Section 3
Organisms exchange substances with their environment

Chapter titles

Introduction

All cells and organisms exchange material between themselves and their environment. To enter or leave an organism, substances must pass across a plasma membrane. Single-celled and small multicellular organisms can satisfactorily exchange materials over their body surfaces using diffusion alone, especially if their metabolic rate is low. As organisms evolved and became larger, their surface area to volume ratios decreased and specialised respiratory surfaces evolved to meet the increasing requirement to exchange ever larger quantities of materials.

Where large size is combined with a high metabolic rate there is a requirement for a mass transport system to move substances between the exchange surface and the cells of which the organism is composed. In animals these systems often involve circulating a specialised transport medium (blood) through vessels using a pump (heart).

Plants do not move from place to place and have a relatively low metabolic rate and consequently reduced demand for oxygen and glucose. Coupled with their large surface area, essential for obtaining light for photosynthesis, they have not evolved a pumped circulatory system. Plants do, however, transport water up from their roots to the leaves and distribute the products of photosynthesis. Their mass transport system comprises vessels too – xylem and phloem, but the movement of fluid within them is largely a passive process.

The internal environment of a cell or organism differs from the environment around it. The cells of large multicellular animals are surrounded by tissue fluid, the composition of which is kept within a suitable metabolic range. In both plants and animals, it is the mass transport system that maintains the final diffusion gradients which allows substances to be exchanged across cell-surface membranes.

Working scientifically

Studying exchange between organisms and the environment allows you to carry out practical work and to develop practical skills. A required practical activity is the dissection of an animal or plant gas exchange system or mass transport system or of an organ within such a system.

You will require a range of mathematical skills; in particular the ability to change the subject of an equation and calculate the surface areas and volumes of various shapes.

What you already know

The material in this unit is intended to be self-explanatory. However, there is some knowledge from GCSE that will aid your understanding of this section. This information includes:

- ▢ The effectiveness of a gas-exchange surface is increased by having a large surface area, being thin, having an efficient blood supply and being ventilated.
- ▢ In humans the surface area of the lungs is increased by alveoli and that of the small intestine by villi. The villi provide a large surface area with an extensive network of capillaries to absorb the products of digestion by diffusion and active transport.
- ▢ Breathing in involves the ribcage moving out and up and the diaphragm becoming flatter. Breathing out involves these changes being reversed.
- ▢ In plants, water and mineral ions are absorbed by roots, the surface area of which is increased by root hairs.
- ▢ Plants have stomata in their leaves through which carbon dioxide and oxygen are exchanged with the atmosphere by diffusion. The size of stomata is controlled by guard cells that surround them and help control water loss.
- ▢ In flowering plants, xylem tissue transports water and mineral ions from the roots to the stem and leaves and phloem tissue carries dissolved sugars from the leaves to the rest of the plant.
- ▢ In animals a circulatory system transports substances using a heart, which is a muscular organ with four main chambers – left and right atria and ventricles.
- ▢ Blood flows from the heart to the organs through arteries and returns through veins. Arteries have thick walls containing muscle and elastic fibres. Veins have thinner walls and often have valves to prevent back-flow of blood.
- ▢ Blood is a tissue and consists of plasma in which red blood cells, white blood cells and platelets are suspended.
- ▢ Red blood cells have no nucleus and are packed with haemoglobin. In the lungs haemoglobin combines with oxygen to form oxyhaemoglobin. In other organs oxyhaemoglobin splits up into haemoglobin and oxygen.
- ▢ White blood cells have a nucleus and form part of the body's defence system against microorganisms.

6 Exchange

6.1 Exchange between organisms and their environment

Learning objectives

- → Explain how the size of an organism and its structure relate to its surface area to volume ratio.
- → Describe how larger organisms increase their surface area to volume ratio.
- → Explain how surfaces are specially adapted to facilitate exchange.

Specification reference: 3.3.1

The external environment is different from the internal environment found within an organism and within its cells. To survive, organisms transfer materials between the two environments. This transfer takes place at exchange surfaces and always involves crossing cell plasma membranes. The environment around the cells of multicellular organisms is called **tissue fluid**. The majority of cells are too far from exchange surfaces for diffusion alone to supply or remove their tissue fluid with the various materials needed to keep its composition relatively constant. Therefore, once absorbed, materials are rapidly distributed to the tissue fluid and the waste products returned to the exchange surface for removal. This involves a mass transport system. It is this mass transport system that maintains the diffusion gradients that bring materials to and from the cell-surface membranes.

The size and metabolic rate of an organism will affect the amount of each material that is exchanged. For example, organisms with a high metabolic rate exchange more materials and so require a larger surface area to volume ratio. In turn this is reflected in the type of exchange surface and transport system that evolved to meet the requirements of each organism. In this chapter we will investigate the adaptations of exchange surfaces and transport systems in a variety of organisms.

Examples of things that need to be interchanged between an organism and its environment include: respiratory gases (oxygen and carbon dioxide); nutrients (glucose, fatty acids, amino acids, vitamins, minerals); excretory products (urea and carbon dioxide); and heat.

Except for heat, these exchanges can take place in two ways:

- passively (no metabolic energy is required), by **diffusion** and **osmosis**
- actively (metabolic energy is required), by **active transport**.

Surface area to volume ratio

Exchange takes place at the surface of an organism, but the materials absorbed are used by the cells that mostly make up its volume. For exchange to be effective, the exchange surface(s) of the organism must be large compared with its volume.

Small organisms have a surface area that is large enough, compared with their volume, to allow efficient exchange across their body surface. However, as organisms become larger, their volume increases at a faster rate than their surface area (Table 1). Because of this, simple diffusion of substances across the outer surface can only meet the needs of relatively inactive organisms. Even if the outer surface could supply enough of a substance, it would still take too long for it to reach the middle of the organism if diffusion alone was the method of transport. Organisms have evolved one or more of the following features:

Study tip

In a cell the lowest oxygen concentration is inside the mitochondria, where oxygen is used up in respiration. Mitochondria also contain the highest concentration of carbon dioxide. This maintains the diffusion gradient for these gases in and out of the cell.

Maths link

MS 4.1, see Chapter 11.

Table 1 *How the surface area to volume ratio gets smaller as an object becomes larger*

Length of edge of a cube / cm	Surface area of whole cube (area of one side × 6 sides) / cm^2	Volume of cube (length × width × height) / cm^3	Ratio of surface area to volume (surface area ÷ volume)
1	1 × 6 = **6**	1 × 1 × 1 = **1**	$\frac{6}{1}$ = **6.0 : 1**
2	4 × 6 = **24**	2 × 2 × 2 = **8**	$\frac{24}{8}$ = **3.0 : 1**
3	9 × 6 = **54**	3 × 3 × 3 = **27**	$\frac{54}{27}$ = **2.0 : 1**
4	16 × 6 = **96**	4 × 4 × 4 = **64**	$\frac{96}{64}$ = **1.5 : 1**
5	25 × 6 = **150**	5 × 5 × 5 = **125**	$\frac{150}{125}$ = **1.2 : 1**
6	36 × 6 = **216**	6 × 6 × 6 = **216**	$\frac{216}{216}$ = **1.0 : 1**

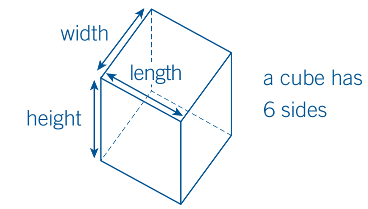


Figure 1 *Calculating volume*

- a flattened shape so that no cell is ever far from the surface (e.g. a flatworm or a leaf)
- specialised exchange surfaces with large areas to increase the surface area to volume ratio (e.g., lungs in mammals, gills in fish).

You may be asked to calculate the surface area to volume ratio of cells with different shapes. To make these calculations reasonably straightforward, cells or organisms may have to be assumed to have a uniform shape although in practice they almost never do.

Maths link

MS 0.3 and 4.1, see Chapter 11.

Calculating the surface area to volume ratio of cells with different shapes

For example, let us assume a cell has the shape of a sphere that is 10 μm in diameter. The surface area of a sphere is calculated using the formula: $4\pi r^2$

In our example: r = 5 μm (radius = half the diameter) and we will use the value of π as 3.14.

Therefore the surface area of the cell = 4 × 3.14 × (5 × 5) = 314 μm^2

The volume of a sphere is calculated using the formula: $\frac{4}{3}\pi r^3$

Therefore the volume of the cell = $\frac{4}{3}$ × 3.14 × (5 × 5 × 5) = 523.33 μm^3

The surface area to volume ratio is therefore 314 ÷ 523.33 = 0.6: 1

Features of specialised exchange surfaces

To allow effective transfer of materials across specialised exchange surfaces by diffusion or active transport, exchange surfaces show the following characteristics:

- a large surface area relative to the volume of the organism which increases the rate of exchange
- very thin so that the diffusion distance is short and therefore materials cross the exchange surface rapidly
- selectively permeable to allow selected materials to cross

Hint

Remember that substances not only have to move into cells through the cell-surface membrane but also into organelles like mitochondria through the plasma membrane that surrounds them. All plasma membranes are therefore thin not just cell-surface membranes.

Summary questions

1. Name **four** general things that need to be exchanged between organisms and their environment.
2. Calculate the surface area to volume ratio of a cube that has sides 10 mm long.
3. Name **three** factors that affect the rate of diffusion of substances into cells.

- movement of the environmental medium, for example, air, to maintain a diffusion gradient
- A transport system to ensure the movement of the internal medium, for example blood, in order to maintain a diffusion gradient.

We saw in Topic 4.2 that the relationship between certain of these factors can be expressed as:

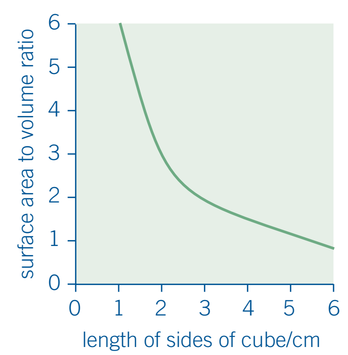
$$\textbf{diffusion} \propto \frac{\textbf{surface area} \times \textbf{difference in concentration}}{\textbf{length of diffusion path}}$$

Being thin, specialised exchange surfaces are easily damaged and dehydrated. They are therefore often located inside an organism. Where an exchange surface is located inside the body, the organism needs to have a means of moving the external medium over the surface, e.g. a means of ventilating the lungs in a mammal.

Significance of the surface area to volume ratio in organisms

The graph in Figure 2 shows the surface area to volume ratios of different-sized cubes. The ratios are actually 1:1, 2:1,3:1 etc. but are shown as single numbers for ease of plotting.

1. Microscopic organisms obtain their oxygen by diffusion in across their body surface. Using the graph, explain how they are able to obtain sufficient oxygen for their needs.
2. The blue whale (Figure 3) is the largest organism on the planet. It spends much of its life in cold waters with temperatures between 0 °C and 6 °C. Use the graph to explain one way in which large size is an advantage to blue whales.



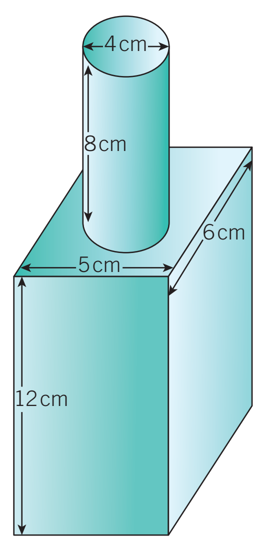
▲ **Figure 2** *Surface area to volume ratios*

Calculating a surface area to volume ratio

Consider the shape shown in Figure 4, which has dimensions marked on it. Use the information below to calculate the ratio of surface area to volume of this shape (to two decimal places).

The area of a disc (like those at the ends of an enclosed cylinder) is calculated using the formula πr^2

The external surface area of an enclosed cylinder is calculated using the formula $2\pi rh + 2\pi r^2$.



▲ **Figure 4**

Maths link

MS 0.3 and 4.1, see Chapter 11.

6.2 Gas exchange in single-celled organisms and insects

Learning objectives

- → Describe how single-celled organisms exchange gases.
- → Explain how terrestrial insects balance the need to exchange gases with the need to conserve water
- → Explain how insects exchange gases.

Specification reference: 3.3.2

Gas exchange in single-celled organisms

Single-celled organisms are small and therefore have a large surface area to volume ratio. Oxygen is absorbed by diffusion across their body surface, which is covered only by a cell-surface membrane. In the same way, carbon dioxide from respiration diffuses out across their body surface. Where a living cell is surrounded by a cell wall, this is no additional barrier to the diffusion of gases.

Gas exchange in insects

As with all terrestrial organisms, insects have evolved mechanisms to conserve water. The increase in surface area required for gas exchange conflicts with conserving water because water will evaporate from it. How insects overcome water loss is discussed in Topic 6.5. For gas exchange, insects have evolved an internal network of tubes called **tracheae**. The tracheae are supported by strengthened rings to prevent them from collapsing. The tracheae divide into smaller dead-end tubes called **tracheoles**. The tracheoles extend throughout all the body tissues of the insect. In this way atmospheric air, with the oxygen it contains, is brought directly to the respiring tissues, as there is a short diffusion pathway from a tracheole to any body cell.

Respiratory gases move in and out of the tracheal system in three ways.

- **Along a diffusion gradient**. When cells are respiring, oxygen is used up and so its concentration towards the ends of the tracheoles falls. This creates a diffusion gradient that causes gaseous oxygen to diffuse from the atmosphere along the tracheae and tracheoles to the cells. Carbon dioxide is produced by cells during respiration. This creates a diffusion gradient in the opposite direction. This causes gaseous carbon dioxide to diffuse along the tracheoles and tracheae from the cells to the atmosphere. As diffusion in air is much more rapid than in water, respiratory gases are exchanged quickly by this method.
- **Mass transport**. The contraction of muscles in insects can squeeze the trachea enabling mass movements of air in and out. This further speeds up the exchange of respiratory gases.
- **The ends of the tracheoles are filled with water**. During periods of major activity, the muscle cells around the tracheoles respire carry out some anaerobic respiration. This produces lactate, which is soluble and lowers the water potential of the muscle cells. Water therefore moves into the cells from the tracheoles by osmosis. The water in the ends of the tracheoles decreases in volume and in doing so draws air further into them. This means the final diffusion pathway is in a gas rather than a liquid phase, and therefore diffusion is more rapid. This increases the rate at which air is moved in the tracheoles but leads to greater water evaporation.

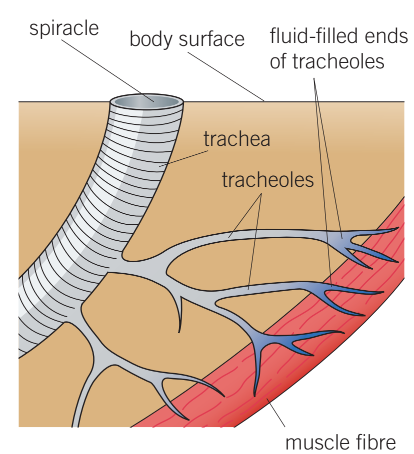
Gases enter and leave tracheae through tiny pores, called **spiracles**, on the body surface. The spiracles may be opened and closed by a valve. When the spiracles are open, water vapour can evaporate from

Synoptic link

As a starting point for this topic, it would be useful to revise Topics 4.2 and 4.3.

Hint

Every cell of an insect is only a very short distance from one of the tracheae or tracheoles and so the diffusion pathway is always short.

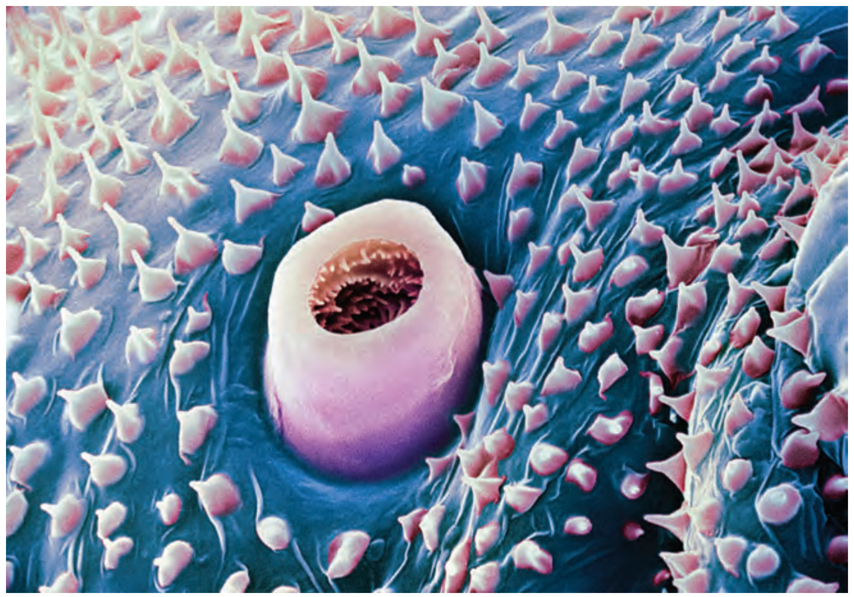


▲ **Figure 1** *Part of an insect tracheal system* the insect. For much of the time insects keep their spiracles closed to prevent this water loss. Periodically they open the spiracles to allow gas exchange. Part of an insect tracheal system is illustrated in Figure 1.

The tracheal system is an efficient method of gas exchange. It does, however, have some limitations. It relies mostly on diffusion to exchange gases between the environment and the cells. For diffusion to be effective, the diffusion pathway needs to be short which is why insects are of a small size. As a result the length of the diffusion pathway limits the size that insects can attain. Not that being small has hindered insects. They are one of the most successful groups of organisms on Earth.

Practical link

Required practical 5. Dissection of animal or plant gas exchange system or mass transport system or of an organ within such a system.



▲ **Figure 2** *Scanning electron micrograph (SEM) of a spiracle of an insect*

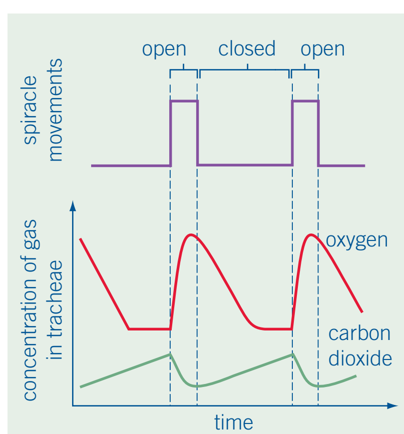
Summary questions

1. Name the process by which carbon dioxide is removed from a single-celled organism.
2. Explain why there is a conflict in terrestrial insects between gas exchange and conserving water.
3. Explain how the tracheal system limits the size of insects.

Spiracle movements

An experiment was carried out to measure the concentration of oxygen and carbon dioxide in the tracheal system of an insect over a period of time. During the experiment the opening and closing of the insect's spiracles was observed and recorded. The results are shown in Figure 3.

1. Describe what happens to the concentration of oxygen in the tracheae when the spiracles are closed.
2. Suggest an explanation for this change in the concentration of oxygen when the spiracles are closed.
3. Use the information provided by the graph to suggest what causes the spiracles to open.
4. Suggest an advantage of these spiracle movements to a terrestrial insect.
5. Fossil insects have been discovered that are larger than insects that occur on Earth today. What does this suggest about the composition of the atmosphere at the time when these fossil insects lived.



▲ **Figure 3**

6.3 Gas exchange in fish

Learning objectives

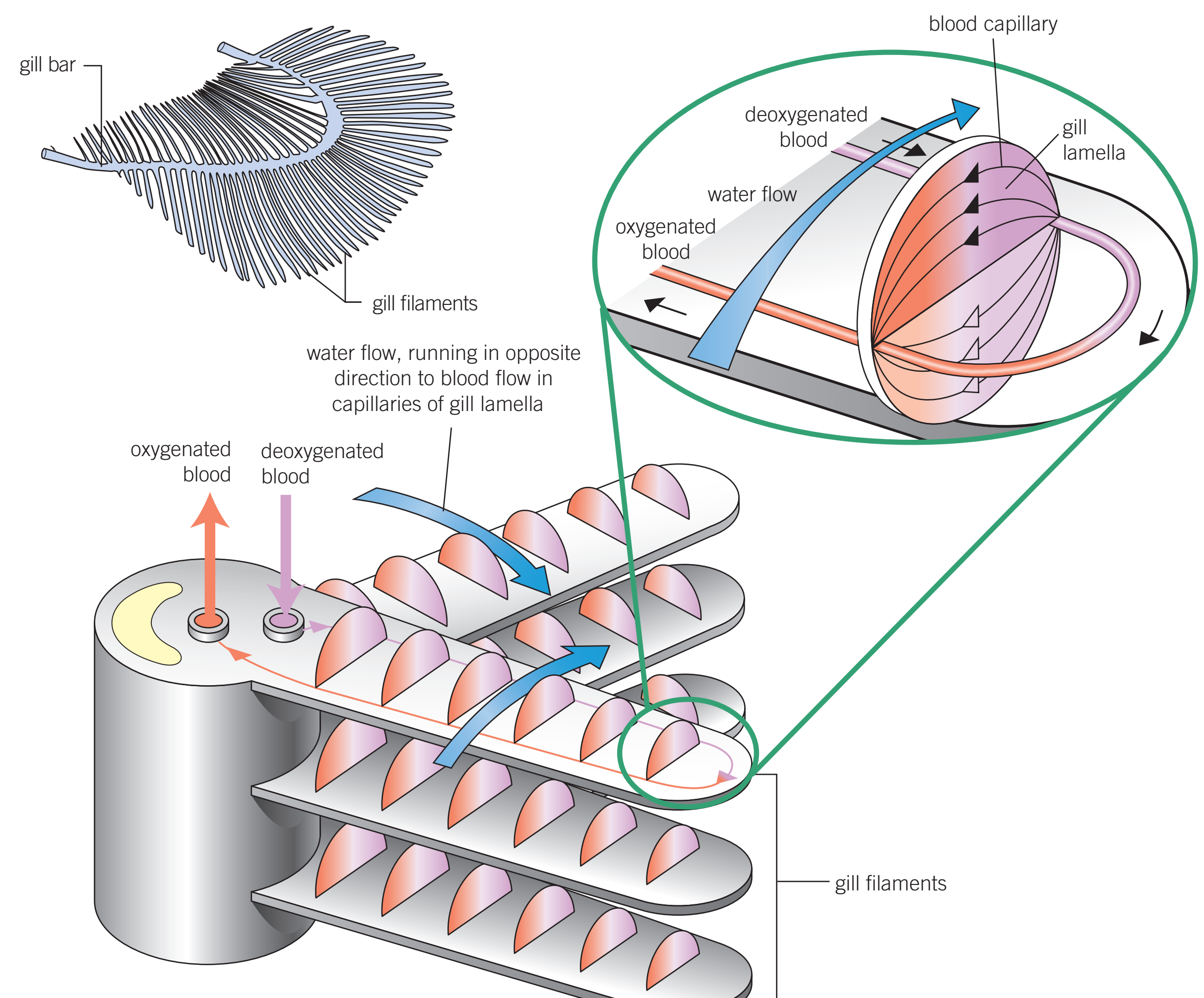
- → Describe the structure of fish gills.
- → Describe how water is passed along fish gills.
- → Explain the difference between parallel flow and countercurrent flow.
- → Explain how countercurrent flow increases the rate of gas exchange.

Specification reference: 3.3.2

Fish have a waterproof, and therefore a gas-tight, outer covering. Being relatively large they also have a small surface area to volume ratio. Their body surface is therefore not adequate to supply and remove their respiratory gases and so, like insects and humans, they have evolved a specialised internal gas exchange surface: the gills.

Structure of the gills

The gills are located within the body of the fish, behind the head. They are made up of **gill filaments**. The gill filaments are stacked up in a pile, rather like the pages in a book. At right angles to the filaments are **gill lamellae**, which increase the surface area of the gills. Water is taken in through the mouth and forced over the gills and out through an opening on each side of the body. The position and arrangement of the gill filaments and gill lamellae are shown in Figure 1. From this figure you will notice that the flow of water over the gill lamellae and the flow of blood within them are in opposite directions. This is known as a **countercurrent flow**.



▲ **Figure 1** *Arrangement of gills in a fish and direction of water flow over them*

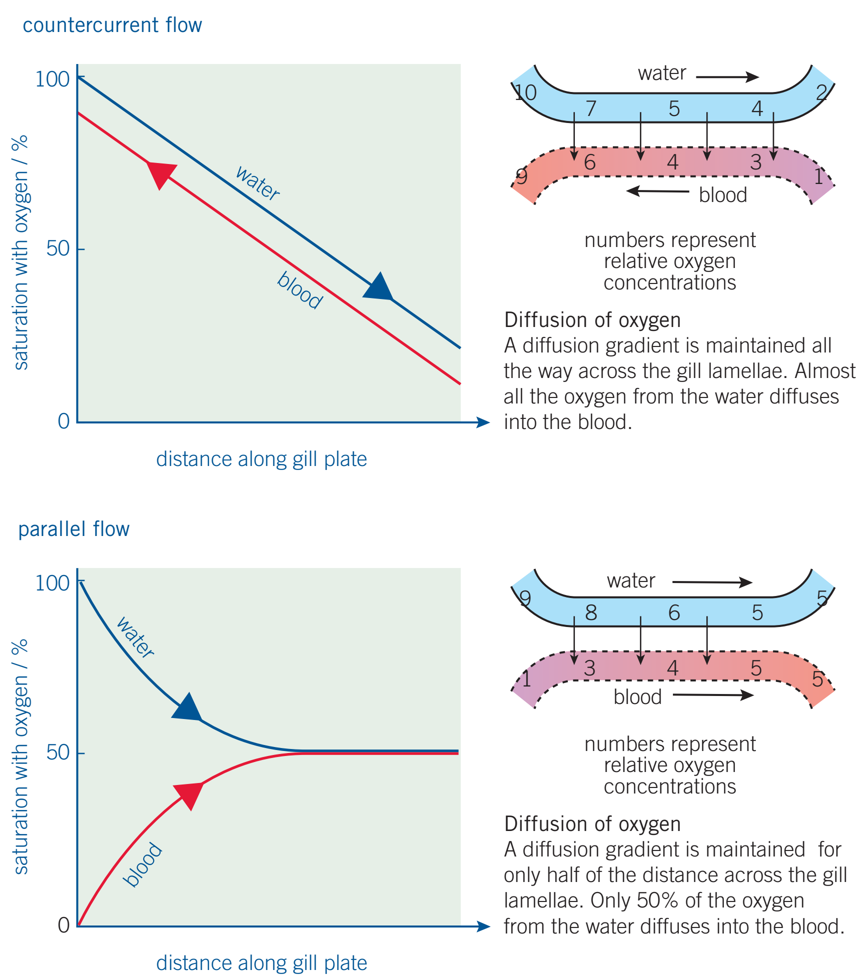
It is important for ensuring that the maximum possible gas exchange is achieved. If the water and blood flowed in the same direction, far less gas exchange would take place.

The countercurrent exchange principle

The essential feature of the countercurrent exchange system is that the blood and the water that flow over the gill lamellae do so in opposite directions. This arrangement means that:

- Blood that is already well loaded with oxygen meets water, which has its maximum concentration of oxygen. Therefore **diffusion** of oxygen from the water to the blood takes place.
- Blood with little oxygen in it meets water which has had most, but not all, of its oxygen removed. Again, diffusion of oxygen from the water to blood takes place.

As a result, a diffusion gradient for oxygen uptake is maintained across the entire width of the gill lamellae. In this way, about 80% of the oxygen available in the water is absorbed into the blood of the fish. If the flow of water and blood had been in the same direction (parallel flow), the diffusion gradient would only be maintained across part of the length of the gill lamellae and only 50% of the available oxygen would be absorbed by the blood.



▲ **Figure 2** *Parallel flow and countercurrent flow in the gills of a fish*

Study tip

Maintaining steep diffusion gradients for oxygen involves bringing it constantly to the exchange surface (by ventilation) and carrying it away from the surface (by mass transport in the blood).

Study tip

Always refer to blood and water flowing in opposite directions in the countercurrent system. Describe how this maintains a difference in oxygen concentration and a diffusion gradient across the whole length of the gill lamellae.

Summary questions

1. In relation to fish gills, describe what is meant by countercurrent flow.
2. Outline why countercurrent flow is an efficient means of exchanging gases across the gills of fish.
3. Mackerel are active, fast-swimming fish while plaice spend most of their lives moving slowly on the sea bed. There are differences in the gills of these two types of fish. Suggest what these differences might be
4. Water flow over fish gills is one-way whereas the flow of air in and out of the lungs is two-way. Suggest why one-way flow is an advantage to fish.

6.4 Gas exchange in the leaf of a plant

Learning objectives

→ Describe how plants exchange gases.
→ Describe the structure of a dicotyledonous plant leaf.
→ Explain the adaptations of leaves for efficient gas exchange.

Specification reference: 3.3.2

Like animal cells, all plant cells require oxygen and produce carbon dioxide during respiration. When it comes to gas exchange, however, plants show one important difference from animals. Some plant cells carry out photosynthesis. During photosynthesis, plant cells take in carbon dioxide and produce oxygen. At times the gases produced in one process can be used for the other. This reduces gas exchange with the external air. Overall, this means that the volumes and types of gases that are being exchanged by a plant leaf change. This depends on the balance between the rates of photosynthesis and respiration.

- When photosynthesis is taking place, although some carbon dioxide comes from respiration of cells, most of it is obtained from the external air. In the same way, some oxygen from photosynthesis is used in respiration but most of it **diffuses** out of the plant.
- When photosynthesis is not occurring, for example, in the dark, oxygen diffuses into the leaf because it is constantly being used by cells during respiration. In the same way, carbon dioxide produced during respiration diffuses out.

Structure of a plant leaf and gas exchange

In some ways, gas exchange in plants is similar to that of insects (see Topic 6.2).

- No living cell is far from the external air, and therefore a source of oxygen and carbon dioxide.
- Diffusion takes place in the gas phase (air), which makes it more rapid than if it were in water.

Overall, therefore, there is a short, fast diffusion pathway. In addition, the air spaces inside a leaf have a very large surface area compared with the volume of living tissue. There is no specific transport system for gases, which simply move in and through the plant by diffusion. Most gaseous exchange occurs in the leaves, which show the following adaptations for rapid diffusion:

- many small pores, called stomata, and so no cell is far from a stoma and therefore the diffusion pathway is short (Figure 1)
- numerous interconnecting air-spaces that occur throughout the mesophyll so that gases can readily come in contact with mesophyll cells
- large surface area of mesophyll cells for rapid diffusion.

The structure of a leaf is shown in Figure 2.

Stomata

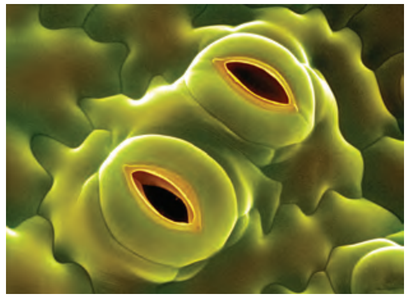
Stomata are minute pores that occur mainly, but not exclusively, on the leaves, especially the underside. Each stoma (singular) is surrounded by a pair of special cells (guard cells). These cells can open and close the stomatal pore (Figure 3). In this way they can control the rate of gaseous exchange. This is important because terrestrial organisms lose water by evaporation. Plants have evolved to balance the conflicting needs of gas exchange and control of water loss. They do this by closing stomata at times when water loss would be excessive.

Study tip

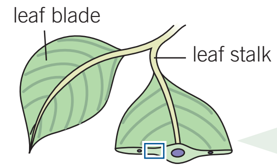
The diffusion gradients in and out of the leaf are maintained by mitochondria carrying out respiration and chloroplasts carrying out photosynthesis.

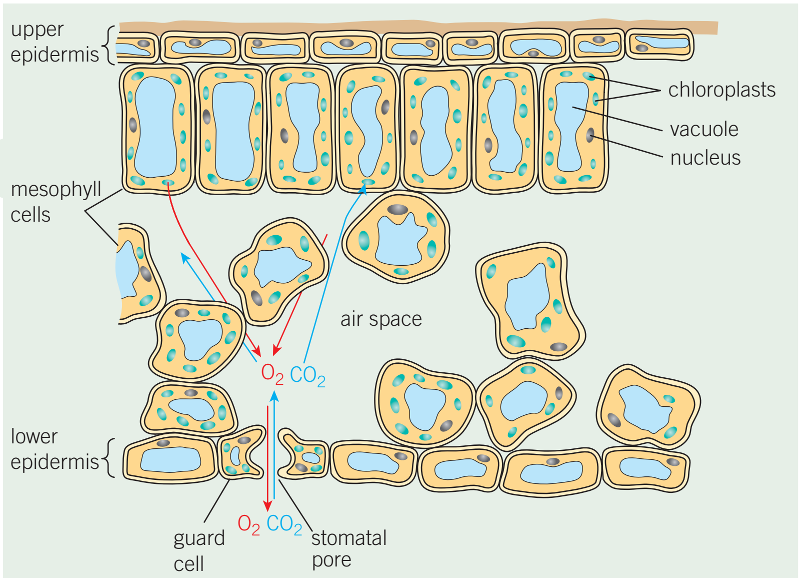
Hint

Remember that plant cells respire all the time, but only plant cells with chloroplasts photosynthesise – and then only when the conditions are right.



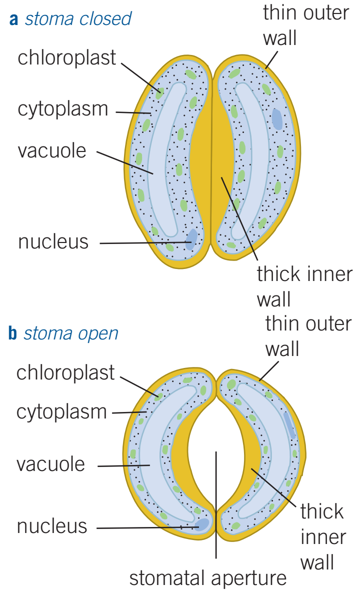
▲ **Figure 1** *False-colour SEM of open stomata on the surface a leaf*





b vertical section through a dicotyledonous leaf

▲ **Figure 2** *Section through a leaf of a dicotyledonous plant showing gas exchange when photosynthesis is taking place*



▲ **Figure 3** *Surface view of a stoma closed and open*

Maths link

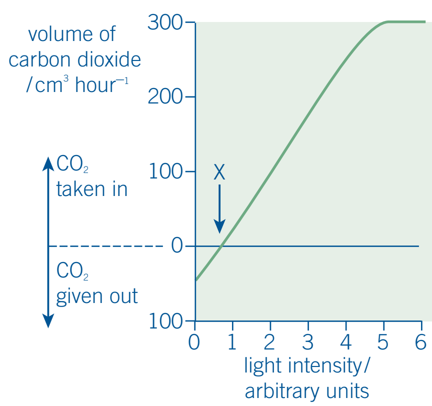
MS 0.3, 1.1 and 3.4, see Chapter 11.

Summary questions

1. State **two** similarities between gas exchange in a plant leaf and gas exchange in a terrestrial insect.
2. State **two** differences between gas exchange in a plant leaf and gas exchange in a terrestrial insect.
3. Explain the advantage to a plant of being able to control the opening and closing of stomata.

Exchange of carbon dioxide

The graph in Figure 4 shows the volume of carbon dioxide produced by a sample of tomato plants at different light intensities.



▲ **Figure 4**

1. Name the process which produces carbon dioxide in the tomato plants.
2. Name the process which uses up carbon dioxide in the tomato plants.
3. Explain why, at point X, carbon dioxide is neither taken up nor given out by the tomato plants.
4. A plant at a light intensity of 10000 lux produced 115 $cm^3 hour^{-1}$ of carbon dioxide. When the light intensity was increased to 15000 lux the amount of carbon dioxide produced was 160 $cm^3 hour^{-1}$. Calculate the percentage increase in carbon dioxide at 15000 lux to four significant figures.
5. Some herbicides cause the stomata of plants to close. Suggest how these herbicides might lead to the death of a plant.
6. Suggest what information is provided by the point at which the line of the graph meets the y-axis.

6.5 Limiting water loss

Learning objectives

→ Explain how terrestrial plants and insects balance the need for gas-exchange and the need to conserve water.

Specification reference: 3.3.2

In terrestrial organisms like insects and plants problems arise from the opposing needs of an efficient gas-exchange system and the requirement to conserve water. The features that make a good gas-exchange system are the same features that increase water loss. In order to survive, terrestrial organisms must limit their water loss without compromising the efficiency of their gas-exchange systems. The gas exchange surfaces of terrestrial organisms are inside the body. The air at the exchange surface is more or less 100% saturated with water vapour. This means there is less evaporation of water from the exchange surface.

Limiting water loss in insects

Most insects are terrestrial (live on land). The problem for all terrestrial organisms is that water easily evaporates from the surface of their bodies and they can become dehydrated. They have evolved adaptations to conserve water.

However, efficient gas exchange requires a thin, permeable surface with a large area. These features conflict with the need to conserve water. Overall, as a terrestrial organism, the insect has to balance the opposing needs of exchanging respiratory gases with limiting water loss.

Insects have evolved the following adaptations that reduce water loss:

- **Small surface area to volume ratio** to minimise the area over which water is lost.
- **Waterproof coverings** over their body surfaces. In the case of insects this covering is a rigid outer skeleton of chitin that is covered with a waterproof cuticle.
- **Spiracles** are the openings of the tracheae at the body surface and these can be closed to reduce water loss. This conflicts with the need for oxygen and so occurs largely when the insect is at rest.

These features mean that insects cannot use their body surface to diffuse respiratory gases in the way a single-celled organism does. Instead they have an internal network of tubes called **tracheae** that carry air containing oxygen directly to the tissues (see Topic 6.2).

▲ **Figure 1** *Conifers have needle-like leaves to reduce water loss*

Limiting water loss in plants

While plants also have waterproof coverings, they cannot have a small surface area to volume ratio. This is because they photosynthesise, and photosynthesis requires a large leaf surface area for the capture of light and for the exchange of gases. So how do plants limit water loss?

To reduce water loss, terrestrial plants have a waterproof covering over parts of the leaves and the ability to close stomata when necessary. Certain plants with a restricted supply of water, have also evolved a range of other adaptations to limit water loss through **transpiration**. These plants are called **xerophytes**.

Xerophytes are plants that are adapted to living in areas where water is in short supply. Without these adaptations these plants would become desiccated and die.

▲ **Figure 2** *Holly has leaves with a thick waxy cuticle that reduces water loss*

Hint

Climate change affects rainfall and rate of evaporation of water. As a result, the distribution of plant species changes. As regions become drier, so the number of xerophytic plants in them increases.

The main way of surviving in habitats where there is a high rate of water loss and a limited water supply is to reduce the rate at which water can be lost through evaporation. As the vast majority of water loss occurs through the leaves, it is these organs that usually show most modifications. Examples of these modifications include:

- **a thick cuticle**. Although the waxy cuticle on leaves forms a waterproof barrier, up to 10% of water loss can still occur by this route. The thicker the cuticle, the less water can escape by this means, for example holly.
- **rolling up of leaves**. Most leaves have their stomata largely, or entirely, confined to the lower epidermis. The rolling of leaves in a way that protects the lower epidermis from the outside helps to trap a region of still air within the rolled leaf. This region becomes saturated with water vapour and so has a very high **water potential**. There is no water potential gradient between the inside and outside of the leaf and therefore no water loss. Marram grass rolls its leaves.
- **hairy leaves**. A thick layer of hairs on leaves, especially on the lower epidermis, traps still, moist air next to the leaf surface. The water potential gradient between the inside and the outside of the leaves is reduced and therefore less water is lost by evaporation. One type of heather plant has this modification.
- **stomata in pits or grooves**. These again trap still, moist air next to the leaf and reduce the water potential gradient. Examples of plants using this mechanism include pine trees.
- **a reduced surface area to volume ratio of the leaves**. We saw in Topic 6.1 that the smaller the surface area to volume ratio, the slower the rate of diffusion. By having leaves that are small and roughly circular in cross-section, as in pine needles, rather than leaves that are broad and flat, the rate of water loss can be considerably reduced. This reduction in surface area is balanced against the need for a sufficient area for photosynthesis to meet the requirements of the plant.

▲ **Figure 3** *This cactus stores water in its swollen stem. The leaves are needle-like to reduce their surface area and hence water loss*

Summary questions

1. Insects and plants face the same problems when it comes to living on land. What is the main problem they share?
2. State **one** modification to reduce water loss that is shared by plants and insects.
3. Insects limit water loss by having a small surface area to volume ratio. Why is this not a feasible way of limiting water loss in plants?
4. Plants such as marram grass roll up their leaves, with the lower epidermis on the inside, to reduce water loss.
   - **a** Explain how rolling up their leaves helps to reduce water loss.
   - **b** Why would rolling the leaf the other way (with the upper epidermis on the inside) not be effective in reducing water loss?

Study tip

When explaining adaptations of xerophytic plants to reduce water loss always relate these adaptations to reducing the water potential gradient and therefore slower diffusion, less water loss from air spaces and hence reduced evaporation of water.

Not only desert plants have problems obtaining water

Xerophytes are typically thought of as desert plants, which show a wide range of adaptations for coping with hot, dry conditions. However, similar adaptations may also be seen in plants found in sand dunes or other dry, windy places in temperate climates where rainfall is high and temperature relatively low. These adaptations are essential because the rain quickly drains away through the sand and out of the reach of the roots, making it difficult for these plants to obtain water. Plants living on salt marshes near the coast may have their roots drenched in water but find it difficult to absorb it. In addition, coastal regions are exposed to high wind speeds, which increase transpiration rates. Plants living in cold regions often have difficulty obtaining water for much of the year. Most plants living in these habitats show xerophytic modifications to enable them to reduce transpiration and so survive.

▲ **Figure 4** *Sand dunes*

1. List **two** reasons why plants growing on sand dunes (Figure 4) need to have xerophytic features even though there is plentiful rainfall.
2. Explain in terms of water potential why salt marsh plants have difficulty absorbing water, despite having plenty around their roots.
3. Explain why plants in cold regions 'have difficulty obtaining water from the soil for much of the year'.
4. Plants living in cold regions often reduce water loss by having leaves with a small surface area to volume ratio. This reduces the surface area available to capture light for photosynthesis. Photosynthesis is, in part, an enzyme-controlled process. Suggest a reason why having a smaller leaf area does not reduce the rate of photosynthesis in the same way as it would for plants in warmer climates.

6.6 Structure of the human gas-exchange system

Learning objectives

- → Describe how the human gas-exchange system is arranged.
- → Explain the functions of the human gas-exchange system.

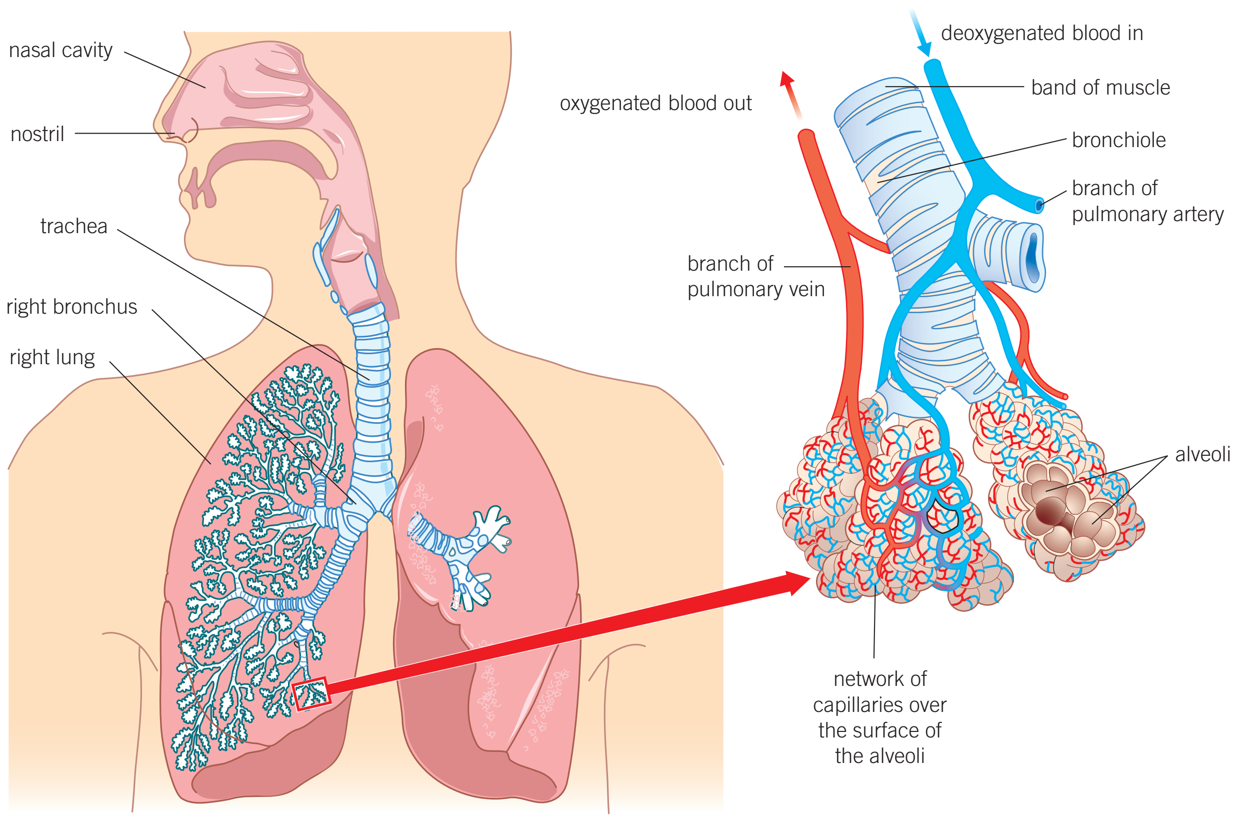
Specification reference: 3.3.2

All aerobic organisms require a constant supply of oxygen to release energy in the form of **ATP** during respiration. The carbon dioxide produced in the process needs to be removed as its build-up could be harmful to the body.

The volume of oxygen that has to be absorbed and the volume of carbon dioxide that must be removed are large in mammals because:

- they are relatively large organisms with a large volume of living cells
- they maintain a high body temperature which is related to them having high metabolic and respiratory rates.

As a result mammals have evolved specialised surfaces, called **lungs**, to ensure efficient gas exchange between the air and their blood.



▲ **Figure 1** *The gross structure of the human gas-exchange system*

Mammalian lungs

The lungs are the site of gas exchange in mammals. They are located inside the body because:

- air is not dense enough to support and protect these delicate structures
- the body as a whole would otherwise lose a great deal of water and dry out.

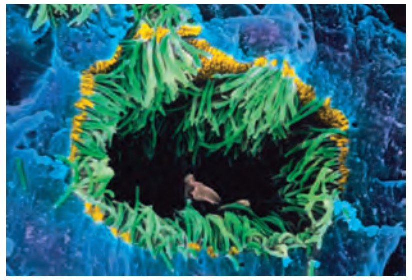
The lungs are supported and protected by a bony box called the **ribcage**. The ribs can be moved by the muscles between them. The lungs are ventilated by a tidal stream of air, thereby ensuring that the air within them is constantly replenished. The main parts of the human gas-exchange system and their structure and functions are described below.

- The **lungs** are a pair of lobed structures made up of a series of highly branched tubules, called bronchioles, which end in tiny air sacs called alveoli.
- The **trachea** is a flexible airway that is supported by rings of cartilage. The cartilage prevents the trachea collapsing as the air pressure inside falls when breathing in. The tracheal walls are made up of muscle, lined with ciliated epithelium and goblet cells.
- The **bronchi** are two divisions of the trachea, each leading to one lung. They are similar in structure to the trachea and, like the trachea, they also produce mucus to trap dirt particles and have cilia that move the dirt-laden mucus towards the throat. The larger bronchi are supported by cartilage, although the amount of cartilage is reduced as the bronchi get smaller.
- The **bronchioles** are a series of branching subdivisions of the bronchi. Their walls are made of muscle lined with epithelial cells. This muscle allows them to constrict so that they can control the flow of air in and out of the alveoli.
- The **alveoli** are minute air-sacs, with a diameter of between 100 μm and 300 μm, at the end of the bronchioles. Between the alveoli there are some **collagen** and elastic fibres. The alveoli are lined with epithelium. The elastic fibres allow the alveoli to stretch as they fill with air when breathing in. They then spring back during breathing out in order to expel the carbon dioxide-rich air. The alveolar membrane is the gas-exchange surface.

Hint

The ending '-ioles' is commonly used in biology to denote a smaller version of a structure. Hence 'bronchioles' are small bronchi, and 'arterioles' are small arteries.

▲ **Figure 2** *False-colour X-ray of the bronchus and bronchioles of a healthy human lung*



▲ **Figure 3** *False-colour SEM of a section of the epithelium of the trachea showing ciliated cells (green)*

Summary questions

1. State **two** reasons why humans need to absorb large volumes of oxygen from the lungs.
2. List in the correct sequence all the structures that air passes through on its journey from the gas-exchange surface of the lungs to the nose.
3. Explain how the cells lining the trachea and bronchus protect the alveoli from damage.

6.7 The mechanism of breathing

Learning objectives

- → Explain how and why air is moved into the lungs when breathing in.
- → Explain how air is moved out of the lungs when breathing out.
- → Explain what is meant by pulmonary ventilation and how it is calculated.

Specification reference: 3.3.2

Hint

Do not write about 'respiration' when you mean 'breathing' and vice versa.

Hint

There are two basic physical laws that will help you to understand the movement of air during breathing:

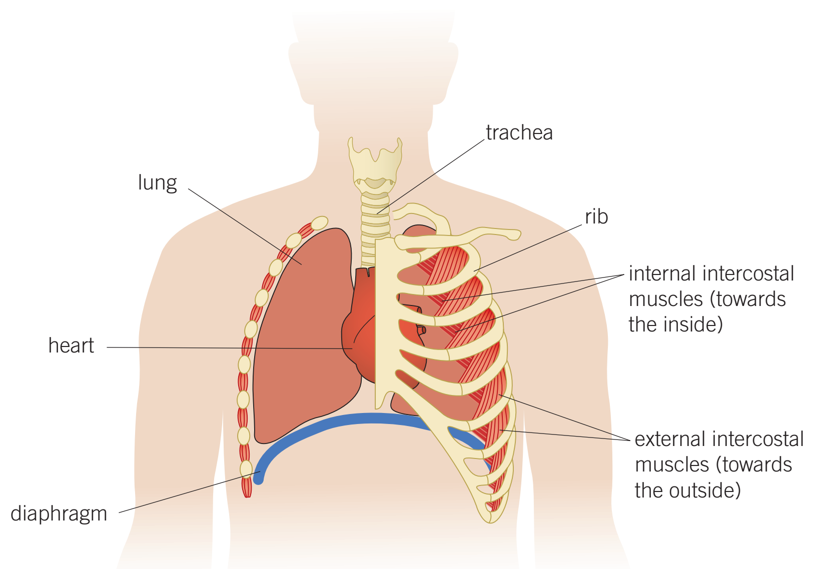
Within a closed container, as the volume of a gas increases its pressure decreases. Similarly, as the volume of a gas decreases so the pressure increases.

Gases move from a region where their pressure is higher to a region where their pressure is lower.

To maintain diffusion of gases across the alveolar epithelium, air is constantly moved in and out of the lungs. This process is called breathing, or **ventilation**. When the air pressure of the atmosphere is greater than the air pressure inside the lungs, air is forced into the lungs. This is called **inspiration** (inhalation). When the air pressure in the lungs is greater than that of the atmosphere, air is forced out of the lungs. This is called **expiration** (exhalation). The pressure changes within the lungs are brought about by the movement of three sets of muscles:

- the diaphragm, which is a sheet of muscle that separates the thorax from the abdomen
- the intercostal muscles, which lie between the ribs. There are two sets of intercostal muscles:
  - the **internal intercostal muscles**, whose contraction leads to expiration
  - the **external intercostal muscles**, whose contraction leads to inspiration.

Figure 1 shows the arrangement of these various muscles.



▲ **Figure 1** *The arrangement of the diaphragm and intercostal muscles*

Inspiration

Breathing in is an active process (it uses energy) and occurs as follows:

- The external intercostal muscles contract, while the internal intercostal muscles relax.
- The ribs are pulled upwards and outwards, increasing the volume of the thorax.
- The diaphragm muscles contract, causing it to flatten, which also increases the volume of the thorax.
- The increased volume of the thorax results in reduction of pressure in the lungs.
- Atmospheric pressure is now greater than pulmonary pressure, and so air is forced into the lungs.

Expiration

Breathing out is a largely passive process (it does not require much energy) and occurs as follows:

- The internal intercostal muscles contract, while the external intercostal muscles relax.
- The ribs move downwards and inwards, decreasing the volume of the thorax.
- The diaphragm muscles relax and so it is pushed up again by the contents of the abdomen that were compressed during inspiration. The volume of the thorax is therefore further decreased.
- The decreased volume of the thorax increases the pressure in the lungs.
- The pulmonary pressure is now greater than that of the atmosphere, and so air is forced out of the lungs.

During normal quiet breathing, the recoil of the elastic tissue in the lungs is the main cause of air being forced out (like air being expelled from a partly inflated balloon). Only under more strenuous conditions such as exercise do the various muscles play a major part.

Summary questions

1. From the graphs in Figure 3, calculate the rate of breathing of this person. Give your answer in breaths per minute. Show how you arrived at your answer.
2. If the volume of air in the lungs when the person inhaled was 3 000 cm^3 calculate the volume of air in the lungs after the person had exhaled. Show your working.
3. Explain how muscles create the change of pressure in the alveoli over the period 0 to 0.5 s.

Pulmonary ventilation

It is sometimes useful to know how much air is taken in and out of the lungs in a given time. To do this we use a measure called pulmonary ventilation rate. Pulmonary ventilation rate is the total volume of air that is moved into the lungs during 1 minute. To calculate it we multiply together two factors:

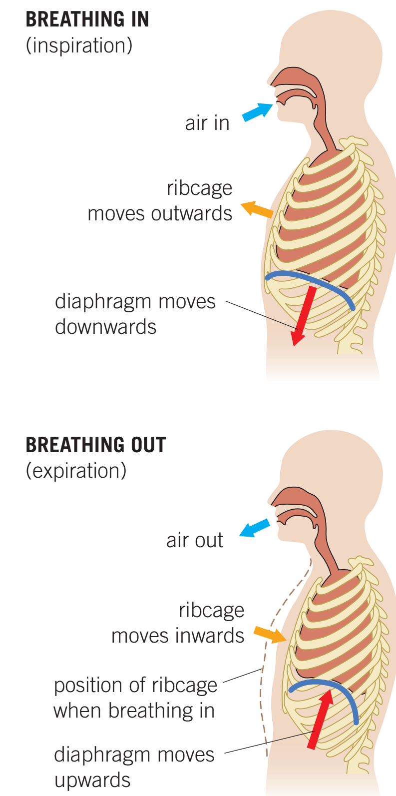
- tidal volume, which is the volume of air normally taken in at each breath when the body is at rest. This is usually around 0.5 dm^3.
- breathing (ventilation) rate, that is, the number of breaths taken in 1 minute. This is normally 12–20 breaths in a healthy adult.

Pulmonary ventilation rate is expressed as $dm^3\,min^{-1}$.

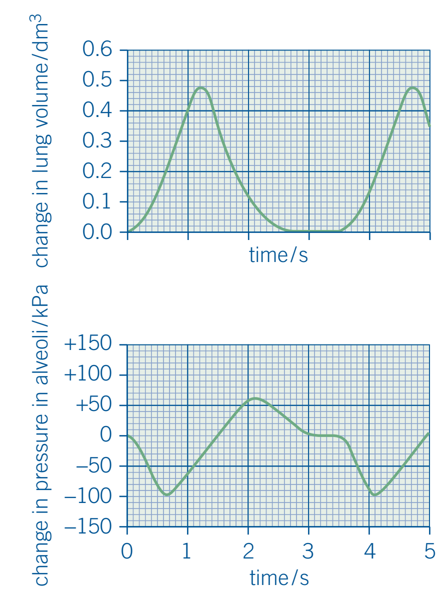
To summarise:

pulmonary ventilation rate = tidal volume × breathing rate
($dm^3\,min^{-1}$) (dm^3) (min^{-1})

1. A person has a pulmonary ventilation rate of 10.2 $dm^3\,min^{-1}$ and a tidal volume of 0.6 dm^3. Calculate the person's breathing rate.



▲ **Figure 2** *Position of ribs and diaphragm during inspiration and expiration*



▲ **Figure 3** *The volume and pressure changes that occurred in the lungs of a person during breathing while at rest*

Maths link

MS 0.1, 2.2, 2.4 and 3.1, see Chapter 11.

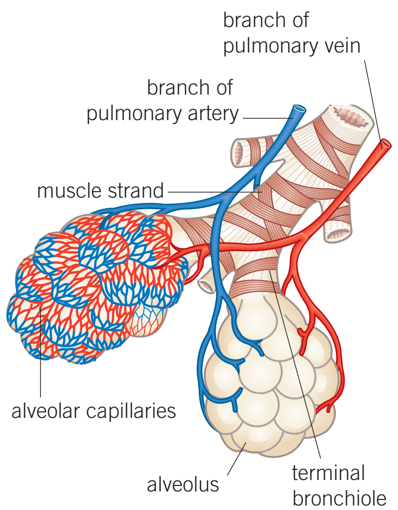
6.8 Exchange of gases in the lungs

Learning objectives

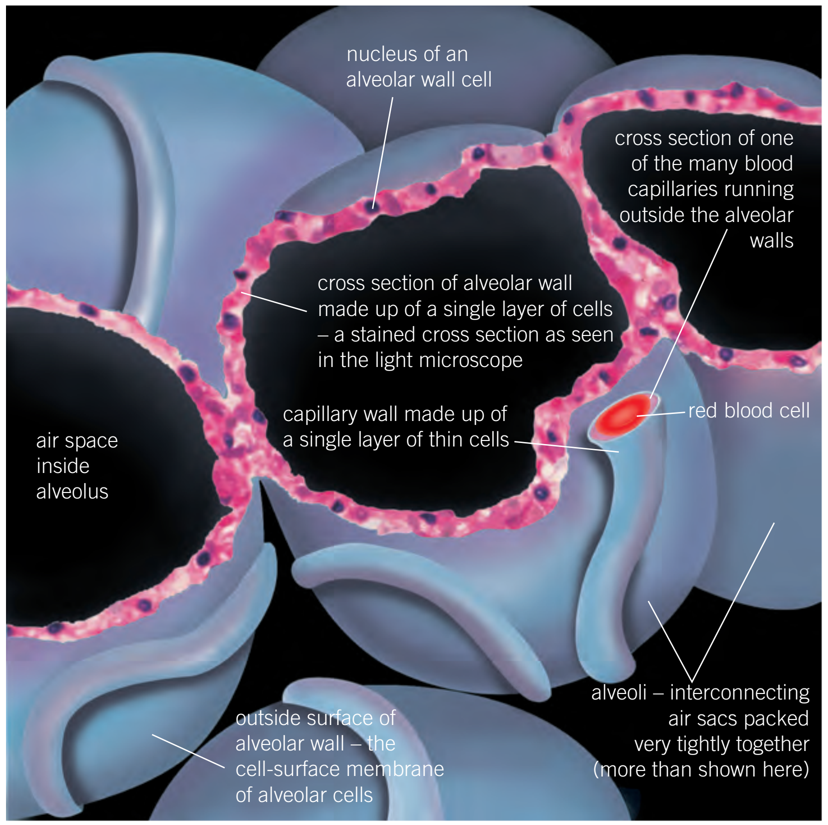
- → Describe the essential features of exchange surfaces.
- → Explain how gases are exchanged in the alveoli of humans.

Specification reference: 3.3.2

The site of gas exchange in mammals is the epithelium of the alveoli. These alveoli are minute air sacs some 100–300 μm in diameter and situated in the lungs. To ensure a constant supply of oxygen to the body, a diffusion gradient must be maintained at the alveolar surface. We saw in Topic 6.1 that, to enable efficient transfer of materials across them, exchange surfaces are thin, partially permeable and have a large surface area. To maintain a diffusion gradient, there also has to be movement of both the environmental medium (for example, air) and the internal medium (for example, blood).

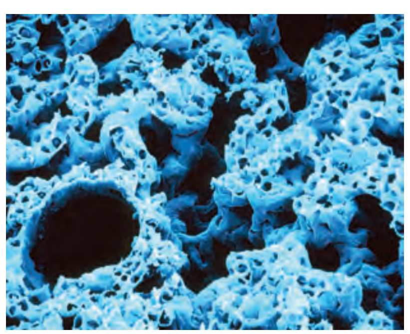


▲ **Figure 1** *Alveoli*



▲ **Figure 2** *External appearance of a group of alveoli*

Being thin, these specialised exchange surfaces are easily damaged and therefore are often located inside an organism for protection. Where an exchange surface, such as the lungs, is located inside the body, the organism has some means of moving the external medium over the surface, for example a means of ventilating the lungs in a mammal. This is because diffusion alone is not fast enough to maintain adequate transfer of oxygen and carbon dioxide along the trachea, bronchi and bronchioles. Breathing is basically a form of mass transport.



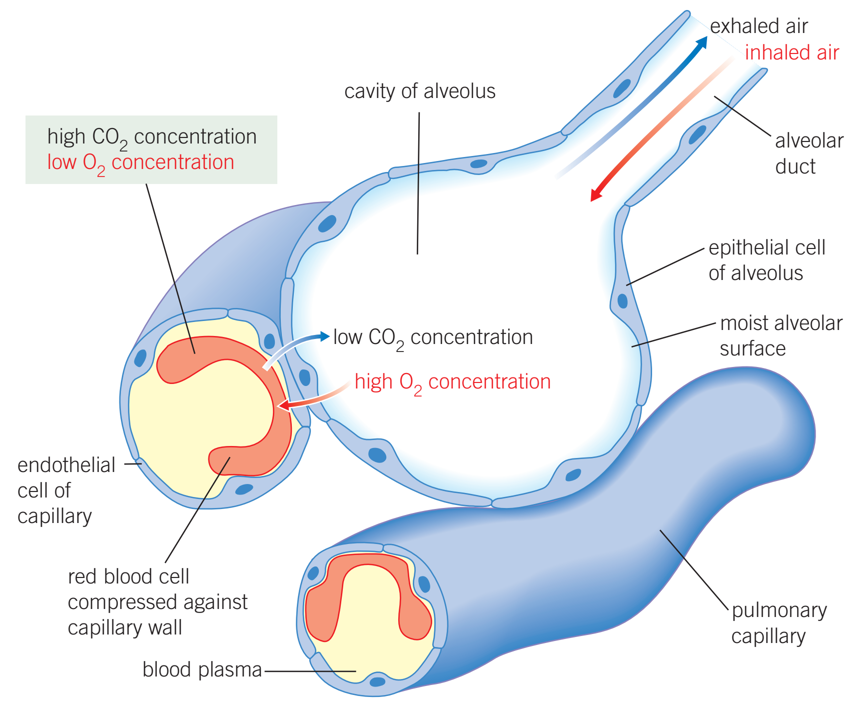
▲ **Figure 3** *False-colour SEM of a section of human lung tissue showing alveoli surrounded by blood capillaries*

Role of the alveoli in gas exchange

There are about 300 million alveoli in each human lung. Their total surface area is around 70 m² – about half the area of a tennis court. Their structure is shown in Figures 1 and 2. Each alveolus is lined with epithelial cells only 0.05 μm to 0.3 μm thick. Around each alveolus is a network of pulmonary capillaries, so narrow (7–10 μm) that red blood cells are flattened against the thin capillary walls in order to squeeze through. These capillaries have walls that are only a single layer of cells thick (0.04–0.2 μm). Diffusion of gases between the alveoli and the blood will be very rapid because:

- red blood cells are slowed as they pass through pulmonary capillaries, allowing more time for diffusion
- the distance between the alveolar air and red blood cells is reduced as the red blood cells are flattened against the capillary walls
- the walls of both alveoli and capillaries are very thin and therefore the distance over which diffusion takes place is very short
- alveoli and pulmonary capillaries have a very large total surface area
- breathing movements constantly ventilate the lungs, and the action of the heart constantly circulates blood around the alveoli. Together, these ensure that a steep concentration gradient of the gases to be exchanged is maintained
- blood flow through the pulmonary capillaries maintains a concentration gradient.

The diffusion of gases in an alveolus is illustrated in Figure 4.



▲ **Figure 4** *Diffusion of gases in an alveolus*

Hint

The diffusion pathway is short because the alveoli have only a single layer of epithelial cells and the blood capillaries have only a single layer of endothelial cells. Don't say they have cells with thin membranes.

Summary questions

1. Explain how each of the following features contributes to the efficiency of gas exchange in alveoli.
   - **a** The wall of each alveolus is not more than 0.3 μm thick.
   - **b** There are 300 million alveoli in each lung.
   - **c** Each alveolus is covered by a dense network of pulmonary blood capillaries.
   - **d** Each pulmonary capillary is very narrow.
2. If the number of alveoli in each lung was increased to 600 million and the pulmonary ventilation was doubled, calculate how many times greater the rate of diffusion would be.

Correlations and causal relationships

A **correlation** occurs when a change in one of two variables is reflected by a change in the other variable.

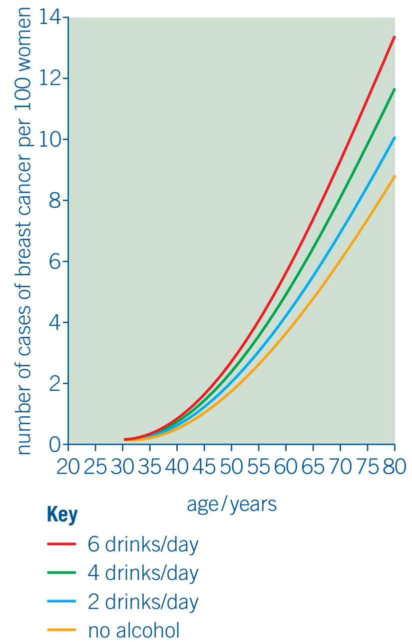
The interpretation of the data in Figure 5 shows that there is a correlation between drinking alcohol and breast cancer. What we *cannot* do from these data, however, is to conclude that drinking alcohol is the **cause** of breast cancer. The data seem to suggest this is the case but there is no actual evidence here to prove it. There needs to be a clear causal connection between drinking alcohol and breast cancer before you we can say that the case is proven. These data alone show only a correlation and not a cause. It could be that women who are stressed drink more alcohol and that it is the stress, rather than the alcohol, that causes breast cancer. To prove that drinking alcohol is the cause of breast cancer we would need experimental evidence to show that some component of the alcoholic drink led directly to women getting breast cancer. Recognising the distinction between a correlation and a causal relationship is a necessary and important skill.

Figure 6 shows how the incidence of lung cancer changes with the number of cigarettes smoked a day. What can we conclude from this data? Well, nothing really. We can see that the more cigarettes that are smoked, the greater are the number of deaths from lung cancer. In other words, there is a positive correlation between the two factors. However, we cannot conclude that it is the cigarette smoke that causes lung cancer. It may just be coincidence, or it could be that smokers are more stressed or drink more alcohol and these factors might be the cause of the cancer. Even though this graph does not itself establish a link, scientists have produced compelling experimental evidence to show that smoking tobacco definitely can cause lung cancer.

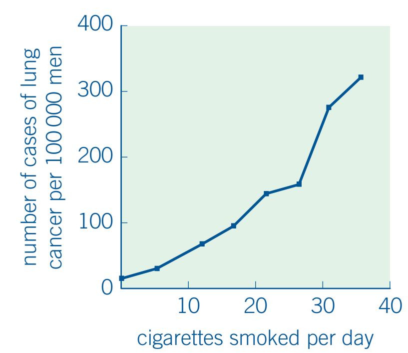
1. State a correlation shown in figure 6.
2. Explain why the information provided does not show a causal relationship with the correlation you have identified.

Study tip

It is important to be clear that a correlation does *not* mean that there is a causal link.



▲ **Figure 5**



▲ **Figure 6** *Annual incidence of lung cancer per 100 000 men in the USA correlated to the daily consumption of cigarettes*

Risk factors for lung disease

Maths link

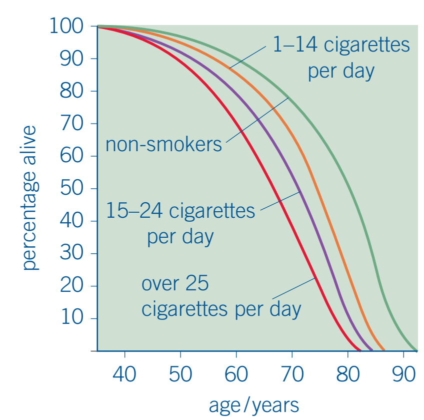
MS 0.3, see Chapter 11.

There are a number of specific risk factors that increase the probability of someone suffering from lung disease. In this context 'lung disease' refers to chronic obstructive pulmonary disease (COPD), which includes emphysema and chronic bronchitis. These risk factors include:

- **Smoking**. 90% of people suffering from COPD are, or have been, heavy smokers.
- **Air pollution**. Pollutant particles and gases (e.g., sulfur dioxide) increase the likelihood of COPD, especially in areas of heavy industry.
- **Genetic make-up**. Some people are genetically more likely to get lung disease, others less so; this explains why some lifelong smokers never get lung disease while others die early.
- **Infections**. People who frequently get other chest infections also show a higher incidence of COPD.
- **Occupation**. People working with harmful chemicals, gases and dusts that can be inhaled have an increased risk of lung disease.

Here is an analysis of some data relating to the most significant risk factor – smoking.

The world's longest-running survey of smoking began in the UK in 1951. This survey and other ones elsewhere in the world have revealed a number of general statistical facts about smokers. Look at Figure 7. What does it tell us



▲ **Figure 7** *Life expectancy related to the number of cigarettes smoked*

- All the lines start at 100%. This shows that the whole of this group of the population were alive at the start of the survey. What else does this tell us? As the scale of the independent variable (age in years) has its origin at 35 it suggests that everyone in this group must have been at least 35 years old at the start of the survey.
- All the lines follow approximately the same pattern: they decline slowly at first and then at an increasing rate until at some point all lines cross the x-axis. This describes the shape but what does it actually show? Namely that only a few people die between the ages of 35 and 60 but that, after age 60, the death rate becomes increasingly rapid until, at some point everyone in the group has died.
- What about the differences between the four separate coloured lines? Each represents a different group distinguished by the number of cigarettes smoked each day. At every age beyond 35 years, the more cigarettes smoked, the fewer people remain alive. This difference is more marked the greater the age.
- At what age did the members of each group die? Well the line representing the group who smoked more than 25 cigarettes a day crosses the x-axis at 82 years, showing that no one in the group lived beyond that age. By contrast, some of the non-smokers lived beyond 90 years.
- What is the overall interpretation? Namely that the more cigarettes smoked per day, the earlier, on average, a smoker dies.

The interpretation of the data in Figure 7 shows there is a **correlation** between smoking and premature death. This does not, however, prove that smoking is the cause of an early death. The data seem to suggest this is the case but there is no evidence here to prove that it is so. There needs to be a clear causal connection between smoking and death before you can say that the case is proven. These data alone show only a correlation and not a cause. To prove that smoking is the cause of early death in smokers the correct scientific process needs to be followed. There are three main stages:

1. Establish a hypothesis to try to explain the correlation; this should be based on current knowledge.
2. Design and perform experiments to test the hypothesis.
3. Establish the causal link and formulate theories to explain it.

This is precisely what happened in establishing the causal link between smoking and lung cancer.

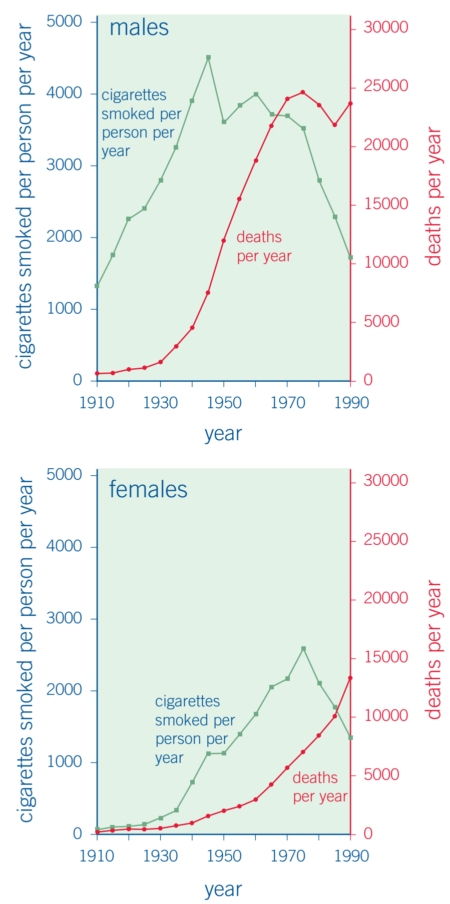
1 List **four** risk factors associated with lung disease.
2 Use Figure 7 to determine what percentage of non-smokers are likely to survive to age 80.
3 Calculate how many times greater is the likelihood of a non-smoker living to age 70 than someone who smokes over 25 cigarettes a day.
4 About 10 to 15 years after giving up smoking the risk of death approaches that of non-smokers. Use this information to explain to a 40-year-old who smokes 30 cigarettes a day the likely impact on her life expectancy of giving up smoking immediately.
5 Data showing a causal link between smoking and lung disease has led to statutory restrictions on the sources of risk factors. Suggest some restrictions that have been introduced and how these might reduce the incidence of lung disease.
6 Pulmonary fibrosis is a lung disease that causes the epithelium of the lungs to become irreversibly thickened. It also leads to reduced elasticity of the lungs.
One symptom of the disease is shortness of breath, especially when exercising. Suggest why this symptom arises.
7 One measure of lung function is Forced Expiratory Volume (FEV). This is the volume of air that can forcibly be blown out in one second, after full inspiration. Suggest how pulmonary fibrosis might effect FEV and explain why.

Smoking and lung cancer

Life insurance companies have calculated that, on average, smoking a single cigarette lowers an individual's life expectancy by 10.7 minutes – longer than it takes to smoke the cigarette! While this is a statistical deduction rather than a scientific one, there is now clear scientific evidence to support the view that smoking cigarettes damages your health and reduces life expectancy. One type of evidence comes from correlations between cigarette smoking and certain diseases.

Figure 8 shows deaths from lung cancer in the UK correlated to the number of cigarettes smoked per year during a period in the last century. Study it carefully and then answer the questions.

1 Determine in which decade smoking reached its peak for the following:
a males **b** females
2 Explain how the graphs show that there is a correlation between the number of cigarettes smoked and deaths from lung cancer in both sexes.
3 In both sexes, the number of deaths per year from lung cancer increased over the period 1910 to 1970. Suggest **three** possible reasons for this.
4 Suggest a reason why there is a time lag between the number of cigarettes smoked and a corresponding change in the number of deaths from lung cancer.



▲ **Figure 8** *Incidence of deaths from lung cancer in the UK correlated to cigarettes smoked per year (1910–90)*

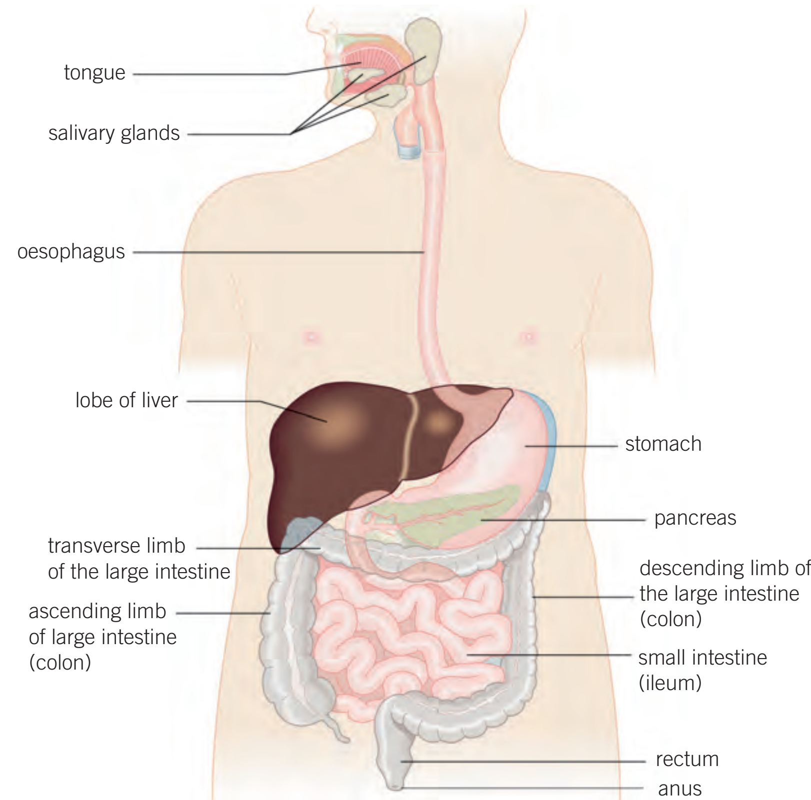
6.9 Enzymes and digestion

Learning objectives

→ Describe the structure and function of the major parts of the digestive system.
→ Explain how the digestive system breaks down food both physically and chemically.
→ Explain the role of enzymes in digestion of carbohydrates, lipids and proteins.

Specification reference: 3.3.3

The human digestive system is made up of a long muscular tube and its associated glands. The glands produce **enzymes** that hydrolyse large molecules into small ones ready for absorption. The digestive system (Figure 1) is therefore an exchange surface through which food substances are absorbed.



▲ **Figure 1** *Human digestive system*

Study tip

Digestion is the process in which *large* molecules are hydrolysed by enzymes into *small* molecules, which can be absorbed and assimilated.

Major parts of the digestive system

- The **oesophagus** carries food from the mouth to the stomach.
- The **stomach** is a muscular sac with an inner layer that produces enzymes. Its role is to store and digest food, especially proteins. It has glands that produce enzymes which digest protein.
- The **ileum** is a long muscular tube. Food is further digested in the ileum by enzymes that are produced by its walls and by glands that pour their secretions into it. The inner walls of the ileum are folded into villi, which gives them a large surface area. The surface area of these villi is further increased by millions of tiny projections, called microvilli, on the epithelial cells of each villus. This adapts the ileum for its purpose of absorbing the products of digestion into the bloodstream.
- The **large intestine** absorbs water. Most of the water that is absorbed is water from the secretions of the many digestive glands.
- The **rectum** is the final section of the intestines. The faeces are stored here before periodically being removed via the anus in a process called **egestion**.

Hint

The contents of the intestines are *not* inside the body. Molecules and ions only truly enter the body when they cross the cells and cell-surface membranes of the epithelial lining of the intestines.

Hint

All organisms are made up of the same biological molecules and therefore your food consists almost entirely of other organisms, or parts of them. You must first hydrolyse them into molecules that are small enough to pass across cell-surface membranes.

Synoptic link

It will help you understand this Topic if you revisit Topics 1.3, 1.5, 1.6 and 1.7.

- The **salivary glands** are situated near the mouth. They pass their secretions via a duct into the mouth. These secretions contain the enzyme amylase, which **hydrolyses** starch into maltose.
- The **pancreas** is a large gland situated below the stomach. It produces a secretion called pancreatic juice. This secretion contains proteases to hydrolyse proteins, lipase to hydrolyse lipids and amylase to hydrolyse starch.

What is digestion?

In humans, as with many organisms, digestion takes place in two stages:

1. physical breakdown,
2. chemical digestion.

Physical breakdown

If the food is large, it is broken down into smaller pieces by means of structures such as the teeth. This not only makes it possible to ingest the food but also provides a large surface area for chemical digestion. Food is churned by the muscles in the stomach wall and this also physically breaks it up.

Chemical digestion

Chemical digestion hydrolyses large, insoluble molecules into smaller, soluble ones. It is carried out by enzymes. All digestive enzymes function by **hydrolysis**. Hydrolysis is the splitting up of molecules by adding water to the chemical bonds that hold them together. Enzymes are specific and so it follows that more than one enzyme is needed to hydrolyse a large molecule. Usually one enzyme hydrolyses a large molecule into sections and these sections are then hydrolysed into smaller molecules by one or more additional enzymes. There are different types of digestive enzymes, three of which are particularly important:

- **Carbohydrases** hydrolyse carbohydrates, ultimately to monosaccharides.
- **Lipases** hydrolyse lipids (fats and oils) into glycerol and fatty acids.
- **Proteases** hydrolyse proteins, ultimately to amino acids.

You can now look at these three groups of digestive enzymes in more detail.

Carbohydrate digestion

It usually takes more than one enzyme to completely hydrolyse a large molecule. Typically one enzyme hydrolyses the molecule into smaller sections and then other enzymes hydrolyse these sections further into their **monomers**. These enzymes are usually produced in different parts of the digestive system. It is obviously important that enzymes are added to the food in the correct sequence. This is true of starch digestion.

Firstly the enzyme **amylase** is produced in the mouth and the pancreas. Amylase hydrolyses the alternate glycosidic bonds of the starch molecule to produce the disaccharide maltose. The maltose is in turn hydrolysed into the monosaccharide α-glucose by a second enzyme, a disaccharidase called **maltase**. Maltase is produced by the lining of ileum.

In humans the process takes place as follows:

- Saliva enters the mouth from the salivary glands and is thoroughly mixed with the food during chewing.
- Saliva contains **salivary amylase**. This starts hydrolysing any starch in the food to maltose. It also contains mineral salts that help to maintain the pH at around neutral. This is the optimum pH for salivary amylase to work.
- The food is swallowed and enters the stomach, where the conditions are acidic. This acid **denatures** the amylase and prevents further hydrolysis of the starch.
- After a time the food is passed into the small intestine, where it mixes with the secretion from the pancreas called pancreatic juice.
- The pancreatic juice contains **pancreatic amylase**. This continues the hydrolysis of any remaining starch to maltose. Alkaline salts are produced by both the pancreas and the intestinal wall to maintain the pH at around neutral so that the amylase can function.
- Muscles in the intestine wall push the food along the ileum. Its epithelial lining produces the disaccharidase **maltase**. Maltase is not released into the lumen of the ileum but is part of to the cell-surface membranes of the epithelial cells that line the ileum. It is therefore referred to as a **membrane-bound disaccharidase**. The maltase hydrolyses the maltose from starch breakdown into α-glucose.

In addition to the digestion of maltose described above, there are two other common disaccharides in the diet that are hydrolysed – sucrose and lactose.

Sucrose is found in many natural foods, especially fruits. Lactose is found in milk, and hence in milk products, such as yoghurt and cheese. Each disaccharide is hydrolysed by a membrane-bound disaccharidase as follows:

- **Sucrase** hydrolyses the single glycosidic bond in the sucrose molecule. This hydrolysis produces the two monosaccharides glucose and fructose.
- **Lactase** hydrolyses the single glycosidic bond in the lactose molecule. This hydrolysis produces the two monosaccharides glucose and galactose.

Lipid digestion

Lipids are hydrolysed by enzymes called **lipases**. Lipases are enzymes produced in the pancreas that hydrolyse the ester bond found in triglycerides to form fatty acids and monoglycerides. A monoglyceride is a glycerol molecule with a single fatty acid molecule attached. Lipids (fats and oils) are firstly split up into tiny droplets called **micelles** (Topic 6.10) by **bile salts**, which are produced by the liver. This process is called **emulsification** and increases the surface area of the lipids so that the action of lipases is speeded up.

Hint

Enzyme names usually end in '-ase' and start with the the first part of the name of their substrate (the substance on which they act). Hence maltase hydrolyses maltose, and sucrase hydrolyses sucrose.

Protein digestion

Proteins are large, complex molecules that are hydrolysed by a group of enzymes called **peptidases** (proteases). There are a number of different peptidases:

- **Endopeptidases** hydrolyse the peptide bonds between amino acids in the central region of a protein molecule forming a series of peptide molecules.
- **Exopeptidases** hydrolyse the peptide bonds on the terminal amino acids of the peptide molecules formed by endopeptidases. In this way they progressively release dipeptides and single amino acids.
- **Dipeptidases** hydrolyse the bond between the two amino acids of a dipeptide. Dipeptidases are membrane-bound, being part of the cell-surface membrane of the epithelial cells lining the ileum.

Summary questions

1. Define hydrolysis.
2. List **two** structures that produce amylase.
3. Suggest why the stomach does not have villi or microvilli.
4. Name the final product of starch digestion in the gut.
5. List **three** enzymes produced by the epithelium of the ileum.

Lactose intolerance

Milk is the only food of human babies and so they produce a relatively large amount of lactase, the enzyme that hydrolyses lactose, the sugar in milk. As milk forms a less significant part of the diet in adults, the production of lactase diminishes as children get older. This reduction can be so great in some adults that they produce little, or no, lactase at all.

This was not a problem to our ancestors but can be to humans of today. Humans that produce no lactase cannot hydrolyse the lactose they consume. When the undigested lactose reaches the large intestines, microorganisms hydrolyse it. This gives rise to small soluble molecules and a large volume of gas. This can result in diarrhoea because the soluble molecules lower the water potential of the material in the colon. The condition is known as lactose intolerance. Some people with the condition cannot consume milk or milk products at all while others can consume them only in small amounts.

▲ **Figure 3** *Milk and milk products*

1. a. Suggest the process by which micoorganisms produce 'a large volume of gas' in lactose intolerant individuals.
   b. Suggest a reason why this gas is unlikely to be carbon dioxide.
2. Suggest an explanation why lactose intolerance is a problem for modern day humans but wasn't for our ancestors.
3. Explain how the lowering of water potential in the colon can cause diarrhoea.

6.10 Absorption of the products of digestion

Learning objectives

- → Describe the structure of the ileum.
- → Explain how the ileum is adapted for the function of absorption.
- → Explain how monosaccharides and amino acids are absorbed.
- → Explain how triglycerides are absorbed.

Specification reference: 3.3.3

We have seen in Topic 6.9 how enzymes hydrolyse carbohydrates, fats and proteins. The products of this hydrolysis are monosaccharides, amino acids, monoglycerides and fatty acids. We will now see how these products are absorbed by the ileum.

Structure of the ileum

The ileum is adapted to the function of absorbing the products of digestion. The wall of the ileum is folded and possesses finger-like projections, about 1 mm long, called **villi** (Figure 2). They have thin walls, lined with epithelial cells on the other side of which is a rich network of blood capillaries. The villi considerably increase the surface area of the ileum and therefore accelerate the rate of absorption.

Villi are situated at the interface between the **lumen** (cavity) of the intestines (in effect outside the body) and the blood and other tissues inside the body. They are part of a specialised exchange surface adapted for the absorption of the products of digestion. Their properties increase the efficiency of absorption in the following ways:

- They increase the surface area for **diffusion**.
- They are very thin walled, thus reducing the distance over which diffusion takes place.
- They contain muscle and so are able to move. This helps to maintain diffusion gradients because their movement mixes the contents of the ileum. This ensures that, as the products of digestion are absorbed from the food adjacent to the villi, new material rich in the products of digestion replaces it.
- They are well supplied with blood vessels so that blood can carry away absorbed molecules and hence maintain a diffusion gradient.
- The epithelial cells lining the villi possess **microvilli** (Figure 1). These are finger-like projections of the cell-surface membrane that further increase the surface area for absorption.

Synoptic link

You will better understand the contents of this Topic if you first read through Topics 4.2, 4.5 and 7.6.

◀ **Figure 1** *Light micrograph of a section through a villus in the small intestine. Villi are projections that increase the surface area for the absorption of food. They are covered in microvilli (smaller, finger-like projections) that further increase this surface area*

▲ **Figure 2** *False-colour SEM of villi (brown) in the lining of the ileum*

Absorption of amino acids and monosaccharides

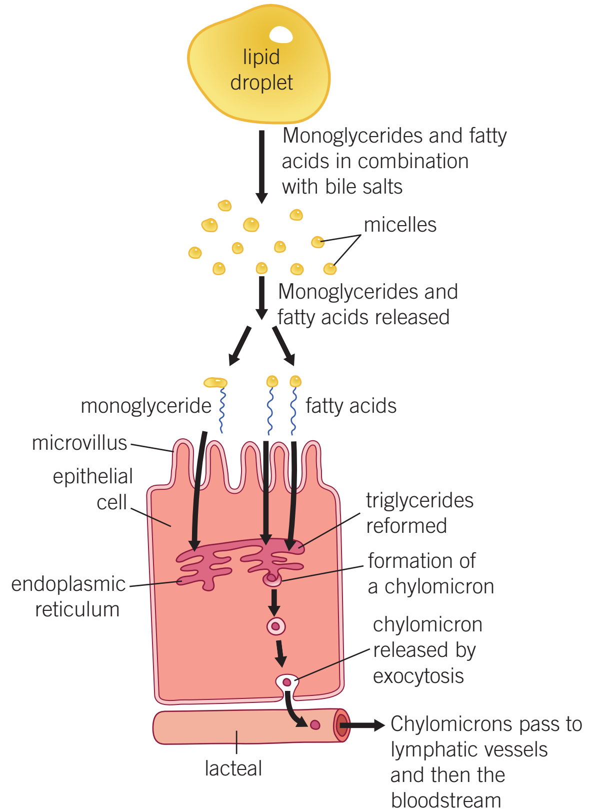
The digestion of proteins produces amino acids, while that of carbohydrates produces monosaccharides such as glucose, fructose and galactose. The methods of absorbing these products are the same, namely diffusion and co-transport. We saw how glucose and amino acids are absorbed in the ileum by these processes in Topic 4.2 and 4.5.

Absorption of triglycerides

Once formed during digestion, monoglycerides and fatty acids remain in association with the bile salts that initially emulsified the lipid droplets (see Topic 6.9). The structures formed are called **micelles**. They are tiny, being around 4–7 nm in diameter. Through the movement of material within the lumen of the ileum, the micelles come into contact with the epithelial cells lining the villi of the ileum. Here the micelles break down, releasing the monoglycerides and fatty acids. As these are non-polar molecules, they easily diffuse across the cell-surface membrane into the epithelial cells.

Once inside the epithelial cells, monoglycerides and fatty acids are transported to the endoplasmic reticulum where they are recombined to form triglycerides. Starting in the endoplasmic reticulum and continuing in the Golgi apparatus, the triglycerides associate with cholesterol and lipoproteins to form structures called **chylomicrons**. Chylomicrons are special particles adapted for the transport of lipids.

Chylomicrons move out of the epithelial cells by **exocytosis**. They enter lymphatic capillaries called **lacteals** that are found at the centre of each villus. The process is illustrated in Figure 2.



▶ **Figure 2** *The absorption of triglycerides*

From here, the chylomicrons pass, via lymphatic vessels, into the blood system. The triglycerides in the chylomicrons are hydrolysed by an enzyme in the endothelial cells of blood capillaries (see Topic 7.6) from where they diffuse into cells.

Absorption of fatty acids

Bile salts play a role in the digestion and absorption of fatty acids. One end of the bile salt molecule is soluble in fat (lipophilic) but not in water (hydrophobic). The other end is soluble in water (hydrophilic) but not in fat (lipophobic). Bile salt molecules therefore arrange themselves with their lipophilic ends in fat droplets, leaving their lipophobic ends sticking out. In this way they prevent fat droplets from sticking to each other to form large droplets, leaving only tiny ones (micelles). It is in this form that fatty acids reach the epithelial cells of the ileum where they break down, releasing the fatty acids for absorption.

An experiment was carried out to investigate the absorption of fatty acids. Six sections of intestine were filled with a fatty acid called oleic acid. To each section were added different mixtures of other contents as shown in Table 1.

Iodoacetate inhibits an enzyme involved in glycolysis – a stage of the respiratory process in cells that involves phosphorylation.

▼ **Table 1**

Contents of section of intestine					Relative amounts of oleic acid absorbed in 10 hours
Bile salts	Glycerol	Phosphate	Glycerol phosphate	Iodoacetate	
✓	✗	✗	✗	✗	2.9
✓	✗	✓	✗	✗	1.1
✓	✓	✗	✗	✗	2.6
✓	✓	✓	✗	✗	5.8
✓	✗	✗	✓	✗	8.5
✓	✗	✗	✓	✓	0.0

✓ = substance present ✗ = substance absent

From the information in Table 1:

1. List **three** pieces of evidence that support the idea that the absorption of fatty acids in the intestine is increased if they are combined with a compound of glycerol and phosphate.
2. Recognise the evidence supporting the view that the absorption of fatty acids involves phosphorylation.

Summary questions

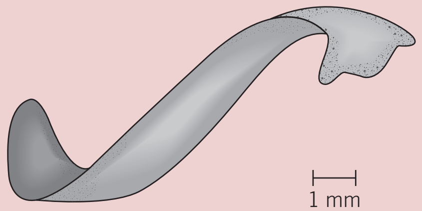
1. List **three** organelles that you would expect to be numerous and/or well developed in an epithelial cell of the ileum, giving a reason for your choice in each case.
2. Name the other chemical that moves across epithelial cells with glucose molecules during co-transport.
3. In addition to having microvilli, state **one** other feature of the epithelial cells of the ileum that would increase the rate of absorption of amino acids.

Maths link

MS 1.3, see Chapter 11.

Practice questions: Chapter 6

1 **(a)** Flatworms are small animals that live in water. They have no specialised gas exchange or circulatory systems. The drawing shows one type of flatworm.



(i) Name the process by which oxygen reaches the cells inside the body of this flatworm. *(1 mark)*

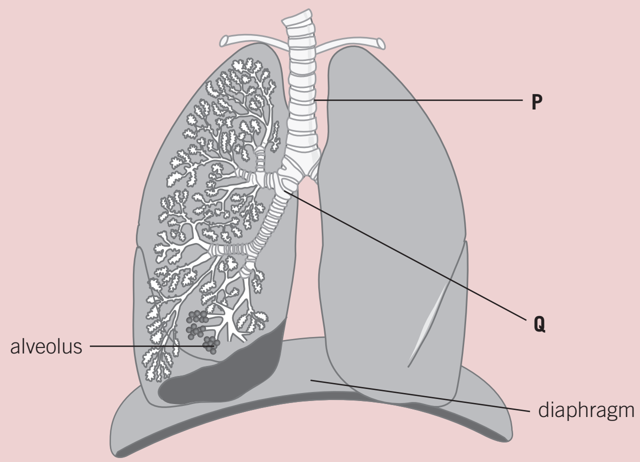
(ii) The body of a flatworm is adapted for efficient gas exchange between the water and the cells inside the body. Using the diagram, explain how two features of the flatworm's body allow efficient gas exchange. *(2 marks)*

(b) (i) A leaf is an organ. What is an organ? *(1 mark)*

(ii) Describe how carbon dioxide in the air outside a leaf reaches mesophyll cells inside the leaf. *(3 marks)*

AQA June 2012

2 **(a)** The diagram shows the structure of the human gas exchange system.

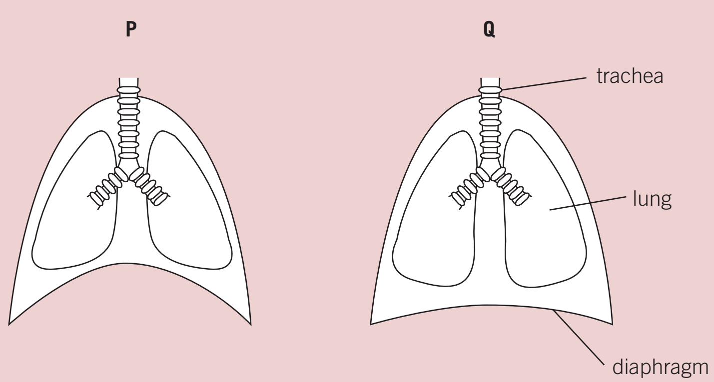


Name organs
P
Q *(1 mark)*

(b) Explain how downward movement of the diaphragm leads to air entering the lungs. *(2 marks)*

AQA Jan 2013

3 The diagram shows the position of the diaphragm at times **P** and **Q**.



(a) Describe what happens to the diaphragm between times **P** and **Q** to bring about the change in its shape. *(2 marks)*

(b) Air moves into the lungs between times P and Q. Explain how the diaphragm causes this. *(3 marks)*

(c) Describe how oxygen in air in the alveoli enters the blood in capillaries. *(2 marks)*

AQA June 2012

4 Insects such as beetles obtain oxygen by drawing air into their tracheae through spiracles. Diving beetles live in ponds. They carry a bubble of air under their wing cases when they swim underwater. The bubble supplies air to the spiracles. When the bubble has been used up, the beetle comes to the surface to collect a new bubble.

An investigation was carried out into the effect of temperature on diving beetles. Three beetles, **A**, **B** and **C**, of the same species, were observed in thermostatically-controlled water baths. The number of times each beetle surfaced to renew its air bubble was counted at three different temperatures.

The results are shown in Table 1 below.

temperature / °C	number of times air bubble was renewed per hour		
	beetle A	beetle B	beetle C
10	10	12	8
20	18	22	18
30	44	48	38

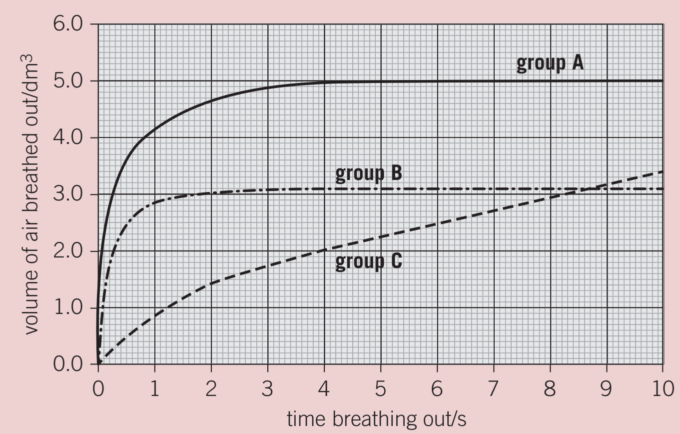
(a) Calculate the mean number of times the air bubble was renewed per hour at each temperature. *(1 mark)*

(b) Sketch a graph to show the relationship between temperature and the mean number of times the air bubble was renewed per hour and name the shape of the line obtained. *(2 marks)*

(c) The number of times the air bubble is renewed per hour is related to a beetle's need for oxygen to carry out aerobic respiration, which is catalysed by enzymes. Explain what the data reveal about the size of the effect of each 10°C rise in temperature on the rate of respiration. *(2 marks)*

5 Forced expiratory volume (FEV) is the greatest volume of air a person can breathe out in 1 second.

Forced vital capacity (FVC) is the greatest volume of air a person can breathe out in a single breath. Figure 2 shows results for the volume of air breathed out by three groups of people, **A**, **B** and **C**. Group **A** had healthy lungs. Groups **B** and **C** had different lung conditions that affect breathing.



(a) Calculate the percentage drop in FEV for group **C** compared with the healthy people. (*1 mark*)

(b) Asthma affects bronchioles and reduces flow of air in and out of the lungs. Fibrosis does not affect bronchioles; it reduces the volume of the lungs. Which group, **B** or **C**, was the one containing people with fibrosis of their lungs? Use the information provided and evidence from **Figure 2** to explain your answer. (*3 marks*)

AQA SAMS A LEVEL PAPER 1

6 An animal cell takes in oxygen over its surface area but uses oxygen in proportion to its volume. Size and shape affect the ratio of surface area to volume of a cell, and therefore affect the efficiency of oxygen uptake.

(a) Complete the table to compare the surface area to volume ratios of the four model cells described. (*4 marks*)

model cell description	surface area / μm^2	volume / μm^3	ratio of surface area to volume
cube, side length 4 μm	96		
sphere, diameter 4 μm	50.3	33.5	
cube, side length 6 μm		216	
sphere, diameter 6 μm			1:1

(b) Summarise what the results show about the effect of size and shape on the ability of a cell to obtain enough oxygen for its needs. (*2 marks*)

7 **(a)** Describe how you would use a simple respirometer to measure the oxygen uptake of 5g of maggots. (*5 marks*)

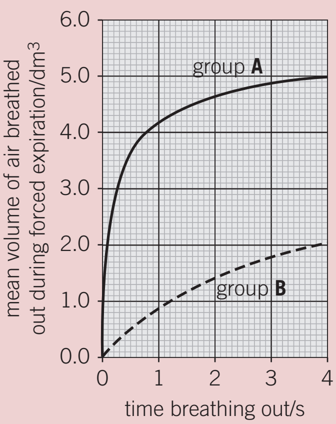
(b) A student takes respirometer readings by measuring the distance moved by the marker fluid along a capillary tube in ten minutes. Explain what calculations need to be performed to obtain an hourly oxygen uptake rate per gram of maggots. (*3 marks*)

8 Breathing out as hard as you can is called forced expiration.

(a) Describe and explain the mechanism that causes forced expiration. (*4 marks*)

Two groups of people volunteered to take part in an experiment.

- People in group **A** were healthy.
- People in group **B** were recovering from an asthma attack.



Each person breathed in as deeply as they could. They then breathed out by forced expiration.

A scientist measured the volume of air breathed out during forced expiration by each person.

Forced expiration volume (FEV) is the volume of air a person can breathe out in 1 second.

(b) Using data from the first second of forced expiration, calculate the percentage decrease in the FEV for group **B** compared with group **A**. (*1 mark*)

(c) The people in group **B** were recovering from an asthma attack. Explain how an asthma attack caused the drop in the mean FEV shown in **Figure 4**. (*4 marks*)

AQA SAMS AS PAPER