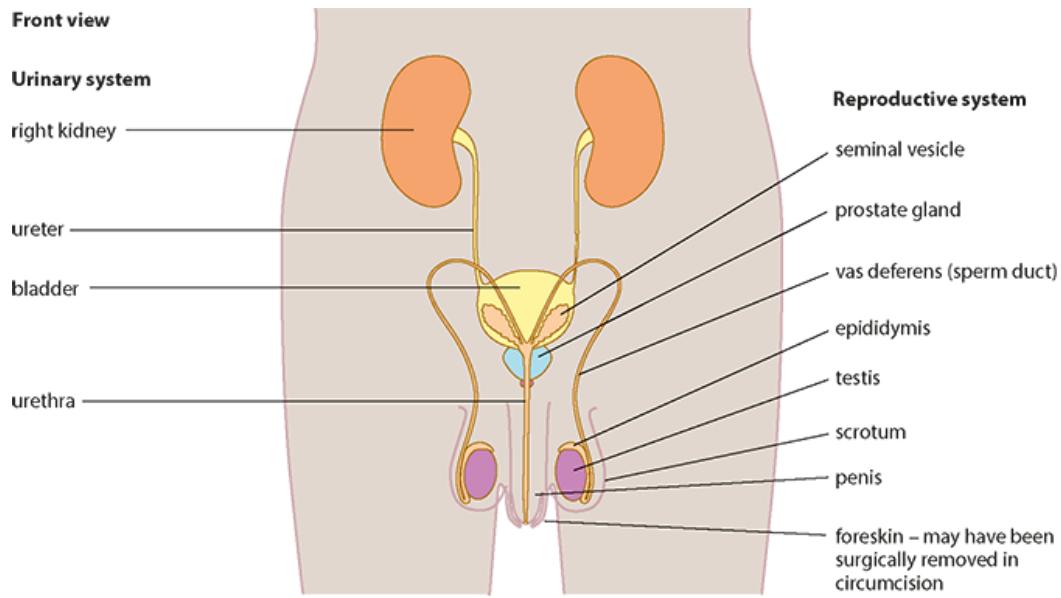


Figure 8.4.3: The male reproductive system. (The diagram also shows the organs of the urinary system.)

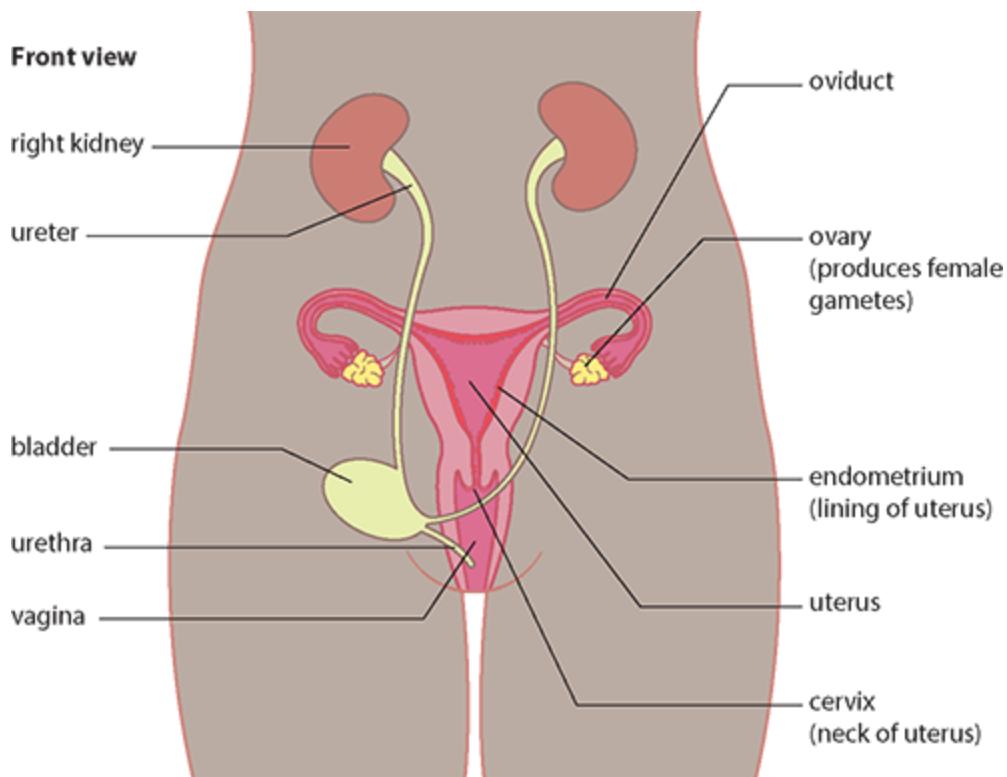


Figure 8.4.4: The female reproductive system. (The diagram also shows the organs of the urinary system – the bladder has been drawn to one side, to reveal the uterus.)

Structure	Function in male reproductive system
testes	sperm production and production of testosterone
epididymis and sperm duct	store male gametes (sperm) and carry them to the urethra
seminal vesicle, prostate gland	produce semen, the fluid in which sperm travel into the female body
urethra	tube that carries semen out of the body; separately, it carries urine out of the body

penis	enters the female body during intercourse to deliver semen to the vagina; contains erectile tissue to enable it to do this
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Table 8.4.1: Summary of the functions of the structures of the male reproductive system.

- During fetal development, testosterone causes the development of the male genitalia.
- At puberty, levels of testosterone rise and cause the development of male secondary sexual characteristics including growth of muscle, deepening of the voice, enlargement of the penis and growth of body hair.

Structure	Function in female reproductive system
ovary	produces and releases female gametes (oocytes) and the hormones estrogen and progesterone
oviduct	site of fertilisation, carries oocytes to the uterus
uterus (womb)	place inside the female body where a fetus grows and develops
endometrium	lining of the uterus that receives a fertilised egg or is shed during menstruation
cervix	the neck of the womb, which remains closed during pregnancy
vagina	birth canal and area where semen are deposited during intercourse

Table 8.4.2: Summary of the functions of the structures of the female reproductive system.

- Testosterone stimulates the continuous production of sperm and behaviour associated with the sex drive.

Female hormones and the menstrual cycle

Humans and other primates secrete hormones that control the production and release of gametes in a cycle known as the menstrual cycle. The menstrual cycle involves changes to the ovaries and uterus to prepare for fertilisation.

Ovaries produce two hormones, **estrogen** and **progesterone**. These hormones stimulate the development of female genitalia before birth. At puberty they are responsible for the development of female secondary sexual characteristics including the onset of the menstrual cycle, development of breasts, growth of body hair and widening of the hips. The two hormones also influence the changes in the uterus lining during the menstrual cycle and pregnancy. The pituitary gland in the brain produces two further hormones: **luteinising hormone (LH)** and **follicle-stimulating hormone (FSH)**. FSH stimulates the development of immature follicles in the ovary, one of which will come to contain a mature egg cell. LH stimulates the follicle to release the egg and subsequently to form the **corpus luteum**.

Production of female gametes is a cyclical process, which lasts approximately 28 days. During the first half of this menstrual cycle the egg cell is produced and in the second half the uterus lining thickens to prepare for implantation of a fertilised egg. The cycle involves hormones that are released by the ovaries and the pituitary gland.

The sequence of events begins at the start of **menstruation**, which is often called a period (Figure 8.4.5). During the first 4 or 5 days of the cycle, the endometrium (lining) of the uterus is

shed and leaves the body through the vagina. This indicates that fertilisation has not occurred during the previous month.

In this early part of the cycle, the pituitary gland secretes FSH, which stimulates the development of an immature follicle in the ovary. The follicle then secretes estrogen, which enhances the follicle's response to FSH. Increasing levels of estrogen cause an increase in the level of FSH released by the pituitary gland. As the level of estrogen rises, it also stimulates the repair of the uterus lining.

As the follicle grows, estrogen levels rise to a peak at around day 12, when they stimulate the release of LH from the pituitary gland. As LH levels reach their highest point, ovulation – the release of the egg cell from the follicle – takes place. Ovulation usually occurs at around the day 14 of the cycle. Immediately afterwards, LH stimulates the empty follicle to form the corpus luteum. Levels of estrogen fall and as a result FSH and LH levels fall.

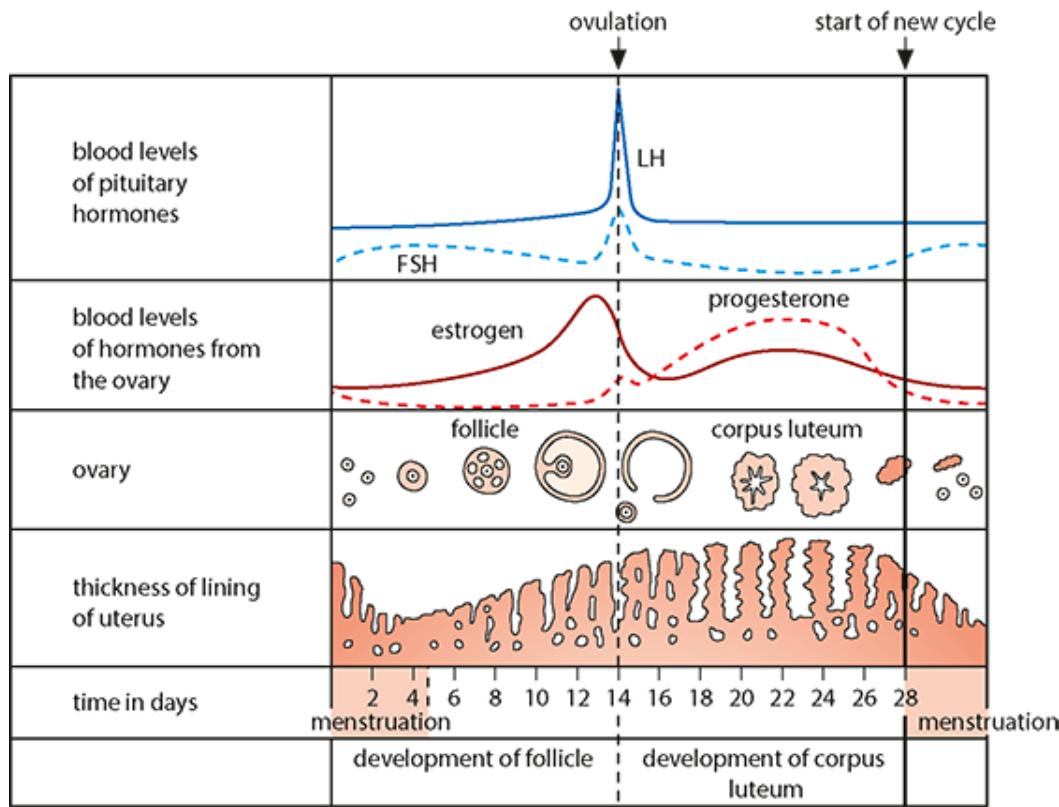


Figure 8.4.5: The menstrual cycle lasts an average of 28 days and involves changes in hormone levels that influence the follicles and lining of the uterus.

The corpus luteum secretes progesterone, which stimulates the thickening of the endometrium and prepares the uterus to receive an embryo. It also inhibits the production of FSH and LH.

If the egg cell is not fertilised, the corpus luteum degenerates and progesterone and estrogen levels fall. The fall in progesterone stimulates the breakdown of the uterus lining. FSH is no longer inhibited, so a new follicle is stimulated and the cycle begins again.

Human fertilisation

Fertilisation usually occurs in one of the oviducts and is the moment when one sperm cell fuses with the secondary oocyte to form a **zygote**. The sequence of events that occur at fertilisation is summarised in Figure 8.4.6.

During sexual intercourse, millions of sperm cells are ejaculated into the vagina and some of them make their way through the cervix and uterus towards the oviducts. Only a very small number of the ejaculated sperm will complete the journey, which is a considerable distance for the tiny cells.

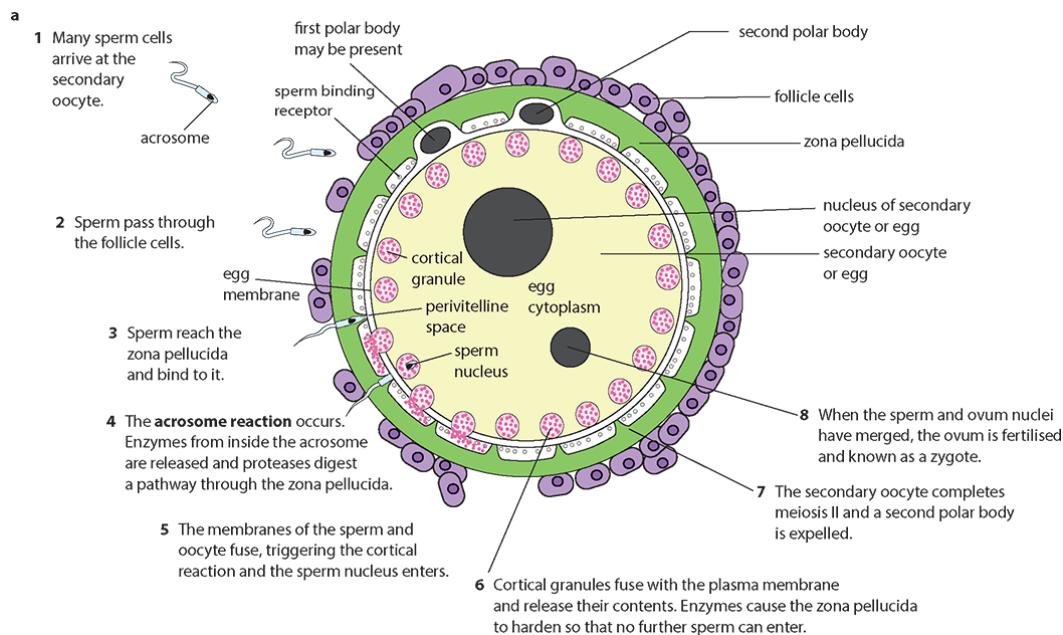


Figure 8.4.6: a The stages of fertilisation. Notice the difference in the sizes of sperm and oocyte.

As sperm cells approach the **zona pellucida**, the thick layer of glycoprotein that surrounds the egg, they go through a process known as the **acrosome reaction**. The contents of their acrosomes, which include many enzymes, are released to penetrate the outer layers of follicle cells covering the secondary oocyte and allow the sperm cells through. For fertilisation to be

successful, many sperm cells must be present to release the contents of their acrosomes, but only one sperm cell will eventually break through and reach the plasma membrane, where the membrane of its empty acrosome fuses with it.

After fusion has occurred, changes known as the **cortical reaction** take place in the membrane of the oocyte, which modify the zona pellucida and also prevent **polyspermy** (the entry of more than one sperm cell nucleus). Cortical granules, the enzyme-containing vesicles found just inside the oocyte, fuse with the plasma membrane in a cascade, away from the point of fusion of the sperm, and release their contents. Some of the enzymes from the cortical granules digest away the sperm cell receptor proteins on the oocyte plasma membrane so that no more sperm cells can attach and fuse.

SCIENCE IN CONTEXT

Oocyte, secondary oocyte or ovum?

Female gametes form in the ovaries during the fetal development of a baby girl. But all the eggs remain at prophase 1 of the first division of meiosis until puberty, and are known as **primary oocytes**. After puberty these primary oocytes continue their development and are released during the menstrual cycle. The immature ovum just after ovulation is known as a **secondary oocyte**. If it is fertilised it completes the final stage of meiosis and becomes a **mature ovum**.

During meiosis, when sperm cells are formed, four mature sperm that are equal in size are produced. But the formation of the ovum involves unequal divisions of the cytoplasm during meiosis. One large cell retains all the cytoplasm from the two divisions of meiosis. The cytoplasm contains materials to nourish a developing embryo and the unwanted chromosomes

are ejected. As the secondary oocyte is fertilised it ejects a polar body containing the final set of chromosomes but no cytoplasm.

8.4.3 Using hormones to treat infertility: *in vitro* fertilisation

***In vitro* fertilisation (IVF)** is a technique used to help couples who have been unable to conceive naturally. *In vitro* are Latin words that mean ‘in glass’ and the process of fertilisation usually takes place in a small glass Petri dish. There are many reasons for infertility. Males may have a low sperm count, blocked or damaged sperm ducts or be unable to achieve an erection. Females may fail to ovulate or have blocked or damaged oviducts, or produce antibodies in cervical mucus that destroy sperm.

The first step in IVF treatment is an assessment of whether the couple are suitable for treatment. If they are, the woman may first be injected with hormones to suppress her natural hormones before being given injections of FSH for about 10 days. In some treatments, FSH may be given alone. This hormone causes a number of egg cells to mature, all at the same time, in her ovaries (which is called superovulation). Just before the egg cells are released from the follicles, they are collected using a laparoscope (a thin tubular instrument that is inserted through an incision, or cut, in the abdominal wall). The egg cells are ‘matured’ in culture medium for up to 24 hours before sperm cells are added to fertilise them. Fertilised egg cells are incubated for about 3 days until they have divided to form a ball of cells. These embryos are checked to make sure they are healthy and developing normally. Usually two will be selected and placed into the woman’s uterus for implantation. The pregnancy is then allowed to continue in the normal way. Any remaining embryos can be frozen and stored for use later. Figure 8.4.7 summarises the stages in IVF treatment.

THEORY OF KNOWLEDGE

Ethical issues associated with IVF treatment

IVF has enabled people who would naturally be infertile to have children, but it has also produced some serious ethical issues. Some of these are outlined in Table 8.4.3.

To consider:

- 1 Discuss these issues, which every society needs to think about.
- 2 Is it ever reasonable to deny treatments such as IVF to individuals who wish to have them?

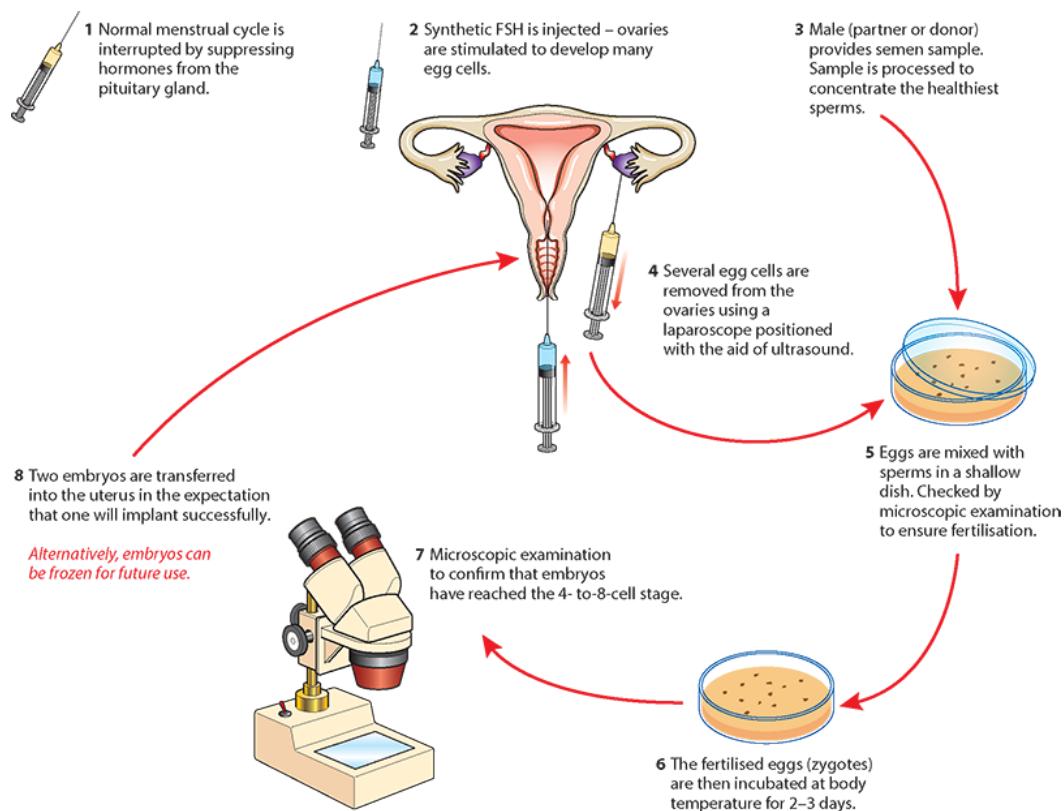


Figure 8.4.7: The stages of IVF treatment.

Arguments in favour of IVF	Arguments against IVF
enables infertile couples to have a family	unused embryos produced by IVF are frozen for a limited period and then destroyed
couples willing to undergo IVF treatment must have determination to become parents	multiple births often result from IVF and this increases the risks to mother and babies
embryos used in IVF treatment can be screened to ensure they are healthy and do not have certain genetic conditions that would be inherited	infertility is natural, whereas IVF is not: some religions object to it on this basis
IVF techniques have led to further understanding of human reproductive biology	some causes of infertility are due to genetic conditions, which may be passed on to children born as a result of IVF
	there may be risks to the health of women who are treated with hormones during IVF

Table 8.4.3: Arguments for and against IVF treatment.

TEST YOUR UNDERSTANDING

- 24** State two differences between sexual and asexual reproduction.

25 Name the four hormones that control the human menstrual cycle.

8.4.4 Hormonal control of developmental changes (puberty)

Puberty is the time when a boy or girl becomes sexually mature and capable of reproduction. The onset of puberty begins when the hypothalamus, a gland in the brain secretes gonadotropin-releasing hormone (GnRH).

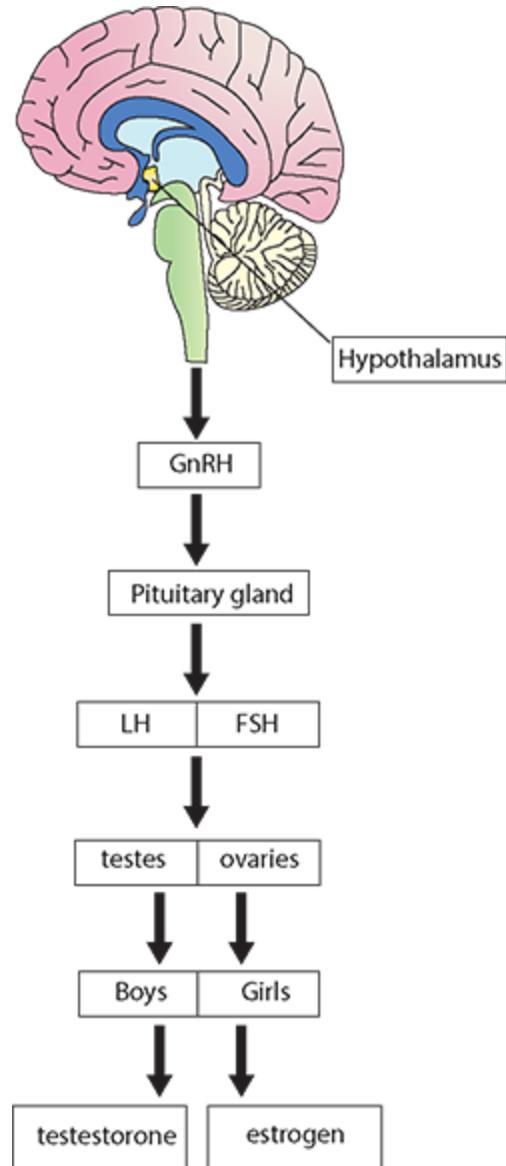


Figure 8.4.8: Hormonal control of puberty.

GnRH stimulates the release of **follicle-stimulating hormone (FSH)** and **luteinising hormone** (LH) from the anterior pituitary gland (APT). Before puberty, FSH and LH levels in the body are low. About one year before the onset of puberty, inhibition of GnRH by the nervous system is reduced so that there is an increase in the release of FSH and LH.

FSH and LH act on the ovaries and testes to stimulate the production and release of sex hormones estrogen and progesterone, and testosterone. Sex hormones have a negative feedback effect on the hypothalamus and pituitary gland to ensure circulating levels remain stable. A rise in FSH stimulates an increase in estrogen synthesis and oogenesis in females and the onset of sperm production in males.

Hormonal changes caused by rises in FSH and LH allow for the physical changes of puberty to begin. For males these include enlargement of the genitals and the growth of body hair and beard, while for females they include development of breasts and widening of the hips.

Spermatogenesis

Spermatogenesis is the production of mature sperm cells (spermatozoa) in the testis. More than 100 million sperm cells are produced each day in a process that takes place in the narrow seminiferous tubules making up each testis (Figures 8.4.9).

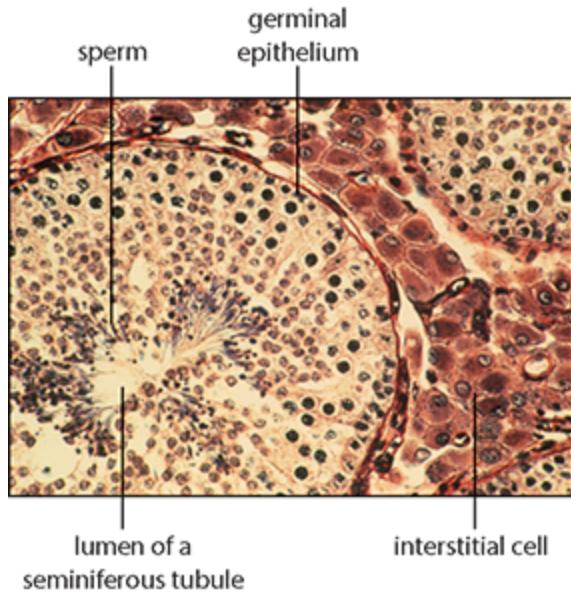


Figure 8.4.9: Coloured light micrograph of transverse section of a testis showing seminiferous tubules with interstitial cells between them ($\times 170$).

Sperm production and development takes place from the outer part of the **seminiferous tubules** towards the central lumen, where sperm cells are eventually released. Each tubule is enclosed in a basement membrane beneath which is an outer layer of germinal epithelium cells. These diploid cells ($2n$) divide regularly by mitosis to produce more diploid cells, which enlarge and are known as **primary spermatocytes**.

Primary spermatocytes divide by meiosis and their first division produces two haploid (n) cells called secondary spermatocytes. The second division of these two cells results in four **spermatids** (n).

Developing sperm are attached to **Sertoli cells** (Figure 8.4.10), which are also called nurse cells. These large cells assist the differentiation of immature spermatids into spermatozoa and provide nourishment for them.

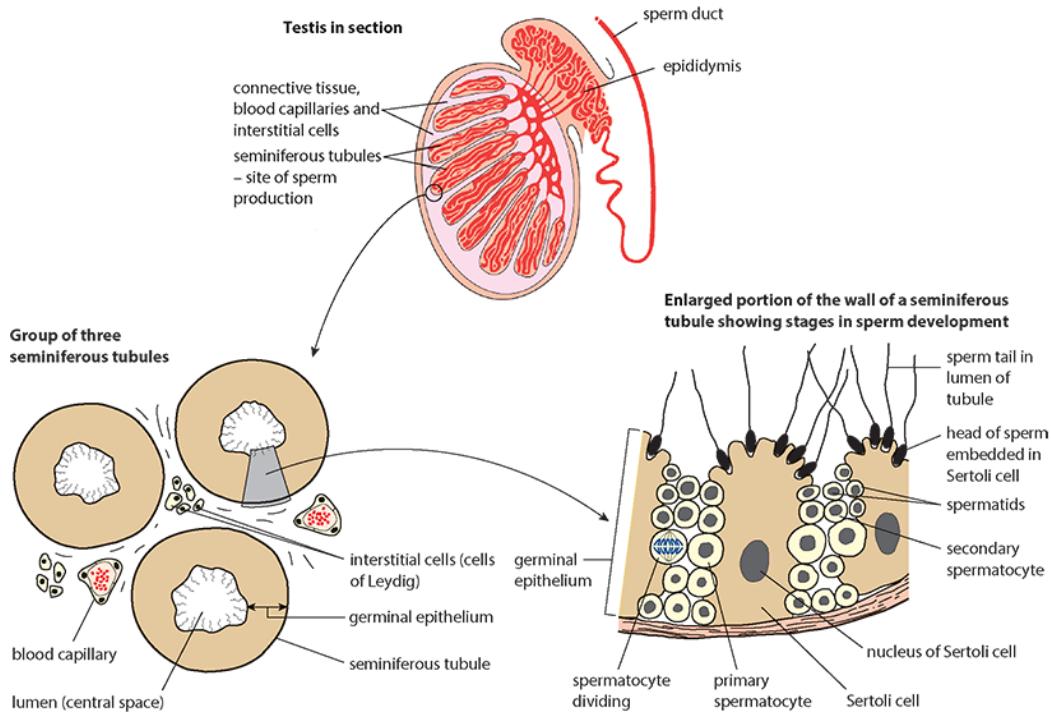


Figure 8.4.10: Structure of the testis.

Spermatozoa that have developed their tails (Figure 8.4.11) detach from the Sertoli cells and are carried down the lumen of the tubule to the epididymis of the testis.

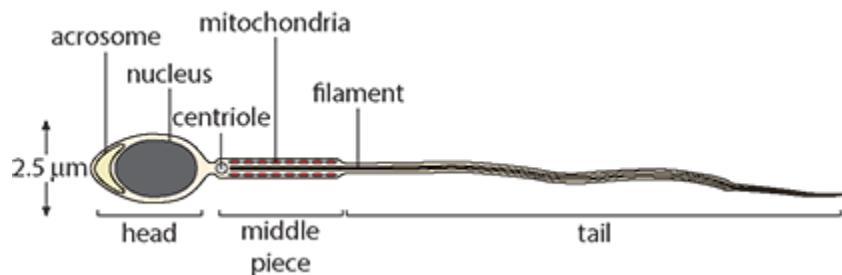


Figure 8.4.11: Structure of a human sperm cell. Total length is 60 μm .

Hormones and sperm production

Sperm production is controlled by three hormones – follicle-stimulating hormone (FSH) and luteinising hormone (LH) from

the pituitary gland, and testosterone produced by the testes.

- **FSH** stimulates meiosis in spermatocytes, to produce haploid cells.
- Testosterone stimulates the maturation of secondary spermatocytes into mature sperm cells.
- LH stimulates the secretion of testosterone by the testis.

Epididymis, seminal vesicles and semen production

Sperm cells are stored and mature in the epididymis, where they also develop the ability to swim. Sperm cells are released at ejaculation in a nutrient-rich fluid known as semen. Semen is produced by two seminal vesicles and the prostate gland. It is mixed with the sperm cells as they leave the epididymis and move along the vas deferens (sperm duct). Fluid from the seminal vesicles makes up about 70% of semen. It is rich in fructose, which provides energy for the sperm cells to swim, and it also contains protective mucus. The prostate gland produces an alkaline fluid that helps the sperm cells to survive in the acidic conditions of the vagina.

Oogenesis

Oogenesis produces female gametes, the ova. Unlike spermatogenesis, which takes place in an adult male, oogenesis begins in the ovaries of a female when she is still a fetus.

Oogonia, the germinal epithelial cells within the ovaries of the female fetus, divide by mitosis to produce more diploid ($2n$) cells. These enlarge to form primary oocytes, which are also diploid. Primary oocytes undergo the first stages of meiosis but this stops during prophase I, leaving the primary oocyte surrounded by a layer of follicle cells in a structure known as the

primary follicle. Development now ceases but the ovaries of a baby girl contain around 300000 primary follicles at birth. The remaining stages of oogenesis are shown in Figure 8.4.12.

At puberty, development of the primary follicles continues. During each menstrual cycle, a few follicles proceed to complete the first division of meiosis, although usually just one will complete its development. Two haploid cells (n) are produced but the cytoplasm divides unequally so that one cell is much larger than the other. The larger cell is known as the secondary oocyte (n) and the smaller cell is the polar body (n). The polar body degenerates and does not develop further.

The secondary oocyte, protected within its follicle, begins meiosis II but stops in prophase II. At the same time, the follicle cells divide and produce a fluid that causes the follicle to swell. At the point of **ovulation**, the follicle bursts, releasing the secondary oocyte, which floats towards the oviduct. Although ovulation is often described as the release of the ovum, the cell that is released is in fact still a secondary oocyte. The detailed structure of a secondary oocyte is shown in Figure 8.4.13, and Figure 8.4.14 shows secondary oocytes in a rabbit ovary in section.

After fertilisation, the secondary oocyte completes meiosis II, becoming a mature ovum, and expels a second polar body, which degenerates. The empty follicle in the ovary develops to become the **corpus luteum**, or ‘yellow body’, which produces the hormone progesterone.

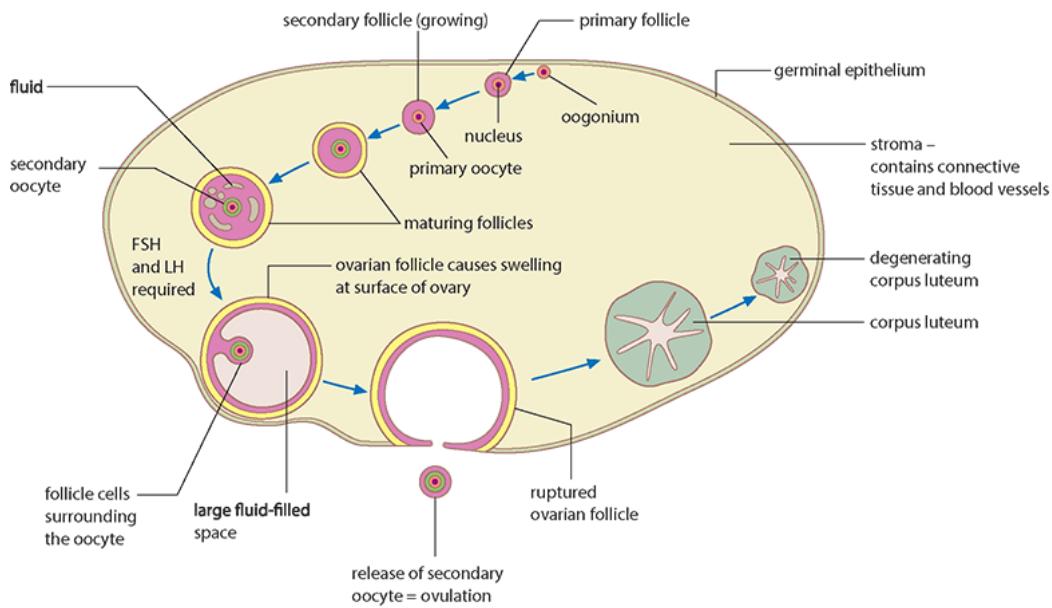


Figure 8.4.12: Stages in the development of one follicle in a human ovary. The arrows show the sequence of events.

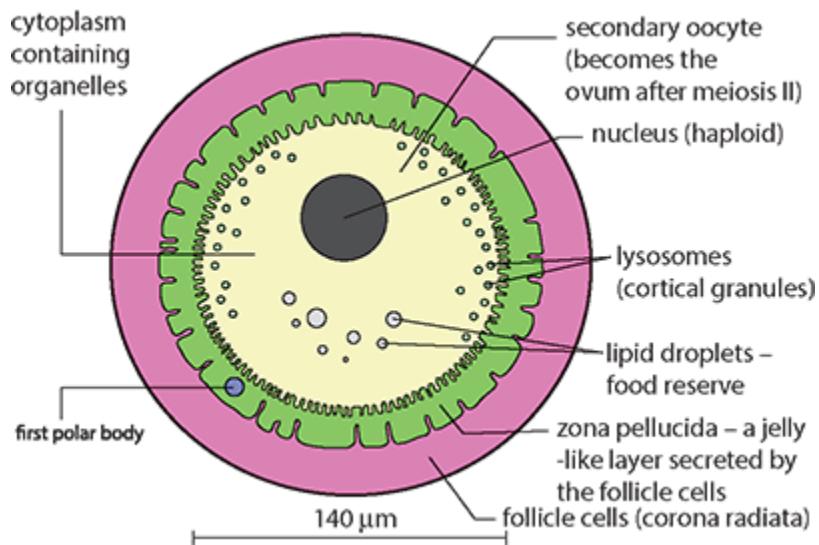


Figure 8.4.13: Structure of the secondary oocyte and ovulation surrounding structures at ovulation.

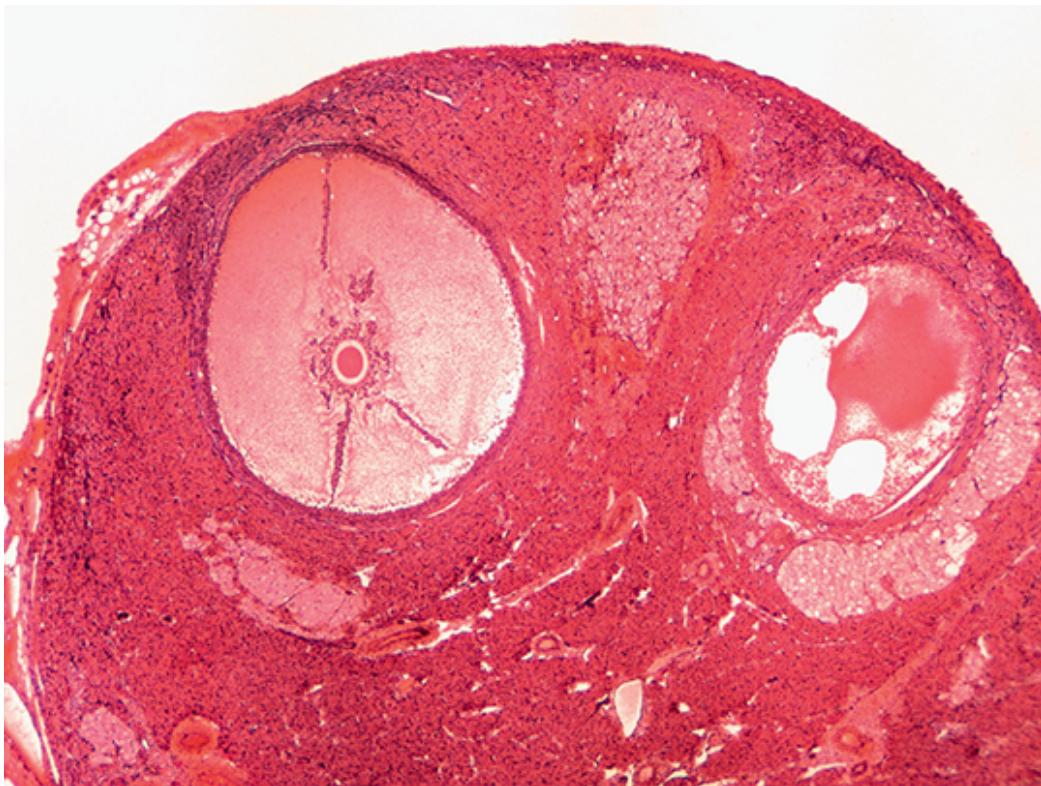


Figure 8.4.14: Longitudinal section of the ovary of a rabbit showing a mature follicle ($\times 22.5$).

Comparing spermatogenesis and oogenesis

There are a number of similarities and also several differences between the processes of spermatogenesis and oogenesis, as shown in Figure 8.4.15. Both involve the division of cells in the germinal epithelium by mitosis, and the growth of cells before they undergo meiosis and differentiation.

In both cases, meiosis produces haploid gametes. Table 8.4.4 summarises the differences and similarities in the two processes.