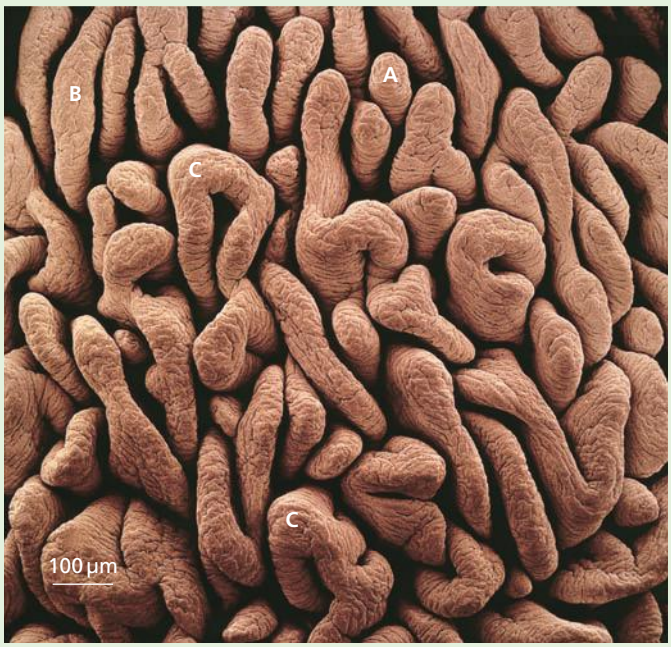


Figure 7.24 Scanning electron micrograph of the human intestinal lining (×60). The villi are about 0.5 mm long. In the duodenum they are mostly leaf-like (C), but further towards the ileum they become narrower (B), and in the ileum they are mostly finger-like (A). This micrograph is of a region in the duodenum.

Absorption of the products of digestion and other dietary items is not just a matter of simple diffusion, except perhaps for alcohol and, sometimes, water. Although the mechanisms for transport across the intestinal epithelium have not been fully worked out, it seems likely that various forms of active transport are involved. Even water can cross the epithelium against an osmotic gradient (Chapter 3). Amino acids, sugars and salts are, almost certainly, taken up by active transport. Glucose, for example, crosses the epithelium faster than fructose (another monosaccharide sugar) although their rates of diffusion would be about the same.

The epithelial cells of the villi are constantly being shed into the intestine. Rapid cell division in the epithelium of the crypts (Figure 7.23) replaces these lost cells. In effect there is a steady procession of epithelial cells moving up from the crypts to the villi.

Use of digested food

The products of digestion are carried around the body in the blood. From the blood, cells absorb and use glucose, fats and amino acids. This uptake and use of food is called **assimilation**.

Glucose

During respiration in the cells, glucose is oxidised to carbon dioxide and water (see 'Aerobic respiration' in Chapter 12). This reaction provides energy to drive the many chemical processes in the cells, which result in, for example, the building-up of proteins, contraction of muscles or electrical changes in nerves.

Fats

These are built into cell membranes and other cell structures. Fats also form an important source of energy for cell metabolism. Fatty acids produced from stored fats or taken in with the food, are oxidised in the cells to carbon dioxide and water. This releases energy for processes such as muscle contraction. Fats can provide twice as much energy as sugars.

Amino acids

These are absorbed by the cells and built up, with the aid of enzymes, into proteins. Some of the proteins will become plasma proteins in the blood (see 'Blood' in Chapter 9). Others may form structures such as cell membranes or they may become enzymes that control the chemical activity within the cell. Amino acids not needed for making cell proteins are converted by the liver into glycogen, which can then be used for energy.

Practical work

Experiments on digestion

1 The action of salivary amylase on starch

- Rinse the mouth with water to remove traces of food.
- Collect saliva* in two test-tubes, labelled A and B, to a depth of about 15 mm (see Figure 7.25).
- Heat the saliva in tube B over a small flame, or in a water bath of boiling water, until it boils for about 30 seconds and then cool the tube under the tap.
- Add about 2 cm^3 of a 2% starch solution to each tube; shake each tube and leave them for 5 minutes.
- Share the contents of tube A between two clean test-tubes.
- To one of these add some iodine solution. To the other add some Benedict's solution and heat in a water bath as described in Chapter 4.
- Test the contents of tube B in exactly the same way.

*If there is some objection to using your own saliva, use a 5 per cent solution of commercially prepared amylase instead.

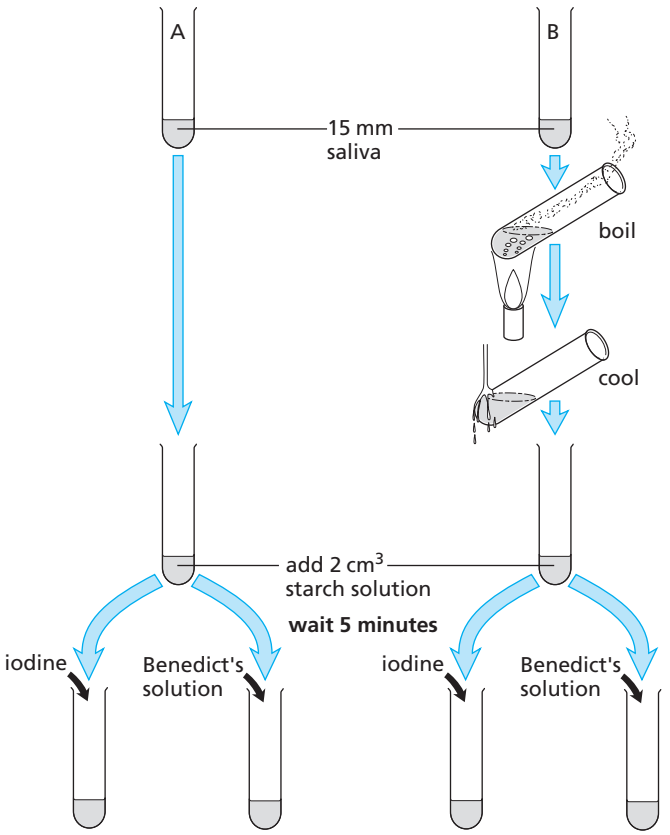


Figure 7.25 Experiment to show the action of salivary amylase on starch

Results

The contents of tube A fail to give a blue colour with iodine, showing that the starch has gone. The other half of the contents, however, gives a red or orange precipitate with Benedict's solution, showing that sugar is present.

The contents of tube B still give a blue colour with iodine but do not form a red precipitate on heating with Benedict's solution.

Interpretation

The results with tube A suggest that something in saliva has converted starch into sugar. The fact that the boiled saliva in tube B fails to do this suggests that it was an enzyme in saliva that brought about the change (see Chapter 5), because enzymes are proteins and are destroyed by boiling. If the boiled saliva had changed starch to sugar, it would have ruled out the possibility of an enzyme being responsible.

This interpretation assumes that it is something in saliva that changes starch into sugar. However, the results could equally well support the claim that starch can turn unboiled saliva into sugar. Our knowledge of (1) the chemical composition of starch and saliva and (2) the effect of heat on enzymes, makes the first interpretation more plausible.

2 Modelling the action of amylase on starch

- Collect a 15 cm length of Visking tubing which has been softened in water.
- Tie one end tightly. Use a syringe to introduce 2% starch solution into the Visking tubing, to about two thirds full.
- Add 2 cm^3 of 5% amylase solution (or saliva if it is permissible).
- Pinch the top of the Visking tubing to keep it closed, before carefully mixing its contents by squeezing the tubing.
- Rinse the outside of the Visking tubing thoroughly with tap water, then place it in a boiling tube, trapping the top of the tubing with an elastic band (see Figure 7.26).
- Add enough distilled water to cover the Visking tubing.
- Test a small sample of the distilled water and the contents of the Visking tubing for starch and reducing sugar, using iodine solution and Benedict's solution (see page 58 for methods).
- Place the boiling tube in a beaker of water or a water bath at 37 °C.
- After 20 minutes, use clean teat pipettes to remove a sample of the water surrounding the Visking tubing and from inside the Visking tubing.
- Test some of each sample for starch, using iodine solution, and for reducing sugar, using Benedict's solution (see Chapter 4 for methods). Also test some of the original starch solution for reducing sugar, to make sure it is not contaminated with glucose.

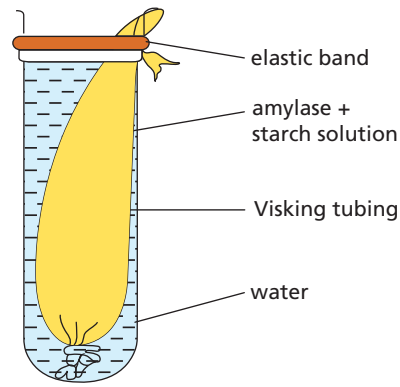


Figure 7.26 Experiment to model the digestion of starch

Result

At the start of the investigation the distilled water tests negative for starch (stays brown) and reducing sugar (stays turquoise). The contents of the Visking tubing are positive for starch (blue-black), but negative for reducing sugars (stays turquoise).

After 20 minutes, the contents of the Visking tubing are yellow/brown with iodine solution, but turn orange or brick red with Benedict's solution. The water sample stays yellow/brown with iodine solution, but turns orange or brick red with Benedict's solution.

Interpretation

The amylase digests the starch in the Visking tubing, producing reducing sugar. The complete digestion of starch results in a negative colour change with iodine solution. The presence of reducing sugar (maltose or glucose) causes the Benedict's solution to turn orange or brick red. The reducing sugar molecules can diffuse through the Visking tubing into the surrounding water, so the water gives a positive result with Benedict's solution. Starch is a large molecule, so it cannot diffuse through the tubing: the water gives a negative result with iodine solution.

This model can be used to represent digestion in the gut. The starch solution and amylase are the contents of the mouth or

duodenum. The Visking tubing represents the duodenum wall and the distilled water represents the bloodstream, into which the products of digestion are absorbed.

3 The action of pepsin on egg-white protein

A cloudy suspension of egg-white is prepared by stirring the white of one egg into 500 cm^3 tap water, heating it to boiling point and filtering it through glass wool to remove the larger particles.

- Label four test-tubes A, B, C and D and place 2 cm^3 egg-white suspension in each of them. Then add pepsin solution and/or dilute hydrochloric acid (HCl) to the tubes as follows (Figure 7.27):

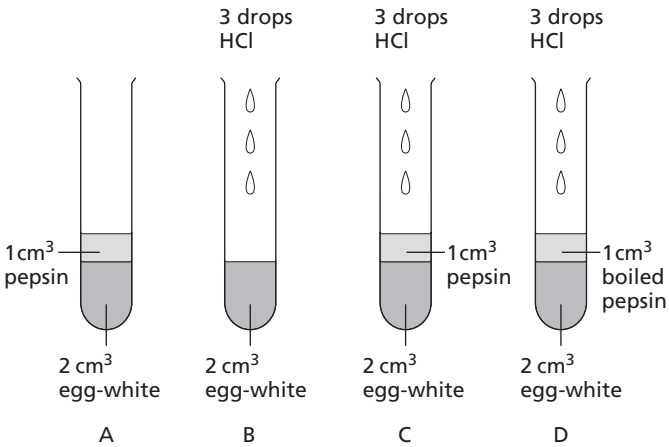


Figure 7.27 Experiment to show the action of pepsin on egg-white

  - **A** egg-white suspension + 1 cm^3 pepsin solution (1%)
  - **B** egg-white suspension + 3 drops dilute HCl
  - **C** egg-white suspension + 1 cm^3 pepsin + 3 drops HCl
  - **D** egg-white suspension + 1 cm^3 boiled pepsin + 3 drops HCl
- Place all four tubes in a beaker of warm water at 35 °C for 10–15 minutes.

Result

The contents of tube C go clear. The rest remain cloudy.

Interpretation

The change from a cloudy suspension to a clear solution shows that the solid particles of egg protein have been digested to soluble products. The failure of the other three tubes to give clear solutions shows that:

- pepsin will only work in acid solutions
- it is the pepsin and not the hydrochloric acid that does the digestion
- pepsin is an enzyme, because its activity is destroyed by boiling.

4 The action of lipase

- Place 5 cm^3 milk and 7 cm^3 dilute (0.05 mol dm^{-3}) sodium carbonate solution into each of three test-tubes labelled 1 to 3 (Figure 7.28).
- Add six drops of phenolphthalein to each to turn the contents pink.
- Add 1 cm^3 of 3% bile salts solution to tubes 2 and 3.
- Add 1 cm^3 of 5% lipase solution to tubes 1 and 3, and an equal volume of boiled lipase to tube 2.

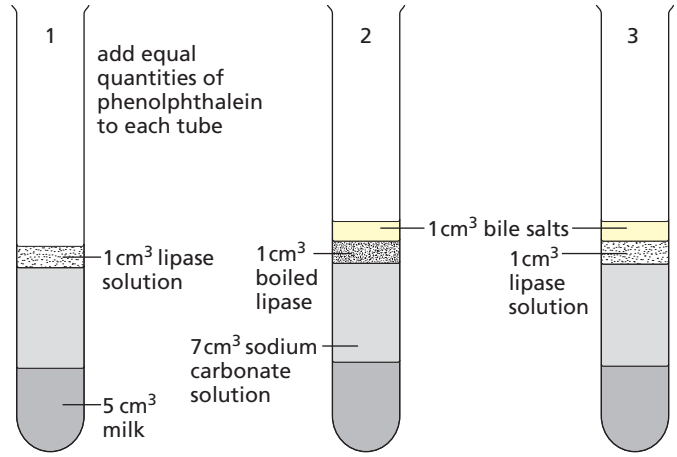


Figure 7.28 Experiment to show the action of lipase

Result

In 10 minutes or less, the colour of the liquids in tubes 1 and 3 will change to white, with tube 3 changing first. The liquid in tube 2 will remain pink.

Interpretation

Lipase is an enzyme that digests fats to fatty acids and glycerol. When lipase acts on milk fats, the fatty acids that have been produced react with the alkaline sodium carbonate and make the solution more acid. In acid conditions the pH indicator, phenolphthalein, changes from pink to colourless. The presence of bile salts in tube 3 seems to speed up the reaction, although bile salts with the denatured enzyme in tube 2 cannot bring about the change on their own.

For experiments investigating the effect of temperature and pH on enzyme action see Chapter 5.

Questions

1. In Experiment 2, why does some reducing sugar remain inside the Visking tubing?
2. In Experiment 3, why does the change from cloudy to clear suggest that digestion has occurred?
3. How would you modify Experiment 3 if you wanted to find the optimum temperature for the action of pepsin on egg-white?
4. Experiment 3 is really two experiments combined because there are two variables.
   - **a** Identify the variables.
   - **b** Which of the tubes could be the control?
5. It was suggested that an alternative interpretation of the result in Experiment 1 might be that starch has turned saliva into sugar. From what you know about starch, saliva and the design of the experiment, explain why this is a less acceptable interpretation.

Questions

Core

1 What sources of protein-rich foods are available to a vegetarian who:
   a will eat animal products but not meat itself
   b will eat only plants and their products?
2 Why must all diets contain some protein?
3 Could you survive on a diet that contained no carbohydrate? Justify your answer.
4 In what sense can the fats in your diet be said to contribute to 'keeping you warm'?
5 How do proteins differ from fats (lipids) in:
   a their chemical composition (Chapter 4)
   b their energy value
   c their role in the body?
6 Construct a flowchart for the digestion and use of proteins, similar to the one for carbohydrates in Figure 7.6.
7 Which tissues of the body need:
   a iron
   b glucose
   c calcium
   d protein?
8 Some examples of the food that would give a balanced diet are shown in Figure 7.29. Consider the picture and say what class of food or item of diet is mainly present. For example, the meat is mainly protein but will also contain some iron.

Figure 7.29 Examples of types of food in a balanced diet (see question 8)

9 What is the value of leafy vegetables, such as cabbage and lettuce, in the diet?
10 Why is a diet consisting mainly of one type of food, e.g. rice or potatoes, likely to be unsatisfactory even if it is sufficient to meet our energy needs?
11 A zoologist is trying to find out whether rabbits need vitamin C in their diet. Assuming that a sufficiently large number of rabbits is used and adequate controls are applied, the best design of experiment would be to give the rabbits:
   a an artificial diet of pure protein, carbohydrate, fats, minerals and vitamins but lacking vitamin C
   b an artificial diet as above but with extra vitamin C
   c a natural diet of grass, carrots, etc. but with added vitamin C
   d natural food but of one kind only, e.g. exclusively grass or exclusively carrots?
   Justify your choice and say why you excluded the other alternatives.
12 Name three functions of the alimentary canal shown in Figure 7.11.
13 Into what parts of the alimentary canal do the following pour their digestive juices?
   a the pancreas
   b the salivary glands
14 Starting from the inside, name the layers of tissue that make up the alimentary canal.
15 a Why is it necessary for our food to be digested?
   b Why do plants not need a digestive system? (See 'Photosynthesis' in Chapter 6.)
16 In which parts of the alimentary canal are the following digested?
   a starch
   b protein
17 Study the characteristics of enzymes in Chapter 5. In what ways does pepsin show the characteristics of an enzyme?
18 In experiments with enzymes, the control often involves the boiled enzyme. Suggest why this type of control is used.
19 a What process in the body enables the *majority* of the reducing sugar in the ileum to be absorbed by the bloodstream?
   b What is needed to achieve this process?
20 Write down the menu for your breakfast and lunch (or supper). State the main food substances present in each item of the meal. State the final digestion product of each.

Extended

21 What are the products of digestion of the following, which are absorbed by the ileum?
   a starch
   b protein
   c fats
22 What characteristics of the small intestine enable it to absorb digested food efficiently?
23 State briefly what happens to a protein molecule in food, from the time it is swallowed, to the time its products are built up into the cytoplasm of a muscle cell.
24 List the chemical changes that a starch molecule undergoes from the time it reaches the duodenum to the time its carbon atoms become part of carbon dioxide molecules. Say where in the body these changes occur.

Checklist

After studying Chapter 7 you should know and understand the following:

- A balanced diet must contain proteins, carbohydrates, fats, minerals, vitamins, fibre and water, in the correct proportions. Dietary needs are affected by the age, gender and activity of humans.
- Growing children and pregnant women have special dietary needs.
- Malnutrition is the result of taking in food that does not match the energy needs of the body, or is lacking in proteins, vitamins or minerals.
- The effects of malnutrition include starvation, coronary heart disease, constipation and scurvy.
- Western diets often contain too much sugar and fat and too little fibre.
- Obesity results from taking in more food than the body needs for energy, growth or replacement.
- Examples of good food sources for the components of a balanced diet.
- Fats, carbohydrates and proteins provide energy.
- Proteins provide amino acids for the growth and replacement of the tissues.
- Mineral salts like calcium and iron are needed in tissues such as bone and blood.
- Vegetable fibre helps to maintain a healthy intestine.
- Vitamins are essential in small quantities for chemical reactions in cells.
- Shortage of vitamin C causes scurvy; inadequate vitamin D causes rickets.
- Mechanical digestion breaks down food into smaller pieces, without any chemical change of the food molecules. This process involves teeth, which can become decayed if not cared for properly.
- Chemical digestion is the process that changes large, insoluble food molecules into small, soluble molecules.
- Digestion takes place in the alimentary canal.
- The changes are brought about by chemicals called digestive enzymes.
- The stomach produces gastric juice, which contains hydrochloric acid as well as pepsin.
- The ileum absorbs amino acids, glucose and fats.
- These are carried in the bloodstream first to the liver and then to all parts of the body.
- The small intestine and the colon both absorb water.
- Undigested food is egested through the anus as faeces.
- Diarrhoea is the loss of watery faeces.
- Cholera is a disease caused by a bacterium.

- Malnutrition includes kwashiorkor and marasmus.
- Cholera bacteria produce a toxin that affects osmosis in the gut.
- Internal folds, villi and microvilli greatly increase the absorbing surface of the small intestine.
- The villi have a special structure to enable efficient absorption of digested food.

8 Transport in plants

Transport in plants
Structure and function of xylem and phloem

Water uptake
Pathway taken by water into and through the plant

Root hairs and surface area, linked to osmosis and active transport

Transpiration
Transport of water through the plant
Loss by evaporation through plant leaves
Causes of changes in transpiration rate

Explanation of the mechanism of water uptake and movement
Wilting

Translocation
(no details needed for the Core syllabus)

Structure and function of phloem
Pathway taken by sucrose and amino acids from sources to sinks

Extension work

Before looking in detail at leaf, stem and root structure, it is useful to consider the relationship between these parts and the whole plant.

A young sycamore plant is shown in Figure 8.1. It is typical of many flowering plants in having a **root system** below the ground and a **shoot system** above ground. The shoot consists of an upright stem, with leaves and buds. The buds on the side of the stem are called **lateral buds**. When they grow, they will produce branches. The bud at the tip of the shoot is the **terminal bud** and when it grows, it will continue the upward growth of the stem. The lateral buds and the terminal buds may also produce flowers.

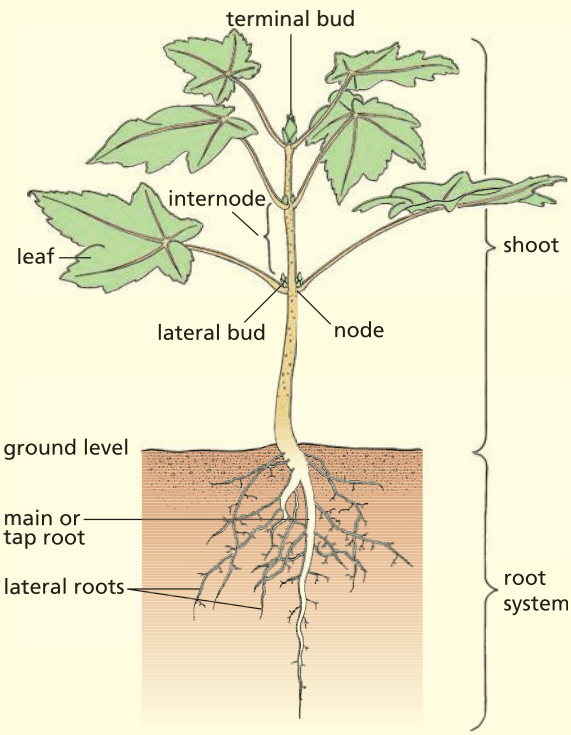


Figure 8.1 Structure of a typical flowering plant

The region of stem from which leaves and buds arise is called a **node**. The region of stem between two nodes is the **internode**.

The **leaves** make food by photosynthesis (Chapter 6) and pass it back to the stem.

The **stem** carries this food to all parts of the plant that need it and also carries water and dissolved salts from the roots to the leaves and flowers.

In addition, the stem supports and spaces out the leaves so that they can receive sunlight and absorb carbon dioxide, which they need for photosynthesis.

An upright stem also holds the flowers above the ground, helping the pollination by insects or the wind (see 'Sexual reproduction in plants' in Chapter 16). A tall stem may help in seed dispersal later on.

The **roots** anchor the plant in the soil and prevent it from falling over or being blown over by the wind. They also absorb the water and salts that the plant needs for making food in the leaves. A third function is sometimes the storage of food made by the leaves.

Transport in plants

Plant structure and function

Leaf

The structure of a leaf has already been described in Chapter 6. Xylem and phloem appear in the midrib of the leaf, as well as in the leaf veins. These features are identified in Chapter 6, Figures 6.18 and 6.19.

Stem

Figure 8.2 shows a stem cut across (transversely) and down its length (longitudinally) to show its internal structure.

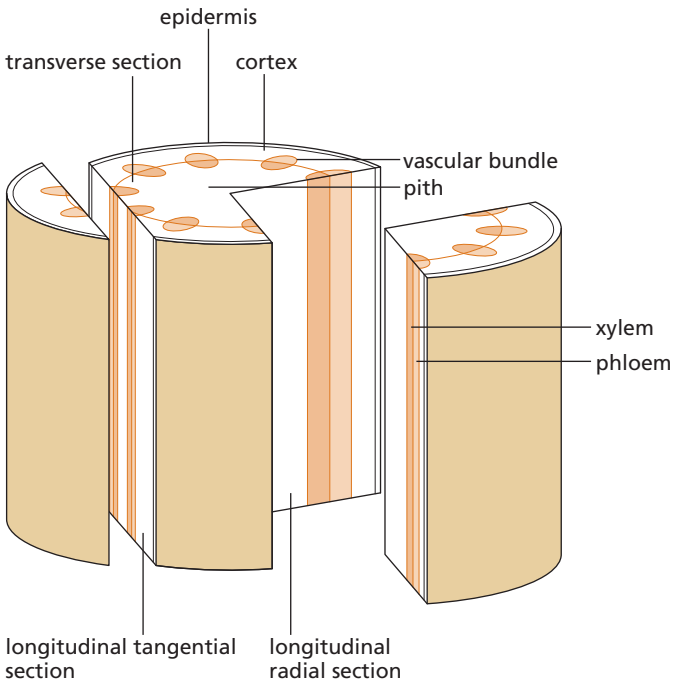


Figure 8.2 Structure of a plant stem

Epidermis

Like the leaf epidermis, this is a single layer of cells that helps to keep the shape of the stem and cuts down the loss of water vapour. Stomata in the epidermis allow the tissues inside to take up oxygen and get rid of carbon dioxide. In woody stems, the epidermis is replaced by bark, which consists of many layers of dead cells.

Vascular bundles

These are made up of groups of specialised cells that conduct water, dissolved salts and food up or down the stem. The vascular bundles in the roots, stem, leaf stalks and leaf veins all connect up to form a transport system throughout the entire plant (Figure 8.3). The two main tissues in the vascular bundles are called **xylem** and **phloem** (Figure 8.4). Food substances travel in the phloem; water and salts travel mainly in the xylem. The cells in each tissue form elongated tubes called **vessels** (in the xylem) or **sieve tubes** (in the phloem) and they are surrounded and supported by other cells.

Vessels

The cells in the xylem that carry water become vessels. A vessel is made up of a series of long cells joined end to end (Figure 8.5(a)). Once a region of the plant has ceased growing, the end walls of these cells are digested away to form a continuous, fine tube (Figure 8.4(c)). At the same time, the cell walls are thickened and impregnated with a substance called **lignin**, which makes the cell wall very strong and impermeable. Since these lignified cell walls prevent the free passage of water and nutrients, the cytoplasm dies. This does not affect the passage of water in the vessels. Xylem also contains many elongated, lignified supporting cells called **fibres**.

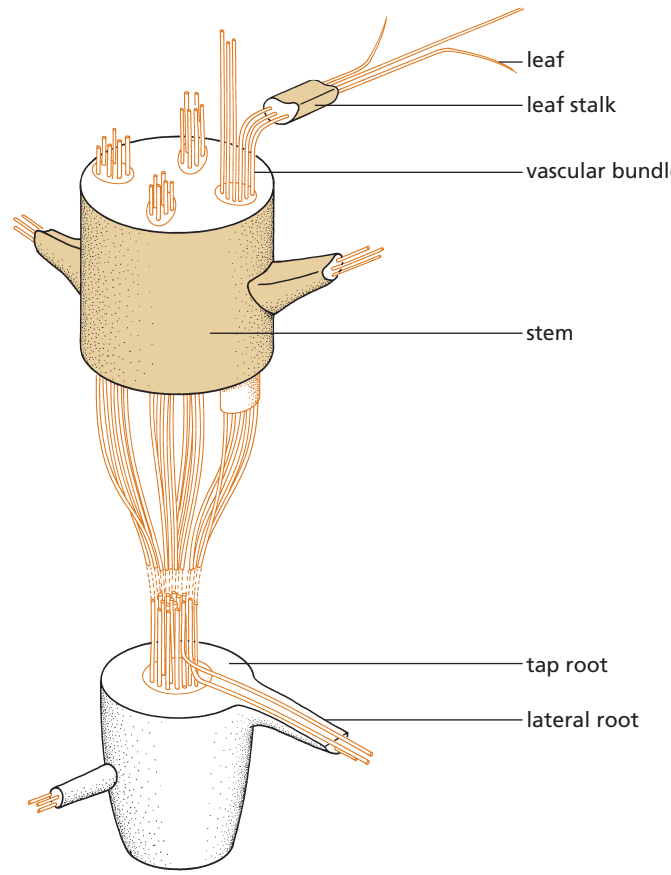
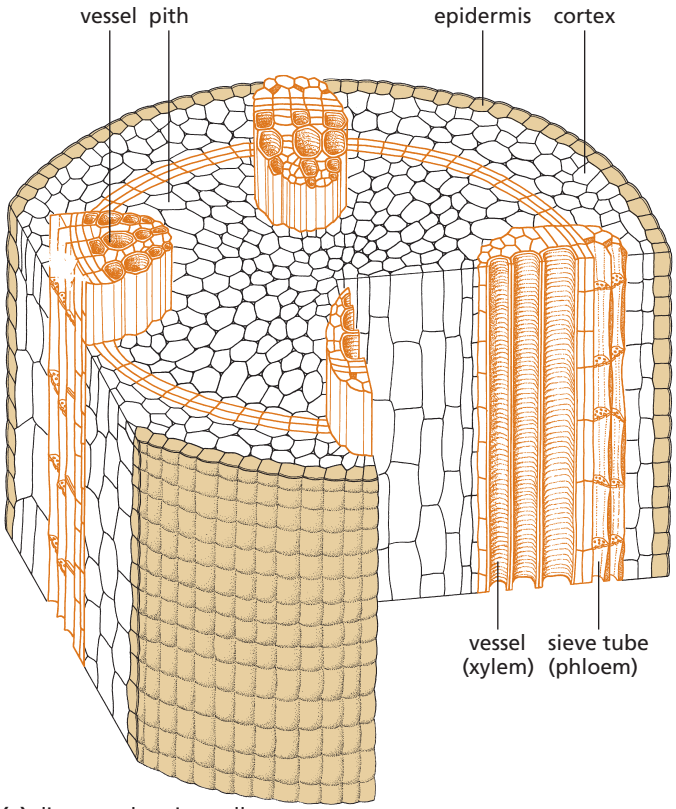


Figure 8.3 Distribution of veins from root to leaf

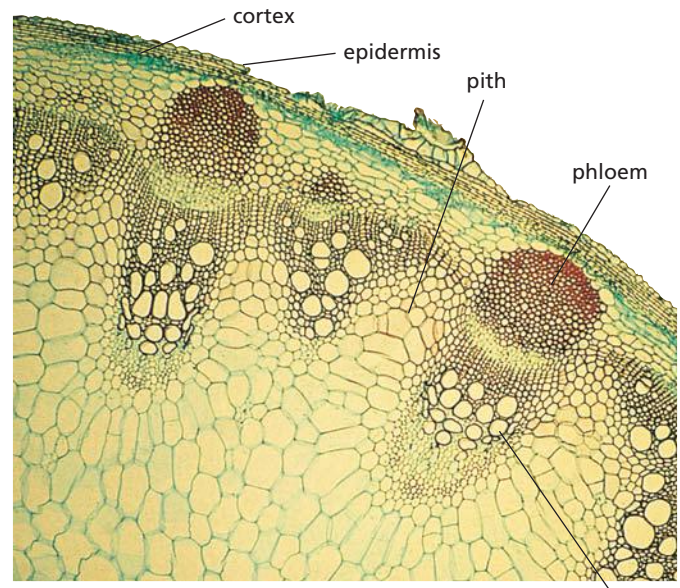
Sieve tubes

The conducting cells in the phloem remain alive and form sieve tubes. Like vessels, they are formed by vertical columns of cells (Figure 8.5(b)). Perforations appear in the end walls, allowing substances to pass from cell to cell, but the cell walls are not lignified and the cell contents do not die, although they do lose their nuclei. The perforated end walls are called **sieve plates**.

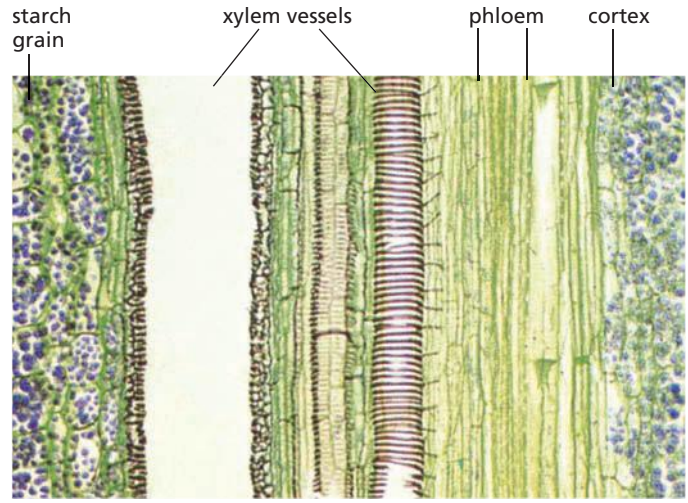
Phloem contains supporting cells as well as sieve tubes.



(a) diagram showing cells



(b) transverse section through sunflower stem (x40)



(c) longitudinal section through sunflower stem (x200)

Figure 8.4 Structure of plant stem

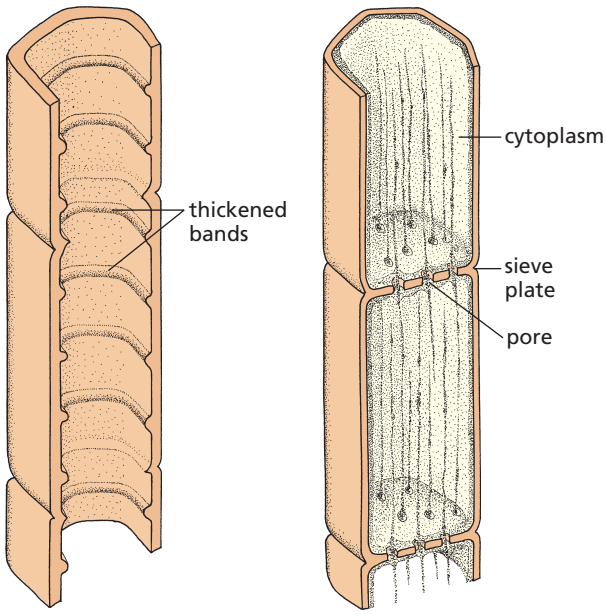
Functions of vascular bundles

In general, water travels up the stem in the xylem from the roots to the leaves. Food may travel either up or down the stem in the phloem, from the leaves where it is made (the '**source**'), to any part of the plant that is using or storing it (the '**sink**').

Vascular bundles have a supporting function as well as a transport function, because they contain vessels, fibres and other thick-walled, lignified, elongated cells. In many stems, the vascular bundles are arranged in a cylinder, a little way in from the epidermis. This pattern of distribution helps the stem to resist the sideways bending forces caused by the wind. In a root, the vascular bundles are in the centre (Figure 8.6) where they resist the pulling forces that the root is likely to experience when the shoot is being blown about by the wind.

The network of veins in many leaves supports the soft mesophyll tissues and resists stresses that could lead to tearing.

The methods by which water, salts and food are moved through the vessels and sieve tubes are discussed in 'Transpiration' and 'Translocation' later in this chapter.



(a) cells forming a xylem vessel

(b) cells forming a phloem sieve tube

Figure 8.5 Conducting structures in a plant

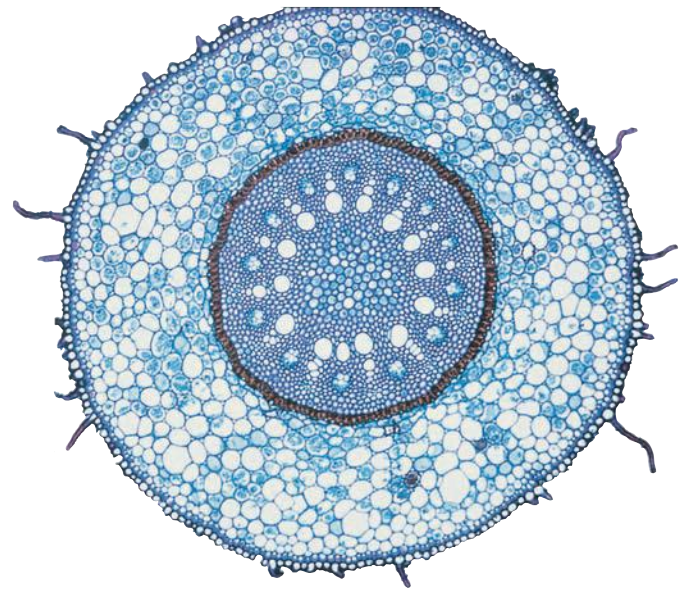


Figure 8.6 Transverse section through a root (×40). Notice that the vascular tissue is in the centre. Some root hairs can be seen in the outer layer of cells.

Cortex and pith

The tissue between the vascular bundles and the epidermis is called the **cortex**. Its cells often store starch. In green stems, the outer cortex cells contain chloroplasts and make food by photosynthesis. The central tissue of the stem is called **pith**. The cells of the pith and cortex act as packing tissues and help to support the stem in the same way that a lot of blown-up balloons packed tightly into a plastic bag would form quite a rigid structure.

Root

The internal structure of a typical root is shown in Figure 8.7. The vascular bundle is in the centre of the root (Figure 8.6), unlike the stem where the bundles form a cylinder in the cortex.

The xylem carries water and salts from the root to the stem. The phloem brings food from the stem to the root, to provide the root cells with substances for their energy and growth.

Outer layer and root hairs

There is no distinct epidermis in a root. At the root tip are several layers of cells forming the **root cap**. These cells are continually replaced as fast as they are worn away when the root tip is pushed through the soil.

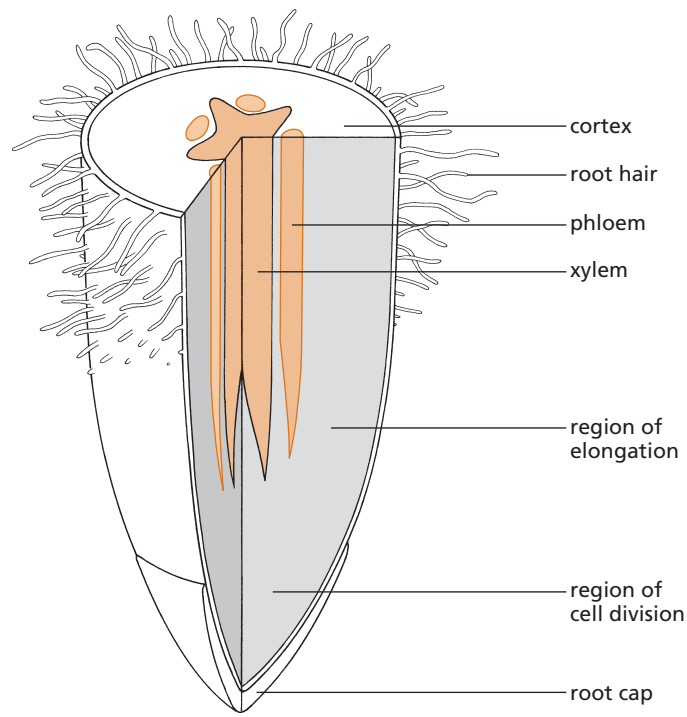


Figure 8.7 Root structure

In a region above the root tip, where the root has just stopped growing, the cells of the outer layer produce tiny, tube-like outgrowths called **root hairs** (Figure 8.11, page 115). These can just be seen as a white furry layer on the roots of seedlings grown in moist air (Figure 8.8). In the soil, the root hairs grow

between the soil particles and stick closely to them. The root hairs take up water from the soil by osmosis and absorb mineral salts (as ions) by active transport (Chapter 3).

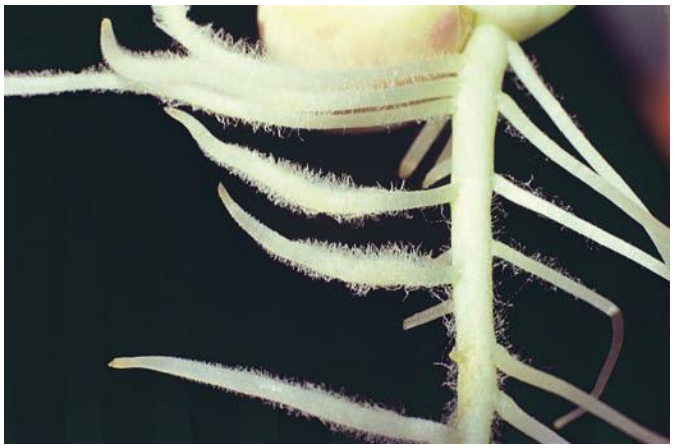


Figure 8.8 Root hairs (×5) as they appear on a root grown in moist air

Root hairs remain alive for only a short time. The region of root just below a root hair zone is producing new root hairs while the root hairs at the top of the zone are shrivelling (Figure 8.9). Above the root hair zone, the cell walls of the outer layer become less permeable. This means that water cannot get in so easily.

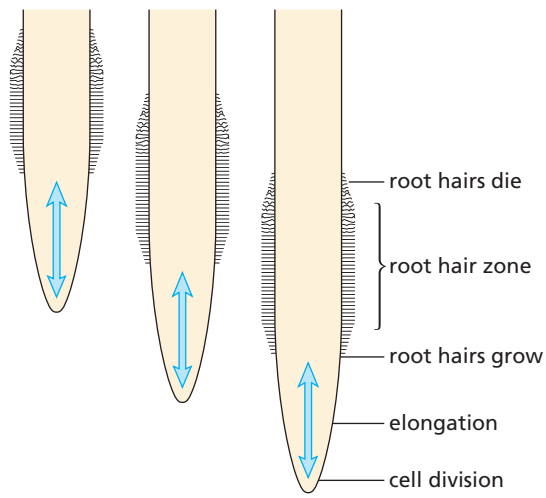


Figure 8.9 The root hair zone changes as the root grows.

Extension work

Tap root

When a seed germinates, a single root grows vertically down into the soil. Later, lateral roots grow from this at an acute angle outwards and downwards, and from these laterals other branches may arise. Where a main root is recognisable the arrangement is called a **tap-root system** (Figure 8.10(a)).

(a) tap-root system e.g. dandelion

(b) fibrous root system e.g. couch grass

Figure 8.10 Types of root system

Fibrous root

When a seed of the grass and cereal group germinates, several roots grow out at the same time and laterals grow from them. There is no distinguishable main root and it is called a **fibrous root system** (Figure 8.10(b)).

Adventitious root

Where roots grow not from a main root, but directly from the stem as they do in bulbs, corms, rhizomes or ivy, they are called **adventitious roots**, but such a system may also be described as a fibrous rooting system.

Water uptake

Pathway taken by water

The water tension developed in the vessels by a rapidly transpiring plant (see next section) is thought to be sufficient to draw water through the root from the soil. The water enters the root hair cells and is then passed on to cells in the root cortex. It enters the xylem vessels to be transported up the stem and into the leaves, arriving at the leaf mesophyll cells.

Practical work

Transport in the vascular bundles

- Place the shoots of several leafy plants in a solution of 1% methylene blue. 'Busy Lizzie' (*Impatiens*) or celery stalks with leaves are usually effective.
- Leave the shoots in the light for up to 24 hours.

Result
If some of the stems are cut across, the dye will be seen in the vascular bundles (see Figure 2.2). In some cases the blue dye will also appear in the leaf veins.

Interpretation
These results show that the dye and, therefore, probably also the water, travel up the stem in the vascular bundles. Closer study would show that they travel in the xylem vessels.

Transport of water in the xylem

- Cut three leafy shoots from a deciduous tree or shrub. Each shoot should have about the same number of leaves.
- On one twig remove a ring of bark about 5 mm wide, about 100 mm up from the cut base.
- With the second shoot, smear a layer of Vaseline over the cut base so that it blocks the vessels. The third twig is a control.
- Place all three twigs in a jar with a little water. The water level must be below the region from which you removed the ring of bark.
- Leave the twigs where they can receive direct sunlight.

Result
After an hour or two, you will probably find that the twig with blocked vessels shows signs of wilting. The other two twigs should still have turgid leaves.

Interpretation
Removal of the bark (including the phloem) has not prevented water from reaching the leaves, but blocking the xylem vessels has. The vessels of the xylem, therefore, offer the most likely route for water passing up the stem.

As Figures 8.7 and 8.8 illustrate, the large number of tiny root hairs greatly increases the absorbing surface of a root system. The surface area of the root system of a mature rye plant has been estimated at about 200 m². The additional surface provided by the root hairs was calculated to be 400 m². The water in the surrounding soil is absorbed by osmosis (see Chapter 3). The precise pathway taken by the water is the subject of some debate, but the path of least resistance seems to be in or between the cell walls rather than through the cells.

When water loss through transpiration is slow, e.g. at night-time or just before bud burst in a deciduous tree, then osmosis may play a more important part in the uptake of water than water tension developed in the vessels. In Figure 8.11, showing a root hair in the soil, the cytoplasm of the root hair is partially permeable to water. The soil water is more dilute than the cell sap and so water passes by osmosis from the soil into the cell sap of the root hair cell. This flow of water into the root hair cell raises the cell's turgor pressure. So water is forced out through the cell wall into the next cell and so on, right through the cortex of the root to the xylem vessels (Figure 8.12).

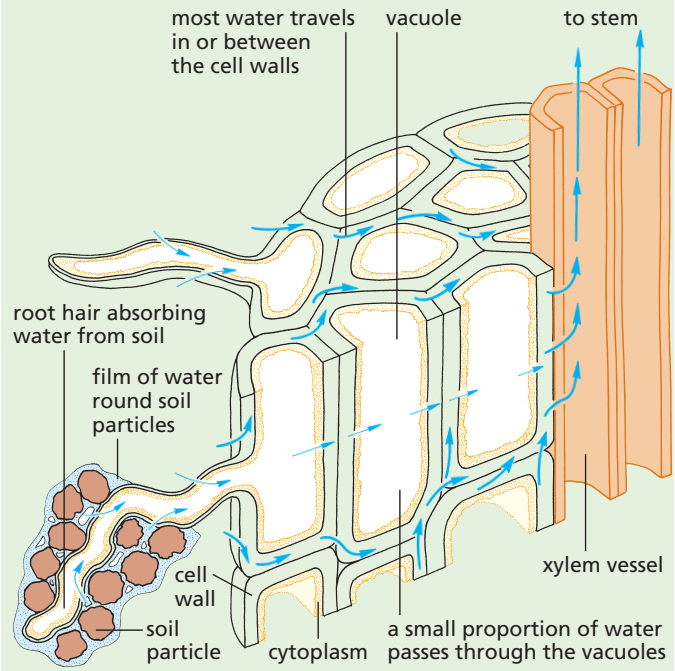


Figure 8.11 The probable pathways of water through a root

One problem for this explanation is that it has not been possible to demonstrate that there is an osmotic gradient across the root cortex that could produce this flow of water from cell to cell. Nevertheless, root pressure developed probably by osmosis does force water up the root system and into the stem.

Uptake of salts

The methods by which roots take up salts from the soil are not fully understood. Some salts may be carried in with the water drawn up by transpiration

and pass mainly along the cell walls in the root cortex and into the xylem.

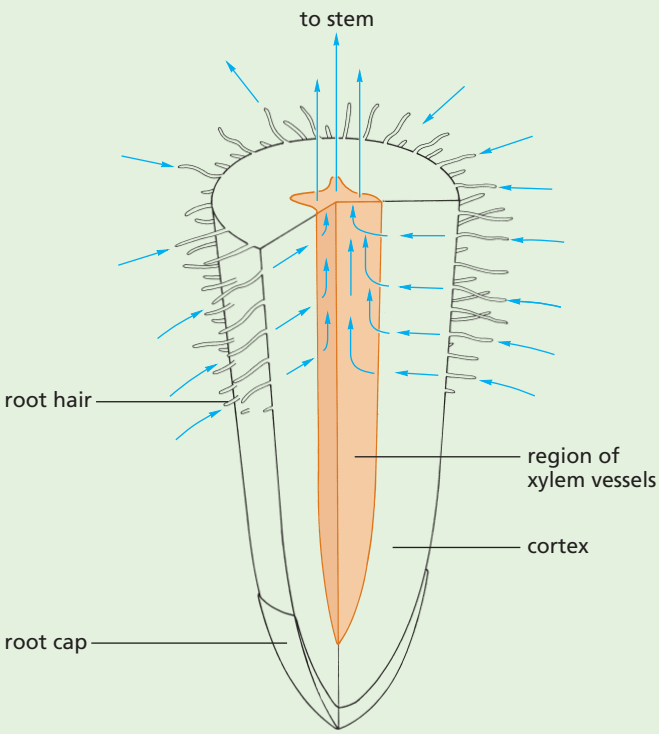


Figure 8.12 Diagrammatic section of root to show passage of water from the soil

It may be that diffusion from a relatively high concentration in the soil to a lower concentration in the root cells accounts for uptake of some individual salts, but it has been shown: (a) that salts can be taken from the soil even when their concentration is below that in the roots, and (b) that anything which interferes with respiration impairs the uptake of salts. This suggests that active transport (Chapter 3) plays an important part in the uptake of salts.

The growing regions of the root and the root hair zone (Figure 8.9) seem to be most active in taking up salts. Most of the salts appear to be carried at first in the xylem vessels, though they soon appear in the phloem as well.

The salts are used by the plant's cells to build up essential molecules. Nitrates, for example, are combined with carbohydrates to make amino acids in the roots. These amino acids are used later to make proteins.

Transpiration

The main force that draws water from the soil and through the plant is caused by a process called **transpiration**. Water evaporates from the leaves and causes a kind of 'suction', which pulls water up the stem (Figure 8.13). The water travels up the xylem vessels in the vascular bundles (see Figure 8.3, page 111) and this flow of water is called the **transpiration stream**.

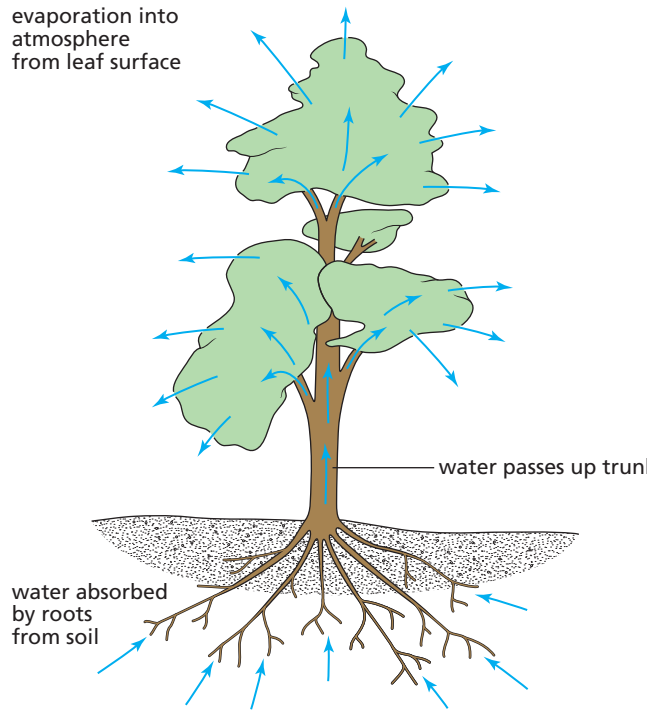


Figure 8.13 The transpiration stream

Key definition

Transpiration is the loss of water vapour from plant leaves by evaporation of water at the surfaces of the mesophyll cells followed by the diffusion of water vapour through the stomata.

Practical work

To demonstrate water loss by a plant

The apparatus shown in Figure 8.14 is called a weight **potometer**. A well-watered potted plant is prepared by surrounding the pot with a plastic bag, sealed around the stem of the plant with an elastic band or string. The plant is then placed on a top-pan balance and its mass is recorded. After a measured time period e.g. 24 hours, the plant is re-weighed and the difference in mass calculated. Knowing the time which has elapsed, the rate of mass loss per hour can be calculated. The process can be repeated, exposing the plant to different environmental conditions, such as higher temperature, wind speed, humidity or light intensity.

Results

The plant loses mass over the measured time period. Increases in temperature, wind speed and light intensity result in larger rates of loss of mass. An increase in humidity would be expected to reduce the rate of loss of mass.

Interpretation

As the roots and soil surrounding the plant have been sealed in a plastic bag, it can be assumed that any mass lost must be due to the evaporation of water vapour from the stem or leaves (transpiration). Increases in temperature, wind speed and light intensity all cause the rate of transpiration to get higher, so the rate of loss of mass from the plant increases. An increase in humidity reduces transpiration, so the rate of loss of mass slows down.

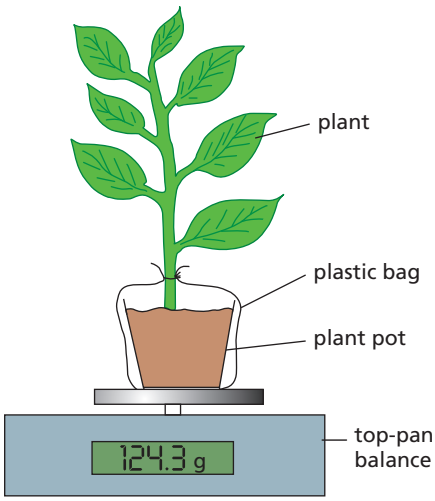


Figure 8.14 A weight potometer

Rates of water uptake in different conditions

The apparatus shown in Figure 8.15 is called a potometer. It is designed to measure the rate of uptake of water in a cut shoot.

- Fill the syringe with water and attach it to the side arm of the 3-way tap.
- Turn the tap downwards (i) and press the syringe until water comes out of the rubber tubing at the top.
- Collect a leafy shoot and push its stem into the rubber tubing as far as possible. Set up the apparatus in a part of the laboratory that is not receiving direct sunlight.
- Turn the tap up (ii) and press the syringe until water comes out of the bottom of the capillary tube. Turn the tap horizontally (iii).
- As the shoot transpires, it will draw water from the capillary tube and the level can be seen to rise. Record the distance moved by the water column in 30 seconds or a minute.
- Turn the tap up and send the water column back to the bottom of the capillary. Turn the tap horizontally and make another measurement of the rate of uptake. In this way obtain the average of three readings.

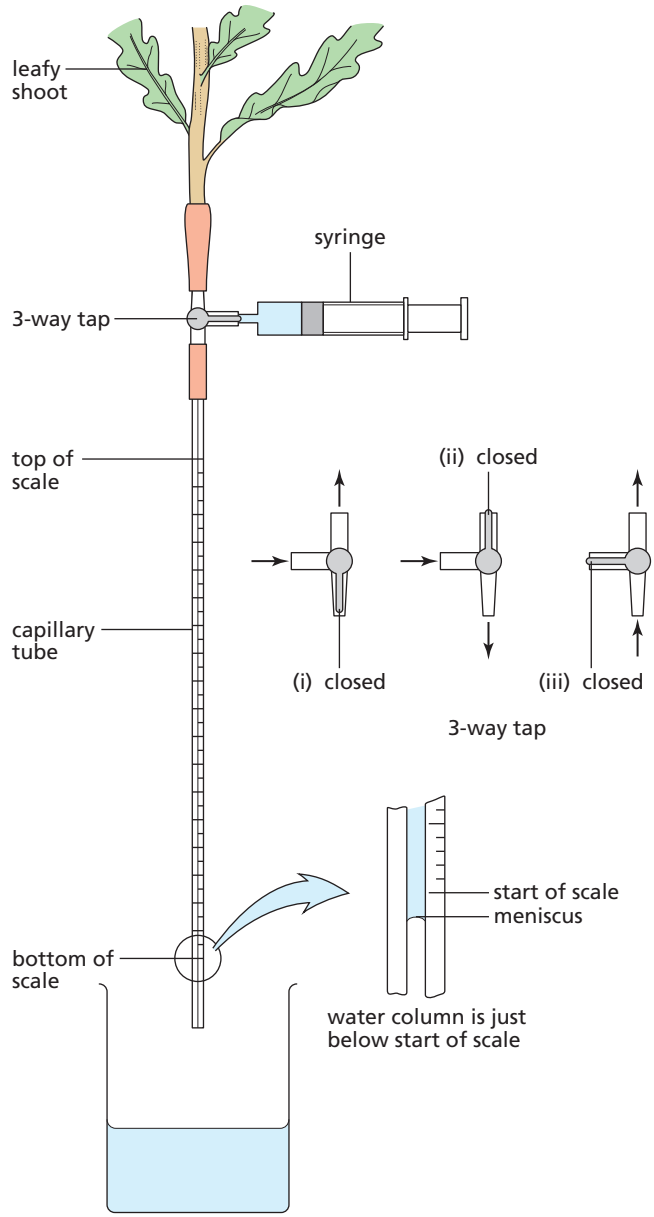


Figure 8.15 A potometer

- The conditions can now be changed in one of the following ways:
  1. Move the apparatus into sunlight or under a fluorescent lamp.
  2. Blow air past the shoot with an electric fan or merely fan it with an exercise book.
  3. Cover the shoot with a plastic bag.
- After each change of conditions, take three more readings of the rate of uptake and notice whether they represent an increase or a decrease in the rate of transpiration.

Results

1. An increase in light intensity should make the stomata open and allow more rapid transpiration.
2. Moving air should increase the rate of evaporation and, therefore, the rate of uptake.
3. The plastic bag will cause a rise in humidity round the leaves and suppress transpiration.

Interpretation
Ideally, you should change only one condition at a time. If you took the experiment outside, you would be changing the light intensity, the temperature and the air movement. When the rate of uptake increased, you would not know which of these three changes was mainly responsible.

To obtain reliable results, you should really keep taking readings until three of them are nearly the same. A change in conditions may take 10 or 15 minutes before it produces a new, steady rate of uptake. In practice, you may not have time to do this, but even your first three readings should indicate a trend towards increased or decreased uptake.

Note: a simpler version of potometer can be used effectively. This does not include the syringe or scaled capillary tubing shown in Figure 8.15.

- The plant stem can be attached directly to a length of capillary tubing with a short section of rubber tubing. This is best carried out in a bowl of water.
- While still in the water, squeeze the rubber tubing to force out any air bubbles.
- Remove the potometer from the water and rub a piece of filter paper against the end of the capillary tubing to introduce an air bubble. The capillary tubing does not need to have a scale: a ruler can be clamped next to the tubing.
- Record the distance moved by the bubble over a measured period of time. Then place the end of the capillary tubing in a beaker of water and squeeze out the air bubble.
- Introduce a new air bubble as previously described and take further readings.

Limitations of the potometer

Although we use the potometer to compare rates of transpiration, it is really the rates of uptake that we are observing. Not all the water taken up will be transpired; some will be used in photosynthesis; some may be absorbed by cells to increase their turgor. However, these quantities are very small compared with the volume of water transpired and they can be disregarded.

The rate of uptake of a cut shoot may not reflect the rate in the intact plant. If the root system were present, it might offer resistance to the flow of water or it could be helping the flow by means of its root pressure.

To find which surface of a leaf loses more water vapour

- Cut four leaves of about the same size from a plant (do not use an evergreen plant). Protect the bench with newspaper and then treat each leaf as follows:
  - a Smear a thin layer of Vaseline (petroleum jelly) on the lower surface.
  - b Smear Vaseline on the upper surface.
  - c Smear Vaseline on both surfaces.
  - d Leave both surfaces free of Vaseline.
- Place a little Vaseline on the cut end of the leaf stalk and then suspend the four leaves from a retort stand with cotton threads for several days.

Result
All the leaves will have shrivelled and curled up to some extent but the ones that lost most water will be the most shrivelled (Figure 8.16).

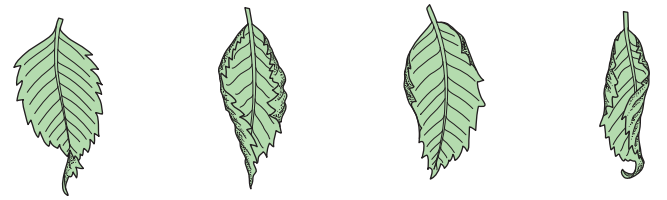


Figure 8.16 The results of evaporation from leaves subjected to different treatments

Interpretation
The Vaseline prevents evaporation. The untreated leaf and the leaf with its upper surface sealed show the greatest degree of shrivelling, so it is from the lower surface that leaves lose most water by evaporation.

More accurate results may be obtained by weighing the leaves at the start and the end of the experiment. It is best to group the leaves from the whole class into their respective batches and weigh each batch. Ideally, the weight loss should be expressed as a percentage of the initial weight.

More rapid results can be obtained by sticking small squares of blue cobalt chloride paper to the upper and lower surface of the same leaf using transparent adhesive tape (Figure 8.17). Cobalt chloride paper changes from blue to pink as it takes up moisture. By comparing the time taken for each square to go pink, the relative rates of evaporation from each surface can be compared.

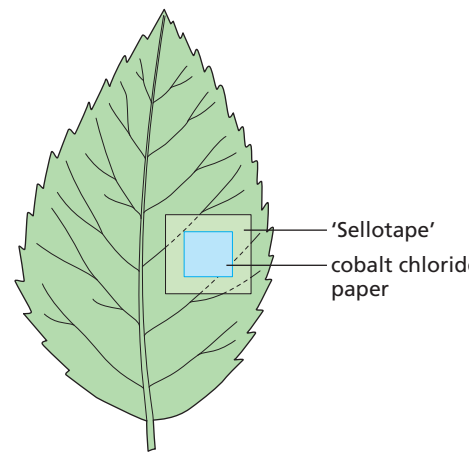


Figure 8.17 To find which surface of a leaf loses more water vapour

The results of either experiment can be correlated with the numbers of stomata on the upper and lower epidermis. This can be done by painting clear nail varnish or 'Germoline New-skin' over each surface and allowing it to dry. The varnish is then peeled off and examined under the microscope. The outlines of the guard cells can be seen and counted.

The cells in part of a leaf blade are shown in Figure 8.18. As explained in 'Osmosis' in Chapter 3, the cell sap in each cell is exerting a turgor pressure outwards on the cell wall. This pressure forces some water out of the cell wall, evaporating into the air space between the cells. The water vapour passes by diffusion through the air spaces in the mesophyll and out of the stomata. It is this loss of water vapour from the leaves that is called 'transpiration'. Each leaf contains many air spaces in the spongy mesophyll and the air becomes saturated with water vapour. There are hundreds of stomata, particularly on the lower epidermis of the leaf, enabling water vapour to diffuse from a high concentration in the air spaces into the atmosphere (representing a lower concentration of water vapour, unless the humidity is high).

The cell walls that are losing water in this way replace it by drawing water from the nearest vein. Most of this water travels along the cell walls without actually going inside the cells (Figure 8.19). Thousands of leaf cells are evaporating water like this: their surfaces represent a very large surface area. More water is drawn up to replace the evaporated water, from the xylem vessels in the veins. As a result, water is pulled through the xylem vessels and up the stem from the roots. This transpiration pull is strong enough to draw up water 50 metres or more in trees (Figure 8.20).

In addition to the water passing along the cell walls, a small amount will pass right through the cells. When leaf cell A in Figure 8.19 loses water, its turgor pressure will fall. This fall in pressure allows the water in the cell wall to enter the vacuole and so restore the turgor pressure. In conditions of water shortage, cell A may be able to get water by osmosis from cell B more easily than B can get it from the xylem vessels. In this case, all the mesophyll cells will be losing water faster than they can absorb it from the vessels, and the leaf will wilt (see 'Osmosis' in Chapter 3). Water loss from the cell vacuoles results in the cells losing their turgor and becoming **flaccid**. A leaf with flaccid cells will be limp and the stem will droop. A plant that loses water to this extent is said to be 'wilting' (see Figure 3.11).

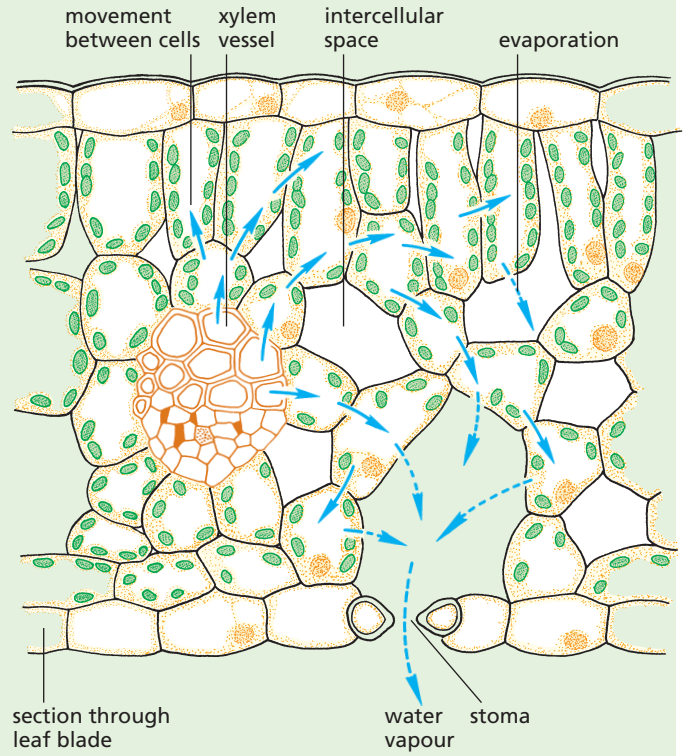


Figure 8.18 Movement of water through a leaf

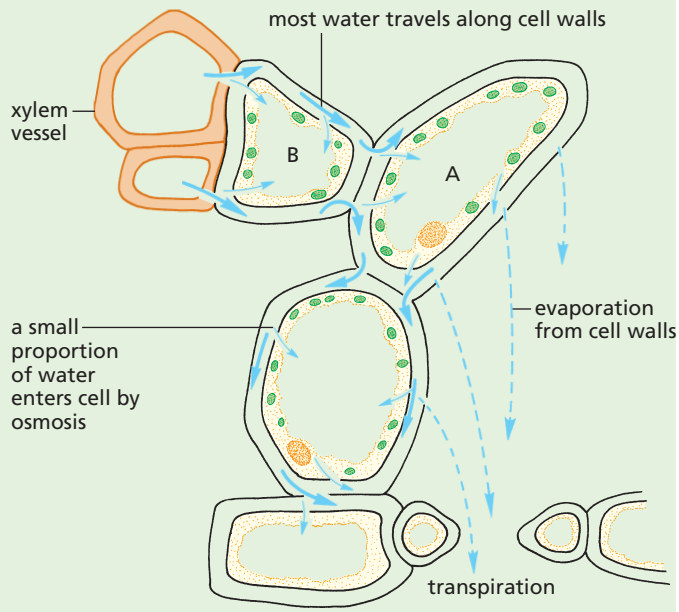


Figure 8.19 Probable pathway of water through leaf cells

Importance of transpiration

A tree, on a hot day, may draw up hundreds of litres of water from the soil (Figure 8.20). Most of this water evaporates from the leaves; only a tiny fraction is retained for photosynthesis and to maintain the turgor of the cells. The advantage to the plant of this excessive evaporation is not clear. A rapid water flow may be needed to obtain sufficient mineral salts, which are in very dilute solution in the soil. Evaporation may also help to cool the leaf when it is exposed to intense sunlight.

Against the first possibility, it has to be pointed out that, in some cases, an increased transpiration rate does not increase the uptake of minerals.

The second possibility, the cooling effect, might be very important. A leaf exposed to direct sunlight will absorb heat and its temperature may rise to a level that could kill the cytoplasm. Water evaporating from a leaf absorbs its latent heat and cools the leaf down. This is probably one value of transpiration. However, there are plants whose stomata close at around midday, greatly reducing transpiration. How do these plants avoid overheating?

Many biologists regard transpiration as an inevitable consequence of photosynthesis. In order to photosynthesise, a leaf has to take in carbon dioxide from the air. The pathway that allows carbon dioxide in will also let water vapour out whether the plant needs to lose water or not. In all probability, plants have to maintain a careful balance between the optimum intake of carbon dioxide and a damaging loss of water. Plants achieve this balance in different ways, some of which are described in 'Adaptive features' in Chapter 18.

The role of stomata

The opening and closing of stomata can be triggered by a variety of factors, principally light intensity, carbon dioxide concentration and humidity. These factors interact with each other. For example, a rise in light intensity will increase the rate of photosynthesis and so lower the carbon dioxide concentration in the leaf. These are the conditions you would expect to influence stomatal aperture if the stomata are to control the balance between loss of water vapour and uptake of carbon dioxide.

The stomata also react to water stress, i.e. if the leaf is losing water by transpiration faster than it is being taken up by the roots. Before wilting sets in, the stomata start to close. Although they do not prevent wilting, the stomata do seem to delay its onset.

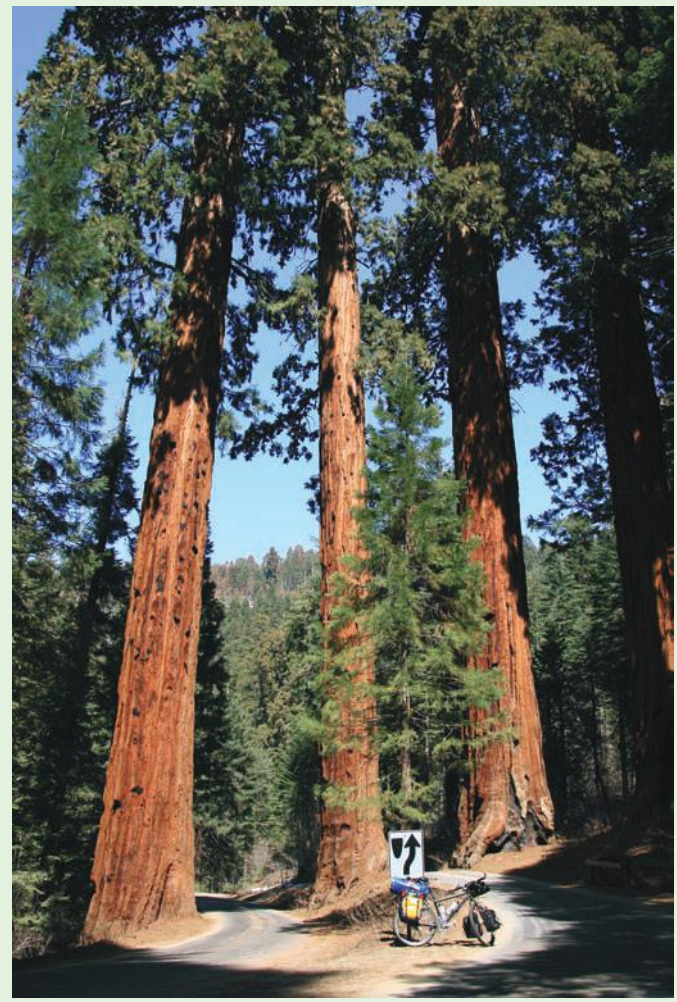


Figure 8.20 Californian redwoods. Some of these trees are over 100 metres tall. Transpiration from their leaves pulls hundreds of litres of water up the trunk.

Rate of transpiration

Transpiration is the evaporation of water from the leaves, so any change that increases or reduces evaporation will have the same effect on transpiration.

Light intensity

Light itself does not affect evaporation, but in daylight the stomata of the leaves are open (see 'Leaf structure' in Chapter 6). This allows the water vapour in the leaves to diffuse out into the atmosphere. At night, when the stomata close, transpiration is greatly reduced.

Generally speaking, then, transpiration speeds up when light intensity increases because the stomata respond to changes in light intensity.

Sunlight may also warm up the leaves and increase evaporation (see below).

Humidity
If the air is very humid, i.e. contains a great deal of water vapour, it can accept very little more from the plants and so transpiration slows down. In dry air, the diffusion of water vapour from the leaf to the atmosphere will be rapid.

Air movements
In still air, the region round a transpiring leaf will become saturated with water vapour so that no more can escape from the leaf. In these conditions, transpiration would slow down. In moving air, the water vapour will be swept away from the leaf as fast as it diffuses out. This will speed up transpiration.

Temperature
Warm air can hold more water vapour than cold air. Thus evaporation or transpiration will take place more rapidly into warm air.

Furthermore, when the Sun shines on the leaves, they will absorb heat as well as light. This warms them up and increases the rate of evaporation of water.

Investigations into the effect of some of these conditions on the rate of transpiration are described earlier in this chapter.

Water movement in the xylem

You may have learned that you cannot draw water up by 'suction' to a height of more than about 10 metres. Many trees are taller than this yet they can draw up water effectively. The explanation offered is that, in long vertical columns of water in very thin tubes, the attractive forces between the water molecules result in **cohesion** (the molecules stick together). The attractive forces are greater than the forces trying to separate them. So, in effect, the transpiration stream is pulling up thin threads of water, which resist the tendency to break.

There are still problems, however. It is likely that the water columns in some of the vessels do have air breaks in them and yet the total water flow is not affected.

Evidence for the pathway of water
The experiment on page 115 uses a dye to show that in a cut stem, the dye and, therefore, presumably the water, travels in the vascular bundles. Closer examination with a microscope would show that it travels in the xylem vessels.

Removal of a ring of bark (which includes the phloem) does not affect the passage of water along a branch. Killing parts of a branch by heat or poisons does not interrupt the flow of water, but anything that blocks the vessels does stop the flow.

The evidence all points to the non-living xylem vessels as the main route by which water passes from the soil to the leaves.

Translocation

Key definition
Translocation is the movement of sucrose and amino acids in the phloem, from regions of production (the 'source') to regions of storage or to regions where they are used in respiration or growth (the 'sink').

The xylem sap is always a very dilute solution, but the phloem sap may contain up to 25% of dissolved solids, the bulk of which consists of sucrose and amino acids. There is a good deal of evidence to support the view that sucrose, amino acids and many other substances are transported in the phloem. This is called **translocation**.

The movement of water and salts in the xylem is always upwards, from soil to leaf, but in the phloem the solutes may be travelling up or down the stem. The carbohydrates made in the leaf during photosynthesis are converted to sucrose and carried out of the leaf (the source) to the stem. From here, the sucrose may pass upwards to growing buds and fruits or downwards to the roots and storage organs (sink). All parts of a plant that cannot photosynthesise will need a supply of nutrients brought by the phloem. It is quite possible for substances to be travelling upwards and downwards at the same time in the phloem.

Some insects feed using syringe-like mouthparts, piercing the stems of plants to extract liquid from the phloem vessels. Figure 8.21 shows aphids feeding on a rose plant. The pressure of sucrose solution in the phloem can be so great that it is forced through the gut of the aphid and droplets of the sticky liquid exude from its anus.

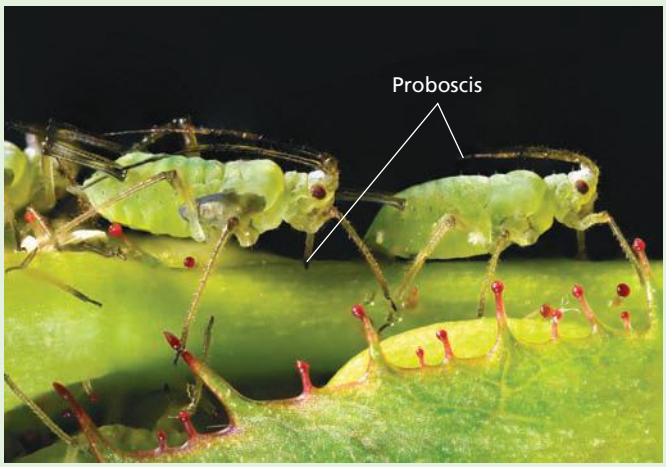


Figure 8.21 Aphids feeding on a rose plant

Some parts of a plant can act as a source and a sink at different times during the life of a plant. For example, while a bud containing new leaves is forming it would require nutrients and therefore act as a sink. However, once the bud has burst and the leaves are photosynthesising, the region would act as a source, sending newly synthesised sugars and amino acids to other parts of the plant. Similarly, the new tuber of a potato plant would act as a sink while it was growing, storing sugars as starch. (Starch is a good storage molecule because it is insoluble and quite compact.) However, once the buds on the tubers start to grow, the stored starch is converted to sucrose, a soluble nutrient, which will be passed to these buds from the tuber. So the tuber becomes the source. The shoots will eventually become sources, once they break through the soil and produce new leaves that can photosynthesise. Bulbs, such as those of the daffodil and snowdrop (see 'Asexual reproduction' in Chapter 16), act in the same way, although they tend to store sugars as well as starch.

There is no doubt that substances travel in the sieve tubes of the phloem, but the mechanism by which they are moved is not fully understood. We do know that translocation depends on living processes because anything that inhibits cell metabolism, e.g. poisons or high temperatures, also arrests translocation.

Questions

Core

1 Make a list of the types of cells or tissues you would expect to find in a vascular bundle.
2 What structures help to keep the stem's shape and upright position?
3 What are the differences between xylem and phloem:
  a in structure
  b in function?
4 State briefly the functions of the following: xylem, root hair, root cap, epidermis.
5 If you were given a cylindrical structure cut from part of a plant, how could you tell whether it was a piece of stem or a piece of root:
  a with the naked eye
  b with the aid of a microscope or hand lens?
6 Describe the path taken by a water molecule from the soil until it reaches a mesophyll cell of a leaf to be made into sugar.
7 Why do you think that root hairs are produced only on the parts of the root system that have stopped growing?
8 Discuss whether you would expect to find a vascular bundle in a flower petal.

Extended

9 If root hairs take up water from the soil by osmosis, what would you expect to happen if so much nitrate fertiliser was put on the soil that the soil water became a stronger solution than the cell sap of the root hairs?
10 A plant's roots may take up water and salts less efficiently from a waterlogged soil than from a fairly dry soil. Revise 'Active transport' (Chapter 3) and suggest reasons for this.
11 Why do you think that, in a deciduous tree in spring, transpiration is negligible before bud burst?
12 Describe the pathway followed by a water molecule from the time it enters a plant root to the time it escapes into the atmosphere from a leaf.
13 What kind of climate and weather conditions do you think will cause a high rate of transpiration?
14 What would happen to the leaves of a plant that was losing water by transpiration faster than it was taking it up from the roots?
15 In what two ways does sunlight increase the rate of transpiration?
16 Apart from drawing water through the plant, what else may be drawn up by the transpiration stream?
17 Transpiration has been described in this chapter as if it takes place only in leaves. In what other parts of a plant might transpiration occur?
18 How do sieve tubes and vessels differ:
  a in the substances they transport
  b in the directions these substances are carried?
19 A complete ring of bark cut from around the circumference of a tree-trunk causes the tree to die. The xylem continues to carry water and salts to the leaves, which can make all the substances needed by the tree. So why does the tree die?
20 Make a list of all the non-photosynthetic parts of a plant that need a supply of sucrose and amino acids.

Checklist

After studying Chapter 8 you should know and understand the following:

- The shoot of a plant consists of the stem, leaves, buds and flowers.
- The roots hold the plant in the soil, absorb the water and mineral salts needed by the plant for making sugars and proteins and, in some cases, store food for the plant.
- The root hairs make very close contact with soil particles and are the main route by which water and mineral salts enter the plant.
- The stem supports the leaves and flowers.
- The stem contains vascular bundles (veins).
- The leaves carry out photosynthesis and allow gaseous exchange of carbon dioxide, oxygen and water vapour.
- Closure of the stomata stops the entry of carbon dioxide into a leaf but also reduces water loss.
- The xylem vessels in the veins carry water up the stem to the leaves.
- The phloem in the veins carries food up or down the stem to wherever it is needed.
- The position of vascular bundles helps the stem to withstand sideways bending and the root to resist pulling forces.
- Transpiration is the evaporation of water vapour from the leaves of a plant.
- The water travelling in the transpiration stream will contain dissolved salts.
- Closure of stomata and shedding of leaves may help to regulate the transpiration rate.
- The rate of transpiration is increased by sunlight, high temperature and low humidity.
- Salts are taken up from the soil by roots, and are carried in the xylem vessels.

- Transpiration produces the force that draws water up the stem.
- Root pressure forces water up the stem as a result of osmosis in the roots.
- The large surface area provided by root hairs increases the rate of absorption of water (osmosis) and mineral ions (active transport).
- The large surface area provided by cell surfaces, interconnecting air spaces and stomata in the leaf encourages water loss.
- Wilting occurs when the volume of water vapour lost by leaves is greater than that absorbed by roots.
- Translocation is the movement of sucrose and amino acids in phloem.
- The point where food is made is called a source.
- The place where food is taken to and used is called a sink.

9 Transport in animals

Transport in animals

Single circulation in fish
Double circulation and its advantages

Heart
Structures of the heart
Monitoring heart activity
Coronary heart disease

Heart valves
Explanation of heart features
Functioning of the heart
Explanation of the effect of exercise
Treatment and prevention of coronary heart disease

Blood and lymphatic vessels
Arteries, veins, capillaries
Main blood vessels of the heart and lungs

Adaptations of blood vessels
Lymphatic system

Blood
Components of blood – appearance and functions

Lymphocyes
Phagocytes
Blood clotting
Transfer of materials between capillaries and tissue fluid

Transport in animals

The blood, pumped by the heart, travels all around the body in blood vessels. It leaves the heart in arteries and returns in veins. Valves, present in the heart and veins, ensure a one-way flow for the blood. As blood enters an organ, the arteries divide into smaller arterioles, which supply capillaries. In these vessels the blood moves much more slowly, allowing the exchange of materials such as oxygen and glucose, carbon dioxide and other wastes. Blood leaving an organ is collected in venules, which transfer it on to larger veins.

Single circulation of fish

Fish have the simplest circulatory system of all the vertebrates. A heart, consisting of one blood-collecting chamber (the atrium) and one blood-ejection chamber (the ventricle), sends blood to the gills where it is oxygenated. The blood then flows to all the parts of the body before returning to the heart (Figure 9.1).This is known as a **single circulation** because the blood goes through the heart once for each complete circulation of the body. However, as the blood passes through capillaries in the gills, blood pressure is lost, but the blood still needs to circulate through other organs of the body before returning to the heart to increase blood pressure. This makes the fish circulatory system inefficient.

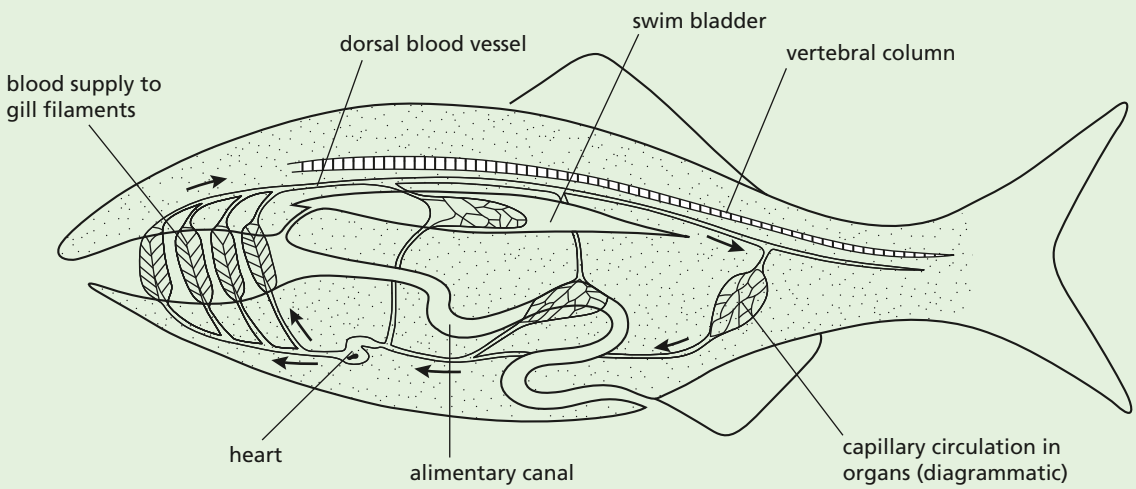


Figure 9.1 Single circulation of a fish

Double circulation of mammals

The route of the circulation of blood in a mammal is shown in Figure 9.2.

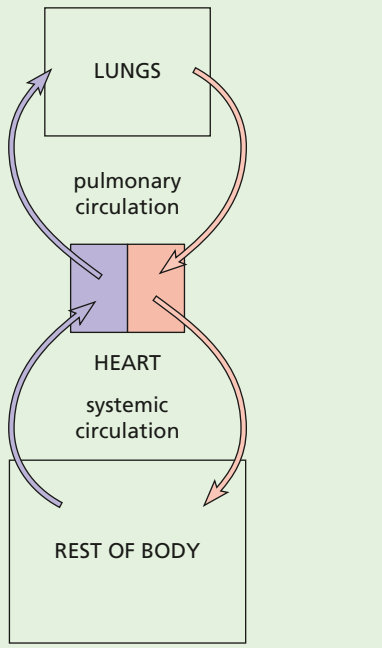


Figure 9.2 Double circulation of a mammal

The blood passes twice through the heart during one complete circuit: once on its way to the body and again on its way to the lungs. The circulation through the lungs is called the **pulmonary circulation**; the circulation around the rest of the body is called the **systemic circulation**. On average, a red blood cell would go around the whole circulation in 45 seconds. A more detailed diagram of the circulation is shown in Figure 9.20.

A **double circulation** has the advantage of maintaining a high blood pressure to all the major organs of the body. The right side of the heart collects blood from the body, builds up the blood pressure and sends it to the lungs to be oxygenated, but the pressure drops during the process. The left side of the heart receives oxygenated blood from the lungs, builds up the blood pressure again and pumps the oxygenated blood to the body.

Heart

The heart pumps blood through the circulatory system to all the major organs of the body. The appearance of the heart from the outside is shown in Figure 9.3. Figure 9.4 shows the left side cut open, while Figure 9.5 is a diagram of a vertical section to show its internal structure. Since the heart is seen as if in a dissection of a person facing you, the left side is drawn on the right.

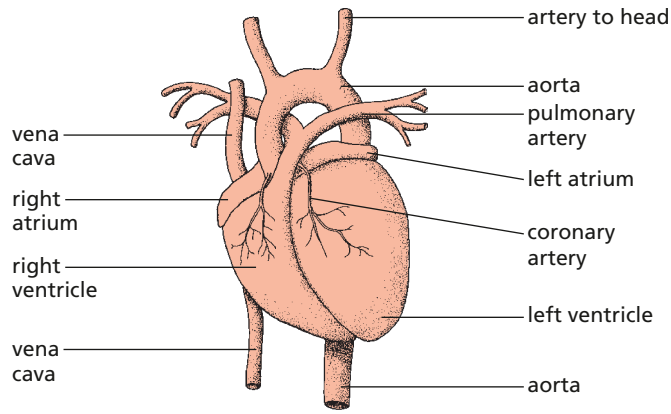


Figure 9.3 External view of the heart

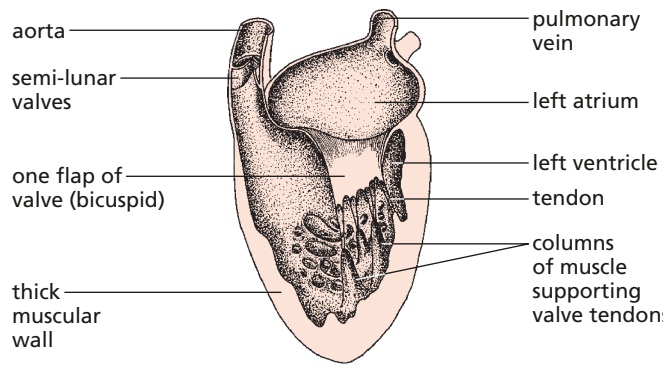


Figure 9.4 Diagram of the heart cut open (left side)

If you study Figure 9.5 you will see that there are four chambers. The upper, thin-walled chambers are the **atria** (singular = atrium) and each of these opens into a thick-walled chamber, the **ventricle**, below.

Blood enters the atria from large veins. The **pulmonary vein** brings oxygenated blood from the lungs into the left atrium. The **vena cava** brings deoxygenated blood from the body tissues into the right atrium. The blood passes from each atrium to its corresponding ventricle, and the ventricle pumps it out into the arteries. The left chambers are separated from the right chambers by a wall of muscle called a **septum**.

The artery carrying oxygenated blood to the body from the left ventricle is the **aorta**. The **pulmonary artery** carries deoxygenated blood from the right ventricle to the lungs.

In pumping the blood, the muscle in the walls of the atria and ventricles contracts and relaxes (Figure 9.6). The walls of the atria contract first and force blood into the two ventricles. Then the ventricles contract and send blood into the arteries. Valves prevent blood flowing backwards during or after heart contractions.

The heart muscle is supplied with food and oxygen by the **coronary arteries** (Figure 9.3).

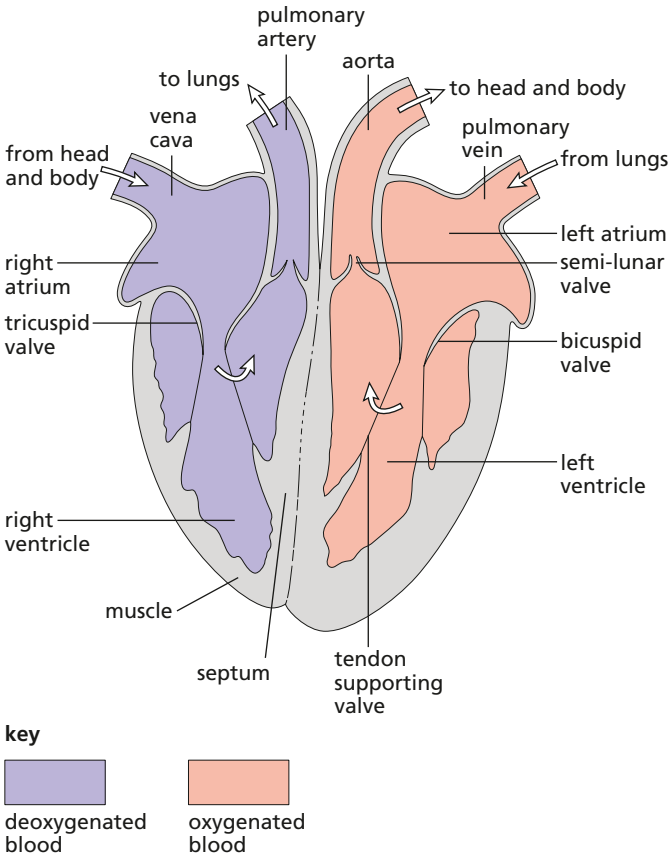


Figure 9.5 Diagram of the heart, vertical section

There are a number of ways by which the activity of the heart can be monitored. These include measuring pulse rate, listening to heart sounds and the use of electrocardiograms (ECGs).

Pulse rate

The ripple of pressure that passes down an artery as a result of the heart beat can be felt as a '**pulse**' when the artery is near the surface of the body. You can feel the pulse in your radial artery by pressing the fingertips of one hand on the wrist of the other (Figure 9.7). It is important that the thumb is *not* used because it has its own pulse. There is also a detectable pulse in the carotid artery in the neck. Digital pulse rate monitors are also available. These can be applied to a finger, wrist or earlobe depending on the type and provide a very accurate reading.

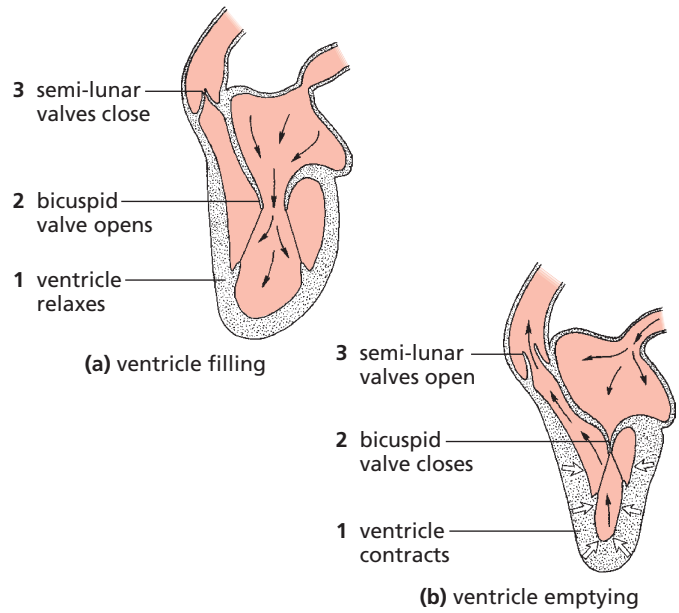


Figure 9.6 Diagram of heartbeat (only the left side is shown)

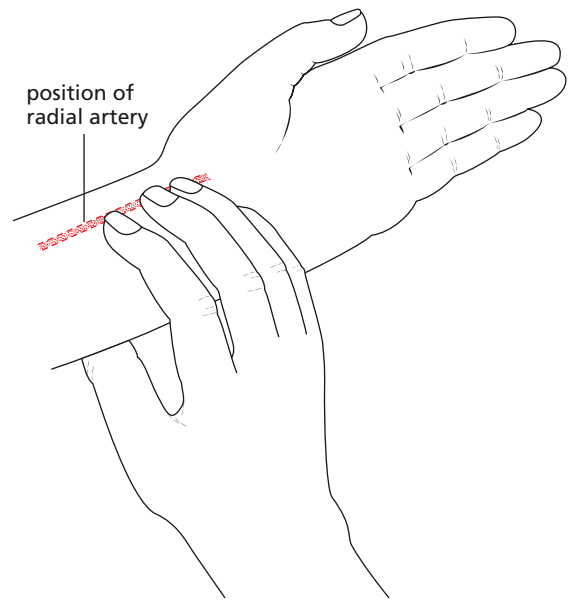


Figure 9.7 Taking the pulse

Heart sounds

These can be heard using a **stethoscope**. This instrument amplifies the sounds of the heart valves opening and closing. A healthy heart produces a

regular 'lub-dub' sound. The first ('lub') sound is caused by the closure of the valves separating the atria from the ventricles. The second ('dub') sound represents the closure of the valves at the entrance of the pulmonary artery and aorta. Observation of irregular sounds may indicate an irregular heartbeat. If the 'lub' or 'dub' sounds are not clear then this may point to a problem with faulty valves.

ECGs

An ECG is an **electrocardiogram**. To obtain an ECG, electrodes, attached to an ECG recording machine, are stuck onto the surface of the skin on the arms, legs and chest (Figure 9.8). Electrical activity associated with heartbeat is then monitored and viewed on a computer screen or printed out (Figure 9.9). Any irregularity in the trace can be used to diagnose heart problems.

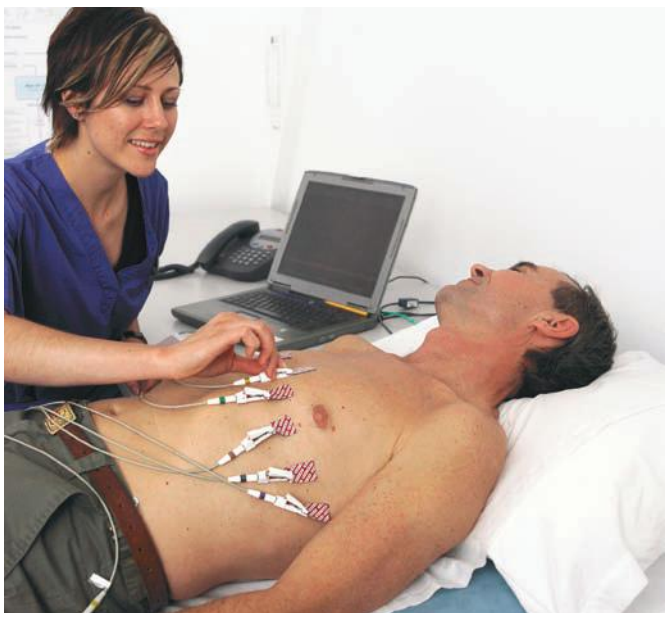


Figure 9.8 A patient undergoing an ECG

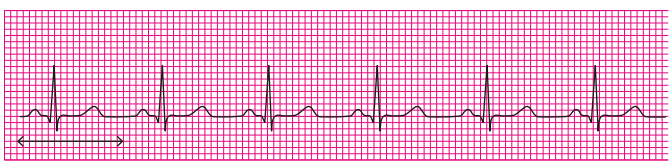


Figure 9.9 ECG trace

The effect of physical activity on the pulse rate

A heartbeat is a contraction. Each contraction squeezes blood to the lungs and body. The pulse is a pressure wave passing through the arteries as a result of the heartbeat. At rest, the heart beats about 70 times a minute, but this varies according to a person's age, gender and fitness: higher if you are younger, higher if you are female and lower if you are fit. An increase in physical activity increases the pulse rate, which can rise to 200 beats per minute. After exercise has stopped, the pulse rate gradually drops to its resting state. How quickly this happens depends on the fitness of the individual (an unfit person's pulse rate will take longer to return to normal).

Coronary heart disease

In the lining of the large and medium arteries, deposits of a fatty substance, called **atheroma**, are laid down in patches. This happens to everyone and the patches get more numerous and extensive with age, but until one of them actually blocks an important artery the effects are not noticed. It is not known how or why the deposits form. Some doctors think that fatty substances in the blood pass into the lining. Others believe that small blood clots form on damaged areas of the lining and are covered over by the atheroma patches. The patches may join up to form a continuous layer, which reduces the internal diameter of the vessel (Figure 9.10).

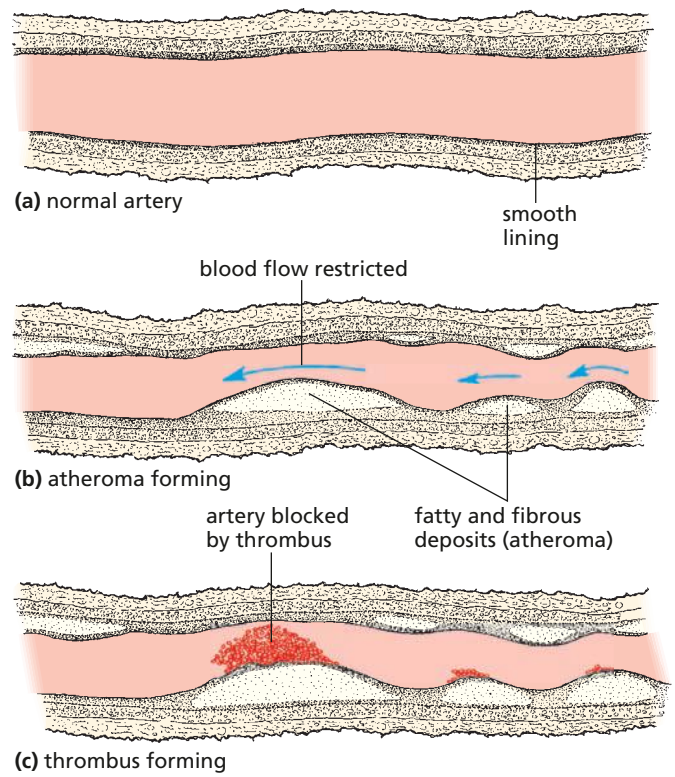


Figure 9.10 Atheroma and thrombus formation

The surface of a patch of atheroma sometimes becomes rough and causes fibrinogen in the plasma to deposit fibrin on it, causing a blood clot (a **thrombus**)

to form. If the blood clot blocks the coronary artery (Figure 9.3), which supplies the muscles of the ventricles with blood, it starves the muscles of oxygenated blood and the heart may stop beating. This is a severe heart attack from **coronary thrombosis**. A thrombus might form anywhere in the arterial system, but its effects in the coronary artery and in parts of the brain (strokes) are the most drastic.

In the early stages of coronary heart disease, the atheroma may partially block the coronary artery and reduce the blood supply to the heart (Figure 9.11). This can lead to **angina**, i.e. a pain in the chest that occurs during exercise or exertion. This is a warning to the person that he or she is at risk and should take precautions to avoid a heart attack.

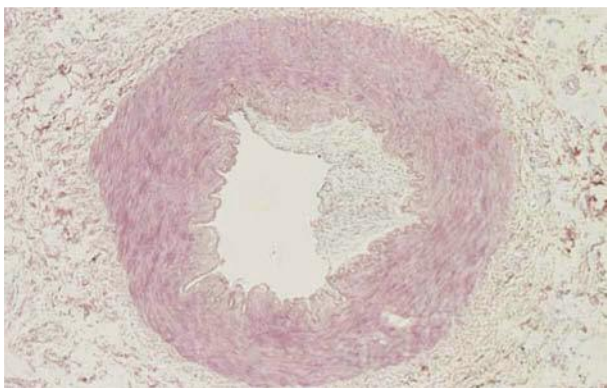


Figure 9.11 Atheroma partially blocking the coronary artery

Possible causes of coronary heart disease

Atheroma and thrombus formation are the immediate causes of a heart attack but the long-term causes that give rise to these conditions are not well understood.

There is an inherited tendency towards the disease but incidences of the disease have increased very significantly in affluent countries in recent years. This makes us think that some features of 'Western' diets or lifestyles might be causing it. The main risk factors are thought to be an unbalanced diet with too much fat, stress, smoking, genetic disposition, age, gender and lack of exercise.

Diet

The atheroma deposits contain **cholesterol**, which is present, combined with lipids and proteins, in the blood. Cholesterol plays an essential part in our physiology, but it is known that people with high levels of blood cholesterol are more likely to suffer from heart attacks than people with low cholesterol levels.

Blood cholesterol can be influenced, to some extent, by the amount and type of fat in the diet. Many doctors and dieticians believe that animal fats (milk, cream, butter, cheese, egg-yolk, fatty meat) are more likely to raise the blood cholesterol than are the vegetable oils, which contain a high proportion of unsaturated fatty acids (see 'Diet' in Chapter 7).

An unbalanced diet with too many calories can lead to obesity. Being overweight puts extra strain on the heart and makes it more difficult for the person to exercise.

Stress

Emotional stress often leads to raised blood pressure. High blood pressure may increase the rate at which atheroma are formed in the arteries.

Smoking

Statistical studies suggest that smokers are two to three times more likely to die from a heart attack than are non-smokers of a similar age (Figure 9.12). The carbon monoxide and other chemicals in cigarette smoke may damage the lining of the arteries, allowing atheroma to form, but there is very little direct evidence for this.

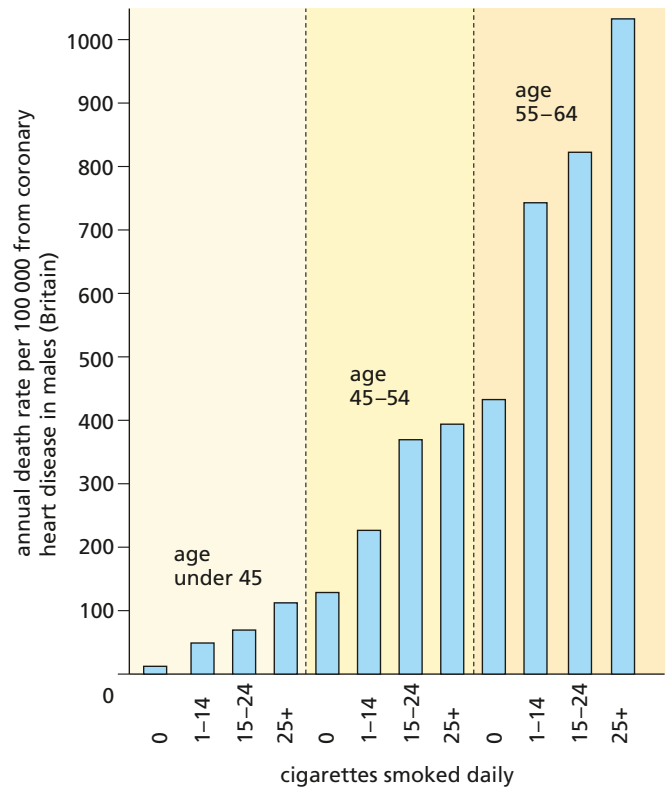


Figure 9.12 Smoking and heart disease. Obviously, as you get older you are more likely to die from a heart attack, but notice that, in any age group, the more you smoke the higher your chances of dying from heart disease.

Genetic predisposition
Coronary heart disease appears to be passed from one generation to the next in some families. This is not something we have any control over, but we can be aware of this risk and reduce some of the other risk factors to compensate.

Age and gender
As we get older our risk of suffering from coronary heart disease increases. Males are more at risk of a heart attack than females: it may be that males tend to have less healthy lifestyles than females.

Lack of exercise
Heart muscle loses its tone and becomes less efficient at pumping blood when exercise is not untaken. A sluggish blood flow, resulting from lack of exercise, may allow atheroma to form in the arterial lining but, once again, the direct evidence for this is slim.

Control of blood flow through the heart

The blood is stopped from flowing backwards by four sets of valves. Valves that separate each atrium from the ventricle below it are known as **atrioventricular valves**. Between the right atrium and the right ventricle is the **tricuspid** (= three flaps) valve. Between the left atrium and left ventricle is the **bicuspid** (= two flaps) valve. The flaps of these valves are shaped rather like parachutes, with 'strings' called **tendons** or **cords** to prevent them from being turned inside out.

In the pulmonary artery and aorta are the **semi-lunar** (= half-moon) valves. These each consist of three 'pockets', which are pushed flat against the artery walls when blood flows one way. If blood tries to flow the other way, the pockets fill up and meet in the middle to stop the flow of blood (Figure 9.13).

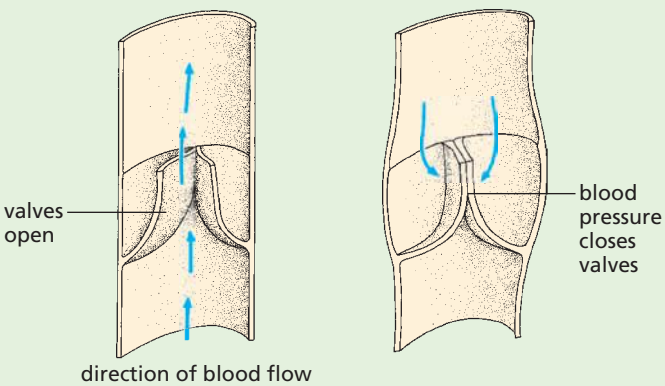


Figure 9.13 Action of the semi-lunar valves

When the ventricles contract, blood pressure closes the bicuspid and tricuspid valves and these prevent blood returning to the atria. When the ventricles relax, the blood pressure in the arteries closes the semi-lunar valves, preventing the return of blood to the ventricles.

From the description above, it may seem that the ventricles are filled with blood as a result of the contraction of the atria. However, the atria have much thinner muscle walls than the ventricles. In fact, when the ventricles relax, their internal volume increases and they draw in blood from the pulmonary vein or vena cava through the relaxed atria. Atrial contraction then forces the final amount of blood into the ventricles just before ventricular contraction.

The left ventricle (sometimes referred to as the 'large left ventricle') has a wall made of cardiac muscle that is about three times thicker than the wall of the right ventricle. This is because the right ventricle only needs to create enough pressure to pump blood to one organ, the lungs, which are next to the heart. However, the left ventricle has to pump blood to all the major organs of the body, as shown in Figure 9.20. It should be noted that the left and right ventricles pump the same volume of blood: the left ventricle does *not* have a thicker wall to pump *more* blood!

Extension work

Blood circulation in the fetus

The septum separating the left and right heart chambers prevents the oxygenated blood in the left chambers from mixing with the deoxygenated blood in the right chambers. When a fetus is developing, there is a hole (the **foramen ovale**) between the right atrium and the left atrium, allowing blood to bypass the lungs. This is because the fetal blood is oxygenated by the placenta rather than the lungs. During the birth sequence, the foramen ovale closes, so all blood in the right atrium passes into the right ventricle and on to the lungs for oxygenation. Occasionally, the foramen ovale does not seal completely and the baby suffers from a 'hole in the

heart'. Babies suffering from this condition tend to look blue because their blood is not being adequately oxygenated: some of it bypasses the lungs.

Control of the heartbeat

Heart muscle has a natural rhythmic contraction of its own, about 40 contractions per minute. However, it is supplied by nerves, which maintain a faster rate that can be adjusted to meet the body's needs for oxygen. At rest, the normal heart rate may lie between 50 and 100 beats per minute, according to age, gender and other factors. During exercise, the rate may increase to 200 beats per minute.

The heart beat is initiated by the '**pacemaker**', a small group of specialised muscle cells at the top of the right atrium. The pacemaker receives two sets of nerves from the brain. One group of nerves speeds up the heart rate and the other group slows it down. These nerves originate from a centre in the brain that receives an input from receptors (See 'Nervous control in humans' in Chapter 14) in the circulatory system that are sensitive to blood pressure and levels of oxygen and carbon dioxide in the blood.

If blood pressure rises, nervous impulses reduce the heart rate. A fall in blood pressure causes a rise in the rate. Reduced oxygen concentration or increased carbon dioxide in the blood also contributes to a faster rate. By this means, the heart rate is adjusted to meet the needs of the body at times of rest, exertion and excitement.

The hormone **adrenaline** (see 'Hormones in humans' in Chapter 14) also affects the heart rate. In conditions of excitement, activity or stress, adrenaline is released into the blood circulation from the adrenal glands. On reaching the heart it causes an increase in the rate and strength of the heartbeat.

Physical activity and heart rate

During periods of physical activity, active parts of the body (mainly skeletal muscle) respire faster, demanding more oxygen and glucose. Increased respiration also produces more carbon dioxide, which needs to be removed. Blood carries the oxygen and glucose, so the heart rate needs to increase to satisfy demand. If the muscle does not get enough oxygen, it will start to respire anaerobically, producing lactic acid (lactate). Lactic acid build-up causes muscle fatigue, leading to cramp. An 'oxygen debt' is created, which needs to be repaid after exercise by continued rapid breathing and higher than normal heart rate (see 'Anaerobic respiration' in Chapter 12).

Correlation and cause

It is not possible or desirable to conduct experiments on humans to find out, more precisely, the causes of heart attacks. The evidence has to be collected from long-term studies on populations of individuals, e.g. smokers and non-smokers. Statistical analysis of these studies will often show a correlation, e.g. more smokers, within a given age band, suffer heart attacks than do non-smokers of the same age. This correlation does not prove that smoking causes heart attacks. It could be argued that people who are already prone to heart attacks for other reasons (e.g. high blood pressure) are more likely to take up smoking. This may strike you as implausible, but until it can be shown that substances in tobacco smoke do cause an increase in atheroma, the correlation cannot be used on its own to claim a cause and effect.

Nevertheless, there are so many other correlations between smoking and ill-health (e.g. bronchitis, emphysema, lung cancer) that the circumstantial evidence against smoking is very strong.

Another example of a positive correlation is between the possession of a television set and heart disease. Nobody would seriously claim that television sets cause heart attacks. The correlation probably reflects an affluent way of life, associated with over-eating, fatty diets, lack of exercise and other factors that may contribute to coronary heart disease.

Prevention of coronary heart disease

Maintaining a healthy, balanced diet will result in less chance of a person becoming obese. There will also be a low intake of saturated fats, so the chances of atheroma and thrombus formation are reduced.

There is some evidence that regular, vigorous exercise reduces the chances of a heart attack. This may be because it increases muscle tone – not only of skeletal muscle, but also of cardiac muscle. Good heart muscle tone leads to an improved coronary blood flow and the heart requires less effort to keep pumping.

Treatment of coronary heart disease

The simplest treatment for a patient who suffers from coronary heart disease is to be given a regular dose of aspirin (salicylic acid). Aspirin prevents the formation of blood clots in the arteries, which can lead to a heart attack. It has been found that long-term use of low-dose aspirin also reduces the risk of coronary heart disease.

Methods of removing or treating atheroma and thrombus formations include the use of **angioplasty**, a **stent** and, in the most severe cases, by-pass surgery.

Angioplasty and stent

Angioplasty involves the insertion of a long, thin tube called a **catheter** into the blocked or narrowed blood vessel. A wire attached to a deflated balloon is then fed through the catheter to the damaged artery. Once in place, the balloon is inflated to widen the artery wall, effectively freeing the blockage. In some cases a stent is also applied. This is a wire-mesh tube that can be expanded and left in place (Figure 9.14). It then acts as scaffolding, keeping the blood vessel open and maintaining the free flow of blood. Some stents are designed to give a slow release of chemicals to prevent further blockage of the artery.

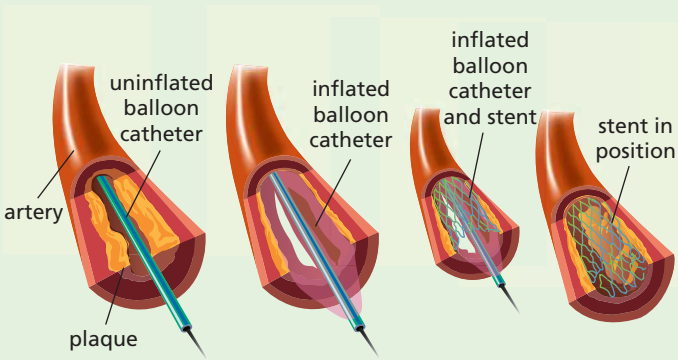


Figure 9.14 Application of a stent to overcome a blockage in an artery

By-pass surgery

The surgeon removes a section of blood vessel from a different part of the body, such as the leg. The blood vessel is then attached around the blocked region of artery to by-pass it, allowing blood to pass freely. This is a major, invasive operation because it involves open-heart surgery.

Practical work

Heart dissection

- Obtain an intact heart (sheep or goat for example) from a butcher's shop or abattoir.
- Rinse it under a tap to remove excess blood.
- Observe the surface of the heart, identifying the main visible features (shown in Figure 9.3). The blood vessels may have been cut off, but it is possible to identify where these would have been attached later in the dissection.
- Gently squeeze the ventricles. They can be distinguished because the wall of the right ventricle is much thinner than that of the left ventricle.
- Using a pair of sharp scissors or a scalpel, make an incision from the base of the left ventricle, up through the left atrium.
- Using a pair of forceps, remove any blood clots lying in the exposed chambers.
- Identify the main features as shown in Figure 9.4.
- If you have not cut open the aorta, gently push the handle of a blunt seeker or an old pencil, behind the bicuspid valve. It should find its way into the aorta. Note how thick the wall of this blood vessel is.
- Compare the semi-lunar valves in the base of the aorta with the bicuspid valve between the atrium and ventricle. Note that the latter has tendons to prevent it turning inside-out.
- Now repeat the procedure on the right side of the heart to expose the right atrium and ventricle.
- Pushing the handle of the seeker behind the tricuspid valve should allow it to enter the pulmonary artery. Cut open the artery to expose semi-lunar valves. Note the relative thinness of the wall, compared to that of the aorta.
- Also compare the thickness of the left ventricle wall to that of the right ventricle.

Investigating the effect of exercise on pulse rate

- Find your pulse in your wrist or neck – see Figure 9.7.
- Count the number of beats in 15 seconds, then multiply the result by four to provide a pulse rate in beats per minute. This is your resting pulse rate.
- Repeat the process two more times and then calculate an average resting pulse rate.
- Carry out 2 minutes of exercise, e.g. running on the spot, then sit down and immediately start a stopwatch and measure your pulse rate over 15 seconds as before.
- Allow the stopwatch to keep timing. Measure your pulse rate every minute for 10 minutes.
- Convert all the readings to beats per minute. Plot a graph of pulse rate after exercise against time, with the first reading being 0 minutes.
- Finally, draw a line across the graph representing your average resting pulse rate.

Result
The pulse rate immediately after exercise should be much higher than the average resting pulse rate. With time the pulse rate gradually falls back to the average resting pulse rate.

Interpretation
During exercise the muscles need more oxygen and glucose for aerobic respiration to provide the energy needed for the increased movement. The heart rate increases to provide these materials. After exercise, demand for oxygen and glucose decreases, so the pulse rate gradually returns to normal.

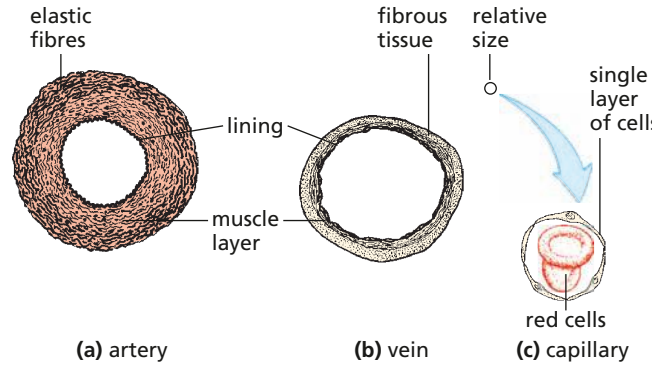


Figure 9.15 Blood vessels, transverse section

Blood and lymphatic vessels

Arteries

These are fairly wide vessels (Figure 9.15) which carry blood from the heart to the limbs and organs of the body (Figure 9.20). The blood in the arteries, except for the pulmonary arteries, is oxygenated.

Arteries have elastic tissue and muscle fibres in their thick walls. The arteries divide into smaller vessels called **arterioles**.

The arterioles divide repeatedly to form a branching network of microscopic vessels passing between the cells of every living tissue. These final branches are called **capillaries**.

Capillaries

These are tiny vessels, often as little as 0.001 mm in diameter and with walls only one cell thick (Figures 9.15(c) and 9.17). Although the blood as a whole cannot escape from the capillary, the thin capillary walls allow some liquid to pass through, i.e. they are permeable. Blood pressure in the capillaries forces part of the plasma out through the walls.

The capillary network is so dense that no living cell is far from a supply of oxygen and food. The capillaries join up into larger vessels, called **venules**, which then combine to form **veins**.

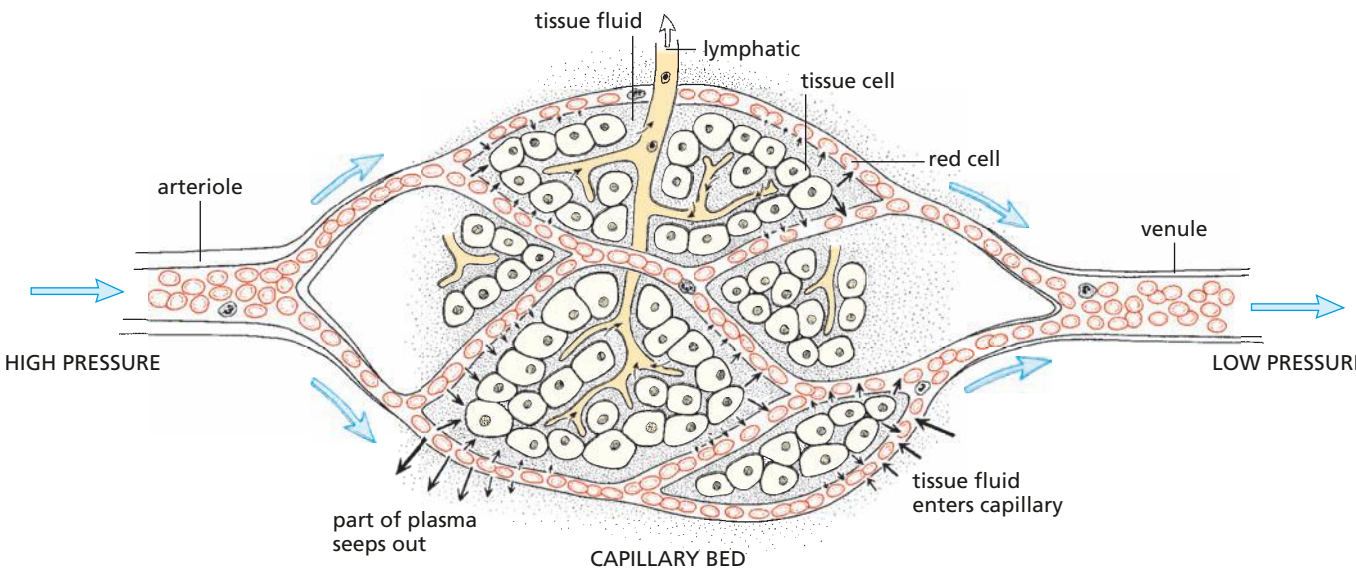


Figure 9.16 Relationship between capillaries, cells and lymphatics. The slow flow rate in the capillaries allows plenty of time for the exchange of oxygen, food, carbon dioxide and waste products.

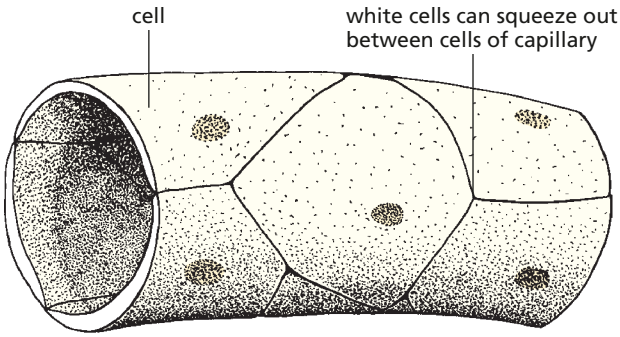


Figure 9.17 Diagram of blood capillary

Veins

Veins return blood from the tissues to the heart (Figure 9.20). The blood pressure in them is steady and is less than that in the arteries. They are wider and their walls are thinner, less elastic and less muscular than those of the arteries (Figures 9.15(b) and 9.18). They also have valves in them similar to the semi-lunar valves (Figure 9.13, page 129).

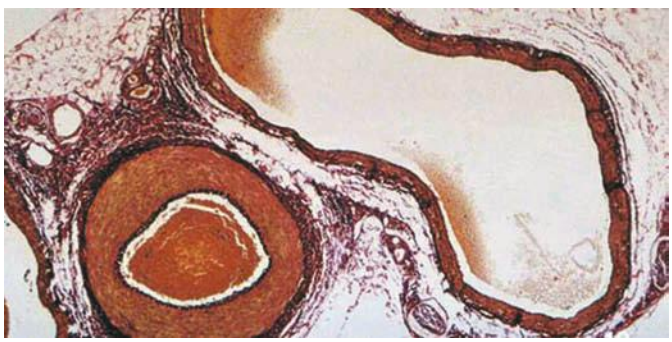


Figure 9.18 Transverse section through a vein and artery. The vein is on the right, the artery on the left. Notice that the wall of the artery is much thicker than that of the vein. The material filling the artery is formed from coagulated red blood cells. These are also visible in two regions of the vein.

The blood in most veins is deoxygenated and contains less food but more carbon dioxide than the blood in most arteries. This is because respiring cells have used the oxygen and food and produced carbon dioxide (Figure 9.19). The pulmonary veins, which return blood from the lungs to the heart, are an exception. They contain oxygenated blood and a reduced level of carbon dioxide.

The main blood vessels associated with the heart, lungs and kidneys are shown in Figure 9.20. The right side of the heart is supplied by the vena cava (the main vein of the body) and sends blood to the lungs along the pulmonary artery. The left side of the heart receives blood from the lungs in the pulmonary vein and sends it to the body in the aorta, the main artery (see Chapter 11). In reality there are two pulmonary arteries and two pulmonary veins, because there are two lungs. There are also two vena cavae: one returns blood from the lower body; the other from the upper body. Each kidney receives blood from a renal artery. Once the blood has been filtered it is returned to the vena cava through a renal vein (see Chapter 13).

Blood pressure

The pumping action of the heart produces a pressure that drives blood around the circulatory system (Figure 9.20). In the arteries, the pressure fluctuates with the heartbeat, and the pressure wave can be felt as a pulse. The millions of tiny capillaries offer resistance to the blood flow and, by the time the blood enters the veins, the surges due to the heartbeat are lost and the blood pressure is greatly reduced.

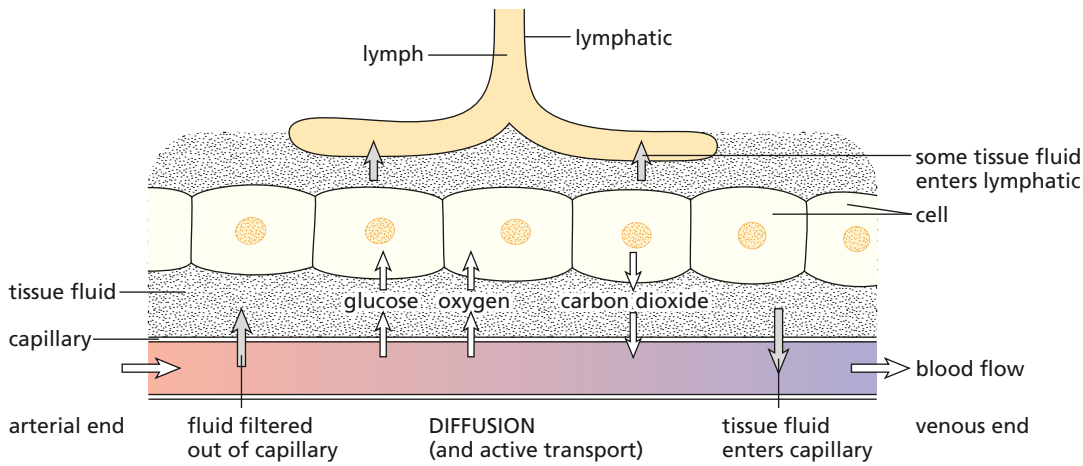


Figure 9.19 Blood, tissue fluid and lymph

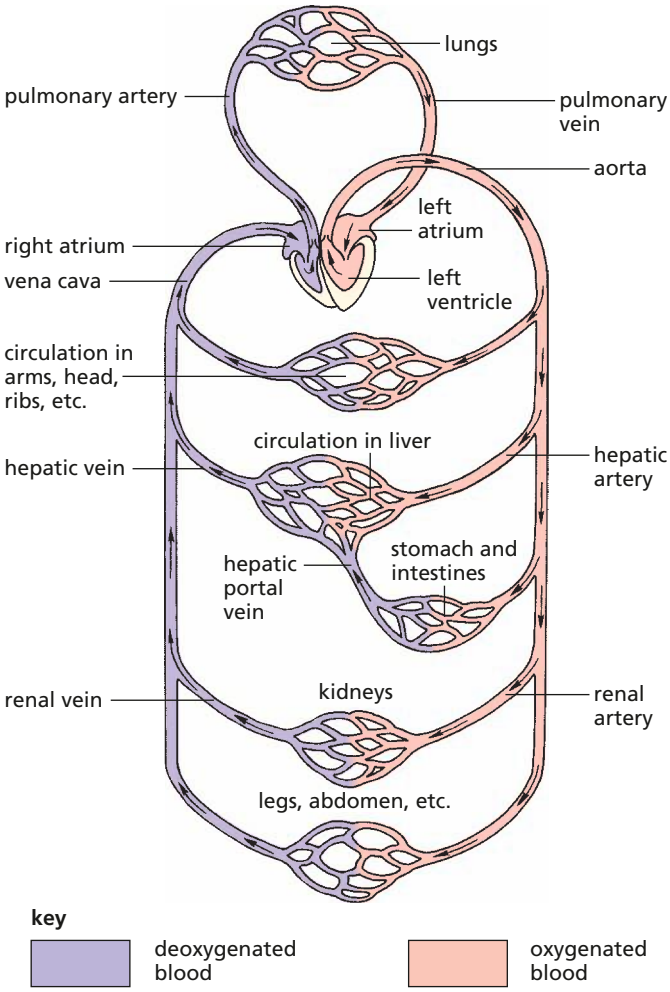


Figure 9.20 Diagram of human circulation

Although blood pressure varies with age and activity, it is normally kept within specific limits by negative feedback (see 'Homeostasis' in Chapter 14). The filtration process in the kidneys (Chapter 13) needs a fairly consistent blood pressure. If blood pressure falls significantly because, for example, of loss of blood or shock, then the kidneys may fail. Blood pressure consistently higher than normal increases the risk of heart disease or stroke.

Table 9.1 compares the structure of arteries, veins and capillaries and provides an explanation of how their structures are related to their functions.

Table 9.1 Comparing arteries, veins and capillaries

Blood vessel	Structure	Explanation of how structure is related to function
artery	thick, tough wall with muscles, elastic fibres and fibrous tissue	Carries blood at high pressure – prevents bursting and maintains pressure wave. The large arteries, near the heart, have a greater proportion of elastic tissue, which allows these vessels to stand up to the surges of high pressure caused by the heartbeat.
	lumen quite narrow, but increases as a pulse of blood passes through	This helps to maintain blood pressure.
	valves absent	High pressure prevents blood flowing backwards.
vein	thin wall – mainly fibrous tissue, with little muscle or elastic fibres	Carries blood at low pressure.
	lumen large	To reduce resistance to blood flow
	valves present	To prevent backflow of blood. Contraction of body muscles, particularly in the limbs, compresses the thin-walled veins. The valves in the veins prevent the blood flowing backwards when the vessels are compressed in this way. This assists the return of venous blood to the heart.
capillary	permeable wall, one cell thick, with no muscle or elastic tissue	This allows diffusion of materials between the capillary and surrounding tissues.
	lumen approximately one red blood cell wide	White blood cells can squeeze between cells of the wall. Blood cells pass through slowly to allow diffusion of materials and tissue fluid.
	valves absent	Blood is still under pressure.

Arterioles, shunt vessels and venules

Arterioles and shunt vessels

The small arteries and the arterioles have proportionately less elastic tissue and more muscle fibres than the great arteries. When the muscle fibres of the arterioles contract, they make the vessels narrower and restrict the blood flow

(a process called **vasoconstriction**). In this way, the distribution of blood to different parts of the body can be regulated. One example is in the skin. If the body temperature drops below normal, arterioles in the skin constrict to reduce the amount of blood flowing through capillaries near the skin surface. **Shunt vessels**, linking the arterioles with venules, dilate to allow the blood to bypass the capillaries (Figure 9.21). This helps to reduce further heat loss. (See also 'Homeostasis' in Chapter 14.)

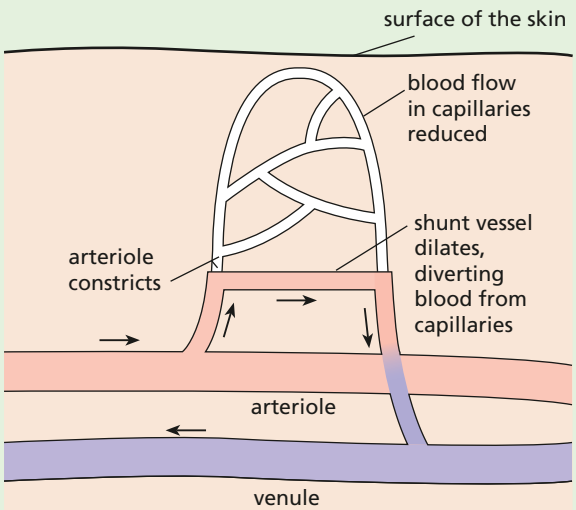


Figure 9.21 Shunt vessels in the skin in cold conditions

The lymphatic system

Not all the tissue fluid returns to the capillaries. Some of it enters blind-ended, thin-walled vessels called **lymphatics** (Figure 9.16). The lymphatics from all parts of the body join up to make two large vessels, which empty their contents into the blood system as shown in Figure 9.22.

The lacteals from the villi in the small intestine (Figure 7.24) join up with the lymphatic system, so most of the fats absorbed in the intestine reach the circulation by this route. The fluid in the lymphatic vessels is called **lymph** and is similar in composition to tissue fluid.

Some of the larger lymphatics can contract, but most of the lymph flow results from the vessels being compressed from time to time when the body muscles contract in movements such as walking or breathing. There are valves in the lymphatics (Figure 9.23) like those in the veins and the pulmonary artery (Figure 9.13), so that when the lymphatics are squashed, the fluid in them is forced in one direction only: towards the heart.

At certain points in the lymphatic vessels there are swellings called **lymph nodes** (Figure 9.22). Lymphocytes are stored in the lymph nodes and released into the lymph to eventually reach the blood system. There are also phagocytes in the lymph nodes. If bacteria enter a wound and are not ingested by the white cells of the blood or lymph, they will be carried in the lymph to a lymph node and white cells there will ingest them. The lymph nodes thus form part of the body's defence system against infection.

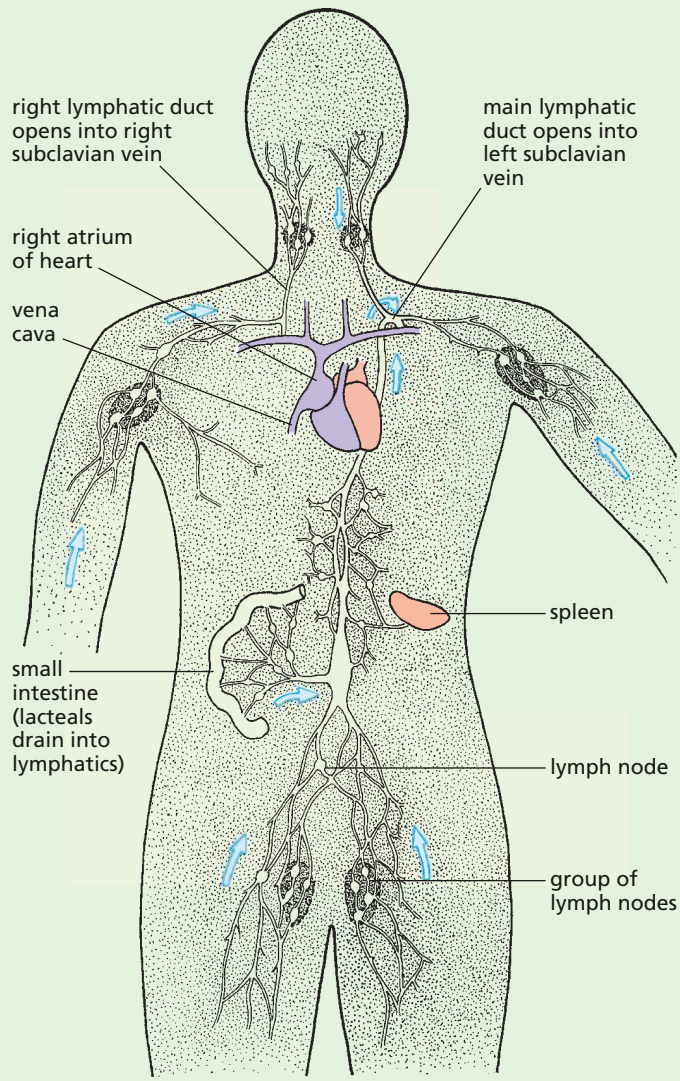


Figure 9.22 The main drainage routes of the lymphatic system

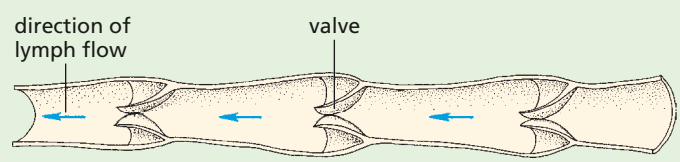


Figure 9.23 Lymphatic vessel cut open to show valves

Blood

Blood consists of red cells, white cells and platelets floating in a liquid called plasma. There are between 5 and 6 litres of blood in the body of an adult, and each cubic centimetre contains about 5 billion red cells.

Red cells

These are tiny, disc-like cells (Figures 9.24(a) and 9.26) which do not have nuclei. They are made of spongy cytoplasm enclosed in an elastic cell membrane. In their cytoplasm is the red pigment haemoglobin, a protein combined with iron. Haemoglobin combines with oxygen in places where there is a high concentration of oxygen, to form **oxyhaemoglobin**. Oxyhaemoglobin is an unstable compound. It breaks down and releases its oxygen in places where the oxygen concentration is low (Figure 9.25). This makes haemoglobin very useful in carrying oxygen from the lungs to the tissues.

Blood that contains mainly oxyhaemoglobin is said to be **oxygenated**. Blood with little oxyhaemoglobin is **deoxygenated**.

Each red cell lives for about 4 months, after which it breaks down. The red haemoglobin changes to a yellow pigment, bilirubin, which is excreted in the bile. The iron from the haemoglobin is stored in the liver. About 200 000 million red cells wear out and are replaced each day. This is about 1% of the total. Red cells are made by the red bone marrow of certain bones in the skeleton – in the ribs, vertebrae and breastbone for example.

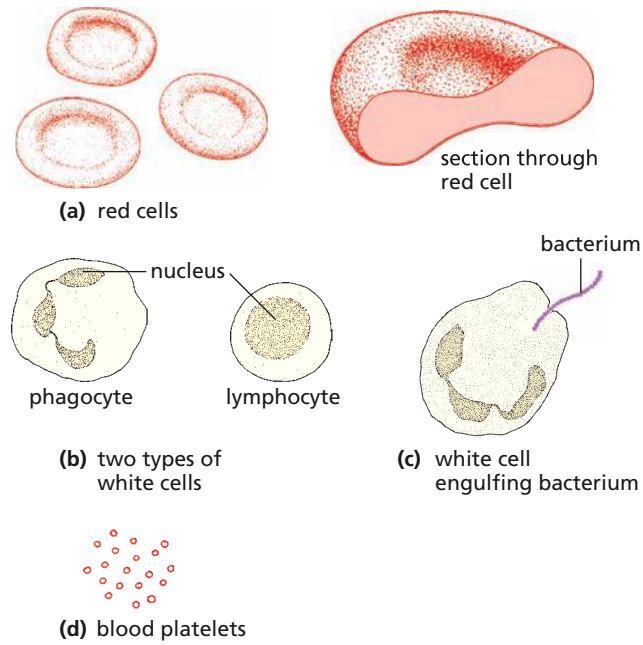


Figure 9.24 Blood cells

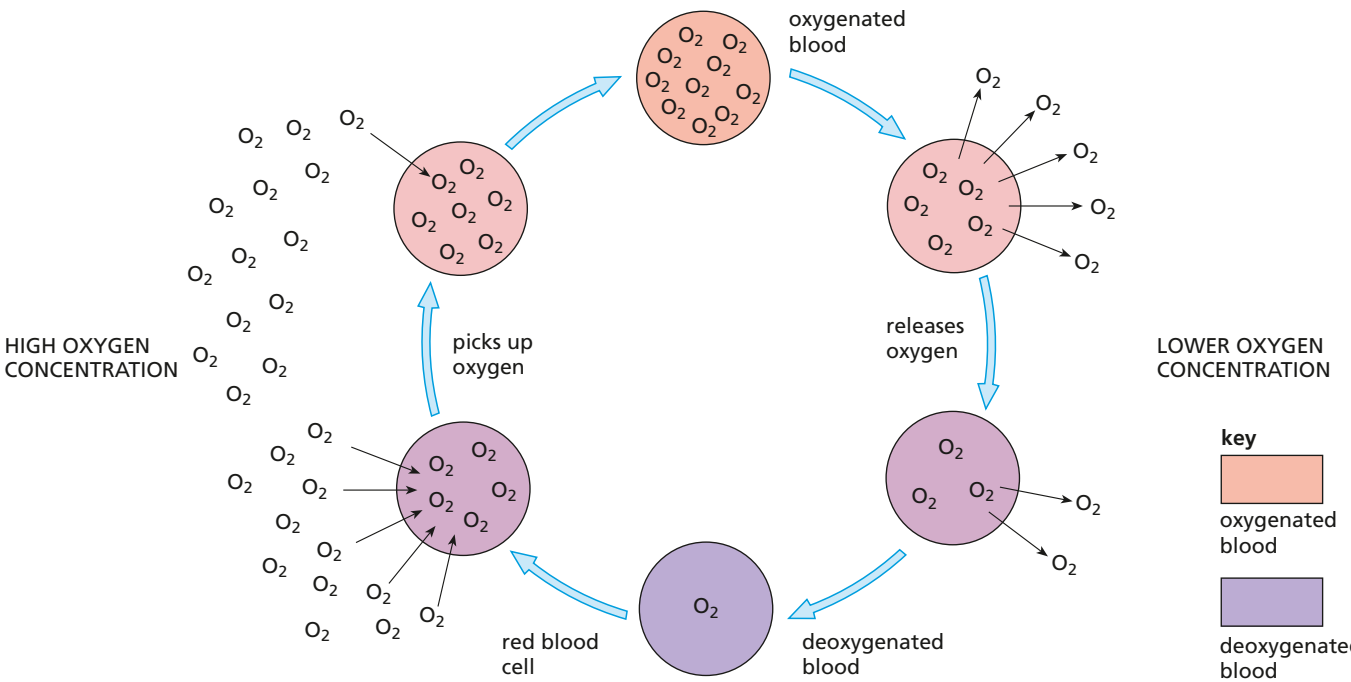


Figure 9.25 The function of the red cells

White cells

There are several different kinds of white cell (Figures 9.24(b) and 9.26). Most are larger than the red cells and they all have a nucleus. There is one white cell to every 600 red cells and they are made in the same bone marrow that makes red cells. Many of them undergo a process of maturation and development in the thymus gland, lymph nodes or spleen. White blood cells are involved with phagocytosis and antibody production.

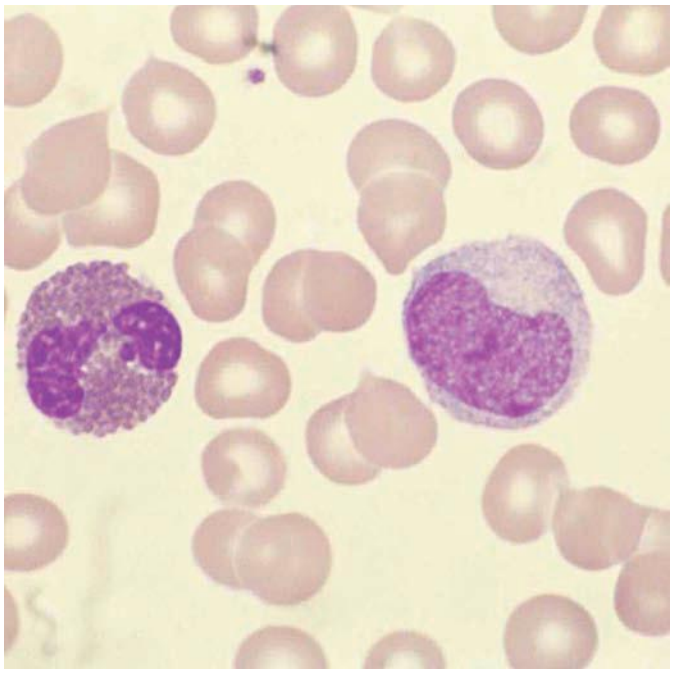


Figure 9.26 Red and white cells from human blood (×2500). The large nucleus can be seen clearly in the white cells.

Platelets

These are pieces of special blood cells budded off in the red bone marrow. They help to clot the blood at wounds and so stop the bleeding.

Plasma

The liquid part of the blood is called plasma. It is water with a large number of substances dissolved in it. The ions of sodium, potassium, calcium, chloride and hydrogen carbonate, for example, are present. Proteins such as fibrinogen, albumin and globulins make up an important part of the plasma. Fibrinogen is needed for clotting (see below), and the globulin proteins include antibodies, which combat bacteria and other foreign matter (page 149). The plasma will also contain varying amounts of food substances such as amino acids, glucose and lipids (fats). There may also be hormones (Chapter 14) present, depending on the activities taking place in the body. The excretory product, urea, is dissolved in the plasma, along with carbon dioxide.

The liver and kidneys keep the composition of the plasma more or less constant, but the amount of digested food, salts and water will vary within narrow limits according to food intake and body activities.

Table 9.2 summarises the role of transport by the blood system

Table 9.2 Transport by the blood system

Substance	From	To
oxygen	lungs	whole body
carbon dioxide	whole body	lungs
urea	liver	kidneys
hormones	glands	target organs
digested food	intestine	whole body
heat	abdomen and muscles	whole body

Note that the blood is not directed to a particular organ. A molecule of urea may go round the circulation many times before it enters the renal artery, by chance, and is removed by the kidneys.

White blood cells

The two most numerous types of white cells are **phagocytes** and **lymphocytes**.

The phagocytes can move about by a flowing action of their cytoplasm and can escape from the blood capillaries into the tissues by squeezing between the cells of the capillary walls. They collect at the site of an infection, engulfing (**ingesting**) and digesting harmful bacteria and cell debris – a process called **phagocytosis** (Figure 9.24(c)). In this way they prevent the spread of infection through the body. One of the functions of lymphocytes is to produce antibodies.

Clotting

When tissues are damaged and blood vessels cut, platelets clump together and block the smaller capillaries. The platelets and damaged cells at the wound also produce a substance that acts, through a series of enzymes, on the soluble plasma protein called fibrinogen. As a result of this action, the fibrinogen is changed into insoluble **fibrin**, which forms a network of fibres across the wound. Red cells become trapped in this network and so form a blood clot. The clot not only stops further loss of blood, but also prevents the entry of harmful bacteria into the wound (Figures 9.27 and 9.28).

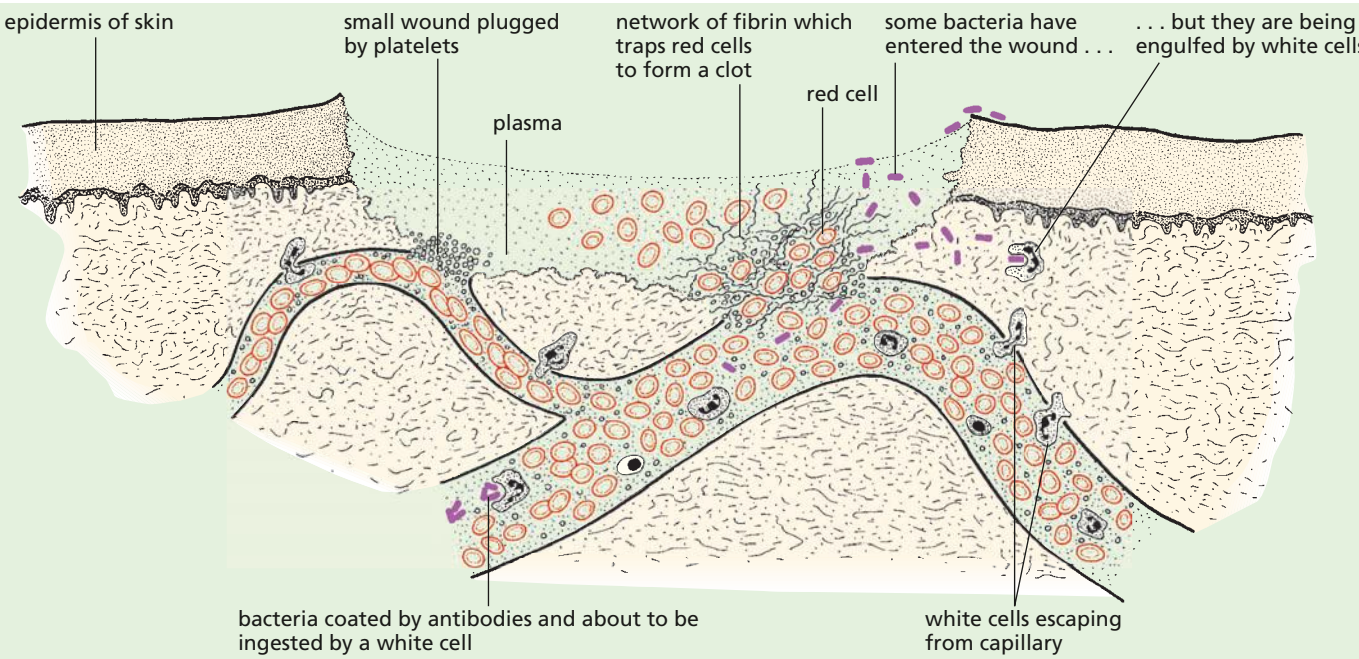


Figure 9.27 The defence against infection by pathogens. An area of skin has been damaged and two capillaries broken open.

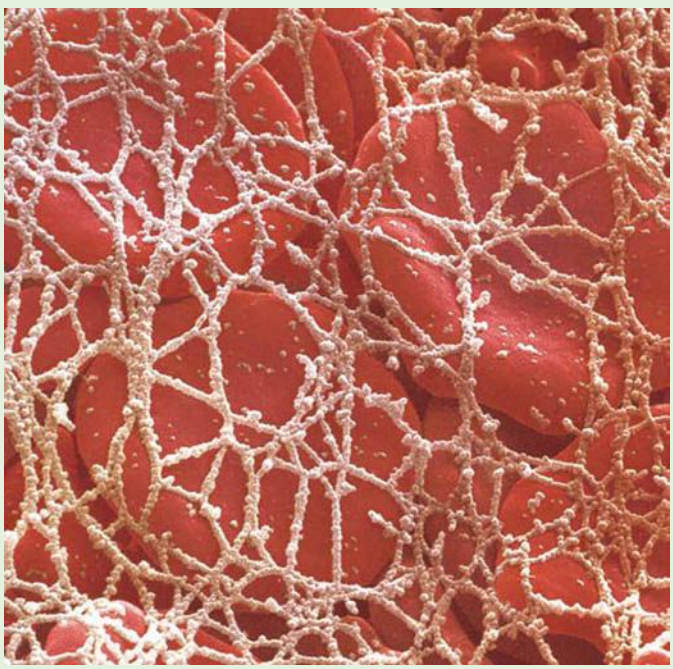


Figure 9.28 Red cells trapped in a fibrin network (×6500)

The transfer of materials between capillaries and tissue fluid

The fluid that escapes from capillaries is not blood, nor plasma, but tissue fluid. Tissue fluid is similar to plasma but contains less protein, because protein molecules are too large to pass through the walls of the capillaries. This fluid bathes all the living cells of the body and, since it contains dissolved food and oxygen from the blood, it supplies the cells with their needs (Figures 9.16 and 9.19). Some of the tissue fluid eventually seeps back into the capillaries, having given up its oxygen and dissolved food to the cells, but it has now received the waste products of the cells, such as carbon dioxide, which are carried away by the bloodstream. The tissue fluid that doesn't return to the capillaries joins the lymphatic system.

Extension work

Ideas about the circulatory system

There must have been knowledge of human internal anatomy thousands of years ago. This might have come, for example, from the practice of removing internal organs before the process of mummification in Ancient Egypt. However, there seems to have been little or no systematic study of human anatomy in the sense that the parts were named, described or illustrated.

Some of the earliest records of anatomical study come from the Greek physician, Galen.

Galen (AD130–200)

Galen dissected goats, monkeys and other animals and produced detailed and accurate records. He was not allowed to dissect human bodies, so his descriptions were often not applicable to human anatomy.

The anatomical knowledge was important but the functions of the various parts could only be guessed at. It was known that the veins contained blood but arteries at death are usually empty and it was assumed that they carried air or, more obscurely, 'animal spirit'. Galen observed the pulse, but thought that it was caused by surges of blood into the veins.

William Harvey (1578–1657)

In the 15th and 16th centuries, vague ideas about the movement of blood began to emerge, but it was William Harvey, an English physician, who produced evidence to support the circulation theory.

Harvey's predecessors had made informed guesses, but Harvey conducted experiments to support his ideas. He noted that the valves in the heart would permit blood to pass in one direction only. So the notion that blood shunted back and forth was false. When he restricted the blood flow in an artery he observed that it bulged on the side nearest the heart, whereas a vein bulged on the side away from the heart.

Figure 9.29 shows a simple experiment that reveals the presence of valves in the veins and supports the idea of a one-way flow.

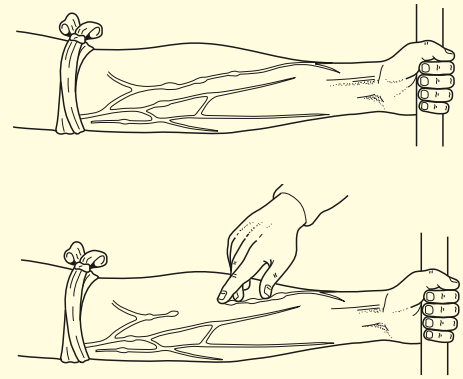


Figure 9.29 Harvey's demonstration of valves and one-way flow in a vein. The vein is compressed and the blood expelled by running a finger up the arm. The vein refills, but only as far as the valve. (Compare with Figure 9.13, page 129.)

Harvey published his results in 1628. They were at first rejected and ridiculed, not because anyone tried his experiments or tested his observations, but simply because his conclusions contradicted the writings of Galen 1500 years previously.

By 1654, Harvey's theory of circulation was widely accepted but it was still not known how blood passed from the arteries to the veins. Harvey observed that arteries and veins branched and re-branched until the vessels were too small to be seen and suggested that the connection was made through these tiny vessels. This was confirmed after the microscope had been invented in 1660 and the vessels were called 'capillaries'.

The significance of this history is that, although it is reasonable to make an informed guess at the function of a structure or organ, it is only by testing these guesses by experiment that they can be supported or disproved.

Questions

Core

1 Starting from the left atrium, put the following in the correct order for circulation of the blood:
left atrium, vena cava, aorta, lungs, pulmonary artery, right atrium, pulmonary vein, right ventricle, left ventricle

2 Why is it incorrect to say 'all arteries carry oxygenated blood and all veins carry deoxygenated blood'?

3 How do veins differ from arteries in:
   a their function
   b their structure?

4 How do capillaries differ from other blood vessels in:
   a their structure
   b their function?

5 Why is it misleading to say that a person 'suffers from blood pressure'?

6 Which important veins are not labelled in Figure 9.3?

7 In what ways are white cells different from red cells in:
   a their structure
   b their function?

8 Where, in the body, would you expect haemoglobin to be combining with oxygen to form oxyhaemoglobin?

9 In what parts of the body would you expect oxyhaemoglobin to be breaking down to oxygen and haemoglobin?

10 a Why is it important for oxyhaemoglobin to be an unstable compound, i.e. easily changed to oxygen and haemoglobin?
   b What might be the effect on a person whose diet contained too little iron?

Extended

11 Which parts of the heart:
   a pump blood into the arteries
   b stop blood flowing the wrong way?

12 Put the following in the correct order:
   a blood enters arteries
   b ventricles contract
   c atria contract
   d ventricles relax
   e blood enters ventricles
   f semi-lunar valves close
   g tri- and bicuspid valves close.

13 Why do you think that:
   a the walls of the ventricles are more muscular than the walls of the atria
   b the muscle of the left ventricle is thicker than that of the right ventricle?

   (Hint: look back at Figure 9.20.)

14 Why is a person whose heart valves are damaged by disease unable to take part in active sport?

15 a What positive steps could you take, and
   b what things should you avoid, to reduce your risk of coronary heart disease in later life?

16 About 95% of patients with disease of the leg arteries are cigarette smokers. Arterial disease of the leg is the most frequent cause of leg amputation.
   a Is there a correlation between smoking and leg amputation?
   b Does smoking cause leg amputation?
   c In what way could smoking be a possible cause of leg amputation?

17 Figure 9.30 shows the relative increase in the rates of four body processes in response to vigorous exercise.
   a How are the changes related physiologically to one another?
   b What other physiological changes are likely to occur during exercise?
   c Why do you think that the increase in blood flow in muscle is less than the total increase in the blood flow?

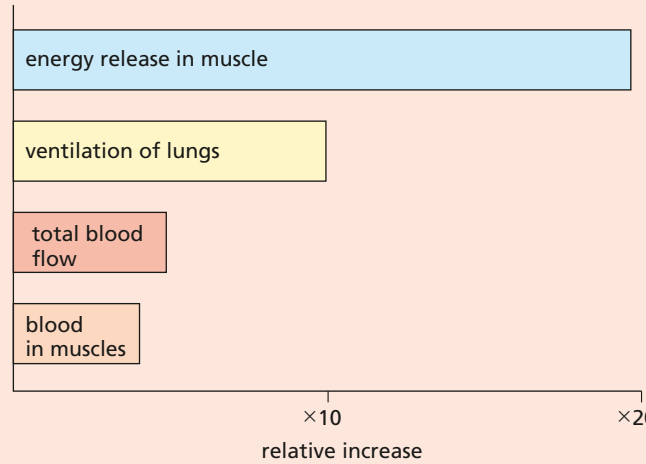


Figure 9.30

18 List the things you would expect to find if you analysed a sample of lymph.

Checklist

After studying Chapter 9 you should know and understand the following:

- The circulatory system is made up of blood vessels with a heart and valves to ensure one-way flow of blood.
- The heart is a muscular pump with valves, which sends blood around the circulatory system.
- The left side of the heart pumps oxygenated blood around the body.
- The right side of the heart pumps deoxygenated blood to the lungs.
- The atria are thin walled and receive blood from veins.
- The ventricles have thick muscular walls to pump blood through arteries.
- Blood pressure is essential in order to pump blood around the body.
- Arteries carry blood from the heart to the tissues.
- Veins return blood to the heart from the tissues.
- Capillaries form a network of tiny vessels in all tissues. Their thin walls allow dissolved food and oxygen to pass from the blood into the tissues, and carbon dioxide and other waste substances to pass back into the blood.
- The main blood vessels to and from the heart are: vena cavae, pulmonary veins, pulmonary arteries and aorta.
- The lungs are supplied by the pulmonary arteries and veins.
- The kidneys are supplied by the renal arteries and veins.
- Heart activity can be monitored by ECG, pulse rate and stethoscope, which transmits the sound of valves closing.
- Blockage of the coronary arteries in the heart leads to a heart attack.
- Smoking, fatty diets, stress, lack of exercise, genetic disposition and age may contribute to heart disease.
- Blood consists of red cells, white cells and platelets suspended in plasma.
- Plasma transports blood cells, ions, soluble nutrients, e.g. glucose, hormones and carbon dioxide.
- The red cells carry oxygen. The white cells attack bacteria by phagocytosis and production of antibodies. Platelets are needed to clot blood.

- Fish have a single circulation; mammals have a double circulation, with advantages over a single circulation.
- The heart contains atrioventricular and semi-lunar valves, preventing backflow of blood.
- The left and right sides of the heart are divided by a septum, keeping oxygenated and deoxygenated blood separate.

- The risk of coronary heart disease can be reduced by an appropriate diet and exercise regime.
- Coronary heart disease can be treated by the use of drugs (aspirin), stents, angioplasty and by-pass.
- Lymphocytes and phagocytes have distinctive shapes and features.
- Antibodies are chemicals made by white cells in the blood. They attack any micro-organisms or foreign proteins that get into the body.
- Blood clotting involves the conversion of the soluble blood protein fibrinogen to insoluble fibrin, which traps blood cells.
- Blood clotting prevents loss of blood and entry of pathogens into the body.
- Materials are transferred between capillaries and tissue fluid.
- All cells in the body are bathed in tissue fluid, which is derived from plasma.
- Lymph vessels return tissue fluid to the lymphatic system and finally into the blood system.
- Lymph nodes are important immunological organs.

10 Diseases and immunity

Pathogens and transmission
Definitions
Transmissible diseases

Defences against diseases
Defences of the body against pathogens
Vaccination
Controlling the spread of disease

How antibodies work
Active immunity, including definition
Vaccination
Passive immunity
Type 1 diabetes

Pathogens and transmission

Key definitions
A **pathogen** is a disease-causing organism.
A **transmissible disease** is a disease in which the pathogen can be passed from one host to another.

Pathogens

Pathogens include many bacteria, viruses and some fungi, as well as a number of protoctista and other organisms. Pathogenic bacteria may cause diseases because of the damage they do to the host's cells, but most bacteria also produce poisonous waste products called **toxins**. Toxins damage the cells in which the bacteria are growing. They also upset some of the systems in the body. This gives rise to a raised temperature, headache, tiredness and weakness, and sometimes diarrhoea and vomiting. The toxin produced by the *Clostridium* bacteria (which causes tetanus) is so poisonous that as little as 0.00023 g is fatal.

Many viruses cause diseases in plants and animals. Human virus diseases include the common cold, poliomyelitis, measles, mumps, chickenpox, herpes, rubella, influenza and AIDS (See 'Sexually transmitted infections' in Chapter 16). Tobacco mosaic virus affects tomato plants as well as tobacco. It causes mottling and discolouration of the leaves, eventually stunting the growth of the plant.

While most fungi are saprophytic (feeding on dead organic matter) some are parasitic, obtaining their nutrients from living organisms. The hyphae of parasitic fungi penetrate the tissues of their host plant and digest the cells and their contents. If the mycelium spreads extensively through the host, it usually causes the death of the plant. The bracket fungus shown in Chapter 1, Figure 1.27, is the fruiting body of a mycelium that is spreading through the tree and will eventually kill it.

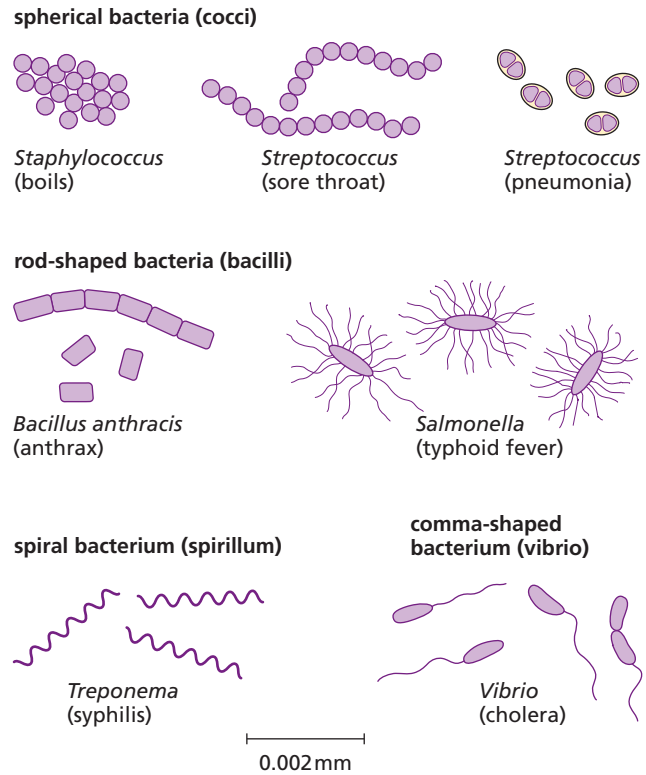


Figure 10.1 Some pathogenic bacteria

Fungus diseases such as blight, mildews or rusts (see Chapter 1, Figure 1.28) are responsible for causing considerable losses to arable farmers, and there is a constant search for new varieties of crop plants that are resistant to fungus disease, and for new chemicals (fungicides) to kill parasitic fungi without harming the host.

A few parasitic fungi cause diseases in animals, including humans. One group of these fungi cause tinea or ringworm. The fungus grows in the epidermis of the skin and causes irritation and inflammation. One form of tinea is athlete's foot, in which the skin between the toes becomes infected. Tinea is very easily spread by contact with infected towels or clothing, but can usually be cured quickly with a fungicidal ointment.

Transmission

Pathogens responsible for transmissible diseases can be spread either through direct contact or indirectly.

Direct contact

This may involve transfer through blood or other body fluids. HIV is commonly passed on by drug addicts who inject the drug into their bloodstream, sharing needles with other drug users. If one user injects himself, the pathogens in his blood will contaminate the syringe needle. If this is then used by a second drug user, the pathogens are passed on. Anyone cleaning up dirty needles is at risk of infection if they accidently stab themselves. Surgeons carrying out operations have to be especially careful not to be in direct contact with the patient's blood, for example by cutting themselves while conducting an operation. A person with HIV or another sexually transmitted disease (see Chapters 15 and 16) who has unprotected sex, can pass on the pathogen to their partner through body fluids. It used to be said that HIV could be transferred from one person to another through saliva, but this is now considered to be a very low risk.

Extension work

Malaria

About 219 million people suffer from malaria in over 100 countries (Figure 10.2). In 2010 there were an estimated 660 000 malaria deaths according to the World Health Organization.

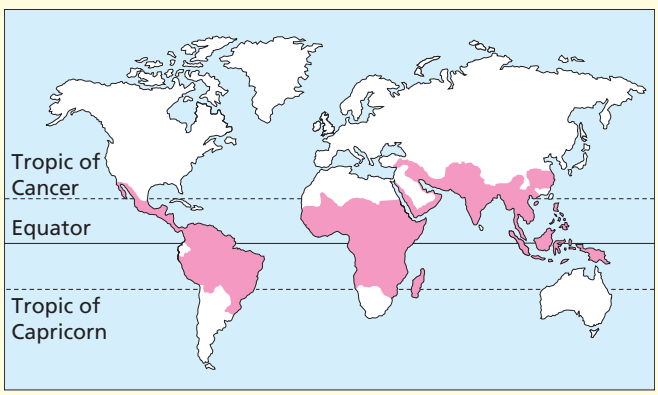
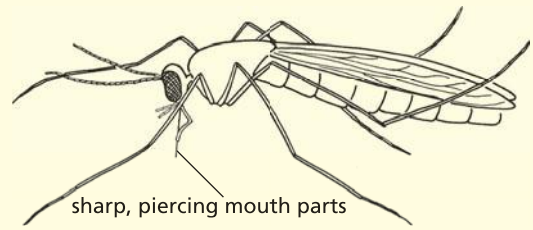
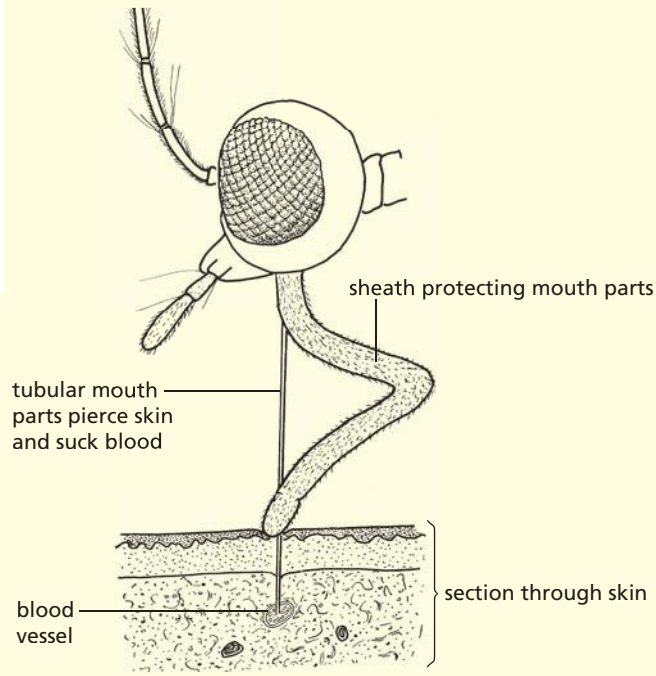


Figure 10.2 The worldwide distribution of malaria

The disease is caused by a protozoan parasite called *Plasmodium* which is transmitted from person to person by the bites of infected mosquitoes of the genus *Anopheles*. The mosquito is said to be the **vector** of the disease. When a mosquito 'bites' a human, it inserts its sharp, pointed mouthparts through the skin till they reach a capillary (Figure 10.3). The mosquito then injects saliva, which stops the blood from clotting. If the mosquito is infected, it will also inject hundreds of malarial parasites.



(a) mosquito about to feed



(b) mosquito head and mouth parts

Figure 10.3 Mosquito feeding on blood

The parasites reach the liver via the circulation and burrow into the liver cells where they reproduce. A week or two later, the daughter cells break out of the liver cells and invade the red blood cells. Here they reproduce rapidly and then escape from the original red cells to invade others (Figure 10.4).

The cycle of reproduction in the red cells takes 2 or 3 days (depending on the species of *Plasmodium*). Each time the daughter plasmodia are released simultaneously from thousands of red cells the patient experiences the symptoms of malaria. These are chills accompanied by violent shivering,

followed by a fever and profuse sweating. With so many red cells being destroyed, the patient will also become anaemic (see 'Diet' in Chapter 7).

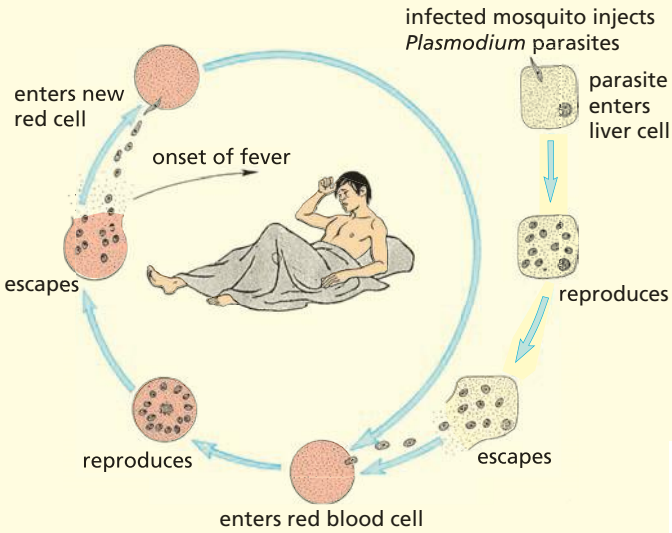


Figure 10.4 *Plasmodium,* the malarial parasite

If a mosquito sucks blood from an infected person, it will take up the parasites in the red cells. The parasites reproduce in the mosquito and finally invade the salivary glands, ready to infect the next human.

Control

There are drugs which kill the parasites in the bloodstream but they do not reach those in the liver. The parasites in the liver may emerge at any time and start the cycle again. If these drugs are taken by a healthy person before entering a malarious country, they kill any parasites as soon as they are injected. This is a protective or **prophylactic** use of the drug.

Unfortunately there are now many mutant forms of *Plasmodium* that have developed resistance to these drugs.

A great deal of work has been devoted to finding an effective vaccine, without much success. Trials are currently taking place of a vaccine that may offer at least partial protection against the disease.

The most far-reaching form of malarial control is based on the elimination of the mosquito. It is known that mosquitoes lay their eggs in stagnant water and that the larvae hatch, feed and grow in the water, but have to come to the surface to breathe air.

Spraying stagnant water with oil and insecticides suffocates or poisons the larvae and pupae. Spraying must include not only lakes and ponds but any accumulation of fresh water that mosquitoes can reach, e.g. drains, gutters, tanks, tin cans and old car tyres. By draining swamps and turning sluggish rivers into swifter streams, the breeding grounds of the mosquito are destroyed.

Spraying the walls of dwellings with chemicals like DDT was once very effective because the insecticide remained active for several months and the mosquito picked up a lethal dose merely by settling on the wall. See page 324 for further details about the use of DDT and its effects on the environment.

However, in at least 60 countries, many species of *Anopheles* have developed resistance to these insecticides and this method of control is now far less effective. The emphasis has changed back to the removal of the mosquito's breeding grounds or the destruction of the larvae and pupae.

Indirect contact

This may involve infection from pathogens on contaminated surfaces, for example during food preparation. Raw meat carries bacteria, which are killed if the meat is adequately cooked. However, if the raw meat is prepared on a surface that is then used for other food preparation, such as cutting up fruit or vegetables that are later eaten raw, then the pathogens from meat can be transferred to the fresh food. The person handling the food is also a potential vector of disease if he or she does not wash their hands after using the toilet, moving rubbish or handling raw produce. In Britain there have been serious cases where customers in butchers' shops have been infected with the bacterium *Escherichia coli* (*E. coli*), because germs from raw meat were transferred to cooked meat unwittingly by shop assistants using poor hygiene practices. For example, in 1996, 21 people died after eating contaminated meat supplied by a butcher's shop in Scotland.

Salmonella food poisoning

One of the commonest causes of food poisoning is the toxin produced by the bacteria *Salmonella typhimurium* and *S. enteritidis.* These bacteria live in the intestines of cattle, chickens and ducks without causing disease symptoms. Humans, however, may develop food poisoning if they drink milk or eat meat or eggs that are contaminated with *Salmonella* bacteria from the alimentary canal of an infected animal.

Intensive methods of animal rearing may contribute to a spread of infection unless care is taken to reduce the exposure of animals to infected faeces.

The symptoms of food poisoning are diarrhoea, vomiting and abdominal pain. They occur from 12 to 24 hours after eating the contaminated food. Although these symptoms are unpleasant, the disease is not usually serious and does not need treatment with drugs. Elderly people and very young children, however, may be made very ill by food poisoning.

The *Salmonella* bacteria are killed when meat is cooked or milk is pasteurised. Infection is most likely if untreated milk is drunk, meat is not properly cooked, or cooked meat is contaminated with bacteria transferred from raw meat (Figure 10.5). Frozen poultry must be thoroughly defrosted before cooking, otherwise the inside of the bird may not get hot enough during cooking to kill the *Salmonella*.

It follows that, to avoid the disease, all milk should be pasteurised and meat should be thoroughly cooked. People such as shop assistants and cooks should not handle cooked food at the same time as they handle raw meat. If they must do so, they should wash their hands thoroughly between the two activities.

The liquid that escapes when a frozen chicken is defrosted may contain *Salmonella* bacteria. The dishes and utensils used while the bird is defrosting must not be allowed to come into contact with any other food.

Uncooked meat or poultry should not be kept alongside any food that is likely to be eaten without cooking. Previously cooked meat should never be warmed up; the raised temperature accelerates the reproduction of any bacteria present. The meat should be eaten cold or cooked at a high temperature.

In the past few years there has been an increase in outbreaks of *Salmonella* food poisoning in which the bacteria are resistant to antibiotics. Some scientists suspect that this results from the practice of feeding antibiotics to farm animals to increase their growth rate. This could allow populations of drug-resistant salmonellae to develop.

Salmonella bacteria, and also bacteria that cause typhoid, are present in the faeces of infected people and may reach food from the unwashed hands of the sufferer.

People recovering from one of these diseases may feel quite well, but bacteria may still be present in their faeces. If they don't wash their hands thoroughly after going to the lavatory, they may have small numbers of bacteria on their fingers. If they then handle food, the bacteria may be transferred to the food. When this food is eaten by healthy people, the bacteria will multiply in their bodies and give them the disease.

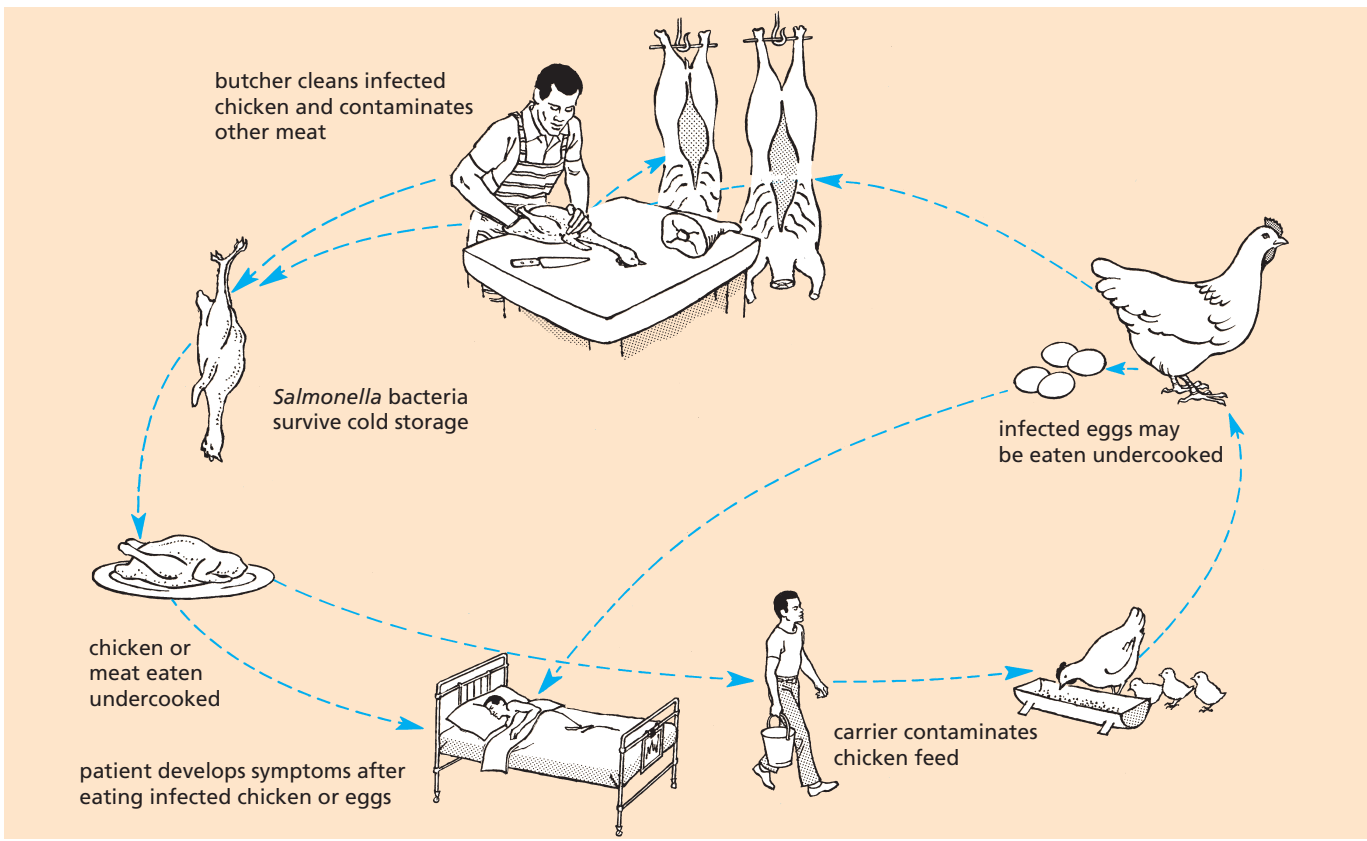


Figure 10.5 Transmission of *Salmonella* food poisoning

People working in food shops, kitchens and food-processing factories could infect thousands of other people in this way if they were careless about their personal cleanliness.

Some forms of food poisoning result from poisons (toxins) that are produced by bacteria that get into food. Cooking kills the bacteria in the food but does not destroy the toxins that cause the illness. Only one form of this kind of food poisoning, called **botulism**, is dangerous. It is also very rare.

In the 1970s another genus of bacteria, *Campylobacter*, was identified as a cause of food poisoning. This bacterium causes acute abdominal pains and diarrhoea for about 24 hours. The sources of infection are thought to be undercooked meat, particularly 'burgers'.

In summary, people who handle and prepare food need to be extremely careful about their personal hygiene. It is essential that they wash their hands before touching food, particularly after they have visited the lavatory (Figure 10.6). Hand-washing is also important after handling raw meat, particularly poultry (see Figure 10.5). Food on display in shops needs to be protected (Figure 10.7).

Some people carry intestinal pathogens without showing any symptoms of disease. These people are called 'carriers'. Once identified, they should not be allowed to work in canteens or food-processing factories.

Figure 10.6 Hygienic handling of food. Shop assistants avoid handling meat and shellfish with their fingers by using disposable gloves.

Figure 10.7 Protection of food on display. The glass barrier stops customers from touching the products, keeps flies off the food and helps stop droplets from coughs and sneezes falling on the food.

Contamination of water

If disease bacteria get into water supplies used for drinking, hundreds of people can become infected. Diseases of the alimentary canal, like typhoid and cholera (see 'Alimentary canal' in Chapter 7), are especially dangerous. Millions of bacteria infest the intestinal lining of a sick person.

Some of these bacteria will pass out with the faeces. If the faeces get into streams or rivers, the bacteria may be carried into reservoirs of water used for drinking. Even if faeces are left on the soil or buried, rainwater may wash the bacteria into a nearby stream.

To prevent this method of infection, drinking water needs to be purified and faeces must be made harmless, a process involving sewage treatment (see 'Conservation' in Chapter 21).

Water treatment

On a small scale, simply boiling the water used for drinking will destroy any pathogens. On a large scale, water supplies are protected by (a) ensuring that untreated human sewage cannot reach them and (b) treating the water to make it safe.

The treatment needed to make water safe for drinking depends on the source of the water. Some sources, e.g. mountain streams, may be almost pure; others, e.g. sluggish rivers, may be contaminated.

The object of the treatment is to remove all micro-organisms that might cause disease. This is done by filtration and chlorination. The water

is passed through beds of sand in which harmless bacteria and protozoa are growing. These produce a gelatinous film which acts as a fine filter and removes pathogens.

Finally, chlorine gas is added to the filtered water and remains in contact with it for long enough to kill any bacteria that have passed through the filter. How much chlorine is added and the length of the contact time both depend on how contaminated the water source is likely to be. Most of the chlorine disappears before the water reaches the consumers.

The purified water is pumped to a high-level reservoir or water tower. These are enclosed to ensure that no pathogens can get into the water. The height of the reservoir provides the pressure needed to deliver the water to the consumer.

Waste disposal

Waste from domestic or commercial premises should be stored in dustbins or garbage cans made of galvanised steel or strong plastic, with a closely fitted lid to exclude flies and keep out scavenging animals. If this is not done, pathogens will breed in the waste and become a source of disease organisms. The waste is taken away and disposed of by burning, or burying deep enough to prevent rats using it as food, or (less effectively) tightly packed to keep out flies and vermin.

Contamination by houseflies

Flies walk about on food. They place their mouthparts on it and pump saliva onto the food. Then they suck up the digested food as a liquid.

This would not matter much if flies fed only on clean food, but they also visit decaying food or human faeces. Here they may pick up bacteria on their feet or their mouthparts. They then alight on our food and the bacteria on their bodies are transferred to the food. Figure 10.8 shows the many ways in which this can happen.

Food poisoning, amoebic dysentery and polio can be spread by houseflies.

Tinea ('ringworm') – a fungal parasite

Several species of fungus give rise to the various forms of this disease. The fungus attacks the epidermis (see 'Homeostasis' in Chapter 14) and produces a patch of inflamed tissue. On the skin the infected patch spreads outwards and heals in the centre, giving a ring-like appearance ('ringworm').

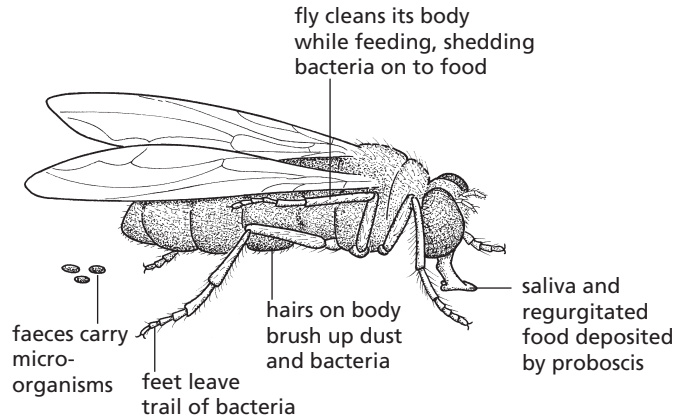


Figure 10.8 Transmission of bacteria by houseflies

The different species of tinea fungi may live on the skin of humans or domestic animals, or in the soil. The region of the body affected will depend on the species of fungus.

One kind affects the scalp and causes circular bald patches. The hair usually grows again when the patient recovers from the disease.

The species of fungus that affects the feet usually causes cracks in the skin between the toes. This is known as 'athlete's foot'.

Tinea of the crutch is a fungus infection, occurring usually in males, which affects the inner part of the thighs on each side of the scrotum. It causes a spreading, inflamed area of skin with an itching or burning sensation.

All forms of the disease are very contagious. That means, they are spread by contact with an infected person or their personal property. Tinea of the scalp is spread by using infected hairbrushes, combs or pillows. Tinea of the crutch can be caught by using towels or bedclothes contaminated by the fungus or its spores, and 'athlete's foot' by wearing infected socks or shoes, or from the floors of showers and swimming pools.

When an infection is diagnosed, the clothing, bed linen, infected hairbrushes, combs or towels must be boiled to destroy the fungus. It is best, anyway, to avoid sharing these items as their owners may be carrying the infection without knowing or admitting it.

In young people, tinea infections often clear up without treatment. Where treatment is needed, a fungicide cream or dusting powder is applied to the affected areas of skin. Infected feet may be dipped in a solution of potassium permanganate (potassium manganate(VII)).

Amoebic dysentery

Entamoeba histolytica is a species of small amoebae that normally live harmlessly in the human intestine, feeding on food particles or bacteria. In certain conditions, however, *Entamoeba* invades the lining of the intestine causing ulceration and bleeding, with pain, vomiting and diarrhoea: the symptoms of amoebic dysentery.

The diarrhoea and vomiting lead to a loss of water and salts from the body and if they persist for very long can cause **dehydration**. Dehydration, if untreated, can lead to kidney failure and death. The treatment for dehydration is to give the patient a carefully prepared mixture of water, salts and sugar. The intestine absorbs this solution more readily than water and it restores the volume and concentration of the body fluids. This simple, effective and inexpensive treatment is called **oral rehydration therapy** and has probably saved thousands of lives since it was first discovered. There are also drugs that attack *Entamoeba*.

The faeces of infected people contain *Entamoeba* amoebae which, if they reach food or drinking water, can infect other people. The disease is prevalent in tropical, sub-tropical and, to some extent, temperate countries and is associated with low standards of hygiene and sanitation.

Airborne, 'droplet' or aerosol infection

When we sneeze, cough, laugh, speak or just breathe out, we send a fine spray of liquid drops into the air. These droplets are so tiny that they remain floating in the air for a long time. They may be breathed in by other people or fall on to exposed food (Figure 10.9). If the droplets contain viruses or bacteria, they may cause disease when they are eaten with food or inhaled.

Virus diseases such as colds, 'flu, measles and chickenpox are spread in this way. So are the bacteria (*Streptococci*) that cause sore throats. When the water in the droplets evaporates, the bacteria often die as they dry out. The viruses remain infectious, however, floating in the air for a long time.

In buses, trains, cinemas and night clubs the air is warm and moist, and full of floating droplets. These are places where you are likely to pick up one of these infections.

Figure 10.9 Droplet infection. The visible drops expelled by this sneeze will soon sink to the floor, but smaller droplets will remain suspended in the air.

Defences against diseases

The body has three main lines of defence against disease. These involve mechanical barriers, chemical barriers and cells.

Mechanical barriers

Although many bacteria live on the surface of the skin, the outer layer of the epidermis (see 'Homeostasis' in Chapter 14) seems to act as a barrier that stops them getting into the body. But if the skin is cut or damaged, the bacteria may get into the deeper tissues and cause infection.

Hairs in the nose help to filter out bacteria that are breathed in. However, if air is breathed in through the mouth, this defence is by-passed.

Chemical barriers

The acid conditions in the stomach destroy most of the bacteria that may be taken in with food. The moist lining of the nasal passages traps many bacteria, as does the mucus produced by the lining of the trachea and bronchi. The ciliated cells of these organs carry the trapped bacteria away from the lungs.

Tears contain an enzyme called **lysozyme**. This dissolves the cell walls of some bacteria and so protects the eyes from infection.

Cells

When bacteria get through the mechanical and chemical barriers, the body has two more lines of defence – white blood cells and antibodies, produced by white blood cells. One type of white blood cells fights infection by engulfing bacteria (a process called phagocytosis) and digesting them. Further details of the way these work is also described in 'Blood' in Chapter 9. Another type produce antibodies that attach themselves to bacteria, making it easier for other white blood cells to engulf them.

Vaccination

The body's defences can be enhanced by **vaccination**. This involves a harmless form of the pathogen (bacteria or virus) being introduced into the body by injection or swallowing. The presence of the pathogen triggers white blood cells to make specific antibodies to combat possible infection. If the person is exposed to the disease later, defences are already in place to prevent it developing (the person is **immune** to that disease). Without vaccination, white blood cells need to be exposed to the disease organism before they make the appropriate antibody. If the disease is potentially lethal, the patient could die before the white blood cells have time to act.

Antibodies and immunity

Key definition
Active immunity is the defence against a pathogen by antibody production in the body.

On the surface of all cells there are chemical substances called **antigens**. Lymphocytes produce proteins called **antibodies** which attack the antigens of bacteria or any alien cells or proteins that invade the body. The antibodies may attach to the surface of the bacteria to mark them, making it easier for the phagocytes to find and ingest them, they may clump the bacteria together or they may neutralise the poisonous proteins (**toxins**) that the bacteria produce.

Each antibody is very **specific**. This means that an antibody that attacks a typhoid bacterium will not affect a pneumonia bacterium. This is illustrated in the form of a diagram in Figure 10.10.

Some of the lymphocytes that produced the specific antibodies remain in the lymph nodes for some time and divide rapidly and make more antibodies if the same antigen gets into the body again. This means that the body has become immune to the disease caused by the antigen and explains why, once you have recovered from measles or chickenpox, for example, you are very unlikely to catch the same disease again. This is called **active immunity**. Active immunity can also be gained by vaccination. You may also inherit some forms of immunity or acquire antibodies from your mother's milk (see 'Sexual reproduction in humans' in Chapter 16). This is **innate immunity**.

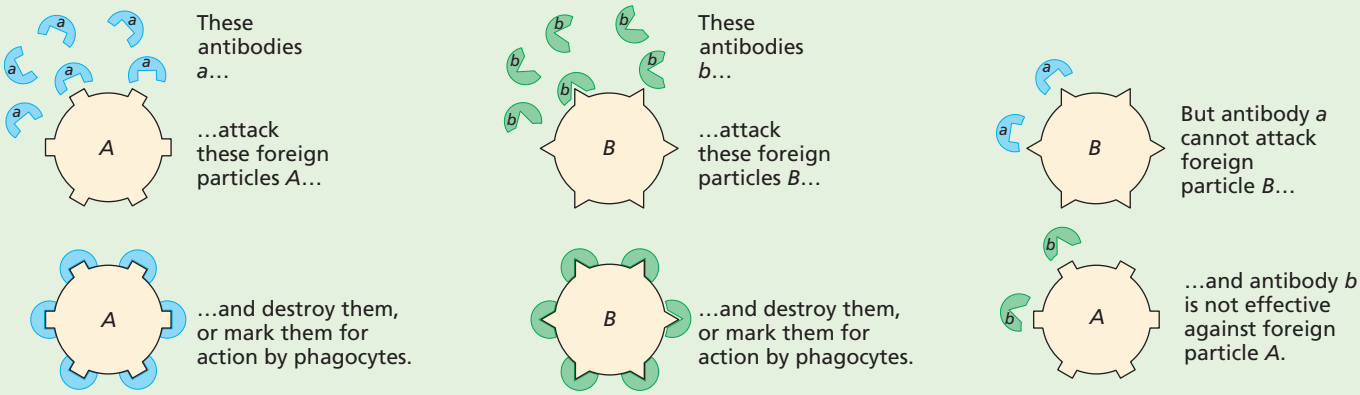


Figure 10.10 Antibodies are specific

Vaccination

When you are **inoculated** (vaccinated) against a disease, a harmless form of the bacteria or viruses is introduced into your body (Figure 10.11). The white cells make the correct antibodies, so that if the real micro-organisms get into the blood, the antibody is already present or very quickly made by the blood.

Figure 10.11 Vaccination. The girl is being vaccinated against rubella (German measles).

The material that is injected or swallowed is called a **vaccine** and is one of the following:

- a harmless form of the micro-organism, e.g. the BCG inoculation against tuberculosis and the Sabin oral vaccine against polio (oral, in this context, means 'taken by mouth')
- the killed micro-organisms, e.g. the Salk anti-polio vaccine and the whooping cough vaccine
- a **toxoid**, i.e. the inactivated toxin from the bacteria, e.g. the diphtheria and tetanus vaccines. (A toxin is the poisonous substance produced by certain bacteria, which causes the symptoms of the disease.)

B and T lymphocytes

There are two main types of lymphocyte. Both types undergo rapid cell division in response to the presence of specific antigens but their functions are different (though interdependent). The **B cells** (from **B**one marrow) become short-lived **plasma** cells and produce antibodies that are released into the blood. These antibodies may attack antigens directly or stick to the surface membrane of infected or alien cells, e.g. cells carrying a virus, bacteria, cancer cells or transplanted cells.

'Killer' T cells (from the **T**hymus gland) have receptor molecules on their surface, which attach them to these surface antibodies. The T cells then kill the cell by damaging its cell membrane.

'Helper' T cells stimulate the B cells to divide and produce antibodies. They also stimulate the phagocytes to ingest any cells carrying antibodies on their surface.

Some of the B cells remain in the lymph nodes as **memory cells**. These can reproduce swiftly and produce antibodies in response to any subsequent invasion of the body by the same foreign organism.

When mass vaccination fails, the population is at risk of infection with potential epidemics resulting. An example of this was with the MMR vaccine in Britain. MMR is a combination of vaccines protecting against measles, mumps and rubella (German measles). A researcher and surgeon called Andrew Wakefield claimed (incorrectly) to have found a link between the MMR vaccine and the incidence of autism and bowel disease in children. The story got into the national press and many parents reacted by refusing to allow their children to have the MMR vaccination, leaving them vulnerable to the three potentially life-threatening diseases. The drop in MMR vaccination rates left whole populations more susceptible to the spread of measles, mumps and rubella. There needs to be a significant proportion of a population immunised to prevent an epidemic of a disease, ideally over 90%. The percentage of people protected against measles, mumps and rubella dropped well below this figure in some areas after the MMR vaccine scare. It has taken years for doctors to restore parents' faith in the safety of the MMR vaccine.

There is a small risk of serious side-effects from vaccines, just as there is with all medicines. These risks are always far lower than the risk of catching the disease itself. For example, the measles vaccine carries a risk of 1 in 87 000 of causing encephalitis (inflammation of the brain). This is much less than the risk of getting encephalitis as a result of catching measles. Also, the vaccines themselves are becoming much safer, and the risk of side-effects is now almost nil.

Routine vaccination not only protects the individual but also prevents the spread of infectious disease. Diseases like diphtheria and whooping cough were once common, and are now quite rare. This is the result of improved social conditions

and routine vaccination. Smallpox was completely wiped out throughout the world by a World Health Organization programme of vaccination between 1959 and 1980.

Global travel

In the 18th and 19th centuries, explorers, traders and missionaries carried European diseases to countries where the population had no natural immunity. It is thought that devastating epidemics of smallpox and measles in, for example, North American Indians and Australian aborigines resulted from contact with infected Europeans.

Today, the ease with which we can travel around the world raises the possibility that travellers may catch a disease in a region where it is **endemic** and subsequently introduce it into a region where the incidence of disease is low or non-existent.

An 'endemic' disease is one that is constantly present in a population. Figure 10.2 shows areas in which malaria is endemic. Small numbers of travellers returning to Britain from such a region may have become infected during their stay. Fortunately, British mosquitoes do not transmit malaria, but global warming might change this.

If you plan to visit a country where an infectious disease is endemic, you are likely to be offered advice on vaccination. There is no vaccine against malaria but, if you are travelling to a malarious country, you will probably be advised to take a drug (e.g. chloroquine) that kills malarial parasites, starting a week or more before your departure, throughout your stay and for a few weeks after your return. Drugs such as this, which help to *prevent* you getting a disease are called **prophylactics**.

Also, you may find your aircraft cabin being sprayed with insecticide to kill any malaria-carrying mosquitoes that might have entered.

If you visit a country where a disease, e.g. yellow fever, is endemic, you may be required to produce a certificate of vaccination (Figure 10.12) before being allowed into a country where the disease does not occur.

Passive immunity

Some diseases can be prevented or cured by injecting the patient with serum from a person who has recovered from the disease. Serum is plasma with the fibrinogen removed. A serum is prepared from the plasma given by blood donors. People who have recently received an anti-tetanus inoculation will have made anti-tetanus antibodies in their blood. Some of these people volunteer to donate their blood, but their plasma is separated at once and the red cells returned to their circulation. The anti-tetanus antibodies are then extracted from the plasma and used to treat patients who are at risk of contracting tetanus, as a result of an accident, for example. Antibodies against chickenpox and rabies can be produced in a similar way.

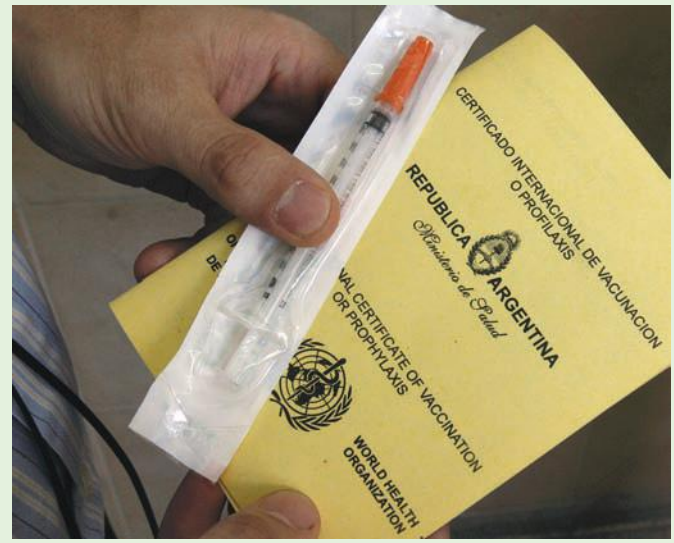


Figure 10.12 International certificate of vaccination

The temporary immunity conferred by these methods is called **passive immunity** because the antibodies have not been produced by the patient. It is only temporary because it does not result in the formation of memory cells.

When a mother breastfeeds her baby, the milk contains some of the mother's white blood cells, which produce antibodies. These antibodies provide the baby with protection against infection at a vulnerable time: the baby's immune responses are not yet fully developed. However, this is another case of passive immunity as it is only short-term protection: memory cells are not produced.

Type 1 diabetes

This type of diabetes, also known as juvenile-onset diabetes, mainly affects young people. It is due to the inability of islet cells in the pancreas to produce sufficient insulin. There is a slight

inherited tendency towards the disease, but it may be triggered by some event, possibly a virus infection, which causes the body's immune system to attack the islet cells that produce insulin. It is therefore classed as an **autoimmune** disease. The outcome is that the patient's blood is deficient in insulin and he or she needs regular injections of the hormone in order to control blood sugar levels and so lead a normal life. This form of the disease is, therefore, sometimes called 'insulin-dependent' diabetes (see 'Homeostasis' in Chapter 14).

Extension work

Ideas about disease transmission and micro-organisms

Edward Jenner (1749–1823)

The history of immunisation centres on the disease **smallpox**, which is caused by a virus. Only a few years ago it was a serious, worldwide disease causing hundreds of thousands of deaths.

It had long been noticed that people who had recovered from smallpox never caught the disease again. In the late 1600s this observation was exploited in countries such as Greece, Turkey, China and India. Fluid from the blisters, which characterised the disease, was introduced into healthy people through cuts in the skin. The patient suffered a mild form of smallpox but was, thereafter, immune to the disease. It was a risky practice, however, and some people developed smallpox and died as a result of the vaccination.

In the 1750s, a Suffolk surgeon, Robert Sutton, refined the technique with considerable success. Edward Jenner is usually given the credit for smallpox vaccination. While using Sutton's technique he noticed that milkmaids who had caught 'cowpox' from infected cows did not develop the mild symptoms of illness after vaccination.

In 1796, Jenner conducted a crucial, if somewhat risky, experiment. He took fluid from a cowpox blister on a milkmaid's hand and injected it into a young boy. Two months later, he inoculated the boy with smallpox and demonstrated that the boy was immune. After publication of the results, the practice spread widely throughout Europe, reducing deaths from smallpox by about two-thirds.

Jenner called his technique 'vaccination' to distinguish it from inoculation with smallpox. 'Vacca' is Latin for 'cow' and 'vaccinia' is the medical name for cowpox. We now know that viruses and bacteria often lose much of their virulence if they are allowed to pass through different animals or are cultured in a particular way. Such non-virulent microbes are said to be **attenuated**. Jenner and his contemporaries, of course, knew nothing about viruses or attenuation but their shrewd observations, logical deductions and bold experiments led to a massive reduction in suffering.

In 1967, the World Health Organization embarked on a programme to eradicate smallpox from the whole world. The strategy was to trace all cases of smallpox and isolate the patients so that they could not pass on the disease. Everyone at risk was then vaccinated. By 1987 the disease had been eradicated.

Louis Pasteur (1822–95)

Pasteur made outstanding contributions to chemistry, biology and medicine. In 1854, as professor of chemistry at the University of Lille, he was called in by the French wine industry to investigate the problem of wines going sour.

Under the microscope he observed the yeast cells that were present and proposed that these were responsible for the fermentation. Thus, he claimed, fermentation was the outcome of a living process in yeast and not caused solely by a chemical change in the grape juice. In time, Pasteur observed that the yeast cells were supplanted by microbes (which we now call 'bacteria'), which appeared to change the alcohol into acetic and lactic acids.

Pasteur showed that souring was prevented by heating the wine to 120 °F (49 °C). He reasoned that this was because the microbes responsible for souring had been killed by the heat and, if the wine was promptly bottled, they could not return. This process is now called 'pasteurisation'.

Spontaneous generation

The micro-organisms in decaying products could be seen under the microscope, but where did they come from? Many scientists claimed that they were the *result* of decay rather than the *cause*; they had arisen 'spontaneously' in the decaying fluids.

In the 17th century, it was believed that organisms could be generated from decaying matter. The organisms were usually 'vermin' such as insects, worms and mice. To contest this notion, an experiment was conducted in 1668, comparing meat freely exposed to the air with meat protected from blowflies by a gauze lid on the container. Maggots appeared only in the meat to which blowflies had access.

This, and other experiments, laid to rest theories about spontaneous generation, as far as visible organisms were concerned, but the controversy about the origin of microbes continued into the 1870s.

It was already known that prolonged boiling, followed by enclosure, prevented liquids from putrefying. Exponents of spontaneous generation claimed that this was because the heat had affected some property of the air in the vessel. Pasteur designed experiments to put this to the test.

He made a variety of flasks, two of which are shown in Figure 10.13, and boiled meat broth in each of them. Fresh air was not excluded from the flask but could enter only through a tube, which was designed to prevent 'dust' (and microbes) from reaching the liquid. The broths remained sterile until either the flask was opened or until it was tilted to allow some broth to reach the U-bend and then tipped back again.

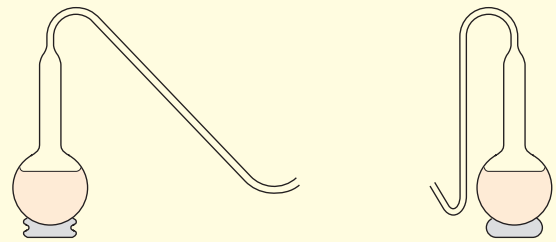


Figure 10.13 Two of Pasteur's flask shapes. The thin tubes admitted air but microbes were trapped in the U-bend.

This series of experiments, and many others, supported the theory that micro-organisms *caused* decay and did not arise spontaneously in the liquids.

The germ theory of disease

In 1865, Pasteur was asked to investigate the cause of a disease of silkworms (silk-moth caterpillars) that was devastating the commercial production of silk. He observed that particular micro-organisms were present in the diseased caterpillars but not in the healthy ones. He demonstrated that, by removing all of the diseased caterpillars and moths, the disease could be controlled. This evidence supported the idea that the microbes passed from diseased caterpillars to healthy ones, thus causing the disease to spread.

He extended this observation to include many forms of transmissible disease, including anthrax. He also persuaded doctors to sterilise their instruments by boiling, and to steam-heat their bandages. In this way, the number of infections that followed surgery was much reduced.

Pasteur's discoveries led to the introduction of antiseptic surgery and also to the production of a rabies vaccine.

Questions

Core

1 a What are the two main lines of attack on malaria?
  b What is the connection between stagnant water and malaria?
  c What are the principal 'set-backs' in the battle against malaria?
2 Study the cartoon shown in Figure 10.14. Identify the potential hygiene risks in Sid's Store.
3 In what ways might improved sanitation and hygiene help to reduce the spread of amoebic dysentery?
4 How might a medical officer try to control an outbreak of amoebic dysentery?
5 Why should people who sell, handle and cook food be particularly careful about their personal hygiene?
6 Coughing or sneezing without covering the mouth and nose with a handkerchief is thought to be inconsiderate behaviour. Why is this?
7 Inhaling cigarette smoke can stop the action of cilia in the trachea and bronchi for about 20 minutes. Why should this increase a smoker's chance of catching a respiratory infection?

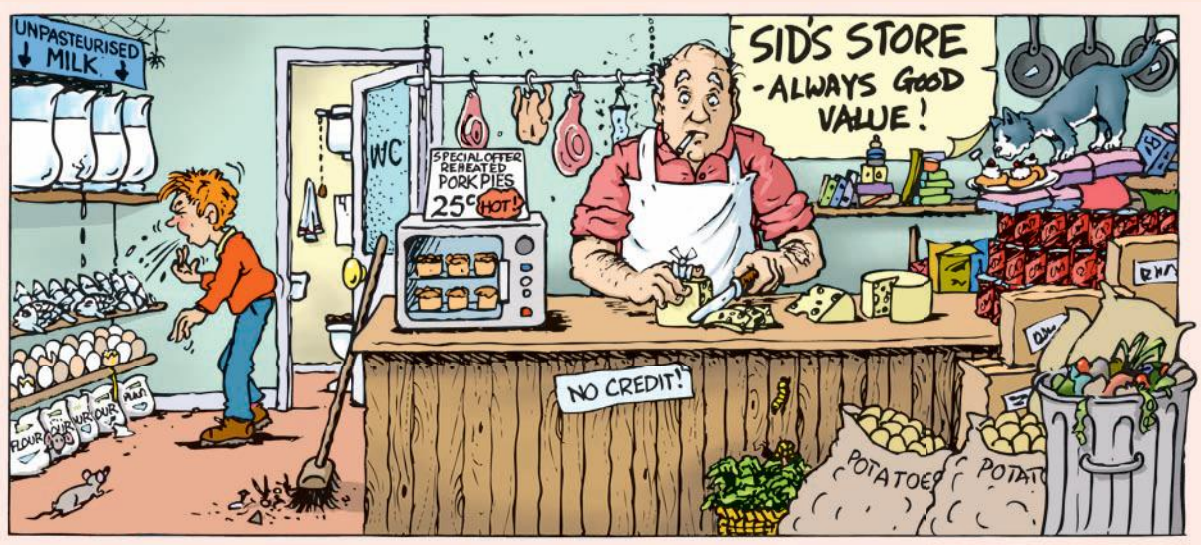


Figure 10.14 An unhygienic shop

Extended

8 Figure 10.15 shows the changes in the levels of antibody in response to an inoculation of a vaccine, followed by a booster injection 3 weeks later. Use your knowledge of the immune reaction to explain these changes.

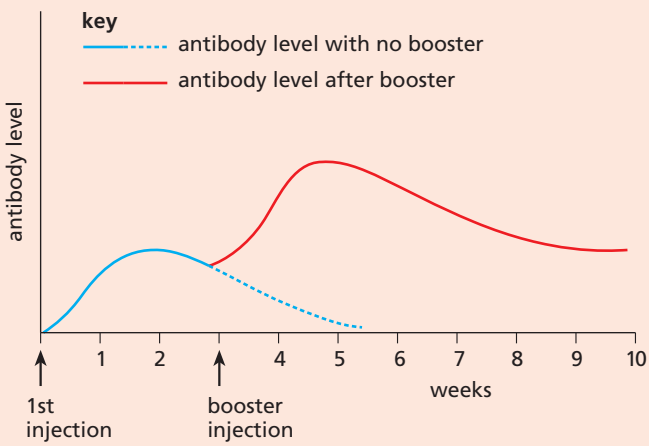


Figure 10.15

9 How might a harmful bacterium be destroyed or removed by the body if it arrived:
  a on the hand
  b in a bronchus
  c in the stomach?
10 After a disaster such as an earthquake, the survivors are urged to boil all drinking water. Why do you think this is so?
11 Explain why vaccination against diphtheria does not protect you against polio as well.
12 Even if there have been no cases of diphtheria in a country for many years, children may still be vaccinated against it. What do you think is the point of this?

Checklist

After studying Chapter 10 you should know and understand the following:

- Transmissible diseases are infections caused by viruses, bacteria, fungi or protoctista.
- Infectious diseases may be transmitted by air, water, food or contact.
- The body has defences against pathogens, including mechanical and chemical barriers and white blood cells.
- A vaccine stimulates the blood system to produce antibodies against a disease, without causing the disease itself.
- The presence of antibodies in the blood, or the ability to produce them rapidly, gives immunity to a disease.
- Water-borne diseases are controlled by sewage treatment and water purification.
- Food-borne diseases can be controlled by hygienic food preparation, hygienic handling and good personal hygiene.
- The spread of disease can be controlled by waste disposal and sewage treatment.
- Antibodies, produced by lymphocytes, work by locking on to antigens.
- Antigens have specific shapes, so each type of antigen needs a different antibody.
- Active immunity is a defence against a pathogen by antibody production in the body.
- Vaccination involves the administration of a dead or inactive form of the pathogen to a patient to stimulate antibody production.
- Memory cells provide long-term immunity.
- Systematic immunisation can protect whole populations.
- Passive immunity only provides short-term protection because memory cells are not produced.
- Type 1 diabetes is caused by the immune system targeting and destroying cells in the pancreas.

11 Gas exchange in humans

Gas exchange in humans
Features of human gas exchange surfaces
Parts of the breathing system
Composition of inspired and expired air
Test for carbon dioxide

Identification of muscles associated with breathing
Roles of parts of the breathing system in ventilation
Explaining differences between inspired and expired air
Role of brain in monitoring carbon dioxide
Protection of the gas exchange system against pathogens

Gas exchange in humans

All the processes carried out by the body, such as movement, growth and reproduction, require energy. In animals, this energy can be obtained only from the food they eat. Before the energy can be used by the cells of the body, it must be set free from the chemicals of the food by a process called 'respiration' (see Chapter 12). Aerobic respiration needs a supply of oxygen and produces carbon dioxide as a waste product. All cells, therefore, must be supplied with oxygen and must be able to get rid of carbon dioxide.

In humans and other mammals, the oxygen is obtained from the air by means of the lungs. In the lungs, the oxygen dissolves in the blood and is carried to the tissues by the circulatory system (Chapter 9).

Characteristics of respiratory surfaces

The exchange of oxygen and carbon dioxide across a respiratory surface, as in the lungs, depends on the diffusion of these two gases. Diffusion occurs more rapidly if:

- there is a large surface area exposed to the gas
- the distance across which diffusion has to take place is small
- there is a good blood supply, and
- there is a big difference in the concentrations of the gas at two points brought about by **ventilation**.

Large surface area

The presence of millions of alveoli in the lungs provides a very large surface for gaseous exchange. The many branching filaments in a fish's gills have the same effect.

Thin epithelium

There is only a two-cell layer, at the most, separating the air in the alveoli from the blood in the capillaries (Figure 11.4). One layer is the alveolus wall; the other is the capillary wall. Thus, the distance for diffusion is very short.

Good blood supply

The alveoli are surrounded by networks of blood capillaries. The continual removal of oxygen by the blood in the capillaries lining the alveoli keeps its concentration low. In this way, a steep diffusion gradient is maintained, which favours the rapid diffusion of oxygen from the air passages to the alveolar lining.

The continual delivery of carbon dioxide from the blood into the alveoli, and its removal from the air passages by ventilation, similarly maintains a diffusion gradient that promotes the diffusion of carbon dioxide from the alveolar lining into the bronchioles.

Ventilation

Ventilation of the lungs helps to maintain a steep diffusion gradient (see 'Diffusion' in Chapter 3) between the air at the end of the air passages and the alveolar air. The concentration of the oxygen in the air at the end of the air passages is high, because the air is constantly replaced by the breathing actions.

The respiratory surfaces of land-dwelling mammals are invariably moist. Oxygen has to dissolve in the thin film of moisture before passing across the epithelium.

Lung structure

The lungs are enclosed in the thorax (chest region) (see Figure 7.13). They have a spongy texture and can be expanded and compressed by movements of the thorax in such a way that air is sucked in and

blown out. The lungs are joined to the back of the mouth by the windpipe or **trachea** (Figure 11.1). The trachea divides into two smaller tubes, called **bronchi** (singular = bronchus), which enter the lungs and divide into even smaller branches. When these branches are only about 0.2 mm in diameter, they are called **bronchioles** (Figure 11.3(a)). These fine branches end in a mass of little, thin-walled, pouch-like air sacs called **alveoli** (Figures 11.3(b), (c) and 11.4).

The **epiglottis** and other structures at the top of the trachea stop food and drink from entering the air passages when we swallow.

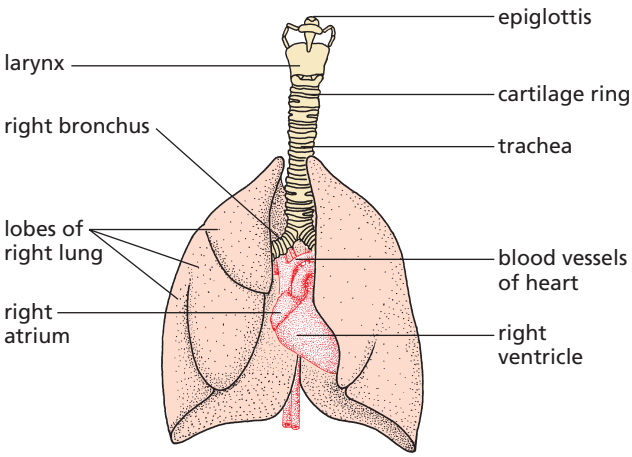


Figure 11.1 Diagram of lungs, showing position of heart

Figure 11.2 shows a section through the thorax. The ribs, shown in cross section, form a cage, which has two main functions:

- to protect the lungs and heart
- to move to ventilate the lungs.

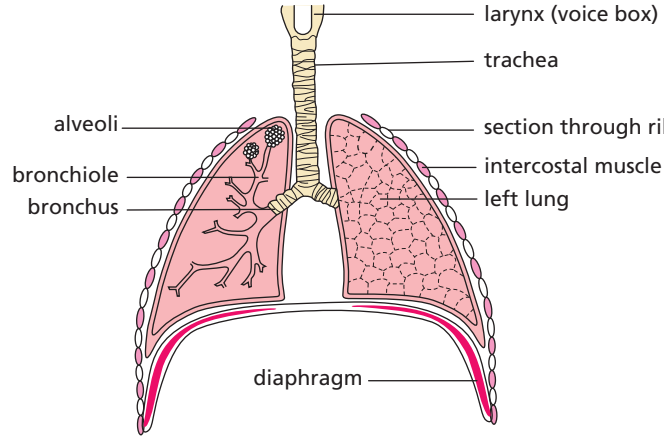
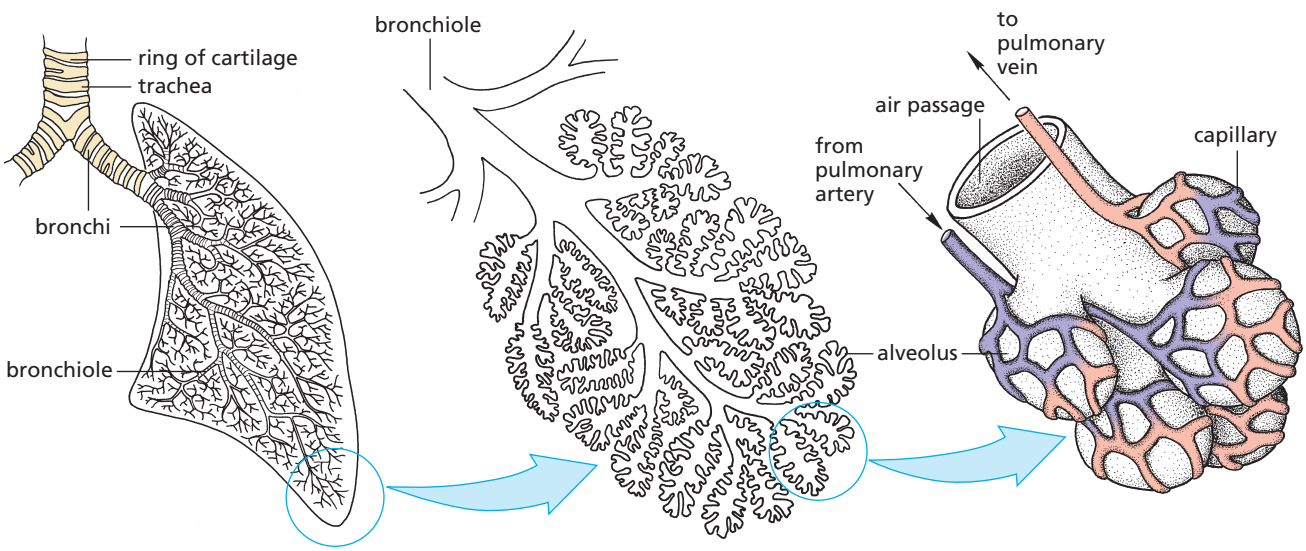


Figure 11.2 Section through the thorax

The alveoli have thin elastic walls, formed from a single-cell layer or **epithelium**. Beneath the epithelium is a dense network of capillaries (Figure 11.3(c)) supplied with deoxygenated blood (see 'Blood' in Chapter 9). This blood, from which the body has taken oxygen, is pumped from the right ventricle, through the pulmonary artery (see Figure 9.20). In humans, there are about 350 million alveoli, with a total absorbing surface of about 90 m^2. This large absorbing surface makes it possible to take in oxygen and give out carbon dioxide at a rate to meet the body's needs.



(a) air passages in the lungs

(b) the air passages end in tiny pockets (alveoli)

(c) blood supply of the alveoli

Figure 11.3 Lung structure

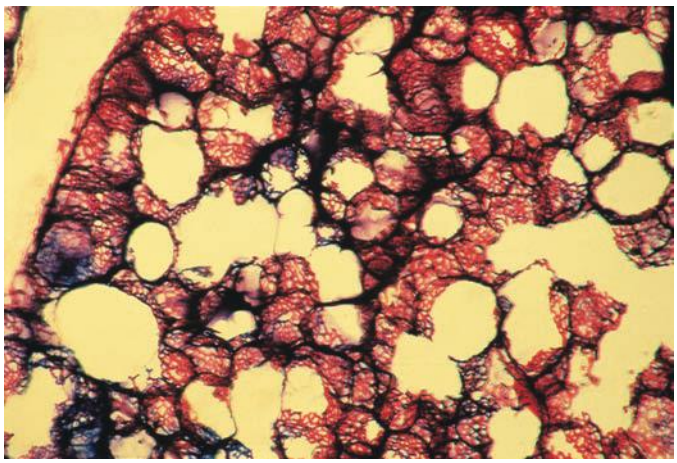


Figure 11.4 Small piece of lung tissue (×40). The capillaries have been injected with red and blue dye. The networks surrounding the alveoli can be seen.

Gaseous exchange

Ventilation refers to the movement of air into and out of the lungs. Gaseous exchange refers to the exchange of oxygen and carbon dioxide, which takes place between the air and the blood vessels in the lungs (Figure 11.5).

The 1.5 litres of residual air in the alveoli is not exchanged during ventilation and oxygen has to reach the capillaries by the slower process of diffusion. Figure 11.5 shows how oxygen reaches the red blood cells and how carbon dioxide escapes from the blood.

The oxygen combines with the haemoglobin in the red blood cells, forming **oxyhaemoglobin** (see 'Blood' in Chapter 9). The carbon dioxide in the plasma is released when the hydrogencarbonate ions ($—HCO_3$) break down to CO_2 and H_2O.

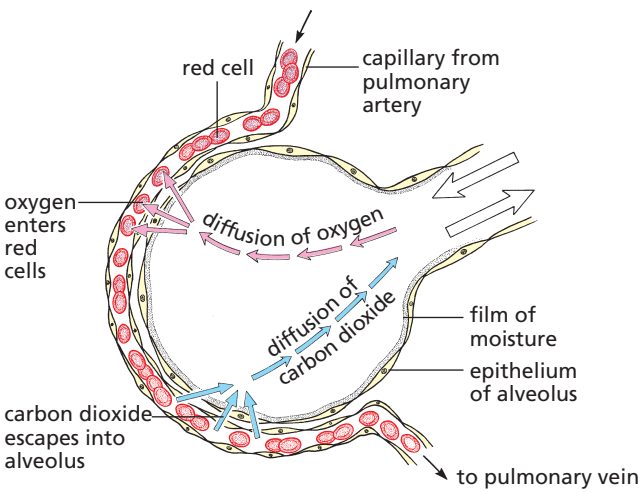


Figure 11.5 Gaseous exchange in the alveolus

The capillaries carrying oxygenated blood from the alveoli join up to form the pulmonary vein (see Figure 9.20), which returns blood to the left atrium of the heart. From here it enters the left ventricle and is pumped all around the body, so supplying the tissues with oxygen.

Table 11.1 shows changes in the composition of air as it is breathed in and out.

Table 11.1 Changes in the composition of breathed air

	Inhaled/%	Exhaled/%
oxygen	21	16
carbon dioxide	0.04	4
water vapour	variable	saturated

Sometimes the word **respiration** or **respiratory** is used in connection with breathing. The lungs, trachea and bronchi are called the **respiratory system**; a person's rate of breathing may be called his or her **respiration rate**. This use of the word should not be confused with the biological meaning of respiration, namely the release of energy in cells (Chapter 12). This chemical process is sometimes called **tissue respiration** or **internal respiration** to distinguish it from breathing.

Lung capacity and breathing rate

The total volume of the lungs when fully inflated is about 5 litres in an adult. However, in quiet breathing, when asleep or at rest, you normally exchange only about 500 cm^3. During exercise you can take in and expel an extra 3 litres. There is a **residual volume** of 1.5 litres, which cannot be expelled no matter how hard you breathe out.

At rest, you normally inhale and exhale about 12 times per minute. During exercise, the breathing rate may rise to over 20 breaths per minute and the depth also increases.

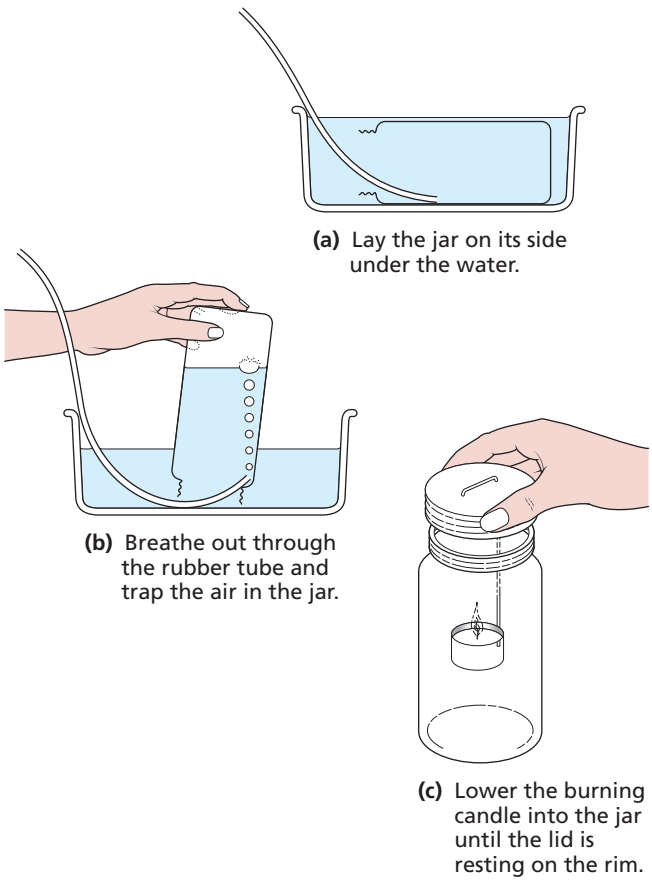
Breathing rate and exercise

The increased rate and depth of breathing during exercise allows more oxygen to dissolve in the blood and supply the active muscles. The extra carbon dioxide that the muscles put into the blood is detected by the brain, which instructs the intercostal muscles and diaphragm muscles to contract and relax more rapidly, increasing the breathing rate. Carbon dioxide will be removed by the faster, deeper breathing.

Practical work

Oxygen in exhaled air

- Place a large screw-top jar on its side in a bowl of water (Figure 11.6(a)).
- Put a rubber tube in the mouth of the jar and then turn the jar upside-down, still full of water and with the rubber tube still in it.
- Start breathing out and when you feel your lungs must be about half empty, breathe the last part of the air down the rubber tubing so that the air collects in the upturned jar and fills it (Figure 11.6(b)).
- Put the screw top back on the jar under water, remove the jar from the bowl and place it upright on the bench.
- Light the candle on the special wire holder (Figure 11.6(c)), remove the lid of the jar, lower the burning candle into the jar and count the number of seconds the candle stays alight.
- Now take a fresh jar, with ordinary air, and see how long the candle stays alight in this.



(a) Lay the jar on its side under the water.

(b) Breathe out through the rubber tube and trap the air in the jar.

(c) Lower the burning candle into the jar until the lid is resting on the rim.

Figure 11.6 Experiment to test exhaled air for oxygen

Results
The candle will burn for about 15–20 seconds in a large jar of ordinary air. In exhaled air it will go out in about 5 seconds.

Interpretation
Burning needs oxygen. When the oxygen is used up, the flame goes out. It looks as if exhaled air contains much less oxygen than atmospheric air.

Carbon dioxide in exhaled air

- Prepare two large test-tubes, A and B, as shown in Figure 11.7, each containing a little clear limewater.
- Put the mouthpiece in your mouth and breathe in and out *gently* through it for about 15 seconds. Notice which tube is bubbling when you breathe out and which one bubbles when you breathe in.

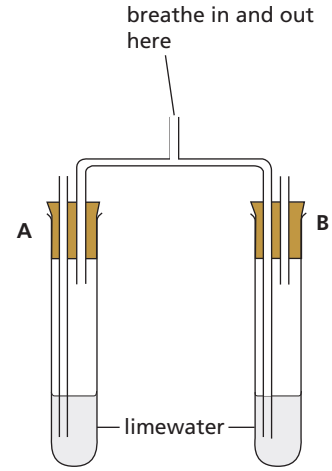


Figure 11.7 Experiment to compare the carbon dioxide content of inhaled and exhaled air

If after 15 seconds there is no difference in the appearance of the limewater in the two tubes, continue breathing through them for another 15 seconds.

Results
The limewater in tube B goes milky. The limewater in tube A stays clear.

Interpretation
Carbon dioxide turns limewater milky. Exhaled air passes through tube B. Inhaled air passes through tube A. Exhaled air must, therefore, contain more carbon dioxide than inhaled air.

Note 1: if the breathing process is carried out for too long, the limewater that had turned milky will revert to being colourless. This is because the calcium carbonate formed (milky precipitate) reacts in water with carbon dioxide to form calcium hydrogencarbonate, which is soluble and colourless.

Note 2: Hydrogencarbonate indicator is an alternative to limewater. It changes from red to yellow when carbon dioxide is bubbled through it.

Volume of air in the lungs

- Calibrate a large (5 litre) plastic bottle by filling it with water, half a litre at a time, and marking the water levels on the outside.
- Fill the bottle with water and put on the stopper.
- Put about 50 mm depth of water in a large plastic bowl.
- Hold the bottle upside-down with its neck under water and remove the screw top. Some of the water will run out but this does not matter.

- Push a rubber tube into the mouth of the bottle to position A, shown on the diagram (Figure 11.8).
- Take a deep breath and then exhale as much air as possible down the tubing into the bottle. The final water level inside the bottle will tell you how much air you can exchange in one deep breath.
- Now push the rubber tubing further into the bottle, to position B (Figure 11.8), and blow out any water left in the tube.
- Support the bottle with your hand and breathe gently in and out through the tube, keeping the water level inside and outside the bottle the same. This will give you an idea of how much air you exchange when breathing normally.

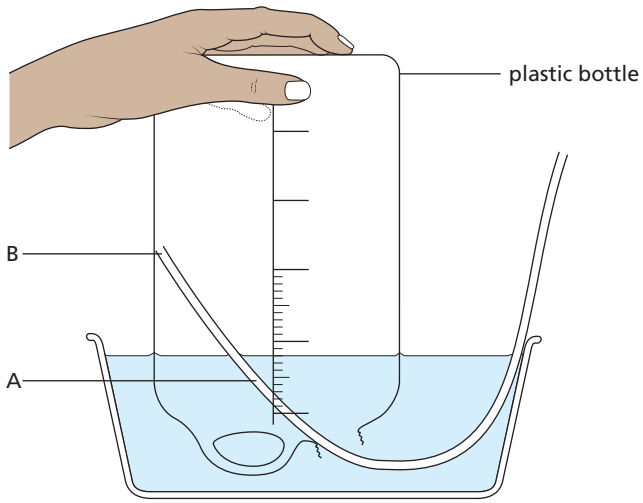


Figure 11.8 Experiment to measure the volume of air exhaled from the lungs. (A) shows the position of the tube when measuring the maximum usable lung volume. (B) is the position for measuring the volume exchanged in gentle breathing.

Investigating the effect of exercise on carbon dioxide production

- Half fill two clean boiling tubes with limewater.
- Place a drinking straw in one of the boiling tubes and gently blow into it, with normal, relaxed breaths.
- Count how many breaths are needed to turn the limewater milky.
- Now exercise for 1 to 2 minutes, e.g. running on the spot.
- Place a drinking straw in the second boiling tube, blowing into it as before.
- Count the number of breaths needed to turn the limewater milky.

Results

The number of breaths needed after exercise will be less than before exercise.

Interpretation

Cells in the body are constantly respiring, even when we are not doing physical work. They produce carbon dioxide, which is expired by the lungs. The carbon dioxide turns limewater milky. During exercise, cells (particularly in the skeletal muscles) respire more rapidly producing more carbon dioxide. This turns the limewater milky more rapidly.

Investigating the effect of exercise on rate and depth of breathing

This investigation makes use of an instrument called a spirometer. It may be one as illustrated in Figure 11.9, or a digital version, connected to a computer. A traditional spirometer has a hinged chamber, which rises and falls as a person breathes through the mouthpiece. The chamber is filled with medical oxygen from a cylinder. There is a filter containing soda lime, which removes any carbon dioxide in the user's breath, so that it is not re-breathed. The hinged chamber has a pen attached (shown in red in Figure 11.9), which rests against the paper-covered drum of a kymograph. This can be set to revolve at a fixed rate so that the trace produced by the user progresses across the paper.

Figure 11.9 A spirometer. This instrument measures the volume of air breathed in and out of the lungs and can be used to measure oxygen consumption.

- A volunteer is asked to breathe in and out through the mouthpiece and the kymograph is set to revolve slowly. This will generate a trace, which will provide information about the volunteer's tidal volume and breathing rate (each peak on the trace represents one breath and the depth between a peak and trough can be used to calculate the tidal volume).
- Next, the volunteer is asked to take a deep breath with the mouthpiece removed, then breathe out through the mouthpiece for one long continuous breath. The depth between the peak and trough produced can be used to calculate the vital capacity.
- Finally, the volunteer is asked insert the mouthpiece, then run on the spot or pedal an exercise bicycle, while breathing through the spirometer. The trace produced (Figure 11.10) can be used to compare the breathing rate and depth during exercise with that at rest. A study of the trace would also show a drop in the trace with time. This can be used to calculate the volume of oxygen consumed over time.

Results

Tidal volume is about 500 cm^3, but tends to appear higher if the person is nervous or influenced by the trace being created.

Vital capacity can be between 2.5 and 5.0 litres, depending on the sex, physical size and fitness of the person.

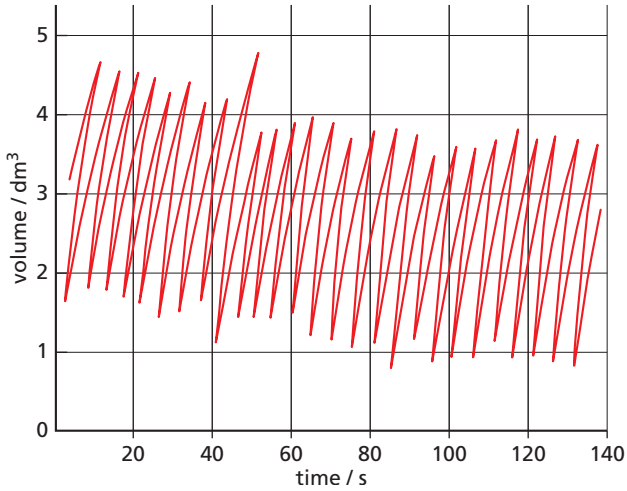


Figure 11.10 Spirometer trace taken during exercise

The breathing rate at rest is around 12 breaths per minute. During exercise this increases and may reach 20 or more breaths per minute.

Note: this experiment makes use of medical oxygen. This has a high purity and is toxic if inhaled for a prolonged period of time. If the volunteer starts to feel dizzy while using the spirometer, he or she should remove the mouthpiece immediately and rest.

Ventilation of the lungs

The movement of air into and out of the lungs, called **ventilation**, renews the oxygen supply in the lungs and removes the surplus carbon dioxide. Horseshoe-shaped hoops of cartilage are present in the trachea and bronchi to prevent them collapsing when we breathe in. The lungs contain no muscle fibres and are made to expand and contract by movements of the ribs and diaphragm.

The **diaphragm** is a sheet of tissue that separates the thorax from the abdomen (see Figure 7.13). When relaxed, it is domed slightly upwards. The ribs are moved by the **intercostal muscles**. The external intercostals (Figure 11.11) contract to pull the ribs upwards and outwards. The internal intercostals contract to pull them downwards and inwards. Figure 11.12 shows the contraction of the external intercostals making the ribs move upwards.

Inhaling

1 The diaphragm muscles contract and pull it down (Figure 11.13(a)).

2 The internal intercostal muscles relax, while the external intercostal muscles contract and pull the ribcage upwards and outwards (Figure 11.14(a)).

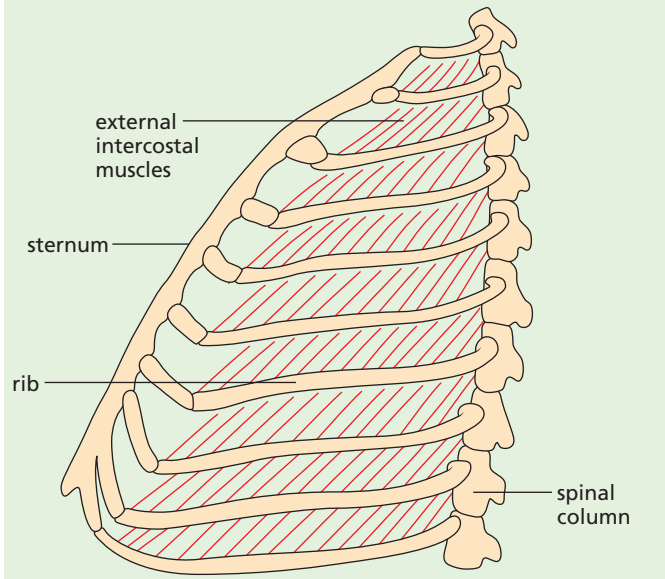


Figure 11.11 Ribcage seen from left side, showing external intercostal muscles

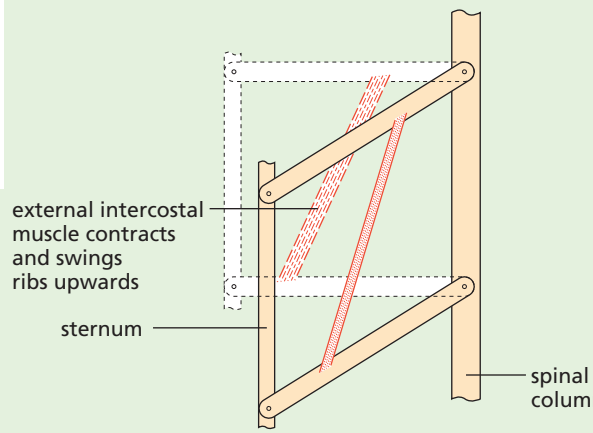


Figure 11.12 Model to show action of intercostal muscles

These two movements make the volume in the thorax bigger, so forcing the lungs to expand. The reduction in air pressure in the lungs results in air being drawn in through the nose and trachea. This movement of air into the lungs is known as ventilation.

Exhaling

1 The diaphragm muscles relax, allowing the diaphragm to return to its domed shape (Figure 11.13(b)).

2 The external intercostal muscles relax, while the internal intercostal muscles contract, pulling the ribs downwards to bring about a forced expiration (Figure 11.14(b)).

The lungs are elastic and shrink back to their relaxed volume, increasing the air pressure inside them. This results in air being forced out again.

The outside of the lungs and the inside of the thorax are lined with a smooth membrane called the **pleural membrane**. This produces a thin layer of liquid called **pleural fluid**, which reduces the friction between the lungs and the inside of the thorax.

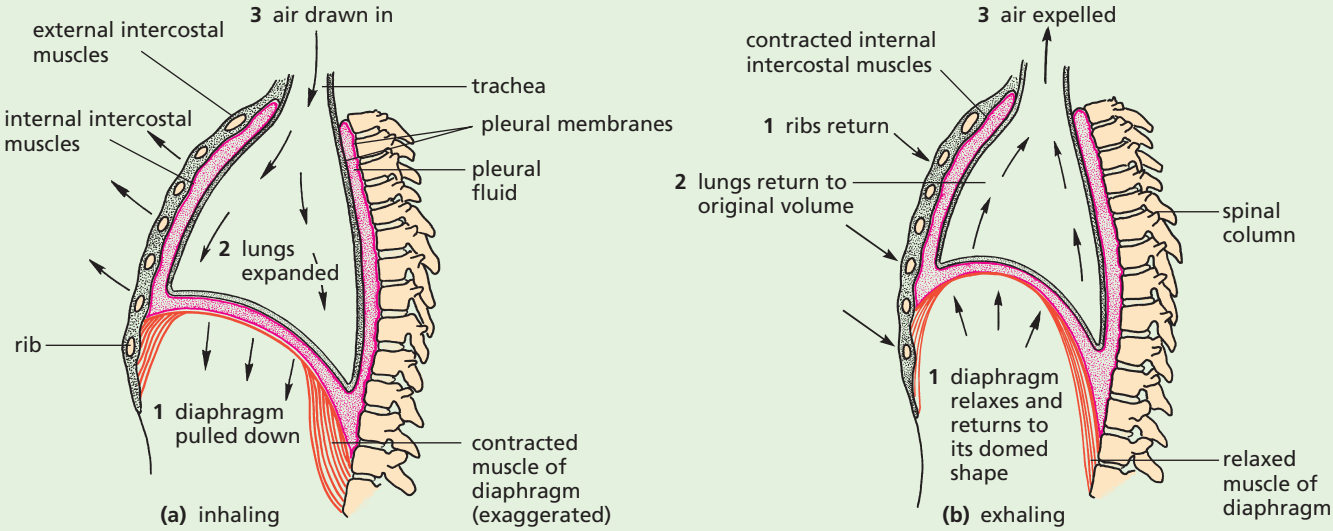


Figure 11.13 Diagrams of thorax to show mechanism of breathing

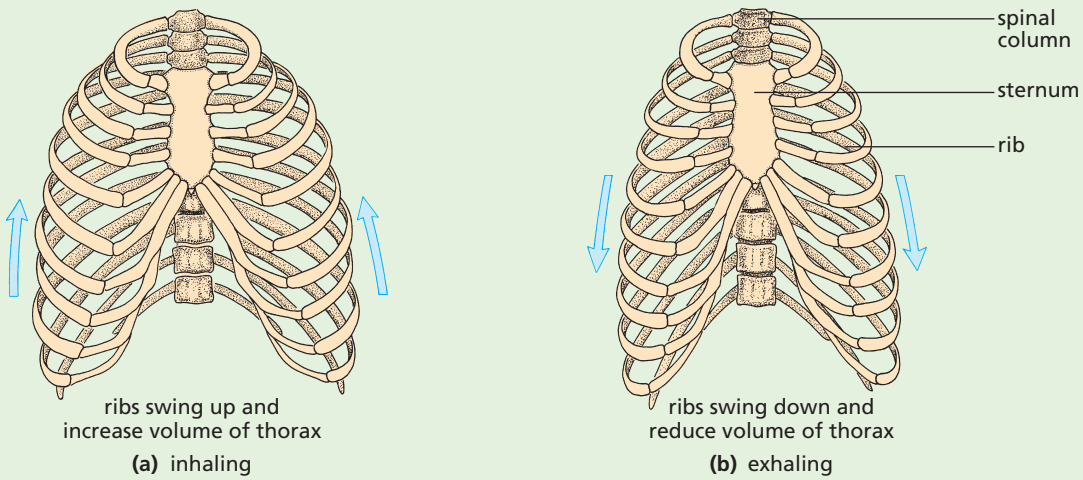


Figure 11.14 Movement of ribcage during breathing

A piece of apparatus known as the 'bell-jar model' (Figure 11.15) can be used to show the way in which movement of the diaphragm results in inspiration and expiration. The balloons start off deflated. When the handle attached to the rubber sheet is pulled down, the balloons inflate. If the handle is released, the balloons deflate again.

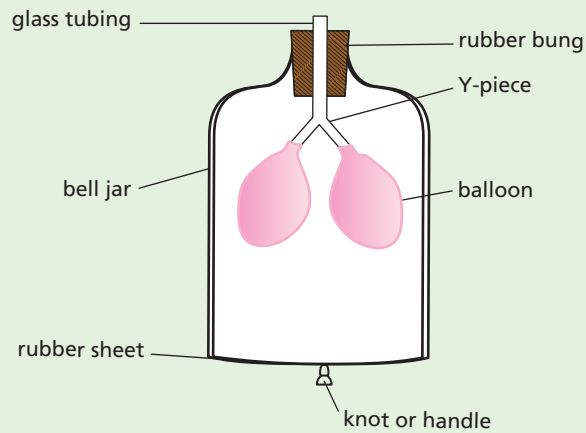


Figure 11.15 Bell-jar model

When the rubber sheet is pulled down, the volume inside the bell jar increases. This reduces the air pressure inside, making it lower than outside. The air rushes in, through the glass tubing, to equalise the air pressure, causing the balloons to inflate.

Differences in composition of inspired and expired air

Air in the atmosphere (which is breathed in) contains about 21% oxygen (see Table 11.1). Some of this is absorbed into the bloodstream when it enters the alveoli, resulting in a reduction of oxygen in exhaled air to 16% (the process of gaseous exchange in the alveoli does not remove all the oxygen from the air). Gas exchange relies on diffusion to transfer the oxygen into red blood cells and the air breathed in mixes with air that has not all been breathed out from the previous breath, so the process of gas exchange is not very efficient.

The remaining 79% of the air consists mainly of nitrogen, the percentage composition of which does not change significantly during breathing.

Inspired air contains 0.04% carbon dioxide. Cells of the body produce carbon dioxide as a waste product during aerobic respiration (see 'Aerobic respiration' in Chapter 12). The bloodstream carries carbon dioxide to the lungs for excretion. It diffuses across the walls of the alveoli to be expired. The percentage breathed out is 4%, 100 times greater than the percentage breathed in.

The lining of the alveoli is coated with a film of moisture in which the oxygen dissolves. Some of this moisture evaporates into the alveoli and saturates the air with water vapour. The air you breathe out, therefore, always contains a great deal more water vapour than the air you breathe in. The presence of water vapour in expired air is easily demonstrated by breathing onto a cold mirror: condensation quickly builds up on the glass surface. The exhaled air is warmer as well, so in cold and temperate climates you lose heat to the atmosphere by breathing.

The relationship between physical activity and the rate and depth of breathing

It has already been stated that the rate and depth of breathing increase during exercise. In order for the limbs to move faster, aerobic respiration in the skeletal muscles increases. Carbon dioxide is a waste product of aerobic respiration. As a result, CO_2 builds up in the muscle cells and diffuses into the plasma in the bloodstream more rapidly. The brain detects increases in carbon dioxide concentration in the blood and stimulates the breathing mechanism to speed up, increasing the rate of expiration of the gas. An increase in the breathing rate also has the advantage of making more oxygen available to the more rapidly respiring muscle cells.

Protection of the gas exchange system from pathogens and particles

Pathogens are disease-causing organisms (see Chapter 10). Pathogens, such as bacteria, and dust particles are present in the air we breathe in and are potentially dangerous if not actively removed. There are two types of cells that provide mechanisms to help achieve this.

Goblet cells are found in the epithelial lining of the trachea, bronchi and some bronchioles of the respiratory tract (Figure 11.16). Their role is to secrete **mucus**. The mucus forms a thin film over the internal lining. This sticky liquid traps pathogens and small particles, preventing them from entering the alveoli where they could cause infection or physical damage.

Ciliated cells are also present in the epithelial lining of the respiratory tract (Figure 11.16; see also 'Levels of organisation' in Chapter 2). They are in a continually flicking motion to move the mucus, secreted by the goblet cells, upwards and away from the lungs. When the mucus reaches the top of the trachea, it passes down the gullet during normal swallowing.

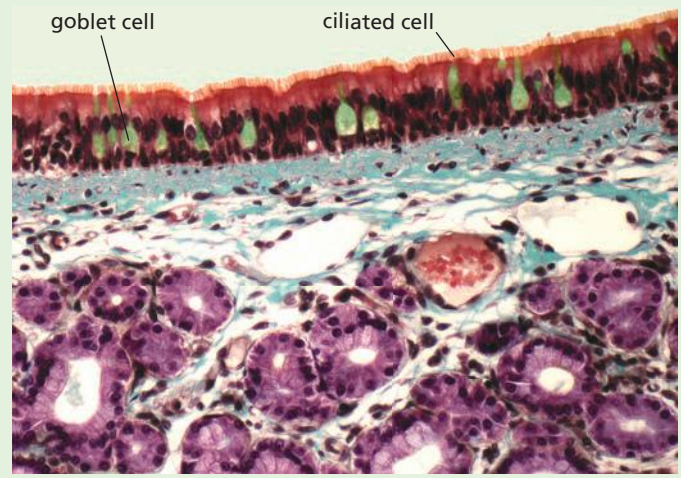


Figure 11.16 Goblet cells and ciliated cells in the trachea

Questions

Core

1 Place the following structures in the order in which air will reach them when breathing in: bronchus, trachea, nasal cavity, alveolus.

2 One function of the small intestine is to absorb food (see 'Absorption' in Chapter 7). One function of the lungs is to absorb oxygen. Point out the basic similarities in these two structures, which help to speed up the process of absorption.

Extended

3 a Compare the bell-jar model in Figure 11.15 with the diagram of the lungs (Figure 11.1). What do the following parts represent on the model?
   i glass tubing
   ii Y-piece
   iii balloons
   iv bell jar
   v rubber sheet

   b Explain why this model does not give a complete simulation of the process of breathing.

4 What are the two principal muscular contractions that cause air to be inhaled?

5 Place the following in the correct order:
lungs expand, ribs rise, air enters lungs, external intercostal muscles contract, thorax expands.

6 During inhalation, which parts of the lung structure would you expect to expand the most?

Checklist

After studying Chapter 11 you should know and understand the following:

- Alveoli in the lungs are very numerous, provide a large surface area, have a thin, moist surface and are well-ventilated for efficient gas exchange.
- Alveoli have a good blood supply.
- Exchange of oxygen and carbon dioxide in the alveoli takes place by diffusion.
- The blood in the capillaries picks up oxygen from the air in the alveoli and gives out carbon dioxide. This is called gaseous exchange.
- The oxygen is carried around the body by the blood and used by the cells for their respiration.
- The ribs, rib muscles and diaphragm make the lungs expand and contract. This causes inhaling and exhaling.
- Air is drawn into the lungs through the trachea, bronchi and bronchioles.
- Inhaled air contains a higher percentage of oxygen and a lower percentage of carbon dioxide and (usually) water vapour than exhaled air.
- Limewater is used as a test for the presence of carbon dioxide. It turns milky.
- During exercise, the rate and depth of breathing increase.

- Cartilage, present in the trachea, keeps the airway open and unrestricted.
- The diaphragm, internal and external intercostal muscles play a part in ventilation of the lungs.
- During exercise, the rate and depth of breathing increase. This supplies extra oxygen to the muscles and removes their excess carbon dioxide.
- Movement of the ribcage and diaphragm results in volume and pressure changes in the thorax, leading to ventilation of the lungs.
- During physical activity, increases in levels of carbon dioxide in the blood are detected in the brain, causing an increased rate of breathing.
- Goblet cells make mucus to trap pathogens and particles to protect the gas exchange system.
- Ciliated cells move mucus away from the alveoli.

12 Respiration

Respiration
Use of energy in humans
Role of enzymes

Aerobic respiration
Define aerobic respiration
Word equation
Investigating uptake of oxygen in respiring organisms

Balanced chemical equation
Investigating the effect of temperature on respiration

Anaerobic respiration
Define anaerobic respiration
Word equations
Energy output compared with aerobic respiration

Balanced chemical equation
Effects of lactic acid
Oxygen debt

Respiration

Most of the processes taking place in cells need energy to make them happen. Examples of energy-consuming processes in living organisms are:

- the contraction of muscle cells – to create movement of the organism, or peristalsis to move food along the alimentary canal, or contraction of the uterus wall during childbirth
- building up proteins from amino acids
- the process of cell division (Chapter 17) to create more cells, or replace damaged or worn out cells, or to make reproductive cells
- the process of active transport (Chapter 3), involving the movement of molecules across a cell membrane against a concentration gradient
- growth of an organism through the formation of new cells or a permanent increase in cell size
- the conduction of electrical impulses by nerve cells (Chapter 14)
- maintaining a constant body temperature in homoiothermic (warm-blooded) animals ('Homeostasis' in Chapter 14) to ensure that vital chemical reactions continue at a predictable rate and do not slow down or speed up as the surrounding temperature varies.

This energy comes from the food that cells take in. The food mainly used for energy in cells is glucose.

The process by which energy is produced from food is called **respiration**.

Respiration is a chemical process that takes place in cells and involves the action of enzymes. It must not be confused with the process of breathing, which is also sometimes called 'respiration'. To make the difference quite clear, the chemical process in cells is sometimes called **cellular respiration**, **internal respiration** or **tissue respiration**. The use of the word 'respiration' for breathing is best avoided altogether.

Aerobic respiration

Key definition
Aerobic respiration is the term for the chemical reactions in cells that use oxygen to break down nutrient molecules to release energy.

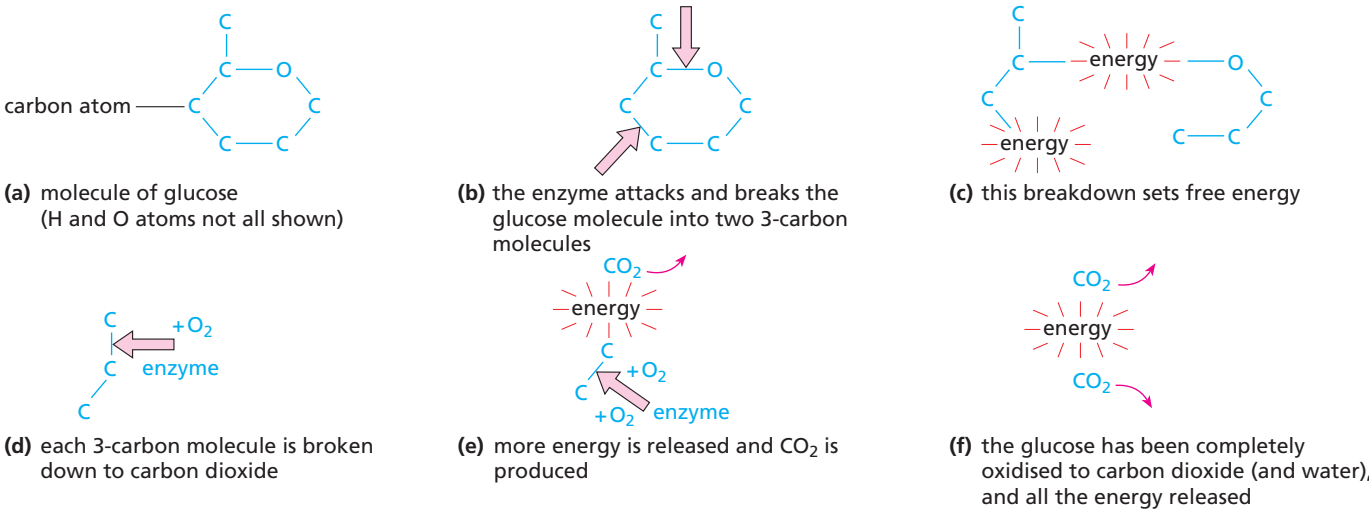
The word **aerobic** means that oxygen is needed for this chemical reaction. The food molecules are combined with oxygen. The process is called **oxidation** and the food is said to be **oxidised**. All food molecules contain carbon, hydrogen and oxygen atoms. The process of oxidation converts the carbon to carbon dioxide (CO_2) and the hydrogen to water (H_2O) and, at the same time, sets free energy, which the cell can use to drive other reactions.

Aerobic respiration can be summed up by the equation

$$\text{glucose} + \text{oxygen} \xrightarrow{\text{enzymes}} \underset{\text{dioxide}}{\text{carbon}} + \text{water} + \underset{\text{energy}}{2830\,\text{kJ}}$$

The amount of energy you would get by completely oxidising 180 grams (g) of glucose to carbon dioxide and water is 2830 kilojoules (kJ). In the cells, the energy is not released all at once. The oxidation takes place in a series of small steps and not in one jump as the equation suggests. Each small step needs its own enzyme and at each stage a little energy is released (Figure 12.1).

Although the energy is used for the processes mentioned above, some of it always appears as heat. In 'warm-blooded' animals (birds and mammals) some of this heat is retained to maintain their body temperature.



(a) molecule of glucose (H and O atoms not all shown)

(b) the enzyme attacks and breaks the glucose molecule into two 3-carbon molecules

(c) this breakdown sets free energy

(d) each 3-carbon molecule is broken down to carbon dioxide

(e) more energy is released and CO_2 is produced

(f) the glucose has been completely oxidised to carbon dioxide (and water), and all the energy released

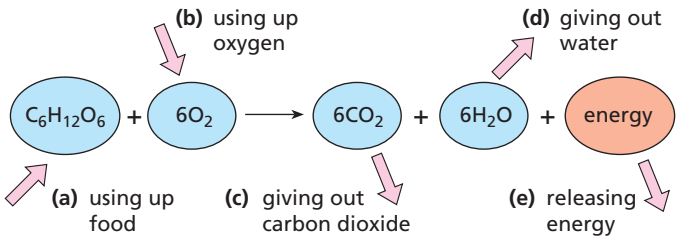
Figure 12.1 Aerobic respiration

In 'cold-blooded' animals (e.g. reptiles and fish) the heat may build up for a time in the body and allow the animal to move about more quickly. In plants the heat is lost to the surroundings (by conduction, convection and evaporation) as fast as it is produced.

Practical work

Experiments on respiration and energy

If you look below at the chemical equation that represents aerobic respiration you will see that a tissue or an organism that is respiring should be (a) using up food, (b) using up oxygen, (c) giving off carbon dioxide, (d) giving out water and (e) releasing energy, which can be used for other processes.



If we wish to test whether aerobic respiration is taking place:

- '(d) giving out water' is not a good test because non-living material will give off water vapour if it is wet to start with.
- '(a) using up food' can be tested by seeing if an organism loses weight. This is not as easy as it seems because most organisms lose weight as a result of evaporation of water and this may have nothing to do with respiration. It is the decrease in 'dry weight' that must be measured.

We will focus on the uptake of oxygen and the production of carbon dioxide as indications that respiration is taking place.

Seeds are often used as the living organisms because when they start to grow (germinate) there is a high level of chemical activity in the cells. Seeds are easy to obtain and to handle and they fit into small-scale apparatus. In some cases blowfly maggots or woodlice can be used as animal material. Yeast is useful when studying anaerobic respiration.

1 Using up oxygen during respiration

The apparatus in Figure 12.2 is a **respirometer** (a 'respire meter'), which can measure the rate of respiration by seeing how quickly oxygen is taken up. Germinating seeds, or blowfly larvae or woodlice are placed in the test-tube and, as they use up the oxygen for respiration, the level of liquid in the delivery tubing will go up.

There are two drawbacks to this. One is that the organisms usually give out as much carbon dioxide as they take in oxygen. So there may be no change in the total amount of air in the test-tube and the liquid level will not move. This drawback is overcome by placing **soda-lime** in the test-tube. Soda-lime will absorb carbon dioxide as fast as the organisms give it out. So only the uptake of oxygen will affect the amount of air in the tube. The second drawback is that quite small changes in temperature will make the air in the test-tube expand or contract and so cause the liquid to rise or fall whether or not respiration is taking place. To overcome this, the test-tube is kept in a beaker of water (a water bath). The temperature of water changes far more slowly than that of air, so there will not be much change during a 30-minute experiment.

Control

To show that it is a living process that uses up oxygen, a similar respirometer is prepared but containing an equal quantity of germinating seeds that have been killed by boiling. (If blowfly larvae or woodlice are used, the control can consist of an equivalent volume of glass beads. This is not a very good control but is probably more acceptable than killing an equivalent number of animals.)

The apparatus is finally set up as shown in Figure 12.2 and left for 30 minutes (10 minutes if blowfly larvae or woodlice are used).

The capillary tube and reservoir of liquid are called a **manometer**.

Result
The level of liquid in the experiment goes up more than in the control. The level in the control may not move at all.

Interpretation
The rise of liquid in the delivery tubing shows that the living seedlings have taken up part of the air. It does not prove that it is oxygen that has been taken up. Oxygen seems the most likely gas, however, because (1) there is only 0.03% carbon dioxide in the air to start with and (2) the other gas, nitrogen, is known to be less active than oxygen.

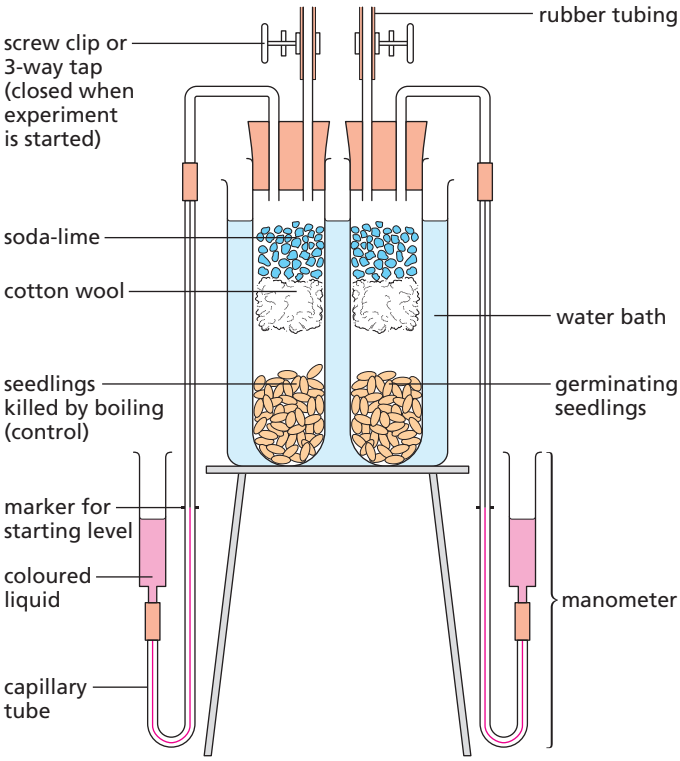


Figure 12.2 Experiment to see if oxygen is taken up in respiration

If the experiment is allowed to run for a long time, the uptake of oxygen could be checked at the end by placing a lighted splint in each test-tube in turn. If some of the oxygen has been removed by the living seedlings, the flame should go out more quickly than it does in the tube with dead seedlings.

2 Using up oxygen during respiration (alternative method)

A respirometer such as the one illustrated in Figure 12.2 is not an easy piece of apparatus to set up and collect data from. An alternative way of showing that oxygen is used up during respiration can be achieved using a simple respirometer (Figure 12.3).

- A larger invertebrate such as a locust, or a group of woodlice or blowfly maggots, is placed in the boiling tube (an alternative is a large plastic syringe, linked to the capillary tube with a short section of rubber or silicone tubing). The organisms are protected from the soda-lime by means of cotton wool or a wire gauze (soda-lime is caustic).

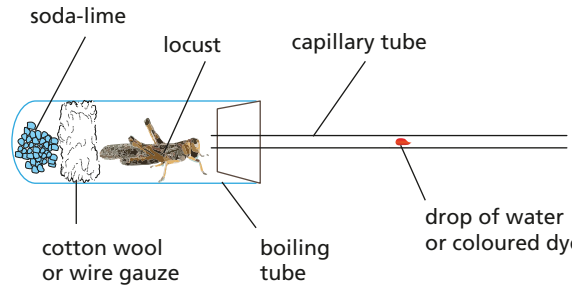


Figure 12.3 A simple respirometer

- A drop of water or coloured dye is introduced to the capillary tube by touching it against the liquid.
- The capillary tube is rested against a ruler and the position of the water drop is noted.
- After 1 minute (or longer if the drop moves very slowly) the new position of the water drop is recorded.

Note: Care must be taken when handling living organisms. Wash hands thoroughly with water if they come into contact with caustic soda.

Results
The water drop moves towards the organism. If the diameter of the bore of the capillary tube is measured, the volume of air taken in by the organism can be calculated:

$$\text{volume} = \pi r^2 l$$

where r = radius of the capillary tube bore

l = distance travelled by the water drop

This value can be converted into a rate if the volume is divided by the time taken.

Interpretation
The movement of the water drop towards the organism shows that it is taking in air. By using a range of organisms (locust, woodlice, blowfly larvae, germinating seeds) the rates of uptake can be compared to see which is respiring most actively.

A control could be set up using the same apparatus, but with glass beads instead of the organism(s). The bubble may still move because the soda-lime will absorb any carbon dioxide in the air in the boiling tube, but the movement should be less than that for living organisms.

If you are following the extended curriculum you need to be able to state the balanced chemical equation for aerobic respiration:

$$C_6H_{12}O_6 + 6O_2 \longrightarrow 6CO_2 + 6H_2O + 2830\,kJ$$

glucose oxygen carbon dioxide water energy

Mitochondria

It is in the mitochondria that the chemistry of aerobic respiration takes place (Chapter 2). The mitochondria generate a compound called **ATP**, which is used by the cell as the source of energy for driving other chemical reactions in the cytoplasm and nucleus.

Practical work

More experiments on respiration and energy

3 Investigating the effect of temperature on the rate of respiration of germinating seeds

- Use the same apparatus as shown in Experiment 2, but set up the boiling tube so it is vertical and supported in a water bath such as a beaker (Figure 12.4).
- Use wheat grains or pea seeds that have been soaked for 24 hours and rinsed in 1% formaldehyde (or domestic bleach diluted 1:4) for 5 minutes. These solutions will kill any bacteria or fungi on the surface of the seeds.
- Kill an equal quantity of soaked seeds by boiling them for 5 minutes.
- Cool the boiled seeds in cold tap water; rinse them in bleach or formaldehyde for 5 minutes as before. These can be used as the control (or, alternatively, use an equivalent volume of glass beads).
- Start with a water bath at about 20 °C and allow the seeds to acclimatise to that temperature for a few minutes before taking any readings. The initial and final positions of the water drop could be recorded on the capillary tube with a permanent marker or chinagraph pencil, or by sticking a small label onto the glass. The distance travelled can then be measured with a ruler.
- Repeat the procedure (introducing a new bubble each time) at a range of different temperatures, remembering to allow time for the seeds to acclimatise to the new conditions before taking further readings.

Results
As the temperature is increased the rate of movement of the water bubble towards the seeds increases. The movement may stop at higher temperatures.

Interpretation
As the temperature increases, the rate of respiration in the germinating seeds increases. This is because the enzymes controlling respiration are more active at higher temperatures. However, respiration may stop above around 40 °C because the enzymes become denatured if they get too hot.

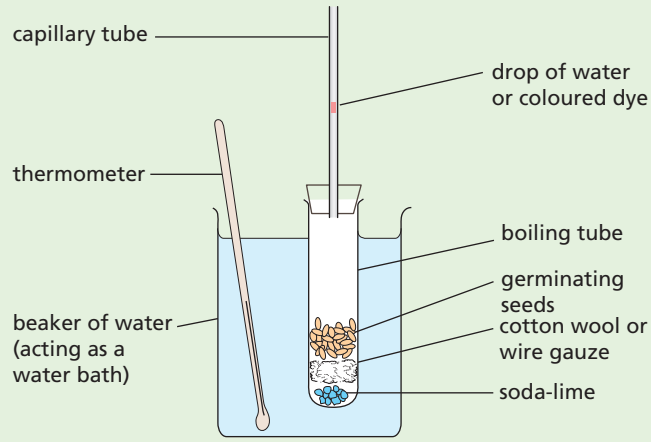


Figure 12.4 Simple respirometer for investigating the effect of temperature on germinating seeds

Controlled experiments

In most biological experiments, a second experiment called a **control** is set up. This is to make sure that the results of the first experiment are due to the conditions being studied and not to some other cause that has been overlooked.

In the experiment in Figure 12.2, the liquid rising up the capillary tube could have been the result of the test-tube cooling down, so making the air inside it contract. The identical experiment with dead seeds – the control – showed that the result was not due to a temperature change, because the level of liquid in the control did not move.

The term 'controlled experiment' refers to the fact that the experimenter (1) sets up a control and (2) controls the conditions in the experiment. In the experiment shown in Figure 12.2 the seeds are enclosed in a test-tube and soda-lime is added. This makes sure that any uptake or output of oxygen will make the liquid go up or down, and that the output of carbon dioxide will not affect the results. The experimenter had controlled both the amount and the composition of the air available to the germinating seeds.

If you did an experiment to compare the growth of plants in the house and in a greenhouse, you could not be sure whether it was the extra light or the high temperature of the greenhouse that caused better growth. This would not, therefore, be a properly controlled experiment. You must alter only

one condition (called a **variable**) at a time, either the light or the temperature, and then you can compare the results with the control experiment.

A properly controlled experiment, therefore, alters only one variable at a time and includes a control, which shows that it is this condition and nothing else that gave the result.

Anaerobic respiration

Key definition

Anaerobic respiration is the term for the chemical reactions in cells that break down nutrient molecules to release energy without using oxygen.

The word **anaerobic** means 'in the absence of oxygen'. In this process, energy is still released from food by breaking it down chemically but the reactions do not use oxygen though they do often produce carbon dioxide. A common example is the action of yeast on sugar solution to produce alcohol. The sugar is not completely oxidised to carbon dioxide and water but converted to carbon dioxide and alcohol. This process is called **fermentation** and is shown by the following equation:

$$\text{glucose} \xrightarrow{\text{enzymes}} \text{alcohol} + \text{carbon dioxide} + \underset{\text{energy}}{118\,\text{kJ}}$$

The processes of brewing and bread-making rely on anaerobic respiration by yeast. As with aerobic respiration, the reaction takes place in small steps and needs several different enzymes. The yeast uses the energy for its growth and living activities, but you can see from the equation that less energy is produced by anaerobic respiration than in aerobic respiration. This is because the alcohol still contains a great deal of energy that the yeast is unable to use.

Anaerobic respiration also occurs in muscles during vigorous exercise, because oxygen cannot be delivered fast enough to satisfy the needs of the respiring muscle cells. The products are different to those produced by anaerobic respiration in yeast. The process is shown by the following equation:

$$\text{glucose} \longrightarrow \text{lactic acid}$$

The lactic acid builds up in the muscles and causes muscle fatigue (cramp).

Anaerobic respiration is much less efficient than aerobic respiration because it releases much less energy per glucose molecule broken down (respired).

Practical work

More experiments on respiration and energy

4 Releasing energy in respiration

- Fill a small vacuum flask with wheat grains or pea seeds that have been soaked for 24 hours and rinsed in 1% formaldehyde (or domestic bleach diluted 1:4) for 5 minutes. These solutions will kill any bacteria or fungi on the surface of the seeds.
- Kill an equal quantity of soaked seeds by boiling them for 5 minutes.
- Cool the boiled seeds in cold tap water, rinse them in bleach or formaldehyde for 5 minutes as before and then put them in a vacuum flask of the same size as the first one. This flask is the control.
- Place a thermometer in each flask so that its bulb is in the middle of the seeds (Figure 12.5).
- Plug the mouth of each flask with cotton wool and leave both flasks for 2 days, noting the thermometer readings whenever possible.

Result

The temperature in the flask with the living seeds will be 5–10 °C higher than that of the dead seeds.

Interpretation

Provided there are no signs of the living seeds going mouldy, the heat produced must have come from living processes in the seeds, because the dead seeds in the control did not give out any heat. There is no evidence that this process is respiration rather than any other chemical change but the result is what you would expect if respiration does produce energy.

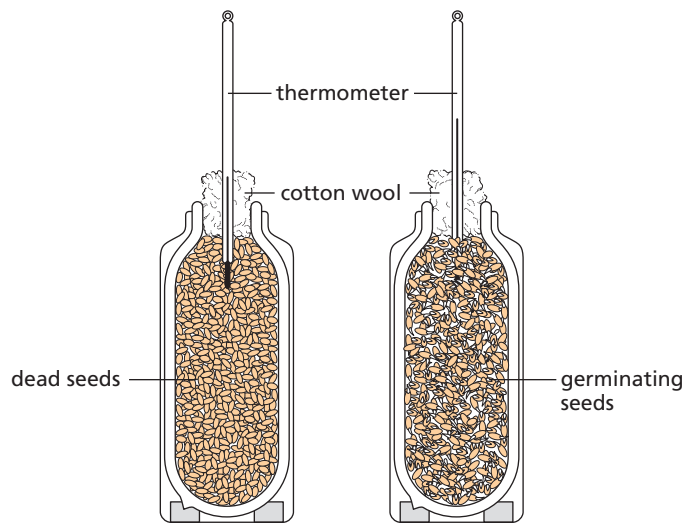


Figure 12.5 Experiment to show energy release in germinating seeds

5 Anaerobic respiration in yeast

- Boil some water to expel all the dissolved oxygen.
- When cool, use the boiled water to make up a 5% solution of glucose and a 10% suspension of dried yeast.
- Place 5 cm³ of the glucose solution and 1 cm³ of the yeast suspension in a test-tube and cover the mixture with a thin layer of liquid paraffin to exclude atmospheric oxygen.
- Fit a delivery tube as shown in Figure 12.6 and allow it to dip into clear limewater.

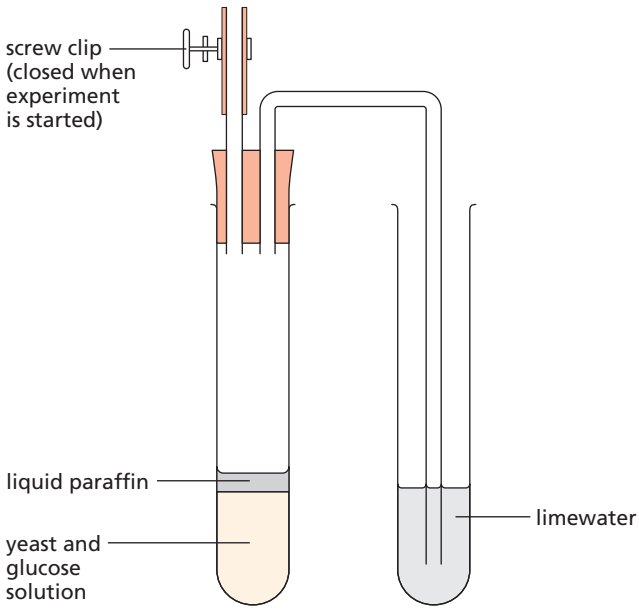


Figure 12.6 Experiment to show anaerobic respiration in yeast

Result
After 10–15 minutes, with gentle warming if necessary, there should be signs of fermentation in the yeast–glucose mixture and the bubbles of gas escaping through the limewater should turn it milky.

Interpretation
The fact that the limewater goes milky shows that the yeast–glucose mixture is producing carbon dioxide. If we assume that the production of carbon dioxide is evidence of respiration, then it looks as if the yeast is respiring. In setting up the experiment, you took care to see that oxygen was removed from the glucose solution and the yeast suspension, and the liquid paraffin excluded air (including oxygen) from the mixture. Any respiration taking place must, therefore, be anaerobic (i.e. without oxygen).

Control
It might be suggested that the carbon dioxide came from a chemical reaction between yeast and glucose (as between chalk and acid), which had nothing to do with respiration or any other living process. A control should, therefore, be set up using the same procedure as before but with yeast that has been killed by boiling. The failure, in this case, to produce carbon dioxide supports the claim that it was a living process in the yeast in the first experiment that produced the carbon dioxide.

The balanced chemical equation for anaerobic respiration in organisms such as yeast is shown below:

$$C_6H_{12}O_6 \xrightarrow{\text{enzymes}} 2C_2H_5OH + 2CO_2 + 118\,kJ$$

glucose — alcohol — carbon dioxide — energy

This amount of energy released per mole of glucose respired is much less than that released in aerobic respiration (2830 kJ per mole).

During vigorous exercise, **lactic acid** may build up in a muscle. In this case it is removed in the bloodstream. The blood needs to move more quickly during and after exercise to maintain this lactic acid removal process, so the heart rate is rapid. On reaching the liver, some of the lactic acid is oxidised to carbon dioxide and water, using up oxygen in the process. After exercise has stopped, a high level of oxygen consumption may persist until the excess of lactic acid has been oxidised. This is characterised by deeper breathing (an athlete pants for breath). The build-up of lactic acid that is oxidised later is said to create an **oxygen debt**.

Accumulation of lactic acid in the muscles results in muscular fatigue, leading to cramp.

Athletes and climbers who are used to working at low altitude (normal air pressure) have problems if they then perform at high altitude (low air pressure). High-altitude air has a lower percentage of oxygen, so an oxygen debt can be experienced much more easily than at low altitude. The problem can be resolved if the person spends time at high altitude before performing to allow the body to acclimatise (making more red blood cells and increasing blood volume).

Extension work

Metabolism

All the chemical changes taking place inside a cell or a living organism are called its **metabolism**. The minimum turnover of energy needed simply to keep an organism alive, without movement or growth, is called the **basal metabolism**. Our basal metabolism maintains vital processes such as breathing, heartbeat, digestion and excretion.

The processes that break substances down are sometimes called **catabolism**. Respiration is an example of catabolism in which carbohydrates

are broken down to carbon dioxide and water. Chemical reactions that build up substances are called **anabolism**. Building up a protein from amino acids is an example of anabolism. The energy released by the **catabolic** process of respiration is used to drive the **anabolic** reactions that build up proteins.

You may have heard of anabolic steroids in connection with drug taking by athletes. These chemicals reduce the rate of protein breakdown and may enhance the build-up of certain proteins. However, their effects are complicated and not fully understood, they have undesirable side-effects and their use contravenes athletics codes (see 'Misused drugs' in Chapter 15).

Practical work

More experiments on respiration and energy

6 The effect of temperature on yeast respiration

- Make some bread dough using flour, water and activated yeast (yeast in a warm sugar solution).
- Rub the inside of a boiling tube with oil (this makes it easier to remove the dough after the experiment).
- Use a glass rod or the end of an old pencil to push a piece of dough into the bottom of the boiling tube, so that the tube is about a quarter full of dough.
- Mark the height of the top of the dough on the boiling tube, using a chinagraph pencil or permanent marker pen.
- Place the boiling tube into a beaker of water set to a preselected temperature, e.g. 20 °C.
- Leave the dough for 20 minutes, checking to make sure the temperature of the water bath remains constant (adding warm or cold water to maintain this).
- Record the new height of the dough.
- Repeat the procedure at different temperatures and compare the rate of rising of the bread dough.

Results

The dough rises faster as the temperature is increased to 35 or 40 °C. Higher temperatures slow down the rate. Low temperatures may result in no change in height of the dough.

Explanation

Yeast respires anaerobically, producing carbon dioxide. This causes the dough to rise. The process is controlled by enzymes, which work faster as the temperature is increased to the optimum (around 35–40 °C). Higher temperatures cause the enzymes to denature (Chapter 5).

Extension work

Hypothesis testing

You will have noticed that none of the experiments described above claim to have *proved* that respiration is taking place. The most we can claim is that they have not disproved the proposal that energy is produced from respiration. There are many reactions taking place in living organisms and, for all we know at this stage, some of them may be using oxygen or giving out carbon dioxide without releasing energy, i.e. they would not fit our definition of respiration.

This inability to 'prove' that a particular proposal is 'true' is not restricted to experiments on respiration. It is a feature of many scientific experiments. One way in which science makes progress is by putting forward a **hypothesis**, making predictions from the hypothesis, and then testing these predictions by experiments.

A hypothesis is an attempt to explain some event or observation using the information currently available. If an experiment's results do not confirm the predictions, the hypothesis must be abandoned or altered.

For example, biologists observing that living organisms take up oxygen might put forward the hypothesis that 'oxygen is used to convert food to carbon dioxide, so producing energy for movement, growth, reproduction, etc.' This hypothesis can be tested by predicting that, '*if* the oxygen is used to oxidise food *then* an organism that takes up oxygen will also produce carbon dioxide'. Experiment 1 on page 166 tests this and fulfils this prediction and, therefore, supports the hypothesis. Looking at the equation for respiration, we might also predict that an organism that is respiring will produce carbon dioxide and take up oxygen. Experiment 5 with yeast, however, does not fulfil this prediction and so does not support the hypothesis as it stands, because here is an organism producing carbon dioxide without taking up oxygen. The hypothesis will have to be modified, e.g. 'energy is released from food by breaking it down to carbon dioxide; some organisms use oxygen for this process, others do not'.

There are still plenty of tests that we have not done. For example, we have not attempted to see whether it is food that is the source of energy and carbon dioxide. One way of doing this is to provide the organism with food, e.g. glucose, in which the

carbon atoms are radioactive. Carbon-14 (^{14}C) is a radioactive form of carbon and can be detected by using a Geiger counter. If the organism produces radioactive carbon dioxide, it is reasonable to suppose that the carbon dioxide comes from the glucose.

$$C_6H_{12}O_6 + 6O_2 \longrightarrow 6CO_2 + 6H_2O + \text{energy}$$

This is **direct evidence** in support of the hypothesis. All the previous experiments have provided only **indirect evidence**.

Criteria for a good hypothesis

A good hypothesis must:

- explain *all* aspects of the observation
- be the simplest possible explanation
- be expressed in such a way that predictions can be made from it
- be testable by experiment.

Questions

Core

1 a If, in one word, you had to say what respiration was about, which word would you choose from this list: breathing, energy, oxygen, cells, food?
  b In which parts of a living organism does respiration take place?
2 What are the main differences between aerobic and anaerobic respiration?
3 What chemical substances must be provided for aerobic respiration to take place:
  a from outside the cell
  b from inside the cell?
  c What are the products of aerobic respiration?
4 Which of the following statements are true? If an organism is respiring you would expect it to be:
  a giving out carbon dioxide
  b losing heat
  c breaking down food
  d using up oxygen
  e gaining weight
  f moving about.
5 What was the purpose of:
  a the soda-lime in the respirometer in Figure 12.2
  b the limewater in Figure 12.6?

Extended

6 What is the difference between aerobic and anaerobic respiration in the amount of energy released from one molecule of glucose?
7 Victims of drowning who have stopped breathing are sometimes revived by a process called 'artificial respiration'. Why would a biologist object to the use of this expression? ('Resuscitation' is a better word to use.)
8 Why do you think your breathing rate and heart rate stay high for some time after completing a spell of vigorous exercise?
9 In an experiment like the one shown in Figure 12.2, the growing seeds took in 5 cm^3 oxygen and gave out 7 cm^3 carbon dioxide. How does the volume change:
  a if no soda-lime is present
  b if soda-lime is present?
10 The germinating seeds in Figure 12.5 will release the same amount of heat whether they are in a beaker or a vacuum flask. Why then is it necessary to use a vacuum flask for this experiment?
11 Experiment 5 with yeast supported the claim that anaerobic respiration was taking place. The experiment was repeated using unboiled water and without the liquid paraffin. Fermentation still took place and carbon dioxide was produced. Does this mean that the design or the interpretation of the first experiment was wrong? Explain your answer.
12 Twenty seeds are placed on soaked cotton wool in a closed glass dish. After 5 days in the light 15 of the seeds had germinated. If the experiment is intended to see if light is needed for germination, which of the following would be a suitable control:
  a exactly the same set-up but with dead seeds
  b the same set-up but with 50 seeds
  c an identical experiment but with 20 seeds of a different species
  d an identical experiment but left in darkness for 5 days?
13 Certain bacteria that live in sulfurous springs in areas of volcanic activity take up hydrogen sulfide (H_2S) and produce sulfates ($-SO_4$). Put forward a hypothesis to account for this chemical activity. Suggest one way of testing your hypothesis.

14 The table below shows the energy used up each day either as kilojoules per kilogram of body mass or as kilojoules per square metre of body surface.

Animal	Mass/kg	kJ per day	
		per kg body mass	per m^2 body surface
man	64.3	134	4360
mouse	0.018	2736	4971

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a According to the table, what is the total amount of energy used each day by
   i a man
   ii a mouse?
b Which of these two shows a greater rate of respiration in its body cells?
c Why, do you think, is there so little difference in the energy expenditure per square metre of body surface?

Checklist

After studying Chapter 12 you should know and understand the following:

- The word equation for aerobic respiration is

  glucose + oxygen $\xrightarrow{\text{enzymes}}$ carbon dioxide + water + energy

- Aerobic respiration is the term for the chemical reactions in cells that convert energy in nutrient molecules using oxygen so that cells can use this energy.
- The word equation for anaerobic respiration in muscles is

  glucose $\xrightarrow{\text{enzymes}}$ lactic acid + energy

- The word equation for anaerobic respiration in yeast is

  glucose $\xrightarrow{\text{enzymes}}$ alcohol + carbon dioxide + energy

- Anaerobic respiration is the term for the chemical reactions in cells that convert energy in nutrient molecules without the use of oxygen so that cells can use this energy.
- Respiration is the process in cells that releases energy from food.
- Aerobic respiration needs oxygen; anaerobic respiration does not.
- Aerobic respiration releases much more energy per glucose molecule than anaerobic respiration.
- The oxidation of food produces carbon dioxide as well as releasing energy.
- Experiments to investigate respiration try to detect uptake of oxygen, production of carbon dioxide, release of energy as heat or a reduction in dry weight.
- The balanced chemical equation for aerobic respiration is

  $C_6H_{12}O_6 + 6O_2 \longrightarrow 6CO_2 + 6H_2O + 2830\,kJ$

- Experiments to investigate the effect of temperature on the rate of respiration of germinating seeds.
- The balanced chemical equation for anaerobic respiration in yeast is

  $C_6H_{12}O_6 \longrightarrow 2C_2H_5OH + 2CO_2 + 118\,kJ$

- Lactic acid builds up in muscles due to anaerobic respiration, causing an oxygen debt.
- An outline of how oxygen is removed during recovery.
- In a controlled experiment, the scientist tries to alter only one condition at a time, and sets up a control to check this.
- A control is a second experiment, identical to the first experiment except for the one condition being investigated.
- The control is designed to show that only the condition under investigation is responsible for the results.
- Experiments are designed to test predictions made from hypotheses; they cannot 'prove' a hypothesis.

13 Excretion in humans

Excretion
Excretory products: urea, carbon dioxide
Contents of urine
Urine output
Parts of urinary system

Role of liver in conversion of amino acids to proteins
Define deamination
Explain the need for excretion
Structure and function of kidney tubule
Dialysis
Compare dialysis with kidney transplant

Excretion

Excretion is the removal from organisms of toxic materials and substances in excess of requirements. These include:

- the waste products of its chemical reactions
- the excess water and salts taken in with the diet
- spent hormones.

Excretion also includes the removal of drugs or other foreign substances taken into the alimentary canal and absorbed by the blood.

Many chemical reactions take place inside the cells of an organism in order to keep it alive. Some products of these reactions are poisonous and must be removed from the body. For example, the breakdown of glucose during respiration (see 'Aerobic respiration' in Chapter 12) produces carbon dioxide. This is carried away by the blood and removed in the lungs. Excess amino acids are deaminated in the liver to form glycogen and **urea**. The urea is removed from the tissues by the blood and expelled by the kidneys.

Urea and similar waste products, like **uric acid**, from the breakdown of proteins, contain the element nitrogen. For this reason they are often called **nitrogenous waste products**.

During feeding, more water and salts are taken in with the food than are needed by the body. So these excess substances need to be removed as fast as they build up.

The hormones produced by the endocrine glands (Chapter 14) affect the rate at which various body systems work. Adrenaline, for example, speeds up the heartbeat. When hormones have done their job, they are modified in the liver and excreted by the kidneys.

The nitrogenous waste products, excess salts and spent hormones are excreted by the kidneys as a watery solution called **urine**.

Excretory organs

Liver

The liver breaks down excess amino acids and produces urea. The yellow/green bile pigment, **bilirubin**, is a breakdown product of haemoglobin (Chapter 9). Bilirubin is excreted with the bile into the small intestine and expelled with the faeces. The pigment undergoes changes in the intestine and is largely responsible for the brown colour of the faeces.

Lungs

The lungs supply the body with oxygen, but they are also excretory organs because they get rid of carbon dioxide. They also lose a great deal of water vapour but this loss is unavoidable and is not a method of controlling the water content of the body (Table 13.1).

Kidneys

The kidneys remove urea and other nitrogenous waste from the blood. They also expel excess water, salts, hormones (Chapter 14) and drugs (Chapter 15).

Skin

Sweat consists of water, with sodium chloride and traces of urea dissolved in it. When you sweat, you will expel these substances from your body so, in one sense, they are being excreted. However, sweating is a response to a rise in temperature and not to a change in the blood composition. In this sense, therefore, skin is not an excretory organ like the lungs and kidneys. See 'Homeostasis' in Chapter 14 for more details of skin structure and its functions.

Table 13.1 Excretory products and incidental losses

Excretory organ	Excretory products	Incidental losses
lungs	carbon dioxide	water
kidneys	nitrogenous waste, water, salts, toxins, hormones, drugs	
liver	bile pigments	
skin		water, salt, urea

The kidneys

The two kidneys are fairly solid, oval structures. They are red-brown, enclosed in a transparent membrane and attached to the back of the abdominal cavity (Figure 13.1). The **renal artery** branches off from the aorta and brings oxygenated blood to them. The **renal vein** takes deoxygenated blood away from the kidneys to the vena cava (see Figure 9.20). A tube, called the **ureter**, runs from each kidney to the bladder in the lower part of the abdomen.

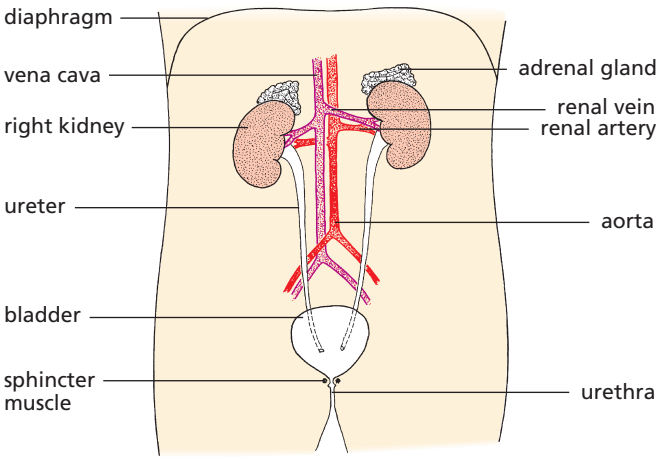


Figure 13.1 Position of the kidneys in the body

Water balance and osmoregulation

Your body gains water from food and drink. It loses water by evaporation, urination and defecation (Chapter 7). Evaporation from the skin takes place all the time but is particularly rapid when we sweat. Air from the lungs is saturated with water vapour, which is lost to the atmosphere every time we exhale. Despite these gains and losses of water, the concentration of body fluids is kept within very narrow limits by the kidneys, which adjust the concentration of the blood flowing through them. If it is too dilute (i.e. has too much water), less water is reabsorbed, leaving more to enter the bladder. After drinking a lot of fluid, a large volume of dilute urine is produced. On a cold day, sweating decreases so more water is removed from the blood by the kidneys, again increasing the volume of dilute urine.

If the blood is too concentrated, more water is absorbed back into the blood from the kidney tubules. So, if the body is short of water, e.g. after sweating profusely on a hot day, or through doing a lot of physical activity, or not having enough to drink, only a small quantity of concentrated urine is produced.

Key definition
Deamination is the removal of the nitrogen-containing part of amino acids to form urea.

The liver and its role in producing proteins

As well as being an excretory organ, the liver plays a very important role in **assimilating** amino acids. Assimilation means the absorption of substances, which are then built into other compounds in the organism. The liver removes amino acids from the plasma of the bloodstream and builds them up into proteins. Proteins are long chains of amino acids, joined together by peptide bonds (see Chapter 4 for details of protein structure). These include plasma proteins such as fibrinogen (Chapter 9), which have a role in blood clotting.

The need for excretion

Some of the compounds made in reactions in the body are potentially toxic (poisonous) if their concentrations build up. Carbon dioxide dissolves in fluids such as tissue fluid and blood plasma to form carbonic acid. This increase in acidity can affect the actions of enzymes and can be fatal. Ammonia is made in the liver when excess amino acids are broken down. However, ammonia is very alkaline and toxic. It is converted to urea which is much less poisonous, making it a safe way of excreting excess nitrogen.

Microscopic structure of the kidneys

The kidney tissue consists of many capillaries and tiny tubes, called **renal tubules**, held together with connective tissue. If the kidney is cut down its length (sectioned), it is seen to have a dark, outer region called the **cortex** and a lighter, inner zone, the **medulla**. Where the ureter joins the kidney there is a space called the **pelvis** (Figure 13.2).

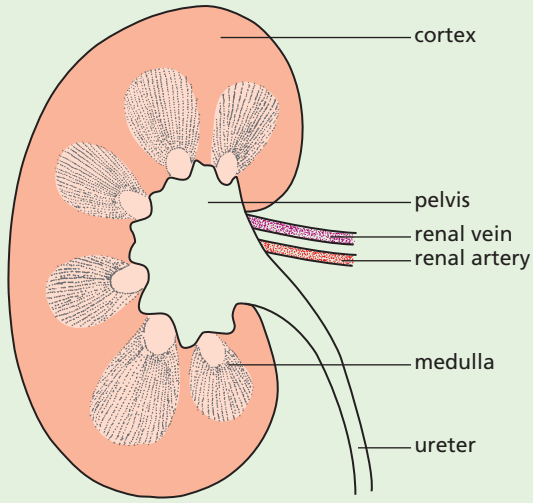


Figure 13.2 Section through the kidney to show regions

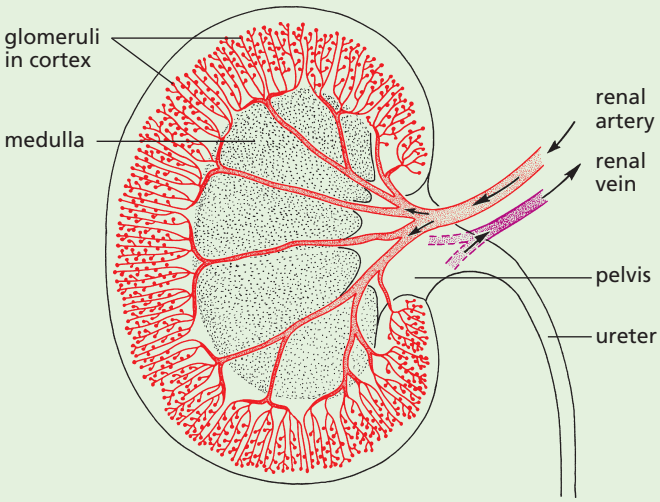


Figure 13.3 Section through kidney to show distribution of glomeruli

The renal artery divides up into a great many arterioles and capillaries, mostly in the cortex (Figure 13.3). Each arteriole leads to a **glomerulus**. This is a capillary repeatedly divided and coiled, making a knot of vessels (Figure 13.4). Each glomerulus is almost entirely surrounded by a cup-shaped organ called a **renal capsule**, which leads to a coiled **renal tubule**. This tubule, after a series of coils and loops, joins a **collecting duct**, which passes through the medulla to open into the pelvis (Figure 13.5). There are thousands of glomeruli in the kidney cortex and the total surface area of their capillaries is very great.

A **nephron** is a single glomerulus with its renal capsule, renal tubule and blood capillaries (see Figure 13.6).

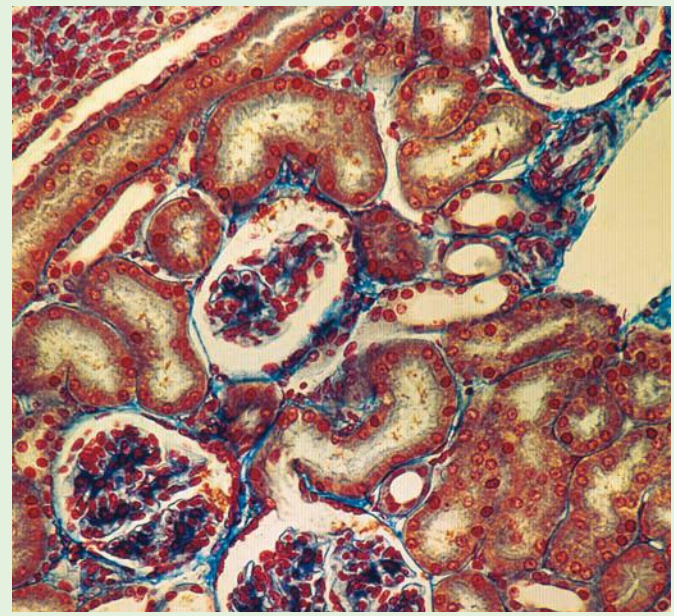


Figure 13.4 Glomeruli in the kidney cortex (×300). The three glomeruli are surrounded by kidney tubules sectioned at different angles. The light space around each glomerulus represents the renal capsule.

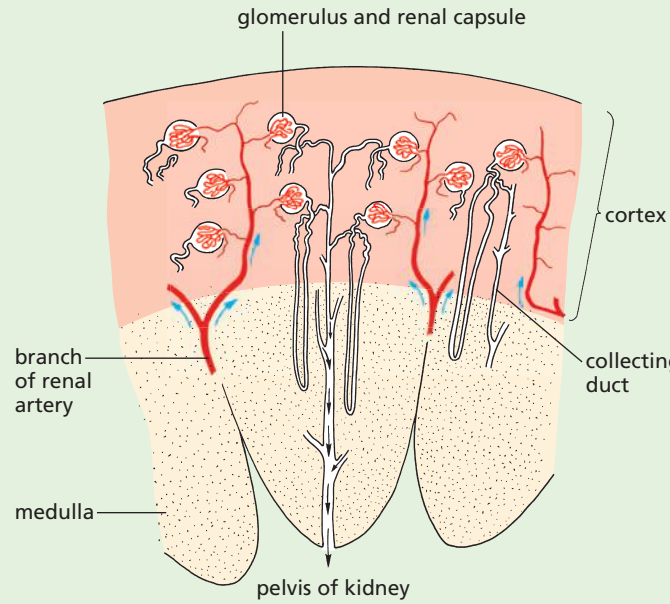


Figure 13.5 There are up to 4 million nephrons in a kidney. Only a few can be represented here, and not to scale.

Function of the kidneys

The blood pressure in a glomerulus causes part of the blood plasma to leak through the capillary walls.

The red blood cells and the plasma proteins are too big to pass out of the capillary, so the fluid that does filter through is plasma without the protein, i.e. similar to tissue fluid (Chapter 9). The fluid thus consists mainly of water with dissolved salts, glucose, urea and uric acid. The process by which the fluid is filtered out of the blood by the glomerulus is called **ultrafiltration**.

The filtrate from the glomerulus collects in the renal capsule and trickles down the renal tubule (Figure 13.6). As it does so, the capillaries that surround the tubule absorb back into the blood those substances which the body needs. First, all the glucose is reabsorbed, with much of the water. Then some of the salts are taken back to keep the correct concentration in the blood. The process of absorbing back the substances needed by the body is called **selective reabsorption**.

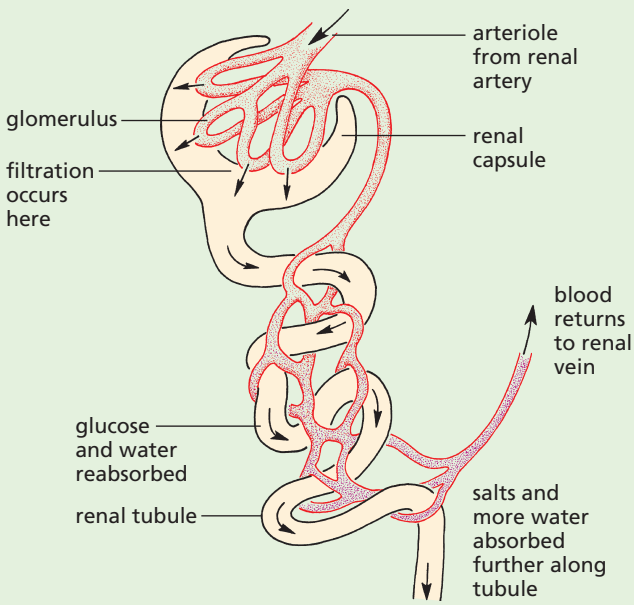


Figure 13.6 Part of a nephron (glomerulus, renal capsule and renal tubule)

Salts not needed by the body are left to pass on down the kidney tubule together with the urea and uric acid. So, these nitrogenous waste products, excess salts and water continue down the renal tube into the pelvis of the kidney. From here the fluid, now called **urine**, passes down the ureter to the bladder.

Table 13.2 shows some of the differences in composition between the blood plasma and the urine. The figures represent average values because the composition of the urine varies a great deal according to the diet, activity, temperature and intake of liquid.

Table 13.2 Composition of blood plasma and urine

	Plasma/%	Urine/%
water	90–93	95.0
urea	0.03	2.0
uric acid	0.003	0.05
ammonia	0.0001	0.05
sodium	0.3	0.6
potassium	0.02	0.15
chloride	0.37	0.6
phosphate	0.003	0.12

The **bladder** can expand to hold about 400 cm^3 of urine. The urine cannot escape from the bladder because a band of circular muscle, called a **sphincter**, is contracted, so shutting off the exit. When this sphincter muscle relaxes, the muscular walls of the bladder expel the urine through the **urethra**. Adults can control this sphincter muscle and relax it only when they want to urinate. In babies, the sphincter relaxes by a reflex action (Chapter 14), set off by pressure in the bladder. By 3 years old, most children can control the sphincter voluntarily.

The dialysis machine ('artificial kidney')

Kidney failure may result from an accident involving a drop in blood pressure, or from a disease of the kidneys. In the former case, recovery is usually spontaneous, but if it takes longer than 2 weeks, the patient may die as a result of a potassium imbalance in the blood, which causes heart failure. In the case of kidney disease, the patient can survive with only one kidney, but if both fail, the patient's blood composition has to be regulated by a **dialysis** machine. Similarly, the accident victim can be kept alive on a dialysis machine until his or her blood pressure is restored.

In principle, a dialysis machine consists of a long cellulose tube coiled up in a water bath. The patient's blood is led from a vein in the arm and pumped through the cellulose (dialysis) tubing (Figures 13.7 and 13.8). The tiny pores in the dialysis tubing allow small molecules, such as those of salts, glucose and urea, to leak out into the water bath. Blood cells and protein molecules are too large to get through the pores (see Experiment 5, Chapter 4). This stage is similar to the filtration process in the glomerulus.

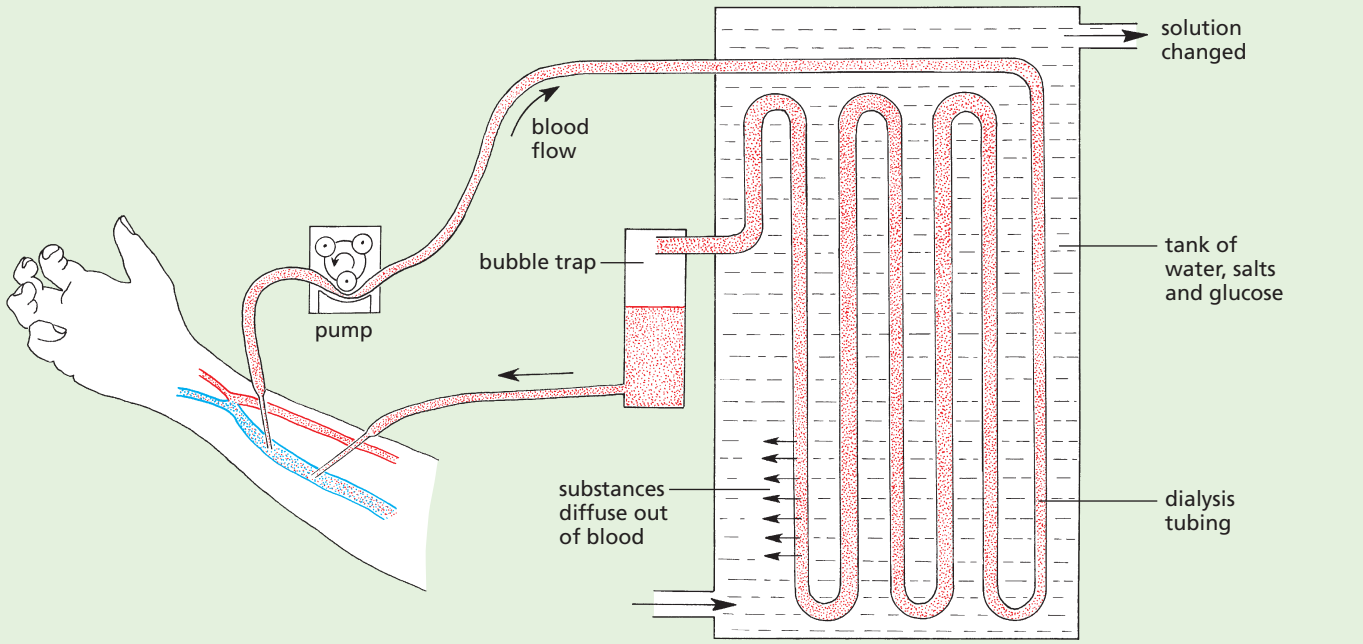


Figure 13.7 The principle of the kidney dialysis machine

To prevent a loss of glucose and essential salts from the blood, the liquid in the water bath consists of a solution of salts and sugar of the correct composition, so that only the substances above this concentration can diffuse out of the blood into the bathing solution. Thus, urea, uric acid and excess salts are removed.

The bathing solution is also kept at body temperature and is constantly changed as the unwanted blood solutes accumulate in it. The blood is then returned to the patient's arm vein.

A patient with total kidney failure has to spend 2 or 3 nights each week connected to the machine (Figure 13.8). With this treatment and a carefully controlled diet, the patient can lead a fairly normal life. A kidney transplant, however, is a better solution because the patient is not obliged to return to the dialysis machine.

The problem with kidney transplants is to find enough suitable donors of healthy kidneys and to prevent the transplanted kidney from being rejected.

The donor may be a close relative who is prepared to donate one of his or her kidneys (you can survive adequately with one kidney). Alternatively, the donated kidney may be taken from a healthy person who dies, for example, as a result of a road accident. People willing for their kidneys to be used after their death can carry a kidney donor card but the relatives must give their permission for the kidneys to be used.

The problem with rejection is that the body reacts to any transplanted cells or tissues as it does to all foreign proteins and produces lymphocytes, which attack and destroy them. This rejection can be overcome by:

- choosing a donor whose tissues are as similar as possible to those of the patient, e.g. a close relative
- using immunosuppressive drugs, which suppress the production of lymphocytes and their antibodies against the transplanted organ.

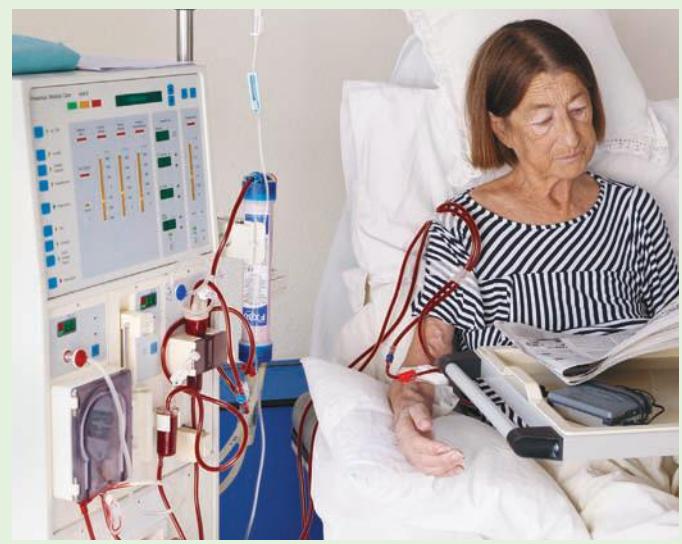


Figure 13.8 Kidney dialysis machine. The patient's blood is pumped to the dialyser, which removes urea and excess salts.

The advantages and disadvantages of kidney transplants, compared with dialysis

Advantages

- The patient can return to a normal lifestyle – dialysis may require a lengthy session in hospital, three times a week, leaving the patient very tired after each session.
- The dialysis machine will be available for other patients to use.
- Dialysis machines are expensive to buy and maintain.

Disadvantages

- Transplants require a suitable donor – with a good tissue match. The donor may be from a dead person, or from a close living relative who is prepared to donate a healthy kidney (we can survive with one kidney).
- The operation is very expensive.
- There is a risk of rejection of the donated kidney – immunosuppressive drugs have to be used.
- Transplants are not accepted by some religions.

Questions

Core

1 Write a list of the substances that are likely to be excreted from the body during the day.
2 Why do you think that urine analysis is an important part of medical diagnosis?

Extended

3 How does the dialysis machine:
   a resemble and
   b differ from
   the nephron of a kidney in the way it functions?

Checklist

After studying Chapter 13 you should know and understand the following:

- Excretion is getting rid of toxic, surplus or unwanted substances produced by chemical reactions in the body or taken in with the diet.
- The lungs excrete carbon dioxide.
- The kidneys excrete urea, unwanted salts and excess water.
- Part of the blood plasma entering the kidneys is filtered out by the capillaries. Substances which the body needs, like glucose, are absorbed back into the blood. The unwanted substances are left to pass down the ureters into the bladder.
- The bladder stores urine, which is discharged at intervals.
- The kidneys help to keep the blood at a steady concentration by excreting excess salts and by adjusting the amounts of water (osmoregulation).
- The volume and concentration of urine produced is affected by water intake, temperature and exercise.
- The ureters, bladder and urethra on diagrams.
- The liver produces urea, formed from excess amino acids.
- Deamination is the removal of the nitrogen-containing part of amino acids to form urea.
- The liver has a role in the assimilation of amino acids by converting them to proteins, including plasma proteins.
- Outline of the structure and function of a kidney tubule.
- Explain the process of dialysis.
- Treatment, in response to damage to kidneys, may involve dialysis or transplant.
- The advantages and disadvantages of kidney transplants and dialysis.

14 Co-ordination and response

Nervous control in humans
Human nervous system
Structure of neurones
Nerve impulse
Reflex arc, spinal cord and reflexes
Define synapse
Structure of synapse

Voluntary and involuntary actions
Transfer of impulse across synapse
Effects of drugs on synapses

Sense organs
Define sense organ
Structure of eye
Pupil reflex

Explanation of pupil reflex
Accommodation
Function of rods and cones

Hormones in humans
Define hormone
Endocrine glands
Adrenaline
Functions of hormones

Role of adrenaline
Compare nervous and hormonal control systems

Homeostasis
Define homeostasis
Skin structure
Control of body temperature
Homeostasis

Negative feedback
Regulation of blood sugar
Type 1 diabetes
Vasodilation and vasoconstriction

Tropic responses
Define phototropism and gravitropism
Investigate tropic responses

Role of auxins in tropisms
Use of plant hormones in weedkillers

Co-ordination is the way all the organs and systems of the body are made to work efficiently together (Figure 14.1). If, for example, the leg muscles are being used for running, they will need extra supplies of glucose and oxygen. To meet this demand, the lungs breathe faster and deeper to obtain the extra oxygen and the heart pumps more rapidly to get the oxygen and glucose to the muscles more quickly.

The brain detects changes in the oxygen and carbon dioxide content of the blood and sends nervous impulses to the diaphragm, intercostal muscles and heart. In this example, the co-ordination of the systems is brought about by the **nervous system**.

The extra supplies of glucose needed for running come from the liver. Glycogen in the liver is changed to glucose, which is released into the bloodstream (see 'Homeostasis' on page 192). The conversion of glycogen to glucose is stimulated by, among other things, a chemical called adrenaline (see 'Hormones in humans' on page 190). Co-ordination by chemicals is brought about by the **endocrine system**.

The nervous system works by sending electrical impulses along nerves. The endocrine system depends on the release of chemicals, called **hormones**, from **endocrine glands**. Hormones are carried by the bloodstream. For example, insulin is carried from the pancreas to the liver by the circulatory system.

Figure 14.1 Co-ordination. The badminton player's brain is receiving sensory impulses from his eyes, ears (sound and balance) and muscle stretch receptors. Using this information, the brain co-ordinates the muscles of his limbs so that even while running or leaping he can control his stroke.

Nervous control in humans

The human nervous system is shown in Figure 14.2. The brain and spinal cord together form the **central nervous system**. Nerves carry electrical impulses from the central nervous system to all parts of the body, making muscles contract or glands produce enzymes or hormones. Electrical impulses are electrical signals that pass along nerve cells (neurones).

Glands and muscles are called **effectors** because they go into action when they receive nerve impulses or hormones. The biceps muscle is an effector that flexes the arm; the salivary gland (see 'Alimentary canal' in Chapter 7) is an effector that produces saliva when it receives a nerve impulse from the brain.

The nerves also carry impulses back to the central nervous system from receptors in the sense organs of the body. These impulses from the eyes, ears, skin, etc. make us aware of changes in our surroundings or in ourselves. Nerve impulses from the sense organs to the central nervous system are called **sensory impulses**; those from the central nervous system to the effectors, resulting in action, are called **motor impulses**.

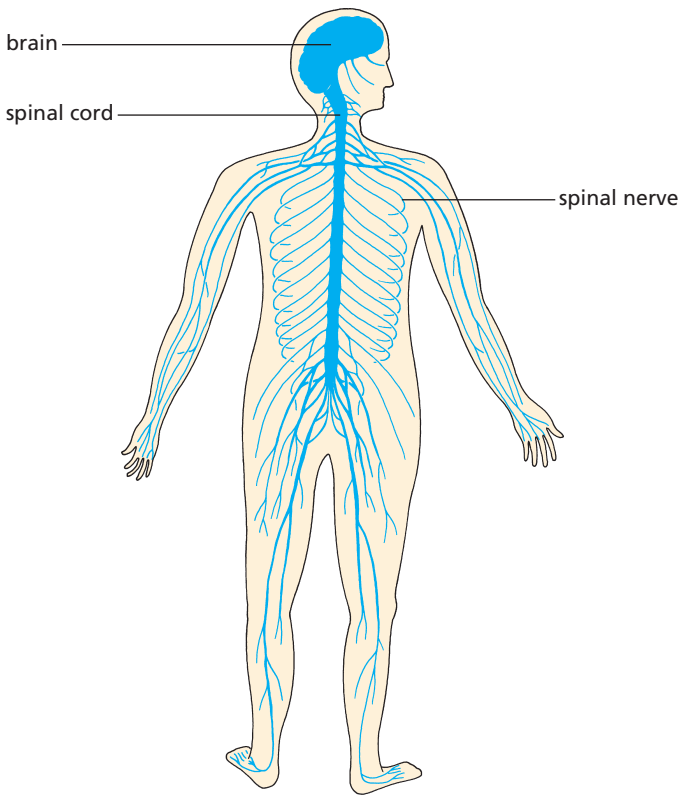


Figure 14.2 The human nervous system

The nerves that connect the body to the central nervous system make up the **peripheral** nervous system.

Nerve cells (neurones)

The central nervous system and the peripheral nerves are made up of nerve cells, called **neurones**. Three types of neurone are shown in Figure 14.3. **Motor neurones** carry impulses from the central nervous system to muscles and glands. **Sensory neurones** carry impulses from the sense organs to the central nervous system. **Relay neurones** (also called multi-polar or connector neurones) are neither sensory nor motor but make connections to other neurones inside the central nervous system.

Each neurone has a **cell body** consisting of a nucleus surrounded by a little cytoplasm. Branching fibres, called **dendrites**, from the cell body make contact with other neurones. A long filament of cytoplasm, surrounded by an insulating sheath, runs from the cell body of the neurone. This filament is called a **nerve fibre** (Figure 14.3(a) and (b)). The cell bodies of the neurones are mostly located in the brain or in the spinal cord and it is the nerve fibres that run in the nerves. A **nerve** is easily visible, white, tough and stringy and consists of hundreds of microscopic nerve fibres bundled together (Figure 14.4). Most nerves will contain a mixture of sensory and motor fibres. So a nerve can carry many different impulses. These impulses will travel in one direction in sensory fibres and in the opposite direction in motor fibres.

Some of the nerve fibres are very long. The nerve fibres to the foot have their cell bodies in the spinal cord and the fibres run inside the nerves, without a break, to the skin of the toes or the muscles of the foot. A single nerve cell may have a fibre 1 m long.

The nerve impulse

The nerve fibres do not carry sensations like pain or cold. These sensations are felt only when a nerve impulse reaches the brain. The impulse itself is a series of electrical pulses that travel down the fibre. Each pulse lasts about 0.001 s and travels at speeds of up to 100 $m\,s^{-1}$. All nerve impulses are similar; there is no difference between nerve impulses from the eyes, ears or hands.

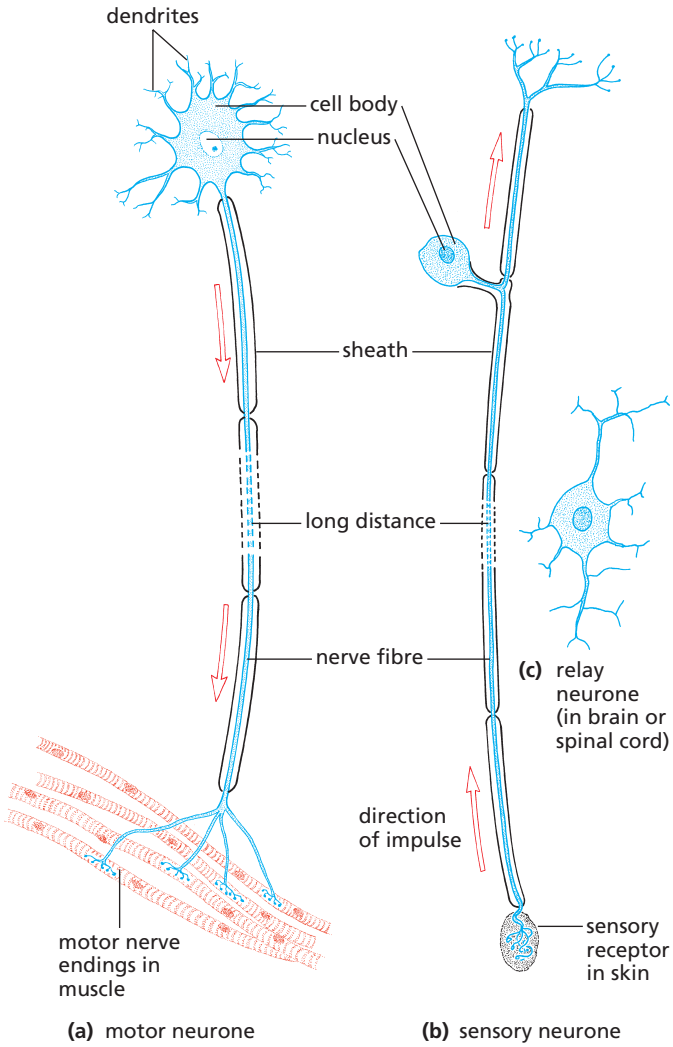


Figure 14.3 Nerve cells (neurones)

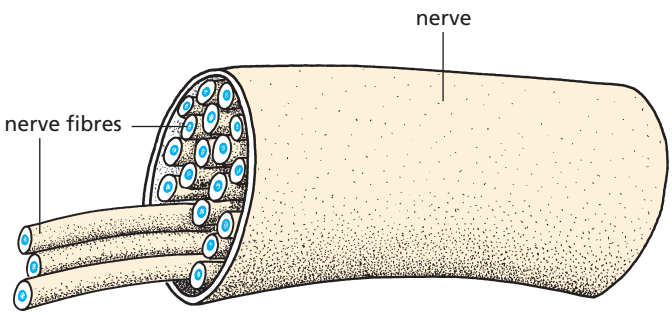


Figure 14.4 Nerve fibres grouped into a nerve

We are able to tell where the sensory impulses have come from and what caused them only because the impulses are sent to different parts of the brain. The nerves from the eye go to the part of the brain concerned with sight. So when impulses are received in this area, the brain recognises that they have come from the eyes and we 'see' something.

The reflex arc

One of the simplest situations where impulses cross synapses to produce action is in the reflex arc. A **reflex action** is an automatic response to a **stimulus**. (A stimulus is a change in the external or internal environment of an organism.) It provides a means of rapidly integrating and co-ordinating a stimulus with the response of an effector (a muscle or a gland) without the need for thought or a decision. When a particle of dust touches the cornea of the eye, you will blink; you cannot prevent yourself from blinking. A particle of food touching the lining of the windpipe will set off a coughing reflex that cannot be suppressed. When a bright light shines in the eye, the pupil contracts (see 'Sense organs' later in this chapter). You cannot stop this reflex and you are not even aware that it is happening.

The nervous pathway for such reflexes is called a **reflex arc**. In Figure 14.5 the nervous pathway for a well-known reflex called the 'knee-jerk' reflex is shown.

One leg is crossed over the other and the muscles are totally relaxed. If the tendon just below the kneecap of the upper leg is tapped sharply, a reflex arc makes the thigh muscle contract and the lower part of the leg swings forward.

The pathway of this reflex arc is traced in Figure 14.6. Hitting the tendon stretches the muscle and stimulates a stretch receptor. The receptor sends off impulses in a sensory fibre. These sensory impulses travel in the nerve to the spinal cord.

In the central region of the spinal cord, the sensory fibre passes the impulse across a synapse to a motor neurone, which conducts the impulse down the fibre, back to the thigh muscle (the effector). The arrival of the impulses at the muscle makes it contract and jerk the lower part of the limb forward. You are aware that this is happening (which means that sensory impulses must be reaching the brain), but there is nothing you can do to stop it.

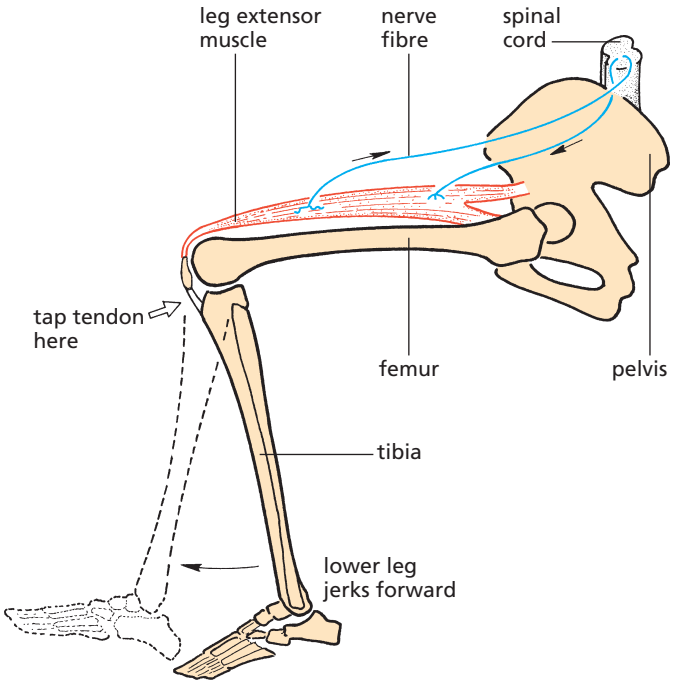


Figure 14.5 The reflex knee jerk

The sequence of events in a simple reflex arc is shown below.

stimulus (tapping the tendon below the kneecap)
↓
receptor (stretch receptor)
↓
sensory neurone
↓
co-ordinator (spinal cord)
↓
motor neurone
↓
effector (leg extensor muscle)
↓
response (leg extensor muscle contracts, making the leg kick forwards)

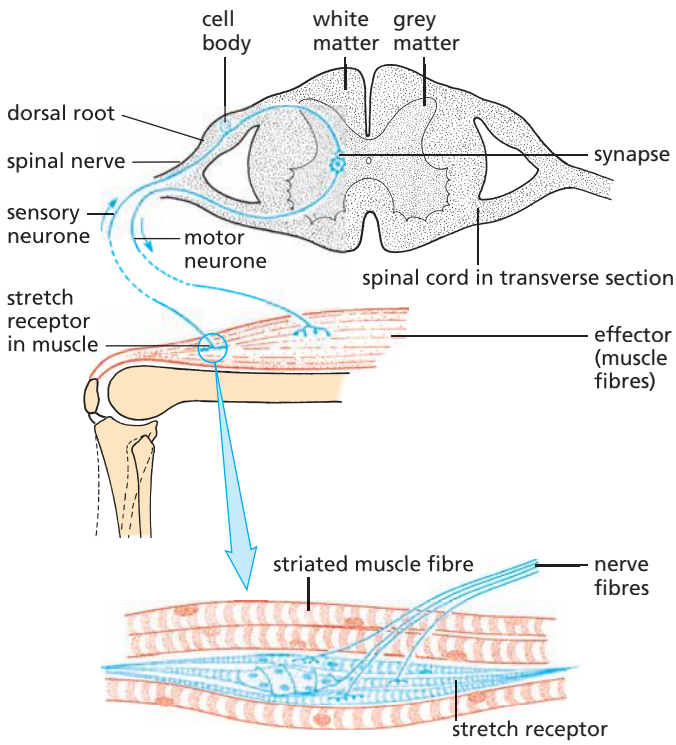


Figure 14.6 The reflex arc. This reflex arc needs only one synapse for making the response. Most reflex actions need many more synapses (i) to adjust other muscles in the body and (ii) to send impulses to the brain.

Extension work

The spinal cord

Like all other parts of the nervous system, the spinal cord consists of thousands of nerve cells. The structure of the spinal cord is shown in Figures 14.6, 14.7 and 14.8.

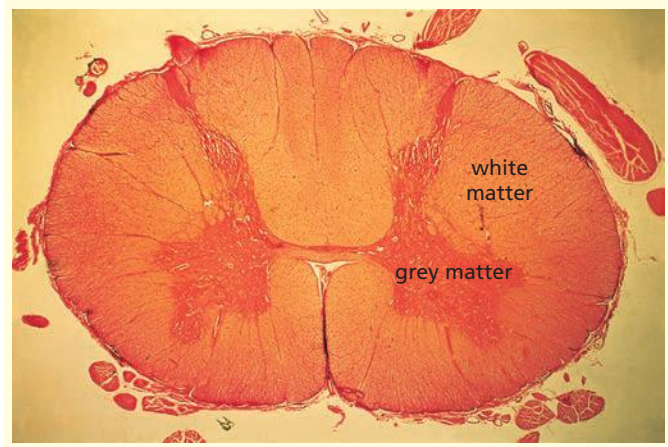


Figure 14.7 Section through spinal cord (×7). The light area is the white matter, consisting largely of nerve fibres running to and from the brain. The darker central area is the grey matter, consisting largely of nerve cell bodies.

All the cell bodies, apart from those in the dorsal root ganglia, are concentrated in the central region called the **grey matter**. The **white matter** consists of nerve fibres. Some of these will be passing from the grey matter to the spinal nerves and others

will be running along the spinal cord connecting the spinal nerve fibres to the brain. The spinal cord is thus concerned with:

- reflex actions involving body structures below the neck
- conducting sensory impulses from the skin and muscles to the brain, and
- carrying motor impulses from the brain to the muscles of the trunk and limbs.

In Figure 14.6 the spinal cord is drawn in transverse section. The spinal nerve divides into two 'roots' at the point where it joins the spinal cord. All the sensory fibres enter through the **dorsal root** and the motor fibres all leave through the **ventral root**, but both kinds of fibre are contained in the same spinal nerve. This is like a group of insulated wires in the same electric cable. The cell bodies of all the sensory fibres are situated in the dorsal root and they make a bulge called a **ganglion** (Figure 14.9).

In even the simplest reflex action, many more nerve fibres, synapses and muscles are involved than are described here. Figure 14.8 illustrates the reflex arc that would result in the hand being removed from a painful stimulus. On the left side of the spinal cord, an incoming sensory fibre makes its first synapse with a relay neurone. This can pass the impulse on to many other motor neurones, although only one is shown in the diagram. On the right side of the spinal cord, some of the incoming sensory fibres are shown making synapses with neurones that send nerve fibres to the brain, thus keeping the brain informed about events in the body. Also, nerve fibres from the brain make synapses with motor neurones in the spinal cord so that 'commands' from the brain can be sent to muscles of the body.

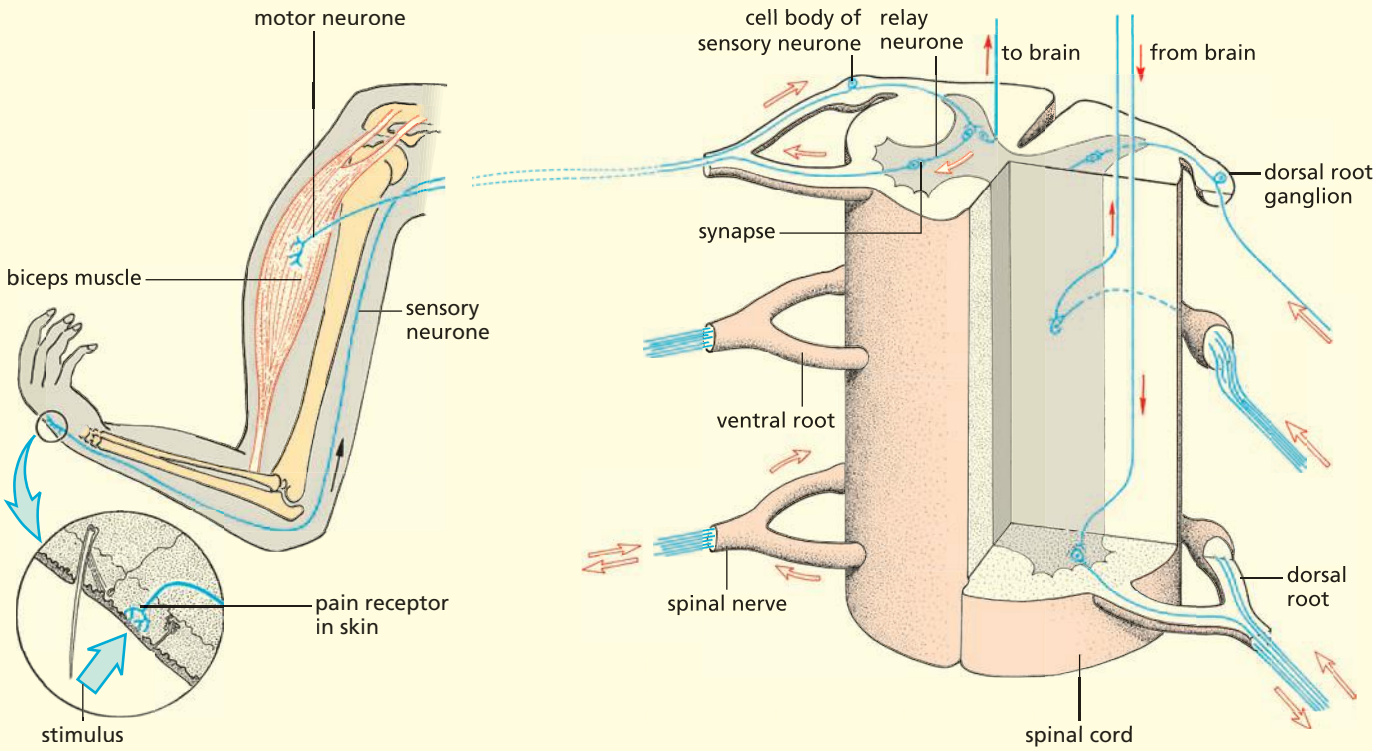


Figure 14.8 Reflex arc (withdrawal reflex)

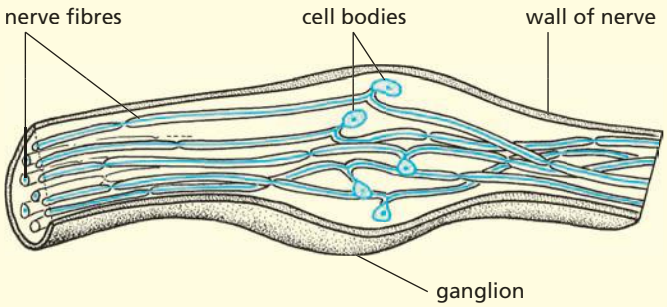


Figure 14.9 Cell bodies forming a ganglion

Reflexes

The reflex just described is a **spinal reflex**. The brain, theoretically, is not needed for it to happen. Responses that take place in the head, such as blinking, coughing and iris contraction, have their reflex arcs in the brain, but may still not be consciously controlled.

Bright light stimulates the light-sensitive cells of the retina. The nerve impulses in the sensory fibres from these receptors travel through the optic nerve

to the brain. In the mid-brain the fibres synapse with relay and motor fibres, which carry impulses back through the optic nerve to the circular muscle of the iris and stimulate it to contract.

Synapses

Key definition
A **synapse** is a junction between two neurones.

Although nerve fibres are insulated, it is necessary for impulses to pass from one neurone to another. An impulse from the fingertips has to pass through at least three neurones before reaching the brain and so produce a conscious sensation. The regions where impulses are able to cross from one neurone to the next are called **synapses**.

Voluntary and involuntary actions

Voluntary actions

A **voluntary action** starts in the brain. It may be the result of external events, such as seeing a book on the floor, but any resulting action, such as picking up the book, is entirely voluntary. Unlike a reflex action it does not happen automatically; you can decide whether or not you carry out the action.

The brain sends motor impulses down the spinal cord in the nerve fibres. These make synapses with motor fibres, which enter spinal nerves and make connections to the sets of muscles needed to produce effective action. Many sets of muscles in the arms, legs and trunk would be brought into play in order to stoop and pick up the book, and impulses passing between the eyes, brain and arm would direct the hand to the right place and 'tell' the fingers when to close on the book.

One of the main functions of the brain is to co-ordinate these actions so that they happen in the right sequence and at the right time and place.

Involuntary actions

The reflex closure of the iris (see 'Sense organs' later in this chapter) protects the retina from bright light; the withdrawal reflex removes the hand from a dangerously hot object; the coughing reflex dislodges a foreign particle from the windpipe. Thus, these reflexes have a protective function and all are **involuntary actions**.

There are many other reflexes going on inside our bodies. We are usually unaware of these, but they maintain our blood pressure, breathing rate, heartbeat, etc. and so maintain the body processes.

How a synapse transmits an electrical impulse

At a synapse, a branch at the end of one fibre is in close contact with the cell body or dendrite of another neurone (Figure 14.10).

When an impulse arrives at the synapse, vesicles in the cytoplasm release a tiny amount of the neurotransmitter substance. It rapidly diffuses across the gap (also known as the **synaptic cleft**) and binds with neurotransmitter receptor molecules in the membrane of the neurone on the other side of the synapse. This then sets off an impulse in the neurone. Sometimes several impulses have to arrive at the synapse before enough transmitter substance is released to cause an impulse to be fired off in the next neurone.

Synapses control the direction of impulses because neurotransmitter substances are only synthesised on one side of the synapse, while receptor molecules are only present on the other side. They slow down the speed of nerve impulses slightly because of the time taken for the chemical to diffuse across the **synaptic gap**.

Many drugs produce their effects by interacting with receptor molecules at synapses. **Heroin**, for example, stimulates receptor molecules in synapses in the brain, triggering the release of dopamine (a neurotransmitter), which gives a short-lived 'high'.

Spider toxin, and also the toxin released by tetanus (an infection caused by *Clostridium* bacteria), breaks down vesicles, releasing massive amounts of transmitter substance and disrupting normal synaptic function. Symptoms caused by the tetanus toxin include muscle spasms, lock-jaw and heart failure.

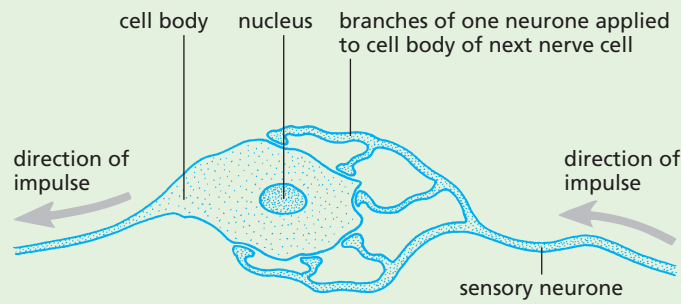


Figure 14.10 Synapses between nerve neurones

Sense organs

Key definition
Sense organs are groups of sensory cells responding to specific stimuli, such as light, sound, touch, temperature and chemicals.

Our senses make us aware of changes in our surroundings and in our own bodies. We have sense cells that respond to stimuli (singular = stimulus). A **stimulus** is a change in light, temperature, pressure, etc., which produces a reaction in a living organism. Structures that detect stimuli are called **receptors**. Some of these receptors are scattered through the skin: this organ has a number of different types of receptor, as shown in Figure 14.21. Other receptors are concentrated into special **sense organs** such as the eye and the ear. Table 14.1 gives examples of these and their stimuli.

Table 14.1 Sense organs and their stimuli

Sense organ	Stimulus
ear	sound, body movement (balance)
eye	light
nose	chemicals (smells)
tongue	chemicals (taste)
skin	temperature, pressure, touch, pain

The special property of sensory cells and sense organs is that they are able to convert one form of energy to another. The eyes can convert light energy into the electrical energy of a nerve impulse. The ears convert the energy in sound vibrations into nerve impulses. The forms of energy that make up the stimuli may be very different, e.g. mechanical, chemical, light, but they are all transduced into pulses of electrical energy in the nerves.

When a receptor responds to a stimulus, it sends a nerve impulse to the brain, which makes us aware of the sensation.

The eye

Note: details of conjunctiva, humours, choroid and tear glands are **not** a syllabus requirement, but are included here to put parts seen in a diagram of the eye in context.

The structure of the eye is shown in Figures 14.11 and 14.12. The **sclera** is the tough, white outer coating. The front part of the sclera is clear and allows light to enter the eye. This part is called the **cornea**. The **conjunctiva** is a thin epithelium, which lines the inside of the eyelids and the front of the sclera and is continuous with the epithelium of the cornea.

The eye contains a clear liquid whose outward pressure on the sclera keeps the spherical shape of the eyeball. The liquid behind the lens is jelly-like and called **vitreous humour**. The **aqueous humour** in front of the lens is watery.

The **lens** is a transparent structure, held in place by a ring of fibres called the **suspensory ligament**. Unlike the lens of a camera or a telescope, the eye lens is flexible and can change its shape. In front of the lens is a disc of tissue called the **iris**. It is the iris we refer to when we describe the colour of the eye as brown or blue. The iris controls how much light enters the **pupil**, which is a hole in the centre of the iris. The pupil lets in light to the rest of the eye.

The pupil looks black because all the light entering the eye is absorbed by the black pigment in the **choroid**. The choroid layer, which contains many blood vessels, lies between the retina and the sclera. In the front of the eyeball, it forms the iris and the **ciliary body**. The ciliary body produces aqueous humour.

The internal lining at the back of the eye is the **retina** and it consists of many thousands of cells that respond to light. When light falls on these cells, they send off nervous impulses, which travel in nerve fibres, through the **optic nerve**, to the brain and so give rise to the sensation of sight. The part of the retina lying directly in front of the optic nerve contains no light-sensitive cells. This region is called the **blind spot**.

Tear glands under the top eyelid produce tear fluid. This is a dilute solution of sodium chloride and sodium hydrogencarbonate. The fluid is spread over the eye surface by the blinking of the eyelids, keeping the surface moist and washing away any dust particles or foreign bodies. Tear fluid also contains an enzyme, **lysozyme**, which attacks bacteria.

Table 14.2 gives the functions of the parts of the eye required for the Core section of the syllabus.

Table 14.2 Functions of parts of the eye

Part	Function
cornea	a transparent, curved layer at the front of the eye that refracts the light entering and helps to focus it
iris	a coloured ring of circular and radial muscle that controls the size of the pupil
lens	a transparent, convex, flexible, jelly-like structure that refracts light to focus it onto the retina
retina	a light-sensitive layer made up of rods, which detect light of low intensity, and cones, which detect different colours
optic nerve	transmits electrical impulses from the retina to the brain

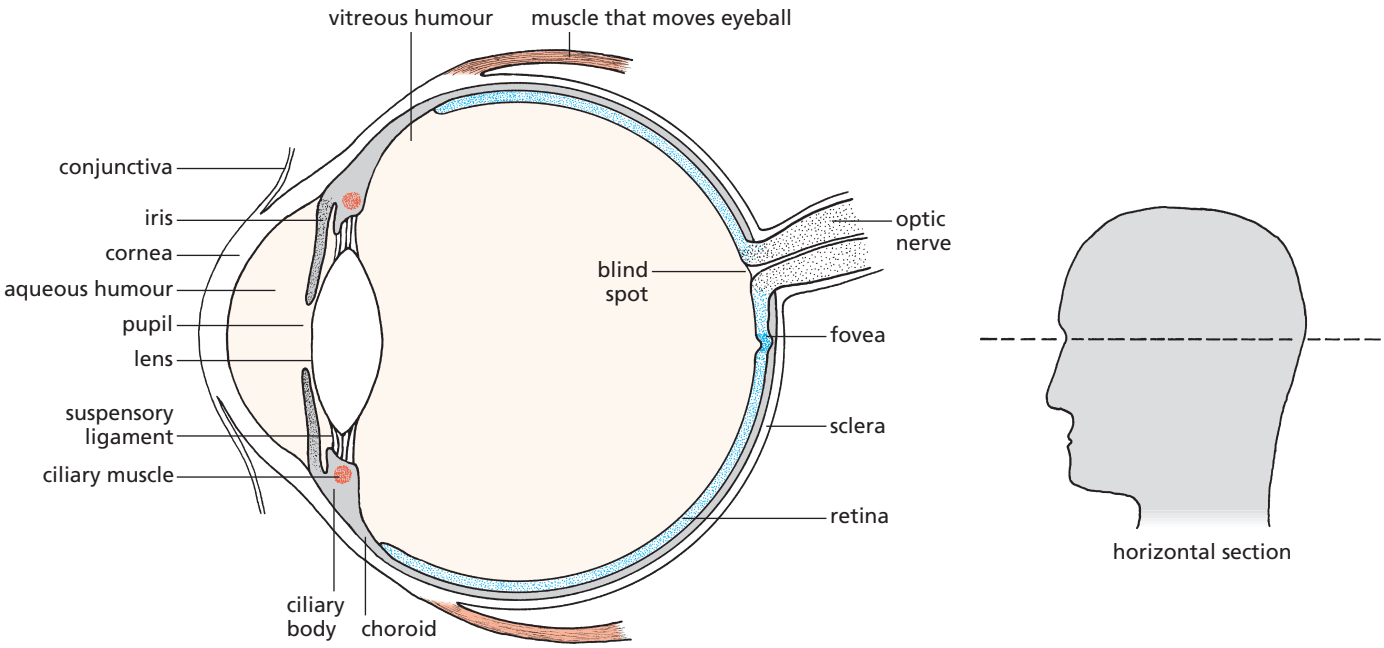


Figure 14.11 Horizontal section through left eye

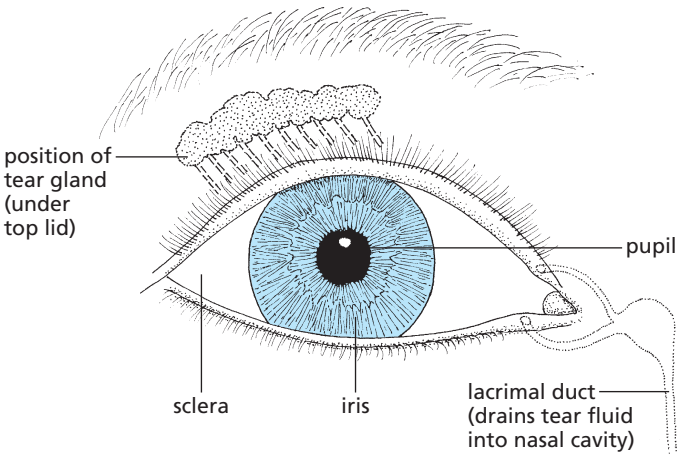


Figure 14.12 Appearance of right eye from the front

Vision

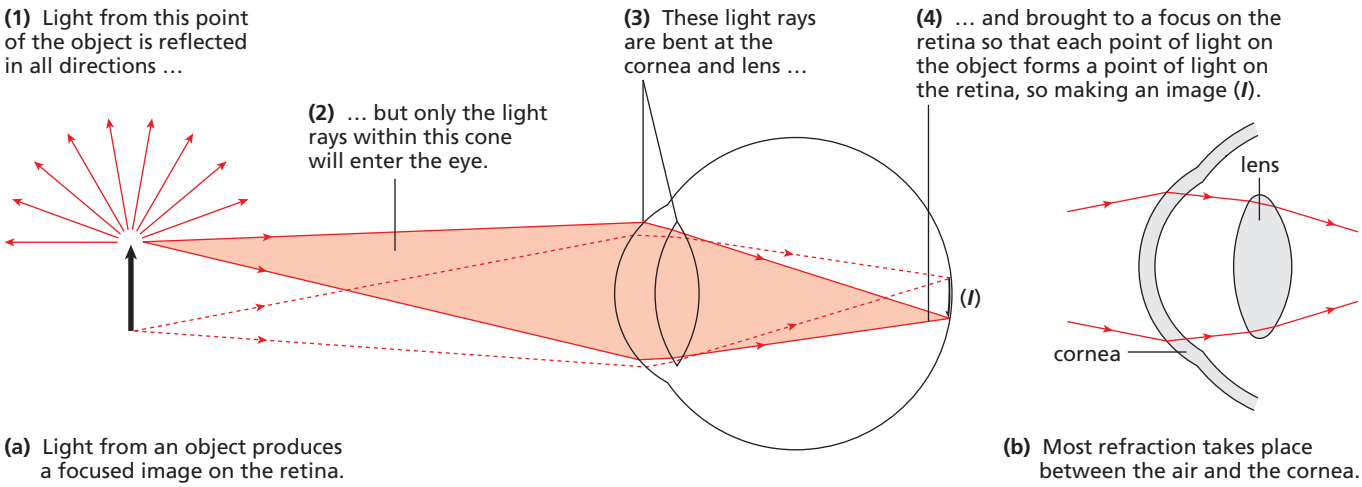
Light from an object produces a focused **image** on the retina (like a 'picture' on a cinema screen) (Figures 14.13 and 14.17). The curved surfaces of the cornea and lens both refract ('bend') the light rays that enter the eye, in such a way that each 'point of light' from the object forms a 'point of light' on the retina. These points of light will form an image, upside-down and smaller than the object.

The cornea and the aqueous and vitreous humours are mainly responsible for the refraction of light. The lens makes the final adjustments to the focus (Figure 14.13(b)).

The pattern of sensory cells stimulated by the image will produce a pattern of nerve impulses sent to the brain. The brain interprets this pattern, using past experience and learning, and forms an impression of the size, distance and upright nature of the object.

The pupil reflex

The change in size of the pupil is caused by exposure of the eye to different light intensities. It is an automatic reaction: you cannot control it. When bright light falls on the eye, the iris responds by making the diameter of the pupil smaller. This restricts the amount of light reaching the retina, which contains the light-sensitive cells. If dim light falls on the eye, the iris responds by making the diameter of the pupil larger, so that as much light as is available can reach the retina to stimulate the light-sensitive cells. Figure 14.12 shows an eye exposed to bright light: the pupil is small. It would become much larger if the light intensity was reduced.



(a) Light from an object produces a focused image on the retina.

(b) Most refraction takes place between the air and the cornea.

Figure 14.13 Image formation on the retina

Control of light intensity

This section gives more detail about the roles of the iris and pupil in controlling light intensity falling on the retina, needed if you are following the extended syllabus.

The amount of light entering the eye is controlled by altering the size of the pupil (Figure 14.14). If the light intensity is high, it causes a contraction in a ring of muscle fibres (**circular muscle**) in the iris. This reduces the size of the pupil and cuts down the intensity of light entering the eye. High-intensity light can damage the retina, so this reaction has a protective function.

In low light intensities, the circular muscle of the iris relaxes and **radial muscle** fibres (which are arranged like the spokes of a bicycle wheel) contract. This makes the pupil enlarge and allows more light to enter. The circular and radial muscles act **antagonistically**. This means that they oppose each other in their actions – when the circular muscles contract they constrict the pupil and when the radial muscles contract the pupil dilates.

The change in size of the pupil is caused by an automatic reflex action; you cannot control it consciously.

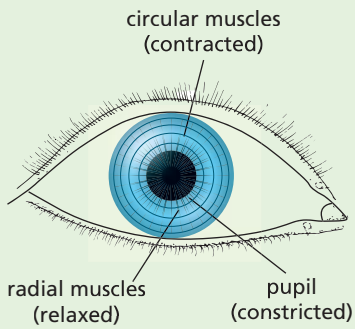


Figure 14.14 The iris reflex

Accommodation (focusing)

The eye can produce a focused image of either a near object or a distant object. To do this the lens changes its shape, becoming thinner for distant objects and fatter for near objects. This change in shape is caused by contracting or relaxing the **ciliary muscle**, which forms a circular band of muscle in the **ciliary body** (Figure 14.15). When the ciliary muscle is relaxed, the outward pressure of the humours on the sclera pulls on the suspensory ligament and stretches the lens to its thin shape. The eye is now accommodated (i.e. focused) for distant objects (Figures 14.15(a) and 14.16(a)). To focus a near object, the ciliary muscle contracts to a smaller circle and this takes the tension out of the suspensory ligament (Figures 14.15(b) and 14.16(b)). The lens is elastic and flexible and so is able to change to its fatter shape. This shape is better at bending the light rays from a close object.

Retina

The millions of light-sensitive cells in the retina are of two kinds, the **rods** and the **cones** (according to shape). The cones enable us to distinguish colours, but the rods are more sensitive to low intensities of light and therefore play an important part in night vision when the light intensity is not sufficient to stimulate the cone cells. Images formed at night appear as shades of grey, with no bright colours detected. There are thought to be three types of cone cell. One type responds best to red light, one to green and one to blue. If all three types are equally stimulated we get the sensation of white. The cone cells are concentrated in a central part of the retina, called the **fovea** (Figure 14.11); when you study an object closely you are making its image fall on the fovea.

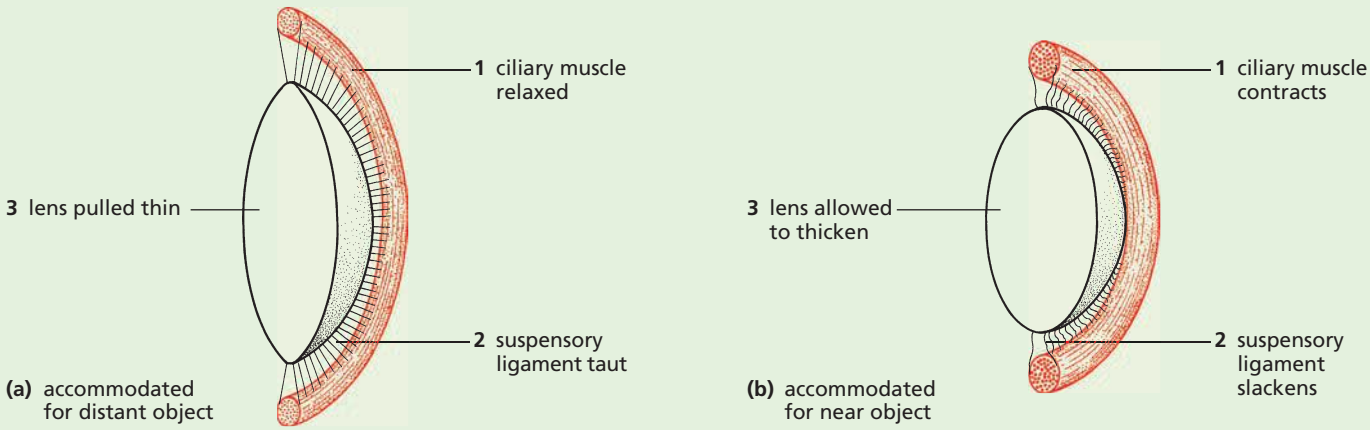


Figure 14.15 How accommodation is brought about

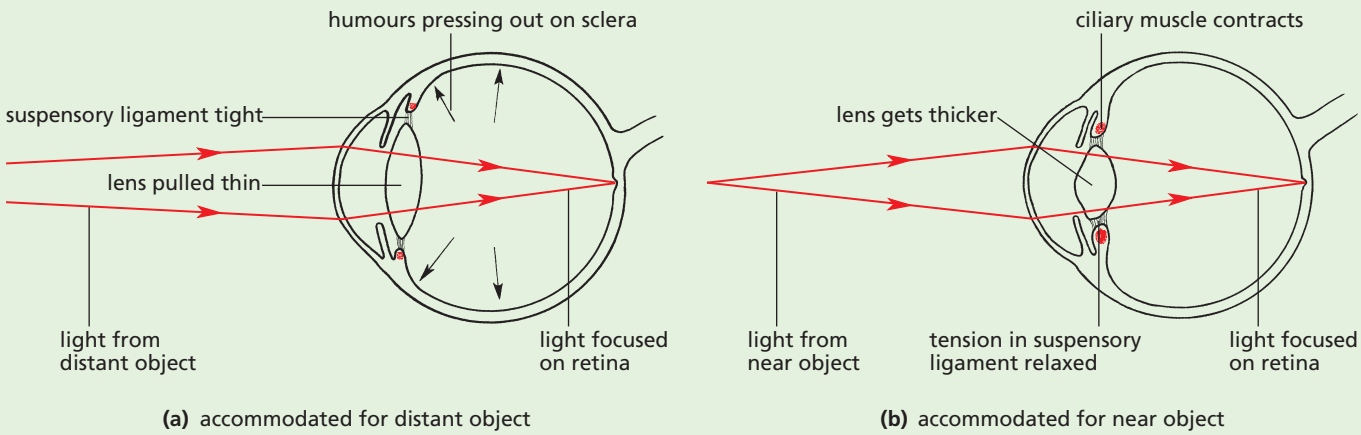


Figure 14.16 Accommodation

Fovea

It is in the fovea that the image on the retina is analysed in detail. Only objects within a 2° cone from the eye form an image on the fovea. This means that only about two letters in any word on this page can be seen in detail. It is the constant scanning movements of the eye that enable you to build up an accurate 'picture' of a scene. The centre of the fovea contains only cones: it is here that colour discrimination occurs.

Blind spot

At the point where the optic nerve leaves the retina, there are no sensory cells and so no information reaches the brain about that part of the image which falls on this blind spot (Figure 14.18).

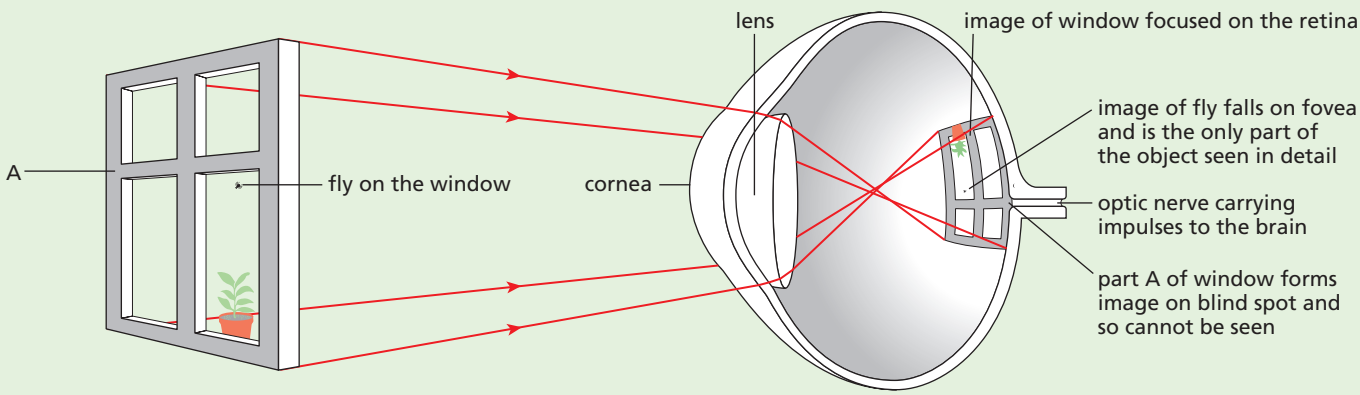


Figure 14.17 Image formation in the eye

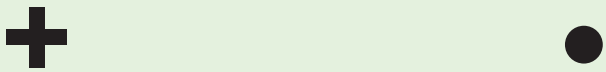


Figure 14.18 The blind spot. Hold the book about 50 cm away. Close your left eye and concentrate on the cross with your right eye. Slowly bring the book closer to your face. When the image of the dot falls on the blind spot it will seem to disappear.

Hormones in humans

Key definition

A **hormone** is a chemical substance, produced by a gland and carried by the blood, which alters the activity of one or more specific target organs.

Co-ordination by the nervous system is usually rapid and precise. Nerve impulses, travelling at up to 100 metres per second, are delivered to specific parts of the body and produce an almost immediate response. A different kind of co-ordination is brought about by the **endocrine system**. This system depends on chemicals, called **hormones**, which are released from special glands, called **endocrine glands**, into the bloodstream. The hormones circulate around the body in the blood and eventually reach certain organs, called **target organs**. Hormones speed up, slow down or alter the activity of those organs. After being secreted, hormones do not remain permanently in the blood but are changed by the liver into inactive compounds and excreted by the kidneys. Insulin, for example, may stay in the bloodstream for just 4–8 hours before being broken down. Table 14.3 compares control by the endocrine and nervous systems.

Table 14.3 Endocrine and nervous control compared

Endocrine	Nervous
transmission of chemicals	transmission of electrical impulses
transmission via blood	transmission in nerves
slow transmission	rapid transmission
hormones dispersed throughout body	impulse sent directly to target organ
long-term effects	short-lived effects

Unlike the digestive glands, endocrine glands do not deliver their secretions through ducts (tubes). For this reason, the endocrine glands are sometimes called 'ductless glands'. The hormones are picked up directly from the glands by the blood circulation.

Responses of the body to hormones are much slower than responses to nerve impulses. They depend, in the first instance, on the speed of the circulatory system and then on the time it takes for the cells to change their chemical activities. Many hormones affect long-term changes such as growth rate, puberty and pregnancy. Nerve impulses often cause a response in a very limited area of the body, such as an eye-blink or a finger movement. Hormones often affect many organ systems at once.

Serious deficiencies or excesses of hormone production give rise to illnesses. Small differences in hormone activity between individuals probably contribute to differences of personality and temperament.

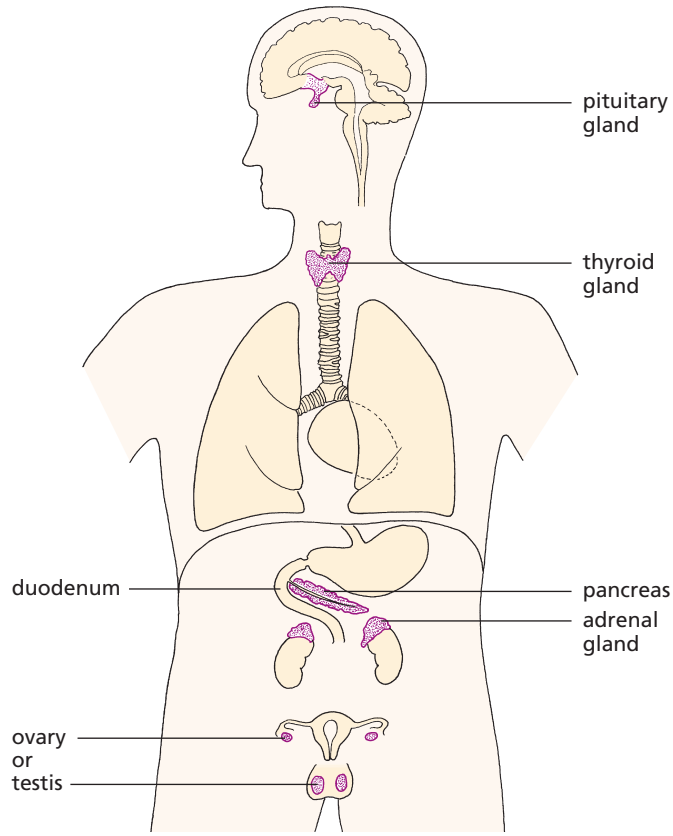


Figure 14.19 Position of endocrine glands in the body

Note: knowledge of the pituitary and thyroid glands is **not** a syllabus requirement

The position of the endocrine glands in the body is shown in Figure 14.19. Notice that the pancreas and the reproductive organs have a dual function.

Extension work

Thyroid gland

The thyroid gland is situated in the front part of the neck and lies in front of the windpipe. It produces a hormone called **thyroxine**. This hormone has a stimulatory effect on the metabolic rate of nearly all the body cells, such as the speed or rate of

cell respiration (Chapter 12) and other chemical reactions. It controls our level of activity, promotes skeletal growth and is essential for the normal development of the brain.

Pituitary gland

This gland is attached to the base of the brain. It produces many hormones. For example, the pituitary releases into the blood **follicle-stimulating hormone** (FSH) which, when it reaches the ovaries, makes one of the follicles start to mature and to produce oestrogen. **Luteinising hormone** (LH), also known as lutropin, is also produced from the pituitary and, together with FSH, induces ovulation (see 'Sex hormones in humans' in Chapter 16).

Adrenal glands

These glands are attached to the back of the abdominal cavity, one above each kidney (see also Figure 13.1). One part of the adrenal gland is a zone called the **adrenal medulla**. The medulla receives nerves from the brain and produces the hormone **adrenaline**.

Adrenaline has obvious effects on the body:

- In response to a stressful situation, nerve impulses are sent from the brain to the adrenal medulla, which releases adrenaline into the blood.
- Its presence causes breathing to become faster and deeper. This may be particularly apparent as we pant for breath.
- The heart beats faster, resulting in an increase in pulse rate. This increase in heart rate can be quite alarming, making us feel as if our heart is going to burst out of our chest.
- The pupils of our eyes dilate, making them look much blacker.

These effects all make us more able to react quickly and vigorously in dangerous situations (known as 'fight or flight situations') that might require us to run away or put up a struggle. However, in many stressful situations, such as taking examinations or giving a public performance, vigorous activity is not called for. So the extra adrenaline in our bodies just makes us feel tense and anxious.

The pancreas

The pancreas is a digestive gland that secretes enzymes into the duodenum through the pancreatic duct (Chapter 7). It is also an endocrine (ductless) gland. Most of the pancreas cells produce digestive enzymes but some of them produce hormones. The hormone-producing cells are arranged in small isolated groups called islets (Figure 14.20) and secrete their hormones directly into the bloodstream. One of the hormones is called **insulin**.

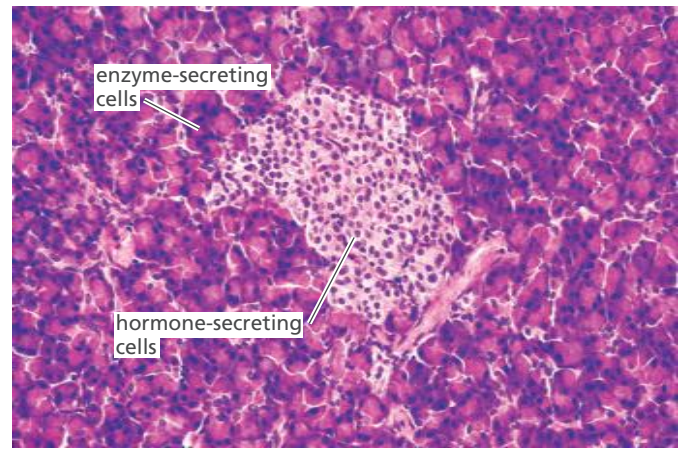


Figure 14.20 Section of pancreas tissue showing an islet (×250)

Insulin controls the levels of glucose in the blood by instructing the liver to remove the sugars and store them. This happens when levels get too high, such as after a meal rich in carbohydrate. (See page 196 for further details of the action of insulin.)

Reproductive organs

The ovaries and testes produce hormones as well as gametes (sperms and ova) and their effects are described in Chapter 16.

One of the hormones from the ovary, **oestrogen**, prepares the uterus for the implantation of the embryo, by making its lining thicker and increasing its blood supply.

The hormones **testosterone** (from the testes) and oestrogen (from the ovaries) play a part in the development of the secondary sexual characteristics.

The role of adrenaline

As adrenaline circulates around the body it affects a number of organs, as shown in Table 14.4.

You will recognise the sensations described in column four of Table 14.4 as characteristic of fear and anxiety.

Table 14.4 Responses to adrenaline

Target organ	Effects of adrenaline	Biological advantage	Effect or sensation
heart	beats faster	sends more glucose and oxygen to the muscles	thumping heart
breathing centre of the brain	faster and deeper breathing	increased oxygenation of the blood; rapid removal of carbon dioxide	panting
arterioles of the skin	constricts them (see 'Homeostasis')	less blood going to the skin means more is available to the muscles	person goes paler
arterioles of the digestive system	constricts them	less blood for the digestive system allows more to reach the muscles	dry mouth
muscles of alimentary canal	relax	peristalsis and digestion slow down; more energy available for action	'hollow' feeling in stomach
muscles of body	tenses them	ready for immediate action	tense feeling; shivering
liver	conversion of glycogen to glucose	more glucose available in blood for energy production, to allow metabolic activity to increase	no sensation
fat deposits	conversion of fats to fatty acids	fatty acids available in blood for muscle contraction	

Adrenaline is quickly converted by the liver to a less active compound, which is excreted by the kidneys. All hormones are similarly altered and excreted, some within minutes, others within days.

Thus their effects are not long-lasting. The long-term hormones, such as thyroxine, are secreted continuously to maintain a steady level.

Homeostasis

Key definition
Homeostasis is the maintenance of a constant internal environment.

Homeostasis literally means 'staying similar'. It refers to the fact that the composition of the tissue fluid (see 'Blood' in Chapter 9) in the body is kept within narrow limits. The concentration, acidity and temperature of this fluid are being adjusted all the time to prevent any big changes.

The skin and temperature control

Skin structure

Figure 14.21 shows a section through skin. In the **basal layer** some of the cells are continually dividing and pushing the older cells nearer the surface. Here they die and are shed at the same rate as they are replaced. The basal layer and the cells above it constitute the **epidermis**. The basal layer also contributes to the hair follicles. The dividing cells give rise to the hair.

There are specialised pigment cells in the basal layer and epidermis. These produce a black pigment, **melanin**, which gives the skin its colour. The more melanin, the darker is the skin.

The thickness of the epidermis and the abundance of hairs vary in different parts of the body (Figure 14.22).

The **dermis** contains connective tissue with hair follicles, sebaceous glands, sweat glands, blood vessels and nerve endings. There is usually a layer of adipose tissue (a fat deposit) beneath the dermis.

Skin function

Protection
The outermost layer of dead cells of the epidermis helps to reduce water loss and provides a barrier against bacteria. The pigment cells protect the skin from damage by the ultraviolet rays in sunlight. In white-skinned people, more melanin is produced in response to exposure to sunlight, giving rise to a tan.

Sensitivity
Scattered throughout the skin are large numbers of tiny sense receptors, which give rise to sensations of touch, pressure, heat, cold and pain. These make us aware of changes in our surroundings and enable us to take action to avoid damage, to recognise objects by touch and to manipulate objects with our hands.

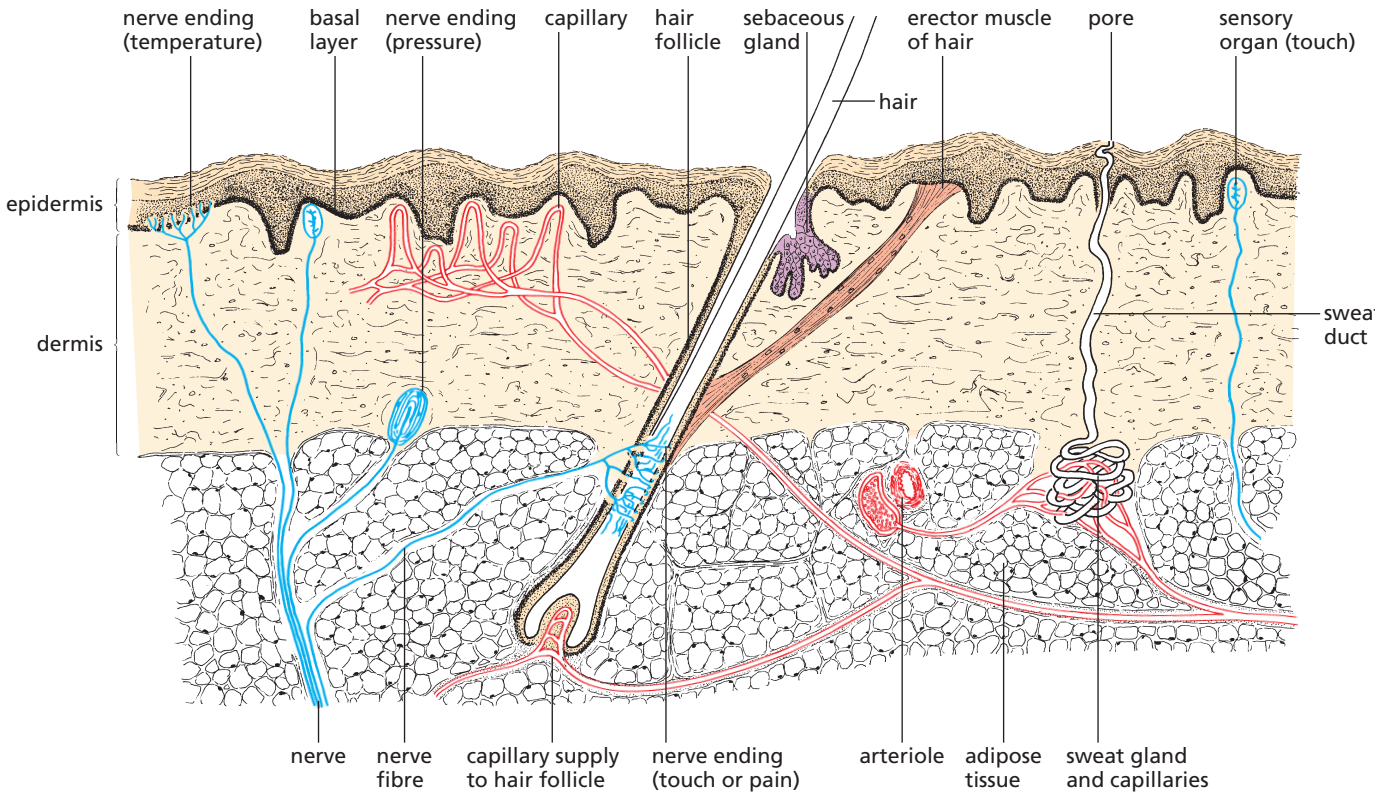


Figure 14.21 Generalised section through the skin

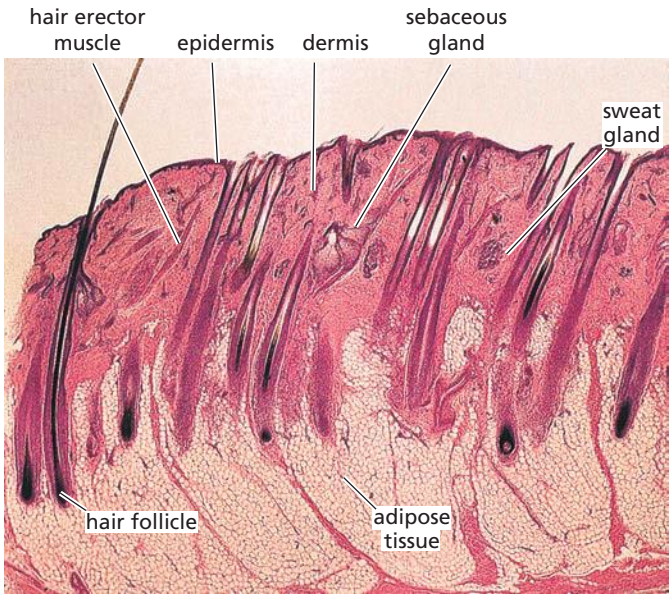


Figure 14.22 Section through hairy skin (×20)

Temperature regulation

The skin helps to keep the body temperature more or less constant. This is done by adjusting the flow of blood near the skin surface and by sweating. These processes are described more fully below.

Temperature control

Normal human body temperature varies between 35.8 °C and 37.7 °C. Temperatures below 34 °C or above 40 °C, if maintained for long, are considered dangerous. Different body regions, e.g. the hands, feet, head or internal organs, will be at different temperatures, but the **core** temperature, as measured with a thermometer under the tongue, will vary by only 1 or 2 degrees.

Heat is lost from the body surface by conduction, convection, radiation and evaporation. The amount of heat lost is reduced to an extent due to the insulating properties of adipose (fatty) tissue in the dermis. Some mammals living in extreme conditions, such as whales and seals, make much greater use of this: they have thick layers of blubber to reduce heat loss more effectively. Just how much insulation the blubber gives depends on the amount of water in the tissue: a smaller proportion of water and more fat provide better insulating properties.

Heat is gained, internally, from the process of respiration (Chapter 12) in the tissues and, externally, from the surroundings or from the Sun.

The two processes of heat gain and heat loss are normally in balance but any imbalance is corrected by a number of methods, including those described below.

Overheating

- More blood flows near the surface of the skin, allowing more heat to be exchanged with the surroundings.
- **Sweating** – the sweat glands secrete sweat on to the skin surface. When this layer of liquid evaporates, it takes heat (latent heat) from the body and cools it down (Figure 14.23).

Overcooling

- Less blood flows near the surface of the skin, reducing the amount of heat lost to the surroundings.
- Sweat production stops – thus the heat lost by evaporation is reduced.
- **Shivering** – uncontrollable bursts of rapid muscular contraction in the limbs release heat as a result of respiration in the muscles.

In these ways, the body temperature remains at about 37 °C. We also control our temperature by adding or removing clothing or deliberately taking exercise.

Whether we feel hot or cold depends on the sensory nerve endings in the skin, which respond to heat loss or gain. You cannot consciously detect changes in your core temperature. The brain plays a direct role in detecting any changes from normal by monitoring the temperature of the blood. A region called the **hypothalamus** contains a thermoregulatory centre in which temperature receptors detect temperature changes in the blood and co-ordinate a response to them. Temperature receptors are also present in the skin. They send information to the brain about temperature changes.

Figure 14.23 Sweating. During vigorous activity the sweat evaporates from the skin and helps to cool the body. When the activity stops, continued evaporation of sweat may overcool the body unless it is towelled off.

Homeostasis

It is vital that there are homeostatic mechanisms in the body to control internal conditions within set limits.

In Chapter 5 it was explained that, in living cells, all the chemical reactions are controlled by enzymes. The enzymes are very sensitive to the conditions in which they work. A slight fall in temperature or a rise in acidity may slow down or stop an enzyme from working and thus prevent an important reaction from taking place in the cell.

The cell membrane controls the substances that enter and leave the cell, but it is the tissue fluid that supplies or removes these substances, and it is therefore important to keep the composition of the tissue fluid as steady as possible. If the tissue fluid were to become too concentrated, it would withdraw water from the cells by osmosis (Chapter 3) and the body would be dehydrated. If the tissue fluid were to become too dilute, the cells would take up too much water from it by osmosis and the tissues would become waterlogged and swollen.

Many systems in the body contribute to homeostasis (Figure 14.24). The obvious example is the kidneys, which remove substances that might poison the enzymes. The kidneys also control the level of salts, water and acids in the blood. The composition of the blood affects the tissue fluid which, in turn, affects the cells.

Another example of a homeostatic organ is the liver, which regulates the level of glucose in the blood. The liver stores any excess glucose as glycogen, or turns glycogen back into glucose if the concentration in the blood gets too low. The brain cells are very sensitive to the glucose concentration in the blood and if the level drops too far, they stop working properly, and the person becomes unconscious and will die unless glucose is injected into the blood system. This shows how important homeostasis is to the body.

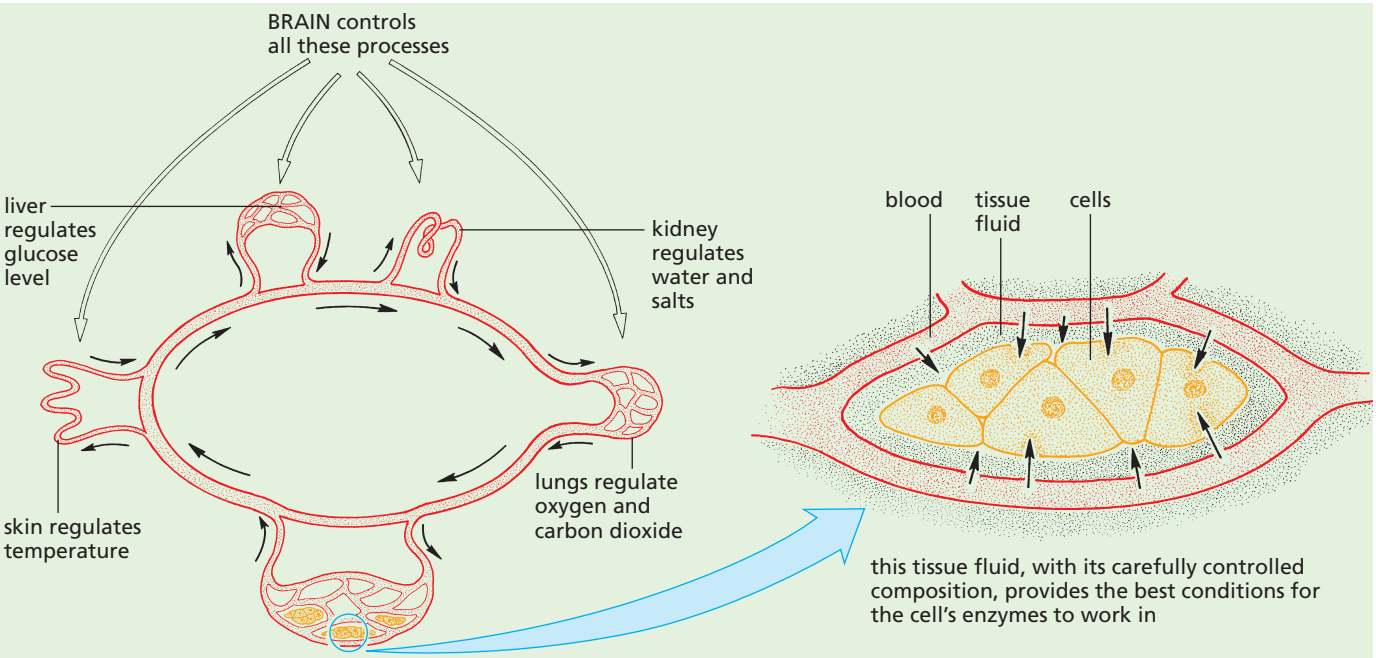


Figure 14.24 The homeostatic mechanisms of the body

The lungs (Chapter 11) play a part in homeostasis by keeping the concentrations of oxygen and carbon dioxide in the blood at the best level for the cells' chemical reactions, especially respiration.

The skin regulates the temperature of the blood. If the cells were to get too cold, the chemical reactions would become too slow to maintain life. If they became too hot, the enzymes would be destroyed.

The brain has overall control of the homeostatic processes in the body. It checks the composition of the blood flowing through it and if it is too warm, too cold, too concentrated or has too little glucose, nerve impulses or hormones are sent to the organs concerned, causing them to make the necessary adjustments.

Homeostasis and negative feedback

Temperature regulation is an example of homeostasis. Maintenance of a constant body temperature ensures that vital chemical reactions continue at a predictable rate and do not speed up or slow down when the surrounding temperature changes. The constant-temperature or **homoiothermic** ('warm-blooded') animals, the birds and mammals, therefore have an advantage over the variable-temperature or **poikilothermic** ('cold-blooded') animals. Poikilotherms such as reptiles and insects can regulate their body temperature to some extent by, for example, basking in the sun or seeking shade. Nevertheless, if their body temperature falls, their vital chemistry slows down and their reactions become more sluggish. They are then more vulnerable to predators.

The 'price' that homoiotherms have to pay is the intake of enough food to maintain their body temperature, usually above that of their surroundings.

In the hypothalamus of a homoiotherm's brain there is a thermoregulatory centre. This centre monitors the temperature of the blood passing through it and also receives sensory nerve impulses from temperature receptors in the skin. A rise in body temperature is detected by the thermoregulatory centre and it sends nerve impulses to the skin, which result in vasodilation and sweating. Similarly, a fall in body temperature will be detected and will promote impulses that produce vasoconstriction and shivering.

This system of control is called **negative feedback**. The outgoing impulses counteract the effects that produced the incoming impulses. For example, a rise in temperature triggers responses that counteract the rise.

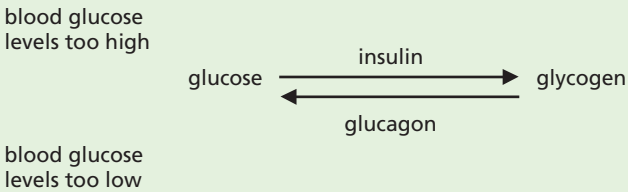
Regulation of blood sugar

If the level of sugar in the blood falls, the islets release a hormone called **glucagon** into the bloodstream. Glucagon acts on the cells in the liver and causes them to convert some of their stored glycogen into glucose and so restore the blood sugar level.

Insulin has the opposite effect to glucagon. If the concentration of blood sugar increases (e.g. after a meal rich in carbohydrate), insulin is released from the islet cells. When the insulin reaches the liver it stimulates the liver cells to take up glucose from the blood and store it as glycogen.

Insulin has many other effects; it increases the uptake of glucose in all cells for use in respiration; it promotes the conversion of carbohydrates to fats and slows down the conversion of protein to carbohydrate.

All these changes have the effect of regulating the level of glucose in the blood to within narrow limits – a very important example of homeostasis.



The concentration of glucose in the blood of a person who has not eaten for 8 hours is usually between 90 and 100 mg 100 cm^{-3} blood. After a meal containing carbohydrate, the blood sugar level may rise to 140 mg 100 cm^{-3} but 2 hours later, the level returns to about 95 mg as the liver has converted the excess glucose to glycogen.

About 100 g glycogen is stored in the liver of a healthy man. If the concentration of glucose in the blood falls below about 80 mg 100 cm^{-3} blood, some of the glycogen stored in the liver is converted by enzyme action into glucose, which enters the circulation. If the blood sugar level rises above 160 mg 100 cm^{-3}, glucose is excreted by the kidneys.

A blood glucose level below 40 mg 100 cm^{-3} affects the brain cells adversely, leading to convulsions and coma. By helping to keep the glucose concentration between 80 and 150 mg, the liver prevents these undesirable effects and so contributes to the homeostasis of the body.

If anything goes wrong with the production or function of insulin, the person will show the symptoms of **diabetes**.

Type 1 diabetes

There are two types of diabetes and type 1 is the less common form, the cause of which has been outlined in Chapter 10. It results from a failure of the islet cells to produce sufficient insulin. The outcome is that the patient's blood is deficient in insulin and he or she needs regular injections of the hormone in order to control blood sugar level and so lead a normal life. This form of the disease is, therefore, sometimes called 'insulin-dependent' diabetes. The patient is unable to regulate the level of glucose in the blood. It may rise to such a high level that it is excreted in the urine, or fall so low that the brain cells cannot work properly and the person goes into a coma.

The symptoms of type 1 diabetes include feeling tired, feeling very thirsty, frequent urination and weight loss. Weight loss is experienced because the body starts to break down muscle and fat.

Diabetics need a carefully regulated diet to keep the blood sugar within reasonable limits. They should have regular blood tests to monitor their blood sugar levels and take regular exercise.

Temperature control

In addition to the methods already described, the skin has another very important mechanism for maintaining a constant body temperature. This involves arterioles in the dermis of the skin, which can widen or narrow to allow more or less blood to flow near the skin surface through the blood capillaries. Further details of this process, involving the use of shunt vessels, are given in Chapter 9.

Vasodilation – the widening of the arterioles in the dermis allows more warm blood to flow through blood capillaries near the skin surface and so lose more heat (Figure 14.25(a)).

Vasoconstriction – narrowing (constriction) of the arterioles in the skin reduces the amount of warm blood flowing through blood capillaries near the surface (Figure 14.25(b)).

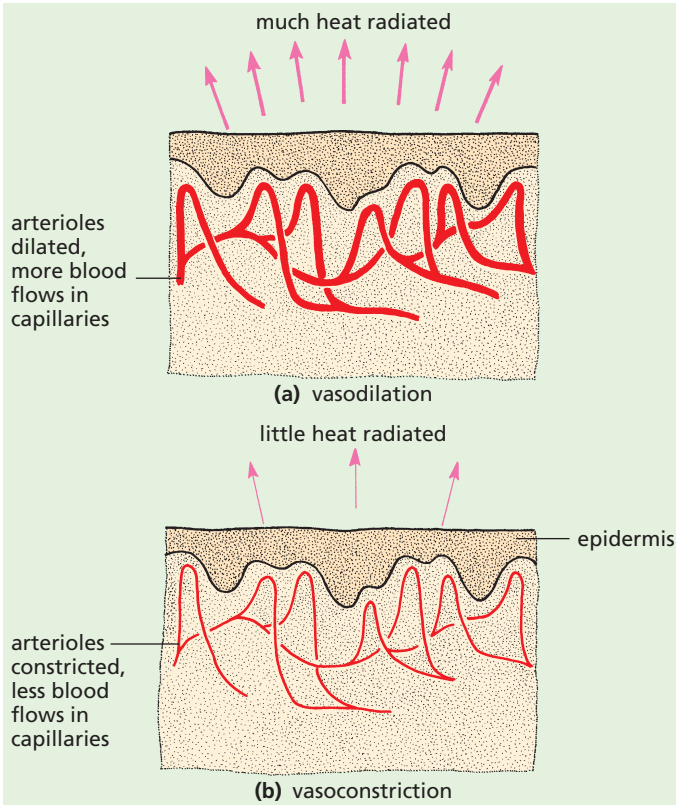


Figure 14.25 Vasodilation and vasoconstriction

Tropic responses

Sensitivity is the ability of living organisms to respond to stimuli. Although plants do not respond by moving their whole bodies, parts of them do respond to stimuli. Some of these responses are described as tropic responses or **tropisms**.

Tropisms

Tropisms are growth movements related to directional stimuli, e.g. a shoot will grow towards a source of light but away from the direction of gravity. Growth movements of this kind are usually in response to the *direction* of light or gravity. Responses to light are called **phototropisms**; responses to gravity are **gravitropisms** (or **geotropisms**).

Key definitions

Gravitropism is a response in which a plant grows towards or away from gravity.

Phototropism is a response in which a plant grows towards or away from the direction from which light is coming.

If the plant organ responds by growing towards the stimulus, the response is said to be 'positive'. If the response is growth away from the stimulus it is said to be 'negative'. For example, if a plant is placed horizontally, its stem will change its direction and grow upwards, away from gravity (Figure 14.26).

Figure 14.26 Negative gravitropism. The tomato plant has been left on its side for 24 hours.

The shoot is **negatively gravitropic**. The roots, however, will change their direction of growth to grow vertically downwards towards the pull of gravity (Experiment 1). Roots, therefore, are **positively gravitropic**.

Phototropism and gravitropism are best illustrated by some simple controlled experiments. Seedlings are good material for experiments on sensitivity because their growing roots (radicles) and shoots respond readily to the stimuli of light and gravity.

Practical work

Experiments on tropisms

1 Gravitropism in pea radicles

- Soak about 20 peas in water for a day and then let them germinate in a vertical roll of moist blotting-paper.
- After 3 days, choose 12 seedlings with straight radicles and pin six of these to the turntable of a clinostat so that the radicles are horizontal.
- Pin another six seedlings to a cork that will fit in a wide-mouthed jar. Leave the jar on its side.
- A **clinostat** is a clockwork or electric turntable, which rotates the seedlings slowly about four times an hour. Although gravity is pulling sideways on their roots, it will pull equally on all sides as they rotate.
- Place the jar and the clinostat in the same conditions of lighting or leave them in darkness for 2 days.

Result
The radicles in the clinostat will continue to grow horizontally but those in the jar will have changed their direction of growth, to grow vertically downwards (Figure 14.27).

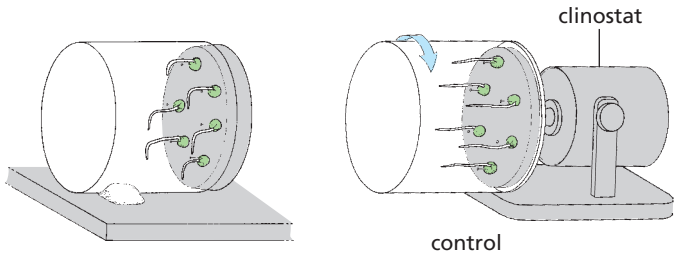


Figure 14.27 Results of an experiment to show gravitropism in roots

Interpretation
The stationary radicles have responded to the stimulus of one-sided gravity by growing towards it. The radicles are positively gravitropic.

The radicles in the clinostat are the controls. Rotation of the clinostat has allowed gravity to act on all sides equally and there is no one-sided stimulus, even though the radicles were horizontal.

2 Phototropism in shoots

- Select two potted seedlings, e.g. sunflower or runner bean, of similar size and water them both.
- Place one of them under a cardboard box with a window cut in one side so that light reaches the shoot from one direction only (Figure 14.28).
- Place the other plant in an identical situation but on a clinostat. This will rotate the plant about four times per hour and expose each side of the shoot equally to the source of light. This is the control.

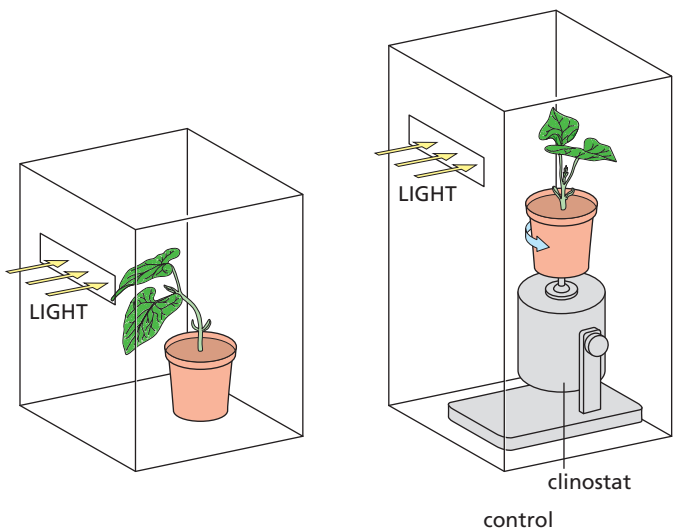


Figure 14.28 Experiment to show phototropism in a shoot

Result
After 1 or 2 days, the two plants are removed from the boxes and compared. It will be found that the stem of the plant with one-sided illumination has changed its direction of growth and is growing towards the light (Figure 14.29). The control shoot has continued to grow vertically.

Figure 14.29 Positive phototropism. The sunflower seedlings have received one-sided lighting for a day.

Interpretation
The results suggest that the young shoot has responded to one-sided lighting by growing towards the light. The shoot is said to be positively phototropic because it grows towards the direction of the stimulus.

However, the results of an experiment with a single plant cannot be used to draw conclusions that apply to green plants as a whole. The experiment described here is more of an illustration than a critical investigation. To investigate phototropisms thoroughly, a large number of plants from a wide variety of species would have to be used.

Advantages of tropic responses

Positive phototropism of shoots

By growing towards the source of light, a shoot brings its leaves into the best situation for photosynthesis. Similarly, the flowers are brought into an exposed position where they are most likely to be seen and pollinated by flying insects.

Negative gravitropism in shoots

Shoots that are negatively gravitropic grow vertically. This lifts the leaves and flowers above the ground and helps the plant to compete for light and carbon dioxide. The flowers are brought into an advantageous position for insect or wind pollination. Seed dispersal may be more effective from fruits on a long, vertical stem. However, these advantages are a product of a tall shoot rather than negative gravitropism.

Stems that form rhizomes (stems that grow underground) are not negatively gravitropic; they grow horizontally below the ground, though the shoots that grow up from them are negatively gravitropic.

Branches from upright stems are not negatively gravitropic; they grow at 90 degrees or, usually, at a more acute angle to the directional pull of gravity. The lower branches of a potato plant must be partially *positively* gravitropic when they grow down into the soil and produce potato tubers (see 'Asexual reproduction' in Chapter 16).

Positive gravitropism in roots

By growing towards gravity, roots penetrate the soil, which is their means of anchorage and their source of water and mineral salts. Lateral roots are not positively gravitropic; they grow at right angles or slightly downwards from the main root. This response enables a large volume of soil to be exploited and helps to anchor the plants securely.

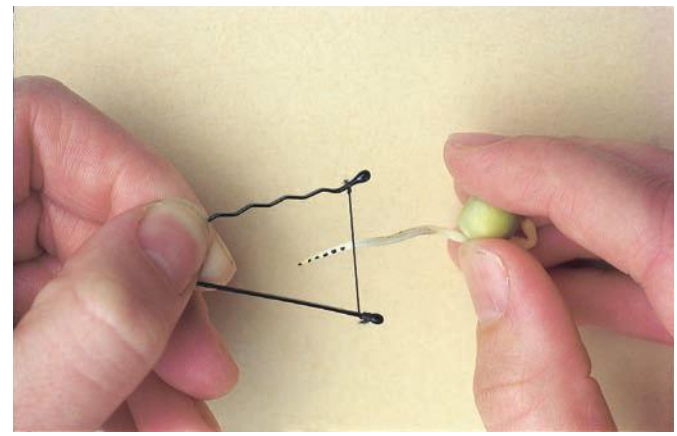


Figure 14.30 Marking a root. A piece of cotton is held by the hairpin and dipped into black ink.

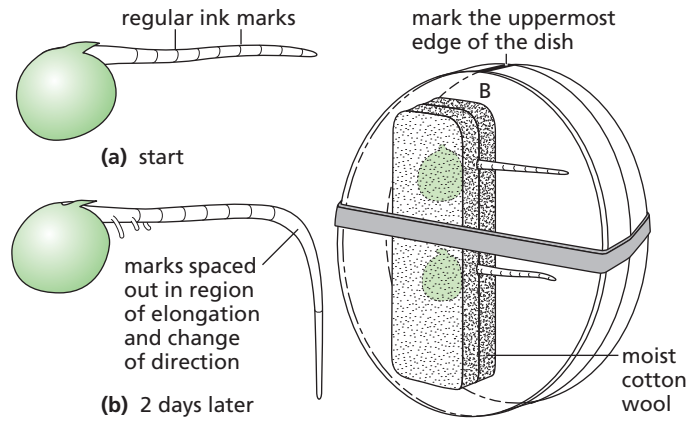


Figure 14.31 Region of response in radicles. Result of Experiment 3 on the B seedlings

Practical work

More experiments on tropisms

3 Region of response

- Grow pea seedlings in a vertical roll of blotting paper and select four with straight radicles about 25 mm long.
- Mark all the radicles with lines about 1 mm apart (Figures 14.30 and 14.31(a)).
- Use four strips of moist cotton wool to wedge two seedlings in each of two Petri dishes (Figure 14.31).
- Leave the dishes on their sides for 2 days, one (A) with the radicles vertical and the other (B) with the radicles horizontal.

Result

The ink marks will be more widely spaced in the region of greatest extension (Figure 14.31(b)). By comparing the seedlings in the two dishes, it can be seen that the region of curvature in the B seedlings corresponds to the region of extension in the A seedlings.

Interpretation

The response to the stimulus of one-sided gravity takes place in the region of extension. It does not necessarily mean that this is also the region which detects the stimulus.

Plant growth substances and tropisms

Control of growth

In animals and plants, the growth rate and extent of growth are controlled by chemicals: **hormones** in animals and **growth substances** in plants. Additionally, growth may be limited in animals by the availability of food, and in plants by light, water and minerals.

There are many different growth substances ('plant hormones') in plants. They are similar in some ways to animal hormones because they are produced in specific regions of the plant and transported to 'target' organs such as roots, shoots and buds. However, the sites of production are not specialised organs, as in animals, but regions of actively dividing cells such as the tips of shoots and roots. Also, plant growth substances are not transported in vessels.

One of the growth substances is **auxin**. Chemically it is indoleacetic acid (IAA). It is produced in the tips of actively growing roots and shoots and carried by active transport (Chapter 3) to the regions of extension where it promotes cell enlargement (Figure 14.32).

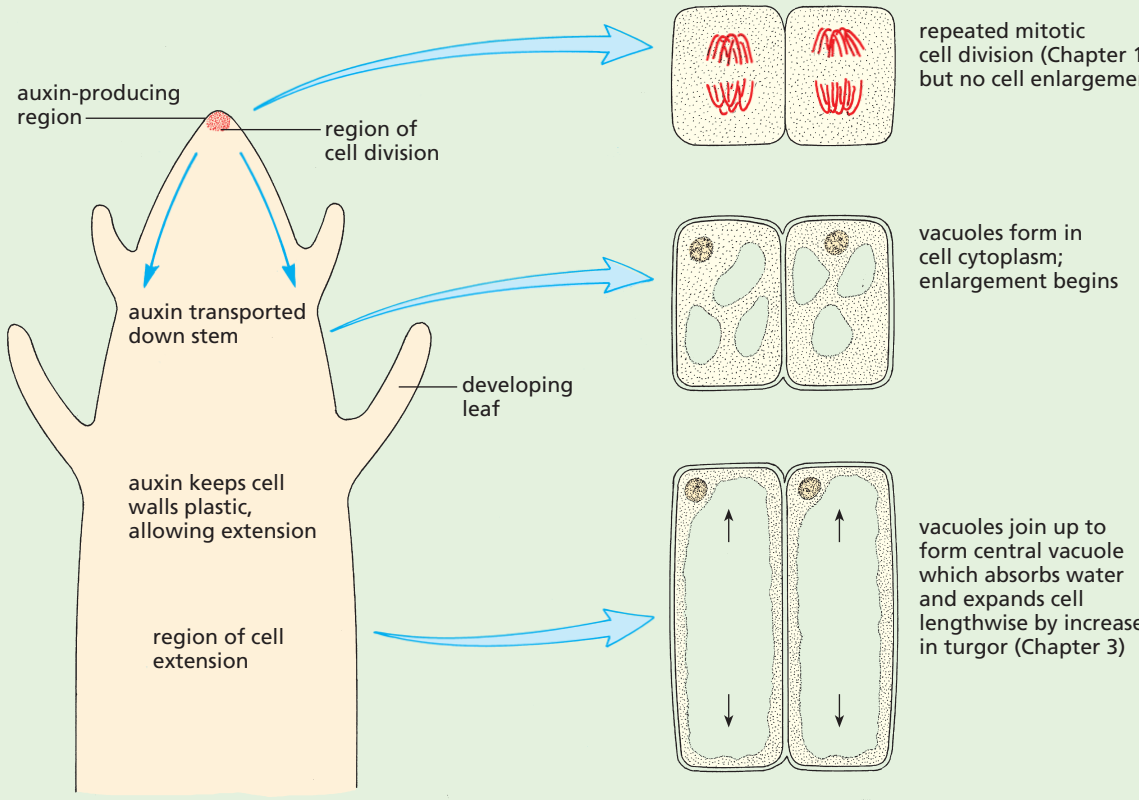


Figure 14.32 Extension growth at shoot tip

The responses made by shoots and roots to light and gravity are influenced by growth substances.

Growth substances also control seed germination, bud burst, leaf fall, initiation of lateral roots and many other processes.

It has already been explained that growth substances, e.g. auxin, are produced by the tips of roots and shoots and can stimulate or, in some cases, inhibit extension growth. Tropic responses could be explained if the one-sided stimuli produced a corresponding one-sided distribution of growth substance.

In the case of positive gravitropism in roots there is evidence that, in a horizontal root, more growth substance accumulates on the lower side. In this case the growth substance is presumed to inhibit extension growth, so that the root tip curves downwards (Figure 14.33).

In the case of phototropism, it is generally accepted that the distribution of growth substance causes reduced extension on the illuminated side and/or increased extension on the non-illuminated side.

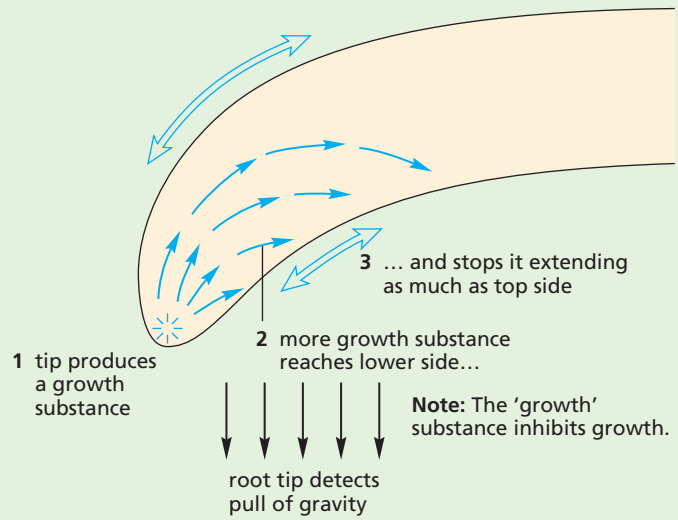


Figure 14.33 Possible explanation of positive gravitropism in roots

Summary of control of shoot growth by auxin

When a shoot is exposed to light from one side, auxins that have been produced by the tip move towards the shaded side of the shoot (or the auxins are destroyed on the light side, causing an unequal

distribution). Cells on the shaded side are stimulated to absorb *more* water than those on the light side, so the unequal growth causes the stem to bend towards the light. Growth of a shoot towards light is called **positive phototropism**.

If a shoot is placed horizontally in the absence of light, auxins accumulate on the lower side of the shoot, due to gravity. This makes the cells on the lower side grow *faster* than those on the upper side, so the shoot bends upwards. This is called **negative gravitropism**.

The opposite applies to roots because root cell elongation appears to be slowed down by exposure to auxin.

Classic experiments to test how auxins work

Wheat and other grass species belong to the monocotyledon group of flowering plants (Chapter 1). When wheat seeds germinate (start to grow) they produce a shoot covered by a protective sheath called a **coleoptile**. This helps to prevent damage to the new leaves as they push through the soil. The coleoptile shows responses to light and gravity in a similar way to other plant parts. Wheat coleoptiles only take 2 or 3 days to grow and they show responses very quickly, so they are ideal for tropism experiments. The tip of the coleoptile, where it is expected that auxins would be produced, can be cut off without killing the plant, but effectively removing the source of the auxin. Figure 14.34 shows an investigation, treating coleoptiles in different ways.

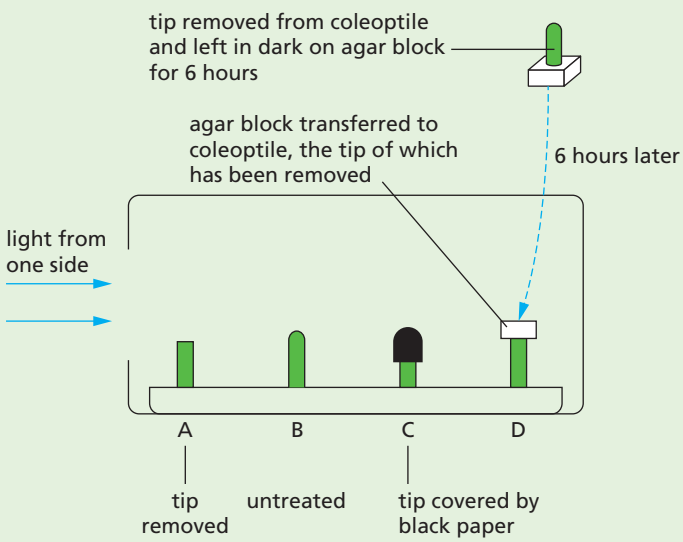


Figure 14.34 Investigation into how auxin works

Results

A No growth of the coleoptile occurs and there is no bending.

B The coleoptile grows taller and bends towards the light.

C The coleoptile grows taller, but there is no bending.

D The coleoptile grows taller and bends towards the light.

Interpretation

In **A**, the source of auxin has been removed. Auxin is needed to stimulate growth and stimulates a response to light. It could also be argued that the tip provides cells for growth and this source of cells has been removed.

In **B**, auxin is produced by the tip of the coleoptile. It diffuses down the coleoptile and collects on the shaded side of the coleoptile (or is destroyed by the light on the light side). Cells on the shaded side respond to the auxin by growing faster than on the light side causing the coleoptile to grow towards the light.

In **C**, auxin is produced by the tip and diffuses down, causing all cells on both sides of the coleoptile to grow at an equal rate, causing an increase in length. However, the black paper prevents the light influencing the auxin, so there is no response to the direction of light.

In **D**, auxin is produced by the tip of the coleoptile. It diffuses into the agar block. When the agar block is replaced on the cut coleoptile, the auxin diffuses down from the agar and collects on the shaded side of the coleoptile (or is destroyed by the light on the light side). Cells on the shaded side respond to the auxin by growing faster than on the light side causing the coleoptile to grow towards the light.

Use of plant growth substances

Chemicals can be manufactured which closely resemble natural growth substances and may be used to control various aspects of growth and development of crop plants.

The weedkiller, 2,4-D, is very similar to one of the auxins. When sprayed on a lawn, it affects the broad-leaved weeds (e.g. daisies and dandelions) but not the grasses. (It is called a 'selective weedkiller'.) Among other effects, it distorts the weeds' growth and speeds up their rate of respiration to the extent that they exhaust their food reserves and die.

Questions

Core

1 What is the difference between a nerve and a nerve fibre?
2 a In what ways are sensory neurones and motor neurones similar:
  i in structure
  ii in function?
  b How do they differ?
3 Can a nerve fibre and a nerve carry both sensory and motor impulses? Explain your answers.
  a a nerve fibre
  b a nerve
4 Put the following in the correct order for a simple reflex arc
  a impulse travels in motor fibre
  b impulse travels in sensory fibre
  c effector organ stimulated
  d receptor organ stimulated
  e impulse crosses synapse.
5 Which receptors and effectors are involved in the reflex actions of:
  a sneezing
  b blinking
  c contraction of the iris?
6 Explain why the tongue may be considered to be both a receptor and an effector organ.
7 Discuss whether coughing is a voluntary or reflex action.
8 What sensation would you expect to feel if a warm pin-head was pressed on to a touch receptor in your skin? Explain your answer.
9 If a piece of ice is pressed on to the skin, which receptors are likely to send impulses to the brain?
10 Apart from the cells that detect chemicals, what other types of receptor must be present in the tongue?
11 a To what directional stimuli do:
  i roots respond
  ii shoots respond?
  b Name the plant organs which are
  i positively phototropic
  ii positively gravitropic
  iii negatively gravitropic.
12 Why is it incorrect to say:
  a 'Plants grow towards the light.'
  b 'If a root is placed horizontally, it will bend towards gravity'?
13 Explain why a clinostat is used for the controls in tropism experiments.
14 Look at Figure 14.26. What will the shoot look like in 24 hours after the pot has been stood upright again? (Just draw the outline of the stem.)
15 What do you think might happen if a potted plant were placed on its side and the shoot illuminated from below (i.e. light and gravity are acting from the same direction)?

Extended

16 Look at Figures 14.6 and Figure 14.8. For each diagram, state
  a how many cell bodies are drawn
  b how many synapses are shown.
17 If you could intercept and 'listen to' the nerve impulses travelling in the spinal cord, could you tell which ones came from pain receptors and which from temperature receptors? Explain your answer.
18 Would you expect synapses to occur in grey matter or in white matter? Explain your answer.
19 Study Figure 14.2. If the spinal cord were damaged at a point about one-third of the way up the vertebral column, what effect would you expect this to have on the bodily functions?
20 Study Table 14.3 and give one example for each point of comparison.
21 The pancreas has a dual function in producing digestive enzymes as well as hormones. Which other endocrine glands have a dual function and what are their other functions? (See also 'Sex hormones in humans' in Chapter 16.)
22 What are the effects on body functions of:
  a too much insulin
  b too little insulin?
23 Why do you think urine tests are carried out to see if a woman is pregnant?
24 What conscious actions do we take to reduce the heat lost from the body?
25 a What sort of chemical reaction in active muscle will produce heat?
  b How does this heat get to other parts of the body?
26 Draw up a balance sheet to show all the possible ways the human body can gain or lose heat. Make two columns, with 'Gains' on the left and 'Losses' on the right.
27 a Which structures in the skin of a furry mammal help to reduce heat loss?
  b What changes take place in the skin of humans to reduce heat loss?
28 Sweating cools you down only if the sweat can evaporate.
  a In what conditions might the sweat be unable to evaporate from your skin?
  b What conditions might speed up the evaporation of sweat and so make you feel very cold?
29 In Figure 14.35 the two sets of pea seedlings were sown at the same time, but the pot on the left was kept under a lightproof box. From the evidence in the picture:
  a what effects does light appear to have on growing seedlings
  b how might this explain positive phototropism?

Figure 14.35 Effect of light on shoots

30 It is suggested that it is the very tip of the radicle that detects the one-sided pull of gravity even though it is the region of extension that responds. How could you modify Experiment 3 to test this hypothesis?

Checklist

After studying Chapter 14 you should know and understand the following:

The nervous system

- The central nervous system consists of the brain and the spinal cord.
- The peripheral nervous system consists of the nerves.
- The nerves consist of bundles of nerve fibres.
- Each nerve fibre is a thin filament that grows out of a nerve cell body.
- The nerve cell bodies are mostly in the brain and spinal cord.
- Nerve fibres carry electrical impulses from sense organs to the brain or from the brain to muscles and glands.
- A reflex is an automatic nervous reaction that cannot be consciously controlled.
- A reflex arc is the nervous pathway that carries the impulses causing a reflex action.
- The simplest reflex involves a sensory nerve cell and a motor nerve cell, connected by synapses in the spinal cord.
- The brain and spinal cord contain millions of nerve cells.
- The millions of possible connections between the nerve cells in the brain allow complicated actions, learning, memory and intelligence.

- Voluntary actions start in the brain, while involuntary actions are automatic.
- Reflexes have a protective function.
- A synapse is a junction between two neurones consisting of a minute gap across which impulses pass by diffusion of a neurotransmitter.
- Identify parts of a synapse and describe how it transmits an impulse from one neurone to another.
- Drugs such as morphine and heroin can affect synapses.
- In reflex arcs, synapses ensure the movement of impulses in one direction.

Sense organs

- Sense organs are groups of receptor cells responding to specific stimuli: light, sound, touch, temperature and chemicals.
- Describe the structure of the eye.
- Describe the function of the parts of the eye.
- Describe the pupil reflex.

- Explain the pupil reflex.
- Explain accommodation to view near and distant objects.
- Describe the roles of parts of the eye in accommodation.
- State the distribution of rods and cones in the retina of a human.
- Describe the function of rods and cones.

Hormones in humans

- A hormone is a chemical substance, produced by a gland, carried by the blood, which alters the activity of one or more specific target organs
- The testes, ovaries and pancreas are also endocrine glands in addition to their other functions.
- The endocrine glands release hormones into the blood system.
- When the hormones reach certain organs they change the rate or kind of activity of the organ.
- Too much or too little of a hormone can cause a metabolic disorder.
- Adrenalin is secreted in 'fight or flight' situations.
- It causes an increased breathing and pulse rate and widened pupils.

- Adrenaline has a role in the chemical control of metabolic activity, including increasing the blood glucose concentration and pulse rate.
- The nervous system is much faster and its action tends to be over a shorter time span than hormonal control systems.

Homeostasis

- Homeostasis is the maintenance of a constant internal environment.
- Skin consists of an outer layer of epidermis and an inner dermis.
- The epidermis is growing all the time and has an outer layer of dead cells.
- The dermis contains the sweat glands, hair follicles, sense organs and capillaries.
- Skin (1) protects the body from bacteria and drying out, (2) contains sense organs which give us the sense of touch, warmth, cold and pain, and (3) controls the body temperature.
- Chemical activity in the body and muscular contractions produce heat.
- Heat is lost to the surroundings by conduction, convection, radiation and evaporation.
- If the body temperature rises too much, the skin cools it down by sweating and vasodilation.
- If the body loses too much heat, vasoconstriction and shivering help to keep it warm.

- Negative feedback provides a means of control: if levels of substances in the body change, the change is monitored and a response to adjust levels to normal is brought about.
- Glucose concentration in the blood is controlled using insulin and glucagon.
- Type 1 diabetes is the result of islet cells in the pancreas failing to produce enough insulin.
- Vasodilation and vasoconstriction of arterioles in the skin are mechanisms to control body temperature.

Tropic responses

- A response related to the direction of the stimulus is a tropism.
- The roots and shoots of plants may respond to the stimuli of light or gravity.
- Gravitropism is a response in which a plant grows towards or away from gravity.
- Phototropism is a response in which a plant grows towards or away from the direction from which light is coming.

- Growth towards the direction of the stimulus is called 'positive'; growth away from the stimulus is called 'negative'.
- Tropic responses bring shoots and roots into the most favourable positions for their life-supporting functions.
- Describe investigations into gravitropism and phototropism in shoots and roots.

- Explain phototropism and gravitropism of a shoot as examples of the chemical control of plant growth by auxin.
- Auxin is only made in the shoot tip and moves through the plant, dissolved in water.
- Auxin is unequally distributed in response to light and gravity.
- Auxin stimulates cell elongation.
- The synthetic plant hormone 2,4-D is used in weedkillers.

15 Drugs

Drugs
Define drug

Medicinal drugs
Use of antibiotics
Development of resistance in bacteria to antibiotics

Development of resistant bacteria
Antibiotics and viral diseases

Misused drugs
Effects of heroin, alcohol, tobacco
Role of liver in breaking down toxins

Effects of heroin on the nervous system
Link between smoking and cancer
Use of performance-enhancing drugs

Drugs

Key definition
A **drug** is any substance taken into the body that modifies or affects chemical reactions in the body.

The drug may be one taken legally to reduce a symptom such as a headache or to treat a bacterial infection (medicinal drugs), but it could also be one taken – often illegally – to provide stimulation or induce sleep or create hallucinations (recreational drugs). Drugs are present in many products such as: tea, coffee and 'energy drinks' (caffeine); tobacco (nicotine); and alcoholic drinks (alcohol) which, although legal, can cause serious effects when taken excessively or over extended periods of time.

Medicinal drugs

Any substance used in medicine to help our bodies fight illness or disease is called a drug.

Antibiotics

The ideal drug for curing disease would be a chemical that destroyed the pathogen without harming the tissues of the host. In practice, modern antibiotics such as penicillin come pretty close to this ideal for bacterial infections.

A tiny minority of bacteria are harmful (pathogenic). Figure 10.1 shows some examples and the diseases they cause.

Most of the antibiotics we use come from bacteria or fungi that live in the soil. The function of the antibiotics in this situation is not clear. One theory suggests that the chemicals help to suppress competition for limited food resources, but the evidence does not support this theory.

One of the most prolific sources of antibiotics is *Actinomycetes*. These are filamentous bacteria that resemble microscopic mould fungi. The actinomycete *Streptomyces* produces the antibiotic **streptomycin**.

Perhaps the best known antibiotic is **penicillin**, which is produced by the mould fungus *Penicillium* and was discovered by Sir Alexander Fleming in 1928. Penicillin is still an important antibiotic but it is produced by mutant forms of a different species of *Penicillium* from that studied by Fleming. The different mutant forms of the fungus produce different types of penicillin.

The penicillin types are chemically altered in the laboratory to make them more effective and to 'tailor' them for use with different diseases. 'Ampicillin', 'methicillin' and 'oxacillin' are examples.

Antibiotics attack bacteria in a variety of ways. Some of them disrupt the production of the cell wall and so prevent the bacteria from reproducing, or even cause them to burst open; some interfere with protein synthesis and thus arrest bacterial growth.

Animal cells do not have cell walls, and the cell structures involved in protein production are different. Consequently, antibiotics do not damage human cells although they may produce some side-effects such as allergic reactions.

Not all bacteria are killed by antibiotics. Some bacteria have a nasty habit of mutating to forms that are resistant to these drugs.

For this reason it is important not to use antibiotics in a diluted form, for too short a period or for trivial complaints. These practices lead to a build-up of a resistant population of bacteria. The drug resistance can be passed from harmless bacteria to pathogens.

It is important to note that antibiotics are ineffective in the treatment of viral diseases.

Development of resistant bacteria

If a course of antibiotics is not completed, some of the bacteria it is being used to destroy will not be killed, but will have been exposed to the drug. Some of the survivors may be drug-resistant mutants. When they reproduce, all their offspring will have the drug resistance, so the antibiotic will become less effective (Figure 15.1).

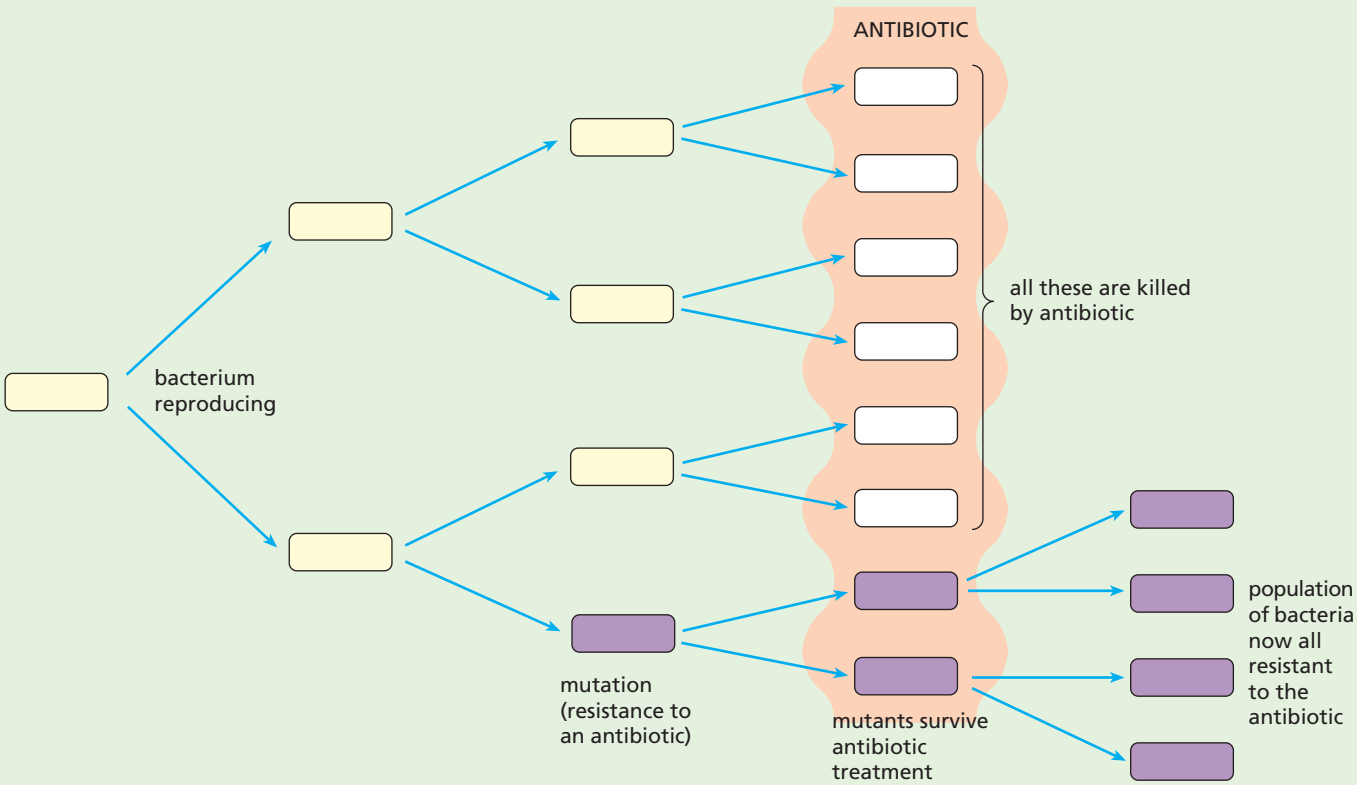


Figure 15.1 Mutation in bacteria can lead to drug resistance

One type of bacteria that has developed resistance to a number of widely used antibiotics is called MRSA (methicillin-resistant *Staphylococcus aureus*). These types of bacteria are sometime referred to as 'superbugs' because they are so difficult to treat. *Staphylococcus aureus* is very common and is found living harmlessly on the skin, the nose and throat, sometimes causing mild infections. It becomes dangerous if there is a break in the skin, allowing it to infect internal organs and causing blood poisoning. This can happen in hospitals with infection during operations, especially if hygiene precautions are not adequate.

Doctors now have to be much more cautious about prescribing antibiotics, to reduce the risk of resistant strains developing. Patients need to be aware of the importance of completing a course of antibiotics, again to reduce the risk of development of resistant strains.

Antibiotics and viral diseases

Antibiotics are not effective against viral diseases. This is because antibiotics work by disrupting structures in bacteria such as cell walls and membranes, or processes associated with protein synthesis and replication of DNA. Viruses have totally different characteristics to bacteria, so antibiotics do not affect them. Compare the image of a virus in Figure 1.34 with that of a bacterium in Figure 1.29.

Extension work

Ideas about antibiotics

Alexander Fleming (1881–1955)

Before 1934 there were few effective drugs. Some herbal preparations may have been useful; after all, many of our present-day drugs are derived from or based on plant products. Quinine, for example, was used for the treatment of malaria and was extracted from a specific kind of tree bark.

In 1935, a group of chemicals called **sulfanilamides** were found to be effective against some bacterial diseases such as blood poisoning, pneumonia and septic wounds.

Fleming had discovered penicillin in 1928, 7 years before the use of sulfanilamides, but he had been unable to purify it and test it on humans. Fleming was a bacteriologist working at St Mary's Hospital in London. In 1928, he was studying different strains of *Staphylococcus* bacteria. He had made some cultures on agar plates and left them on the laboratory bench during a 4-week holiday. When he returned he noticed that one of the plates had been contaminated by a mould fungus and that around the margins of the mould there was a clear zone with no bacteria growing (Figure 15.2).

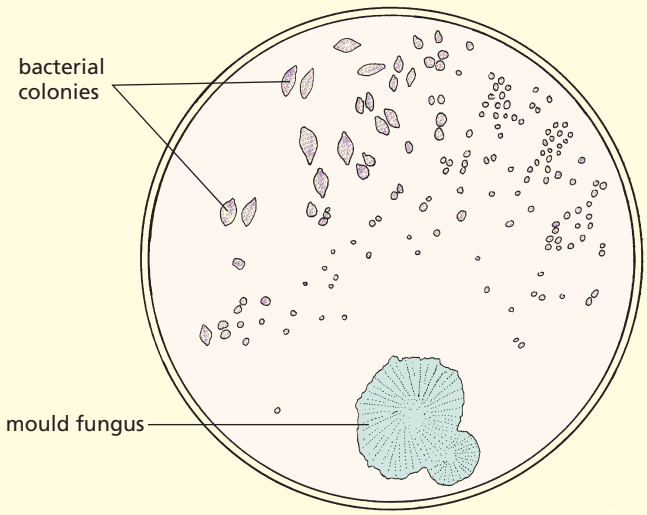


Figure 15.2 Appearance of the *Staphylococcus* colonies on Fleming's petri dish

Fleming reasoned that a substance had diffused out of the mould colony and killed the bacteria. The mould was identified as *Penicillium notatum* and the supposed anti-bacterial chemical was called penicillin. Fleming went on to culture the *Penicillium* on a liquid meat broth medium and showed that the broth contained penicillin, which suppressed the growth of a wide range of bacteria.

Two research assistants at St Mary's then tried to obtain a pure sample of penicillin, free from all the other substances in the broth. Although they succeeded, the procedure was cumbersome and the product was unstable. By this time, Fleming seemed to have lost interest and to assume that penicillin would be too difficult to extract and too unstable to be of medical value.

In 1939, **Howard Florey** (a pathologist) and **Ernst Chain** (a biochemist), working at Oxford University, succeeded in preparing reasonably pure penicillin and making it stable. Techniques of extraction had improved dramatically in 10 years and, in particular, freeze-drying enabled a stable water-soluble powder form of penicillin to be produced.

World War II was an urgent incentive for the production of penicillin in large quantities and this undoubtedly saved many lives that would otherwise have been lost as a result of infected wounds.

Once Ernst Chain had worked out the molecular structure of penicillin, it became possible to modify it chemically and produce other forms of penicillin that attacked a different range of bacteria or had different properties. For example, ampicillin is a modified penicillin that can be taken by mouth rather than by injection.

Because penicillin was the product of a mould, chemists searched for other moulds, particularly those present in the soil, which might produce antibiotics. A large number of these were discovered, including streptomycin (for tuberculosis), chloramphenicol (for typhoid), aureomycin and terramycin (broad spectrum antibiotics, which attack a wide range of bacteria). The ideal drug is one that kills or suppresses the growth of harmful cells, such as bacteria or cancer cells, without damaging the body cells. Scientists have been trying for years to find a 'magic bullet' that 'homes in' exclusively on its target cells. For bacterial diseases, antibiotics come pretty close to the ideal, though the bacteria do seem able to develop resistant forms after a few years.

Misused drugs

Narcotics

Heroin, morphine and codeine belong to a group of drugs called **narcotics**, made from opium. Heroin and morphine act as powerful depressants: they relieve severe pain and produce short-lived feelings of wellbeing and freedom from anxiety. They can both lead to tolerance and physical dependence within weeks, so they are prescribed with caution, to patients in severe pain.

The illegal use of heroin has terrible effects on the unfortunate addict. The overwhelming dependence on the drug leads many addicts into prostitution and crime in order to obtain the money to buy it.

There are severe withdrawal symptoms when an addict tries to give up the drug abruptly. These symptoms are called going 'cold turkey' and can include anxiety, muscle aches, sweating, abdominal cramping, diarrhoea, nausea and vomiting. A 'cure' is a long and often unsuccessful process.

Additional hazards are that blood poisoning, hepatitis and AIDS may result from the use of unsterilised needles when injecting the drug.

Codeine is a less effective analgesic than morphine, but does not lead so easily to dependence. It is still addictive if used in large enough doses.

Alcohol

The alcohol in wines, beer and spirits is a depressant of the central nervous system. Small amounts give a sense of wellbeing, with a release from anxiety. However, this is accompanied by a fall-off in performance in any activity requiring skill. It also gives a misleading sense of confidence in spite of the fact that one's judgement is clouded. A drunken driver usually thinks he or she is driving extremely well.

Even a small amount of alcohol in the blood increases our reaction time (the interval between receiving a stimulus and making a response). In some people, the reaction time is doubled even when the alcohol in the blood is well below the legal limit laid down for car drivers (Figure 15.3). This can make a big difference to the time needed for a driver to apply the brakes after seeing a hazard such as a child running into the road.

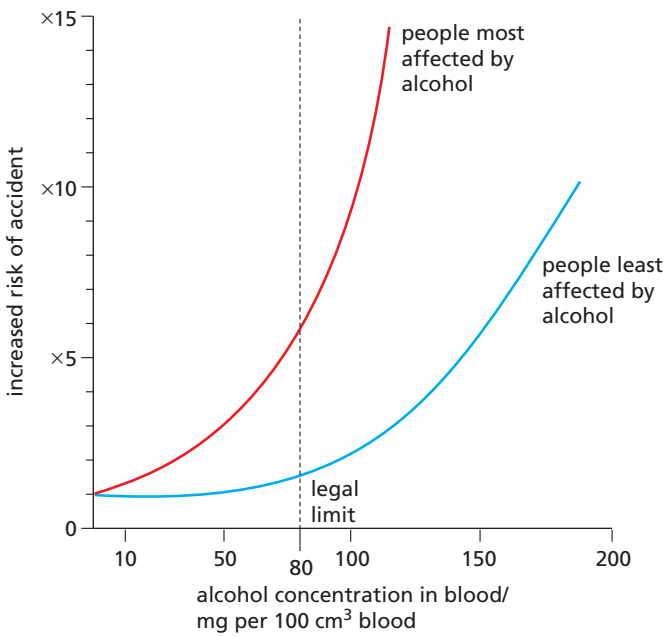


Figure 15.3 Increased risk of accidents after drinking alcohol. People vary in their reactions to alcohol. Body weight, for example, makes a difference.

Alcohol causes vasodilation in the skin, giving a sensation of warmth but in fact leading to a greater loss of body heat (see 'Homeostasis' in Chapter 14). A concentration of 500 mg of alcohol in 100 cm^3 of blood results in unconsciousness. More than this will cause death because it stops the breathing centre in the brain. The liver treats alcohol as a toxin: 90% of alcohol taken in is **detoxified** in the liver (along with other toxins). The process of detoxification involves the oxidation of alcohol to carbon dioxide and water. Only 10% is excreted by the kidneys. On average, the liver can oxidise about 75 mg alcohol per 1 kg body weight per hour. This rate varies considerably from one individual to the next but it indicates that it would take about 3 hours to oxidise the alcohol in a pint of beer or a glass of wine. If the alcohol intake exceeds this rate of oxidation, the level of alcohol in the blood builds up to toxic proportions; that is, it leads to **intoxication**.

Some people build up a tolerance to alcohol and this may lead to both emotional and physical dependence (alcoholism). High doses of alcohol can cause the liver cells to form too many fat droplets, leading to the disease called **cirrhosis**. A cirrhotic liver is less able to stop poisonous substances in the intestinal blood from reaching the general circulation.

Pregnancy

Drinking alcohol during pregnancy can present a major risk to the developing fetus. Further details are given in Chapter 16.

Behaviour

Alcohol reduces inhibitions because it depresses that part of the brain which causes shyness. This may be considered an advantage in 'breaking the ice' at parties. But it can also lead to irresponsible behaviour such as vandalism and aggression.

Moderate drinking

A moderate intake of alcoholic drink seems to do little physiological harm (except in pregnant women). But what is a 'moderate' intake?

A variety of drinks that all contain the same amount of alcohol is shown in Figure 15.4. Beer is a fairly dilute form of alcohol. Whisky, however, is about 40% alcohol. Even so, half a pint of beer contains the same amount of alcohol as a single whisky. This amount of alcohol can be called a 'unit'.

It is the number of units of alcohol, not the type of drink, which has a physiological effect on the body. In Britain, the Health Development Agency recommends upper limits of 21–28 units for men and 14–21 units for women over a 1-week period at the time of publication of this book. Pregnant women should avoid alcohol altogether.

Figure 15.4 Alcohol content of drinks. All these drinks contain the same amount of alcohol (1 unit). Although the alcohol is more dilute in the beer than in the whisky, it has the same effect on the body.

Smoking

The short-term effects of smoking cause the bronchioles to constrict and the cilia lining the air passages to stop beating. The smoke also makes the lining produce more mucus. **Nicotine**, the addictive component of tobacco smoke, produces an increase in the rate of the heartbeat and a rise in blood pressure. It may, in some cases, cause an erratic and irregular heart beat. Tar in cigarette smoke is thought to be the main cause of lung cancer in smokers. **Carbon monoxide** permanently binds with haemoglobin in red blood cells, reducing the smoker's ability to provide oxygen to respiring cells. This results in a smoker getting out of breath more easily and it reduces physical fitness.

The long-term effects of smoking may take many years to develop but they are severe, disabling and often lethal.

Lung cancer

Cancer is a term used for diseases in which cells become abnormal and divide out-of-control. They can then move around the body and invade other tissues. A chemical that causes cancer is known as a **carcinogen**. Carcinogens present in cigarette smoke, such as tar, increase the risk of lung cells becoming cancerous. Tumours develop. These are balls of abnormal cells, which do not allow gaseous exchange like normal lung cells.

Many studies have now demonstrated how cigarette smoke damages lung cells, confirming that smoking does cause cancer. The higher the number of cigarettes smoked, the greater the risk of lung cancer.

Chronic obstructive pulmonary disease (COPD)

This term covers a number of lung diseases, which include chronic bronchitis, emphysema and chronic obstructive airways disease. A person suffering from COPD will experience difficulties with breathing, mainly because of narrowing of the airways (bronchi and bronchioles). Symptoms of COPD include breathlessness when active, frequent chest infections and a persistent cough with phlegm (sticky mucus).

Emphysema

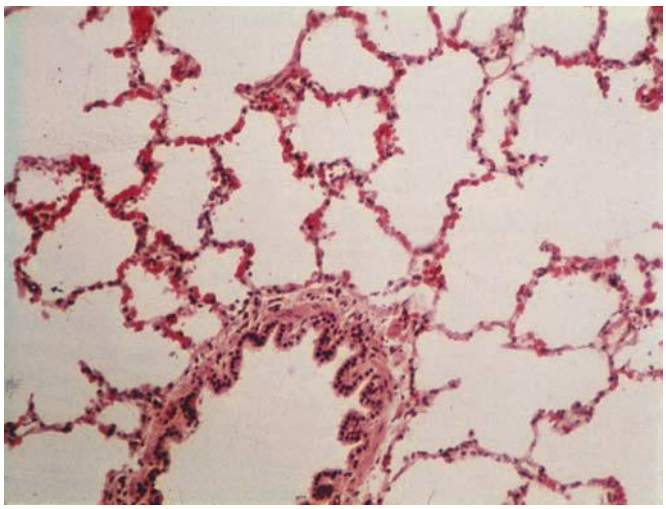
Emphysema is a breakdown of the alveoli. The action of one or more of the substances in tobacco smoke weakens the walls of the alveoli. The irritant substances in the smoke cause a 'smokers' cough' and the coughing bursts some of the weakened alveoli. In time, the absorbing surface of the lungs is greatly reduced (Figure 15.5). Then the smoker cannot oxygenate his or her blood properly and the least exertion makes the person breathless and exhausted.

Chronic bronchitis

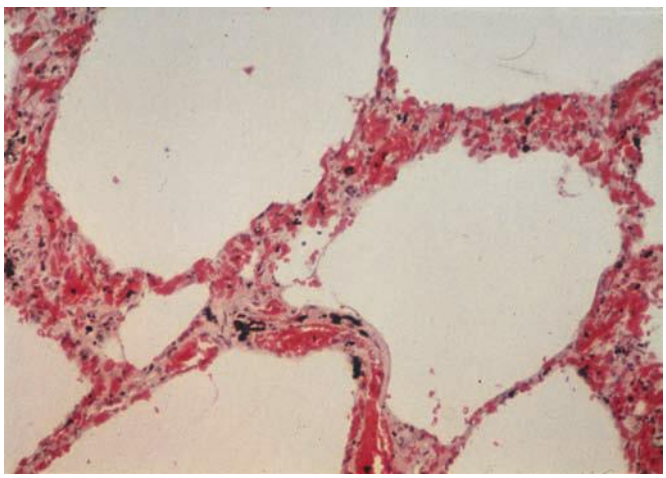
The smoke stops the cilia in the air passages from beating, so the irritant substances in the smoke and the excess mucus collect in the bronchi. This leads to inflammation known as **bronchitis**. Over 95% of people suffering from bronchitis are smokers and they have a 20 times greater chance of dying from bronchitis than non-smokers.

Heart disease

Coronary heart disease is the leading cause of death in most developed countries. It results from a blockage of coronary arteries by fatty deposits. This reduces the supply of oxygenated blood to the heart muscle and sooner or later leads to heart failure (see Chapter 9). High blood pressure, diets with too much animal fat and lack of exercise are also thought to be causes of heart attack, but about a quarter of all deaths due to coronary heart disease are thought to be caused by smoking (see Figure 9.12).



(a) Normal lung tissue showing a bronchiole and about 20 alveoli (×200)



(b) Lung tissue from a person with emphysema. This is the same magnification as **(a)**. The alveoli have broken down leaving only about five air sacs, which provide a much reduced absorbing surface.

Figure 15.5 Emphysema

The nicotine and carbon monoxide from cigarette smoke increase the tendency for the blood to clot and so block the coronary arteries, already partly blocked by fatty deposits. The carbon monoxide increases the rate at which the fatty material is deposited in the arteries.

Other risks

About 95% of patients with disease of the leg arteries are cigarette smokers; this condition is the most frequent cause of leg amputations.

Strokes due to arterial disease in the brain are more frequent in smokers.

Cancer of the bladder, ulcers in the stomach and duodenum, tooth decay, gum disease and tuberculosis all occur more frequently in smokers.

Babies born to women who smoke during pregnancy are smaller than average, probably as a result of reduced oxygen supply caused by the carbon monoxide in the blood. In smokers, there is twice the frequency of miscarriages, a 50% higher still-birth rate and a 26% higher death rate of babies.

A recent estimate is that one in every three smokers will die as a result of their smoking habits. Those who do not die at an early age will probably be seriously disabled by one of the conditions described above.

Passive smoking

It is not only the smokers themselves who are harmed by tobacco smoke. Non-smokers in the same room are also affected. One study has shown that children whose parents both smoke breathe in as much nicotine as if they were themselves smoking 80 cigarettes a year.

Statistical studies also suggest that the non-smoking wives of smokers have an increased chance of lung cancer.

Reducing the risks

By giving up smoking, a person who smokes up to 20 cigarettes a day will, after 10 years, be at no greater risk than a non-smoker of the same age. A pipe or cigar smoker, provided he or she does not inhale, is at less risk than a cigarette smoker but still at greater risk than a non-smoker.

How heroin affects the nervous system

As described in Chapter 14, heroin produces its effects by interacting with receptor molecules at synapses. Synapses are tiny gaps between neurones, across which electrical impulses cannot jump. To maintain the transmission of the impulse, a chemical messenger called a neurotransmitter is released into the gap. When it reaches the neurone on the other side, receptor molecules are stimulated to generate and release new electrical impulses. Heroin mimics the transmitter substances in synapses in the brain, causing the stimulation of receptor molecules. This causes the release of **dopamine** (a neurotransmitter), which gives a short-lived 'high'.

Evidence for a link between smoking and lung cancer

Although all forms of air pollution are likely to increase the chances of lung cancer, many scientific studies show, beyond all reasonable doubt, that the vast increase in lung cancer (4000% in the last century) is almost entirely due to cigarette smoking (Figure 15.6).

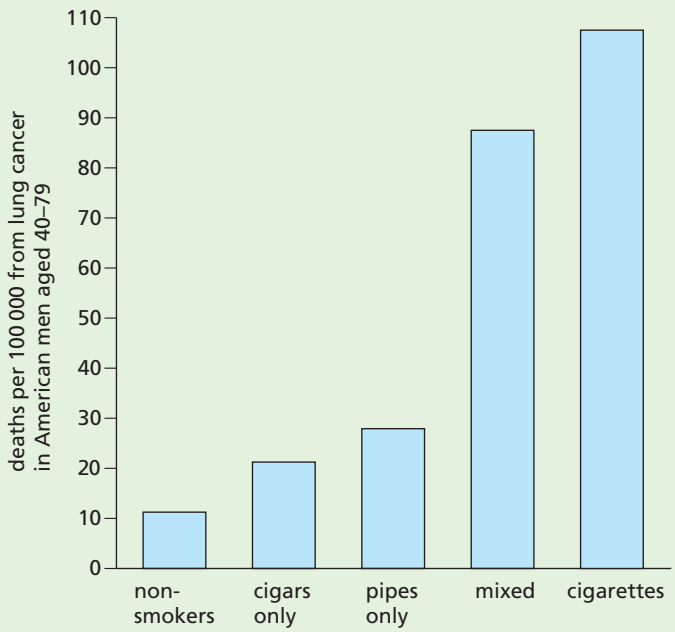


Figure 15.6 Smoking and lung cancer. Cigar and pipe smokers are probably at less risk because they often do not inhale. But notice that their death rate from lung cancer is still twice that of non-smokers. They are also at risk of other cancers such as mouth and throat cancer.

There are at least 17 substances in tobacco smoke known to cause cancer in experimental animals, and it is now thought that 90% of lung cancer is caused by smoking. Table 15.1 shows the relationship between smoking cigarettes and the risk of developing lung cancer.

Table 15.1 Cigarette smoking and lung cancer

Number of cigarettes per day	Increased risk of lung cancer
1–14	×8
15–24	×13
25+	×25

Correlations and causes

In Chapter 9 it was explained that a correlation between two variables does not prove that one of the variables causes the other. The fact that a higher risk of dying from lung cancer is correlated with heavy smoking does not actually prove that smoking is the cause of lung cancer. The alternative explanation is that people who become heavy smokers are, in some way, exposed to other potential causes of lung cancer, e.g. they live in areas of high air pollution or they have an inherited tendency to cancer of the lung. These alternatives are not very convincing, particularly when there is such an extensive list of ailments associated with smoking.

This is not to say that smoking is the only cause of lung cancer or that everyone who smokes will eventually develop lung cancer. There are likely to be complex interactions between life-styles, environments and genetic backgrounds which could lead, in some cases, to lung cancer. Smoking may be only a part, but a very important part, of these interactions.

Performance-enhancing hormones

In the last 30 years or so, some athletes and sports persons have made use of drugs to boost their performance. Some of these drugs are synthetic forms of hormones.

Testosterone is made in the testes of males and is responsible for promoting male primary and secondary sexual characteristics. Taking testosterone supplements (known as 'doping') leads to increased muscle and bone mass. The practice therefore has the potential to enhance a sportsperson's performance.

Anabolic steroids are synthetic derivatives of testosterone. They affect protein metabolism, increasing muscle development and reducing body fat. Athletic performance is thus enhanced. There are serious long-term effects of taking anabolic steroids. The list is a long one but the main effects are sterility, masculinisation in women, and liver and kidney malfunction.

An internationally famous athlete caught using performance enhancing drugs was Ben Johnson (Figure 15.7), who represented Canada as a sprinter. He gained medals in the 1987 World Championships and the 1988 Olympics, but these were withdrawn after a urine sample tested positive for anabolic steroids.

Figure 15.7 Ben Johnson (in red) beating his arch rival Carl Lewis (in blue). Johnson would later be banned from international athletics for life for using anabolic steroids.

Because these drugs enhance performance beyond what could be achieved by normal training, they are deemed unfair and banned by most sports organisations. Anabolic steroids are universally banned but different sports regulatory bodies have different rules for other substances.

The products of the steroid hormones can be detected in the urine and this is the basis of most tests for banned substances. Without these regulations, sport would become a competition between synthetic chemical substances rather than between individuals and teams.

Questions

Core

1 Why are doctors concerned about the over-use of antibiotics?
2 List at least four effects of the excessive consumption of alcohol.
3 Find out the cost of a packet of 20 cigarettes. If a person smokes 20 cigarettes a day, how much would this cost in a year?

Extended

4 What are:
   a the immediate effects and
   b the long-term effects
   of tobacco smoke on the trachea, bronchi and lungs?
5 Why does a regular smoker get out of breath sooner than a non-smoker of similar age and build?
6 If you smoke 20 cigarettes a day, by how much are your chances of getting lung cancer increased?
7 Apart from lung cancer, what other diseases are probably caused by smoking?

Checklist

After studying Chapter 15 you should know and understand the following:

- A drug is any substance taken into the body that modifies or affects chemical reactions in the body.
- Antibiotics are used in the treatment of bacterial infections.
- Some bacteria become resistant to antibiotics, which reduces their effectiveness.
- Antibiotics kill bacteria but not viruses.
- It is possible to minimise the development of resistant bacteria such as MRSA.
- Viruses have a different structure to bacteria, so they are not affected by antibiotics.
- Smoking and excessive drinking contribute to ill-health.
- Mood-influencing drugs may be useful for treating certain illnesses but are dangerous if used for other purposes.
- Tolerance means that the body needs more and more of a particular drug to produce the same effect.
- Dependence means that a person cannot do without a particular drug.
- Withdrawal symptoms are unpleasant physical effects experienced by an addict when the drug is not taken.
- Tobacco smoke affects the gaseous exchange system because it contains toxic components.
- Alcohol is a depressant drug, which slows down reaction time and reduces inhibitions.
- Alcohol in a pregnant woman's blood can damage her fetus.
- The liver is the site of breakdown of alcohol and other toxins.
- Heroin is a strongly addictive drug, which affects the nervous system.
- There is now strong enough evidence to provide a link between smoking and lung cancer.
- Some hormones are used to improve sporting performance.

16 Reproduction

Asexual reproduction
Define asexual reproduction
Examples of asexual reproduction

Advantages and disadvantages of asexual reproduction

Sexual reproduction
Define sexual reproduction and fertilisation

Haploid and diploid cells
Advantages and disadvantages of sexual reproduction

Sexual reproduction in plants
Parts of insect-pollinated and wind-pollinated flowers and their functions
Define pollination
Fertilisation
Adaptations of insect-pollinated and wind-pollinated flowers
Investigate conditions needed for germination

Define self-pollination and cross-pollination
Implications of self-pollination to a species
Growth of pollen tube and fertilisation

Sexual reproduction in humans
Parts of male and female reproductive systems
Describe fertilisation
Adaptive features of sperm and eggs
Development of embryo
Growth and development of fetus
Antenatal care
Labour and birth

Compare male and female gametes
Functions of the placenta and umbilical cord
Passage of toxins and viruses across placenta
Comparing breast feeding and bottle feeding

Sex hormones in humans
Puberty, hormones and secondary sexual characteristics
Menstrual cycle

Sites of production and roles of hormones related to menstrual cycle and pregnancy

Methods of birth control in humans
Methods of birth control

Use of hormones in fertility treatment and contraception
Artificial insemination
In vitro fertilisation
Social implications of contraception and fertility treatments

Sexually transmitted infections (STIs)
Define sexually transmitted infection
HIV
Spread and control of STIs

How HIV affects the immune system

No organism can live for ever, but part of it lives on in its offspring. Offspring are produced by the process of reproduction. This process may be **sexual** or **asexual**, but in either case it results in the continuation of the species.

Asexual reproduction

Key definition
Asexual reproduction is the process resulting in the production of genetically identical offspring from one parent.

Asexual means 'without sex' and this method of reproduction does not involve gametes (sex cells). In the single-celled protoctista or in bacteria, the cell simply divides into two and each new cell becomes an independent organism.

In more complex organisms, part of the body may grow and develop into a separate individual. For example, a small piece of stem planted in the soil may form roots and grow into a complete plant.

Bacteria reproduce by cell division or **fission**. Any bacterial cell can divide into two and each daughter cell becomes an independent bacterium (Figure 1.31). In some cases, this cell division can take place every 20 minutes so that, in a very short time, a large colony of bacteria can be produced. This is one reason why a small number of bacteria can seriously contaminate our food products (see Chapter 10). This kind of reproduction, without the formation of gametes (sex cells), is called **asexual reproduction**.

Asexual reproduction in fungi

Fungi have sexual and asexual methods of reproduction. In the asexual method they produce single-celled, haploid spores. These are dispersed, often by air currents and, if they reach a suitable situation, they grow new hyphae, which develop into a mycelium (see Figures 1.25 and 1.26).

Penicillium and *Mucor* are examples of mould fungi that grow on decaying food or vegetable matter. *Penicillium* is a genus of mould fungi that grows on decaying vegetable matter, damp leather

and citrus fruits. The mycelium grows over the food, digesting it and absorbing nutrients. Vertical hyphae grow from the mycelium and, at their tips, produce chains of spores (Figures 16.1 and 16.2). These give the colony a blue-green colour and a powdery appearance (see Figure 19.17). The spores are dispersed by air currents and, if they reach a suitable substrate, grow into a new mycelium.

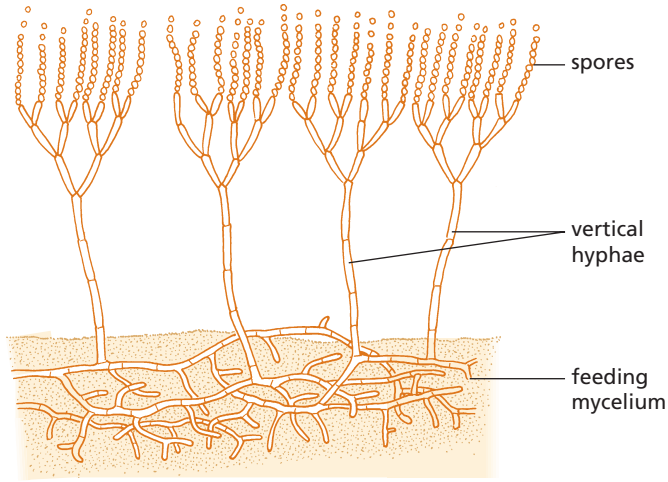


Figure 16.1 *Penicillium sp.*

Figure 16.2 Scanning electron micrograph of *Penicillium* spores

Mucor feeds, grows and reproduces in a similar way to *Penicillium*, but *Mucor* produces spores in a slightly different way. Instead of chains of spores at the tips of the vertical hyphae, *Mucor* forms spherical sporangia, each containing hundreds of spores (Figure 16.3). These are dispersed on the feet of insects or by the splashes of rain drops.

The gills on the underside of a mushroom or toadstool (Figures 16.4 and 16.5) produce spores. Puffballs release clouds of spores (Figure 16.6).

Figure 16.3 Asexual reproduction in *Mucor*. The black spheres are sporangia that have not yet discharged their spores (×160).

Figure 16.4 Toadstools growing on a fallen tree. The toadstools are the reproductive structures that produce spores. The feeding hyphae are inside the tree, digesting the wood.

Figure 16.5 A bracket fungus. The 'brackets' are the reproductive structures. The mycelium in the trunk feeds on living tissue and will eventually kill the tree.

Figure 16.6 Puffball dispersing spores. When a raindrop hits the ripe puffball, a cloud of spores is ejected.

Figure 16.7 Bryophyllum. The plantlets are produced from the leaf margin. When they fall to the soil below, they grow into independent plants.

Asexual reproduction in flowering plants (vegetative propagation)

Although all flowering plants reproduce sexually (that is why they have flowers), many of them also have asexual methods.

Several of these asexual methods (also called '**vegetative propagation**') are described below. When vegetative propagation takes place naturally, it usually results from the growth of a lateral bud on a stem which is close to, or under, the soil. Instead of just making a branch, the bud produces a complete plant with roots, stem and leaves. When the old stem dies, the new plant is independent of the parent that produced it.

An unusual method of vegetative propagation is shown by Bryophyllum (Figure 16.7).

Stolons and rhizomes

The flowering shoots of plants such as the strawberry and the creeping buttercup are very short and, for the most part, below ground. The stems of shoots such as these are called **rootstocks**. The rootstocks bear leaves and flowers. After the main shoot has flowered, the lateral buds produce long shoots, which grow horizontally over the ground (Figure 16.8). These shoots are called **stolons** (or 'runners'), and have only small, scale-leaves at their nodes and very long internodes. At each node there is a bud that can produce not only a shoot, but roots as well. Thus a complete plant may develop and take root at the node, nourished for a time by food sent from the parent plant through the stolon. Eventually, the stolon dries up and withers, leaving an independent daughter plant growing a short distance away from the parent. In this way a strawberry plant can produce many daughter plants by vegetative propagation in addition to producing seeds.

In many plants, horizontal shoots arise from lateral buds near the stem base, and grow under the ground. Such underground horizontal stems are called **rhizomes**. At the nodes of the rhizome are buds, which may develop to produce shoots above the ground. The shoots become independent plants when the connecting rhizome dies.

Many grasses propagate by rhizomes; the couch grass (Figure 16.9) is a good example. Even a small piece of rhizome, provided it has a bud, can produce a new plant.

In the bracken, the entire stem is horizontal and below ground. The bracken fronds you see in summer are produced from lateral buds on a rhizome many centimetres below the soil.