SENIOR FIVE Biology – English Medium

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Cells

Appearance of cells seen with a light microscope

You are probably already familiar with the structure of animal and plant cells, as they are seen when we use a light microscope. Figure 1.7 is a photomicrograph of an animal cell, and Figure 1.9 is a photomicrograph of a plant cell.

Figure 1.8 is a diagram showing the structures that are visible in an animal cell using a light microscope, and Figure 1.10 is a similar diagram of a plant cell. In practice, you would probably not see all of these things at once in any one cell.

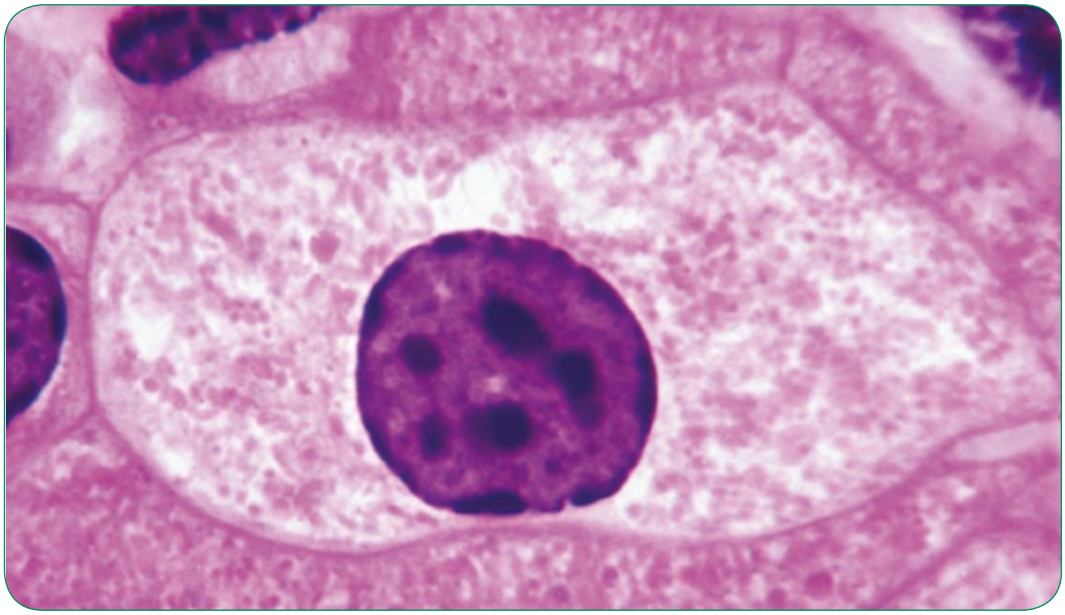

Figure 1.7 Photomicrograph of a stained animal cell (×1800).

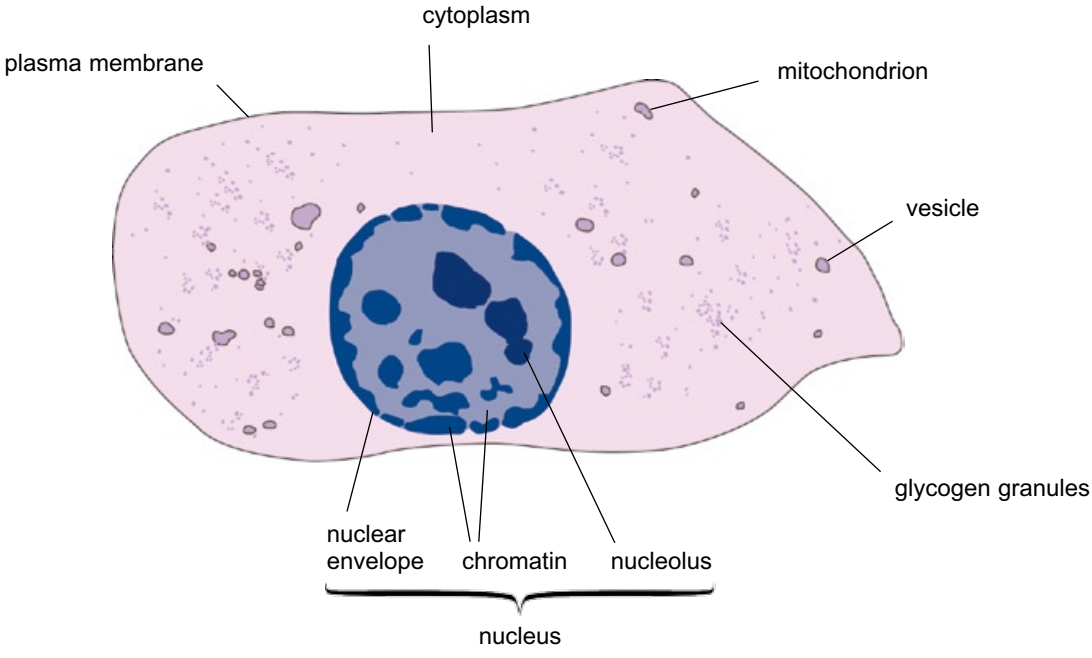

Figure 1.8 A diagram of an animal cell as it appears using a light microscope.

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Figure 1.9 Photomicrograph of a cell in a moss leaf (×750).

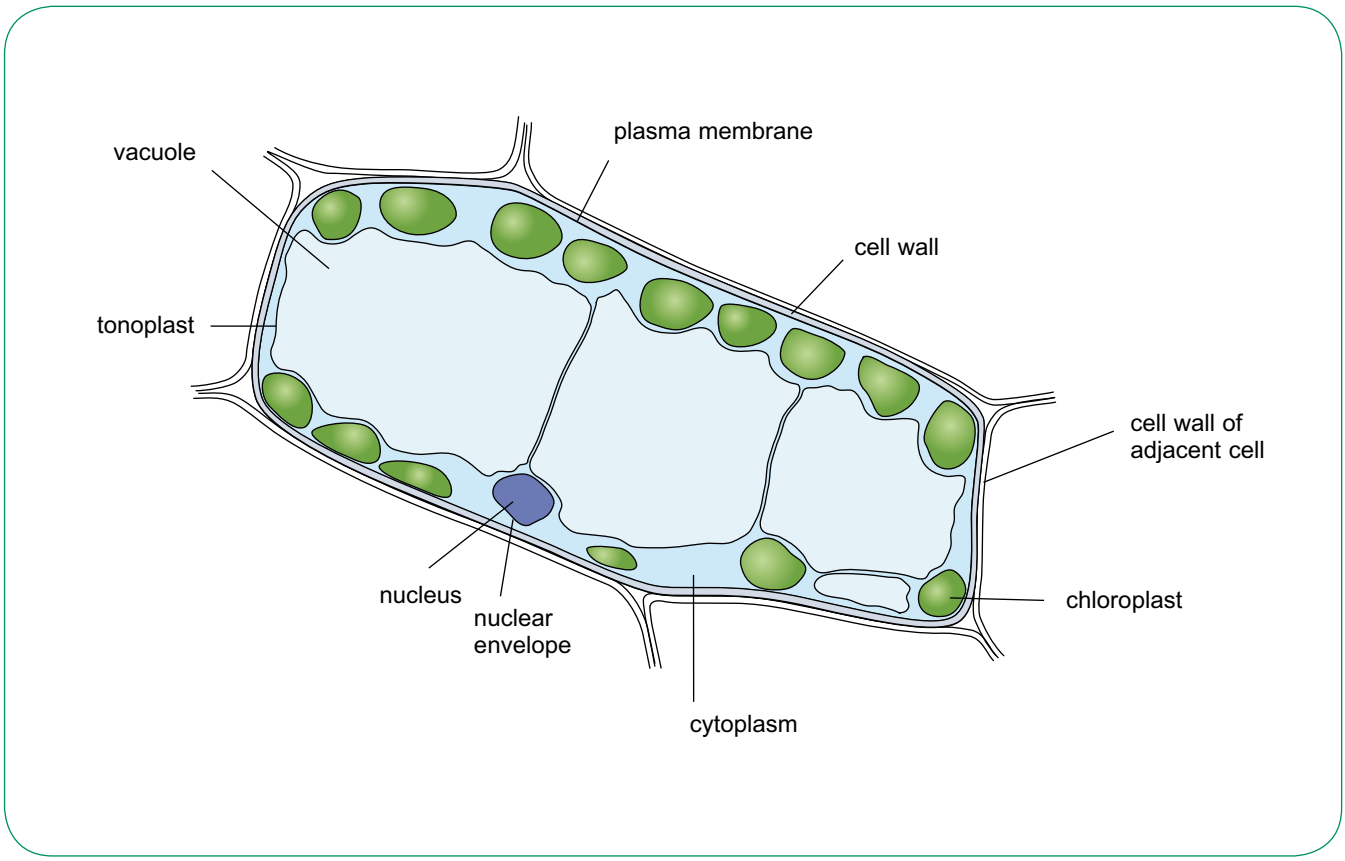

Figure 1.10 A diagram of a plant cell as it appears using a light microscope.

Appearance of cells seen with an electron microscope

As we have seen, electron microscopes are able to resolve much smaller structures than light microscopes. The structure that we can see when we use an electron microscope is called **ultrastructure**.

Figure 1.11 and Figure 1.12 are stylised diagrams summarising the ultrastructure of a typical animal cell and a typical plant cell. Figure 1.13 and Figure 1.15 are electron micrographs of an animal cell and a plant cell. Figure 1.14 and Figure 1.16 are diagrams based on these electron micrographs.

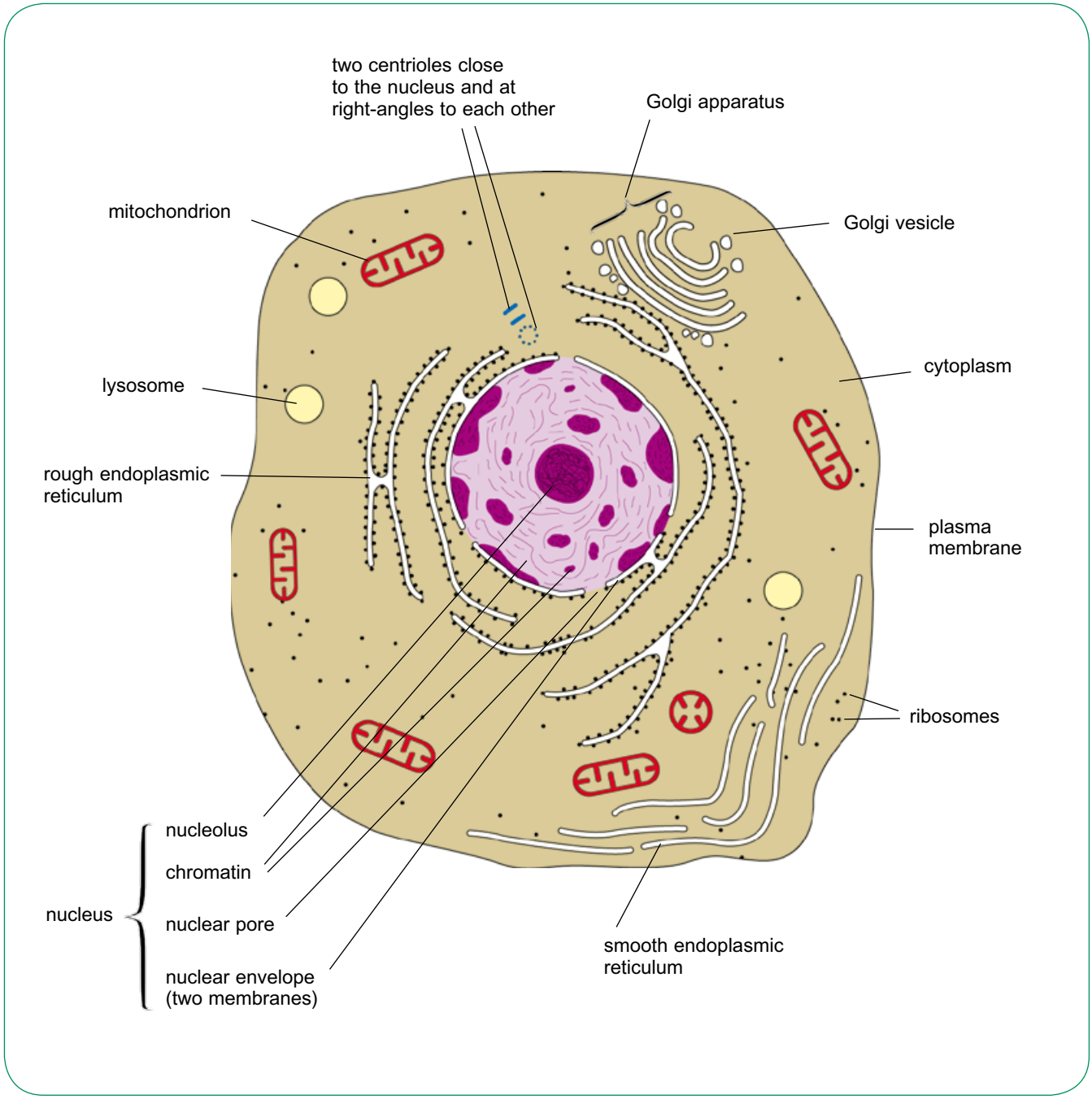

Figure 1.11 Ultrastructure of an animal cell.

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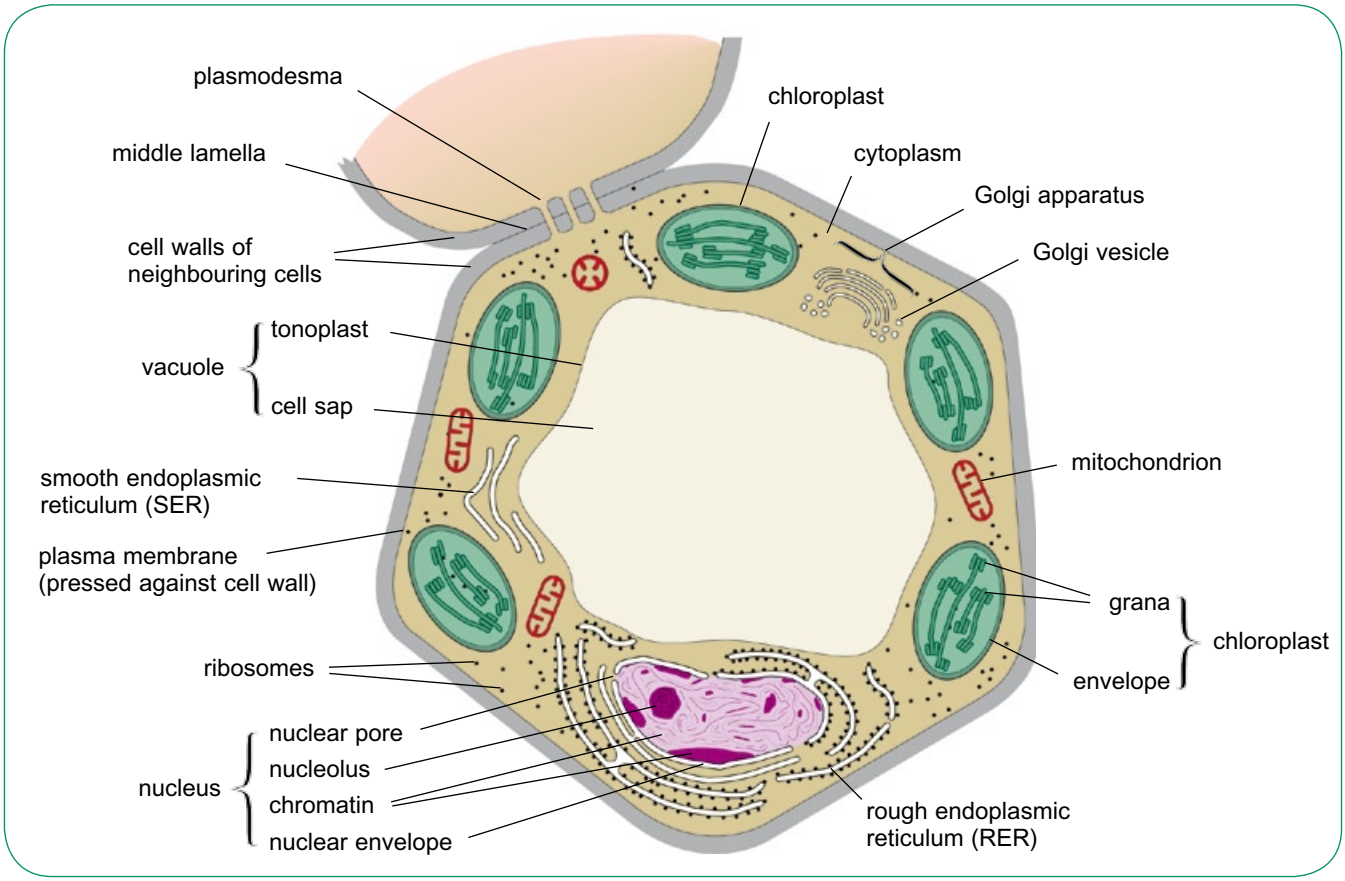

Figure 1.12 Ultrastructure of a plant cell.

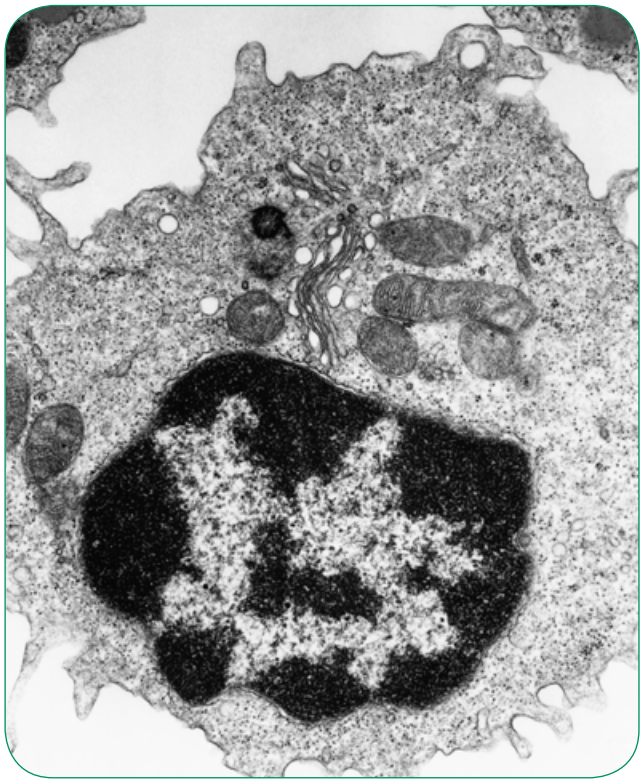

Figure 1.13 Transmission electron micrograph of a white blood cell (×15 000).

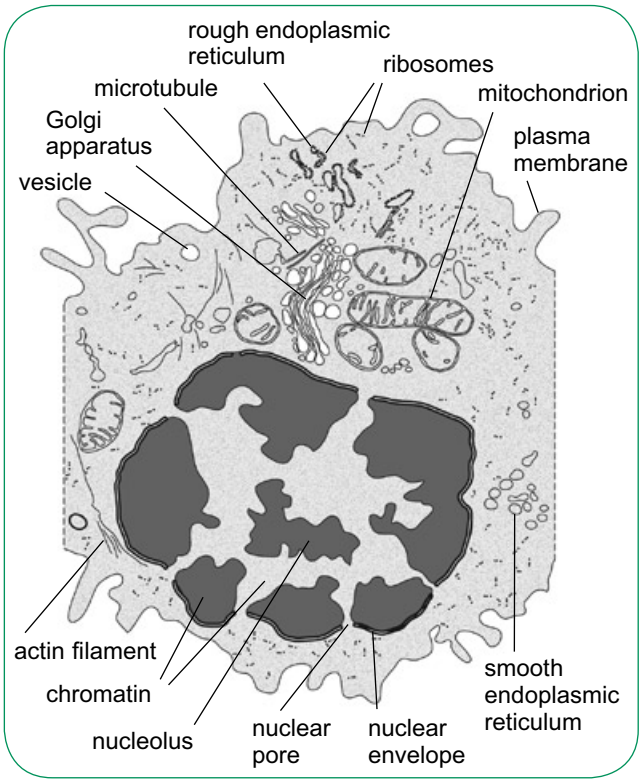

Figure 1.14 Drawing of an animal cell made from the electron micrograph in Figure 1.13.

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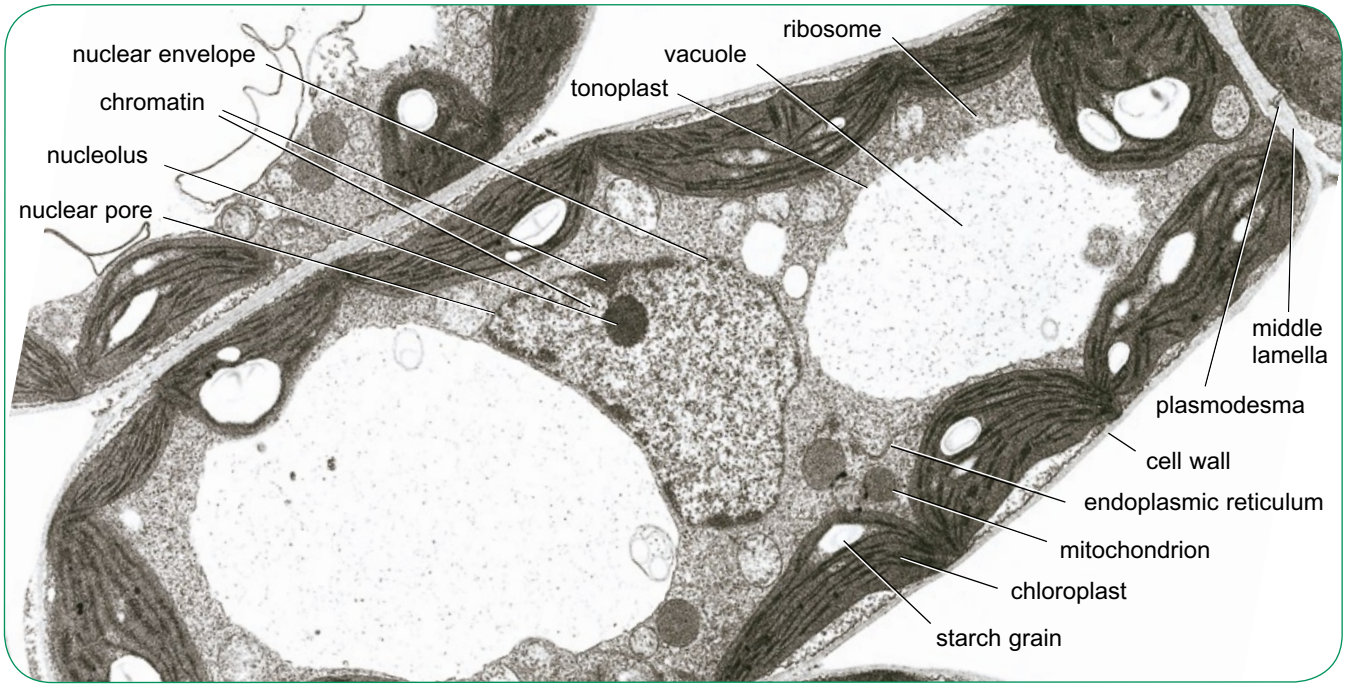

Figure 1.15 Electron micrograph of a plant cell (×5600).

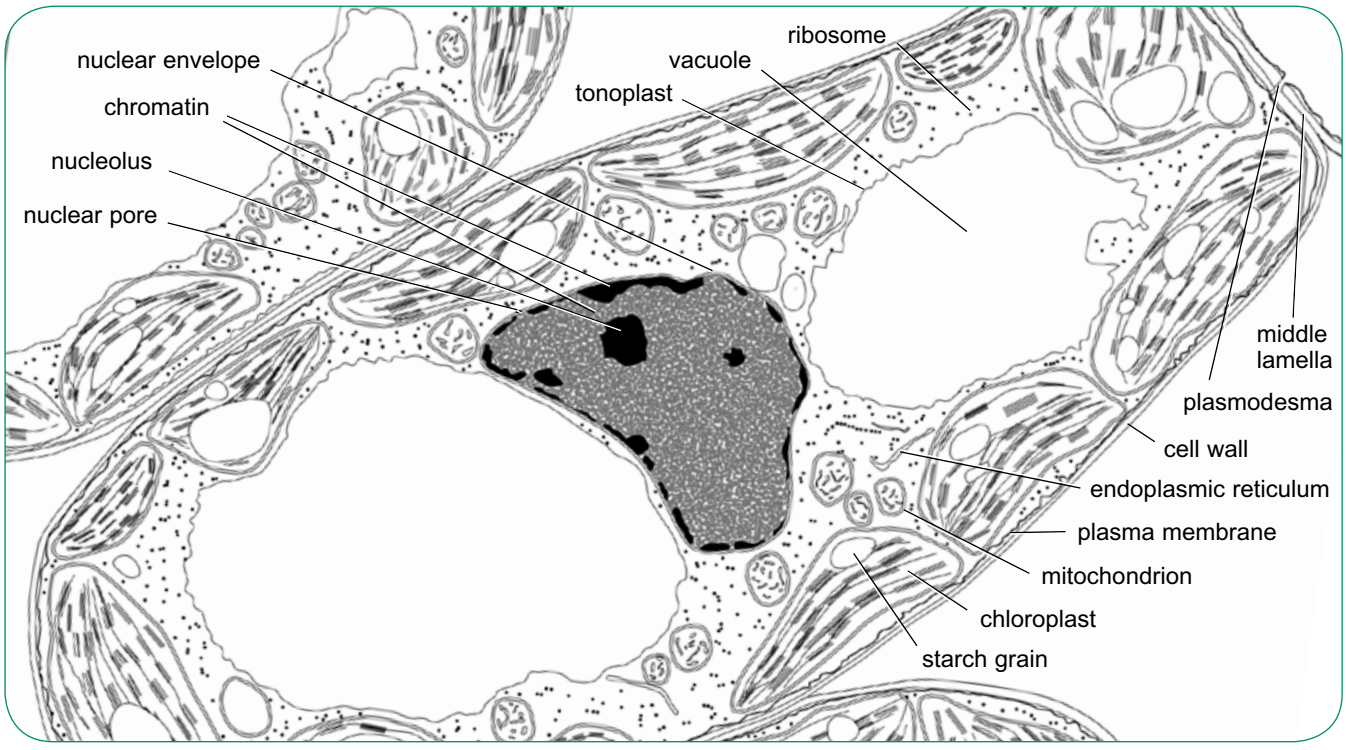

Figure 1.16 Drawing of a plant cell made from the electron micrograph in Figure 1.15.

SAQ

6 State whether the electron micrographs in Figure 1.13 and Figure 1.15 were made using a transmission electron microscope (TEM) or a scanning electron microscope (SEM). How can you tell?

Answer

7 Make a list of all the structures within a cell that are visible with an electron microscope but cannot be clearly seen with a light microscope.

Answer

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Structure and function of organelles

The different structures that are found within a cell are known as **organelles**.

Nucleus

Almost all cells have a **nucleus**. Two important exceptions are red blood cells in mammals, and phloem sieve tubes in plants.

The nucleus is normally the largest cell organelle. It has a tendency to take up stains more readily than the cytoplasm, and so usually appears as a dark area (Figure 1.17).

The nucleus is surrounded by two membranes with a small gap between them. The pair of membranes is known as the **nuclear envelope**. There are small gaps all over the envelope, called **nuclear pores**.

The nucleus contains **chromosomes**. Chromosomes are long molecules of DNA. In a non-dividing cell, they are too thin to be visible as individual chromosomes, but form a tangle known as **chromatin,** often darkly stained.

DNA carries a code that instructs the cell about making proteins, and the DNA in the lighter-staining parts of the chromatin can be used for transcription, the first stage of protein synthesis. During transcription, the information on DNA is copied onto molecules of messenger RNA, which travel out of the nucleus, through the nuclear pores, into the cytoplasm.

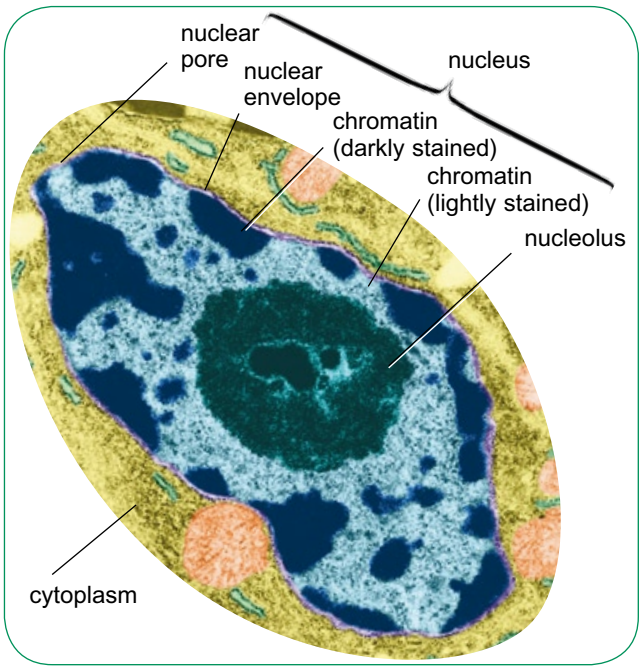

Figure 1.17 Transmission electron micrograph of a nucleus (× 10 000).

An especially darkly staining area in the nucleus, the **nucleolus**, contains DNA that is being used to make **ribosomes**, the tiny organelles where protein synthesis takes place.

Endoplasmic reticulum

Within the cytoplasm of every eukaryotic cell, there is a network of membranes, known as the **endoplasmic reticulum**. Some of these membranes have ribosomes attached to them, forming **rough endoplasmic reticulum,** RER for short (Figure 1.18). Some do not, and these form **smooth endoplasmic reticulum**, SER. The RER is usually continuous with the nuclear envelope.

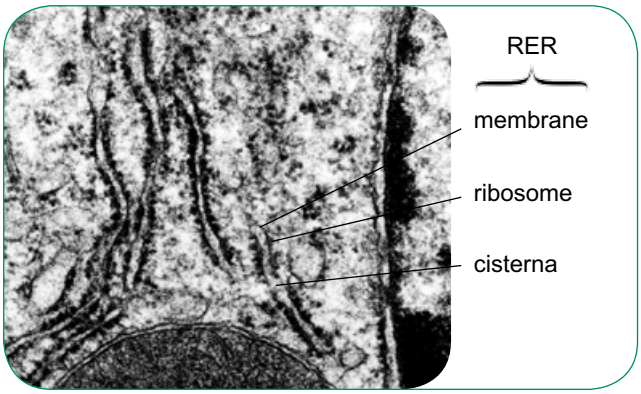

Figure 1.18 Transmission electron micrograph showing endoplasmic reticulum (× 40 000).

The enclosed spaces formed by the membranes are called **cisternae**. The membranes keep these spaces isolated from the cytoplasm.

RER is where most protein synthesis takes place. Protein synthesis happens on the ribosomes that are attached to the membranes. As the protein molecules are made, they collect inside the cisternae. From here, they can be transported to other areas in the cell – to the Golgi apparatus, for example (page 14).

SER has different roles in different cells. For example, in cells in the ovary and testis it is the site of production of steroid hormones such as oestrogen and testosterone. In liver cells, it is the place where toxins are broken down and made harmless.

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Golgi apparatus

In many cells, a stack of curved membranes is visible, enclosing a series of flattened sacs. This is the **Golgi apparatus** (Figure 1.19). Some cells have several Golgi apparatuses.

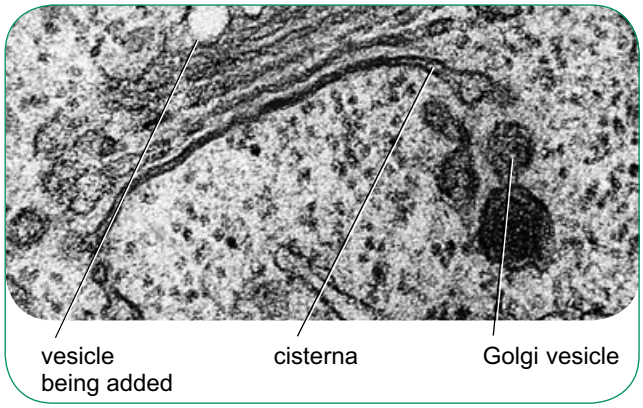

Figure 1.19 Transmission electron micrograph showing a Golgi apparatus (×35 000).

The Golgi apparatus is not a stable structure; it is constantly changing. At one side, tiny membrane-bound **vesicles** move towards the Golgi apparatus and fuse together, forming a new layer to the stack. At the other side, the sacs break down, forming vesicles that move away from the Golgi apparatus (Figure 1.20).

The vesicles that fuse with the Golgi apparatus have come from the endoplasmic reticulum. They contain proteins that were made there. In the Golgi apparatus, these proteins are packaged and processed, changing them into the required product.

Some of the processed proteins are then transported, in the vesicles that bud off from the Golgi apparatus, to the plasma membrane. Here, the vesicles fuse with the membrane and deposit the proteins outside the cell, in a process called **exocytosis**. The production of useful substances in a cell and their subsequent release from it is called **secretion**.

Some vesicles, however, remain in the cell. Some of these contain proteins that function as digestive enzymes, and such vesicles are called **lysosomes**.

Lysosomes

Lysosomes are tiny bags of digestive enzymes. They are surrounded by a single membrane. They are usually about 0.5 µm in diameter. Their main function is to fuse with other vesicles in the cell that contain something that needs to be digested – for example, a bacterium which has been brought into the cell by endocytosis (Chapter 2). They also help to destroy worn-out or unwanted organelles within the cell. The enzymes in the lysosome break down the large molecules in the bacterium or organelle, producing soluble substances that can disperse into the cytoplasm. The head of a sperm cell contains a special type of lysosome called an **acrosome**, whose enzymes digest a pathway into an egg just before fertilisation takes place.

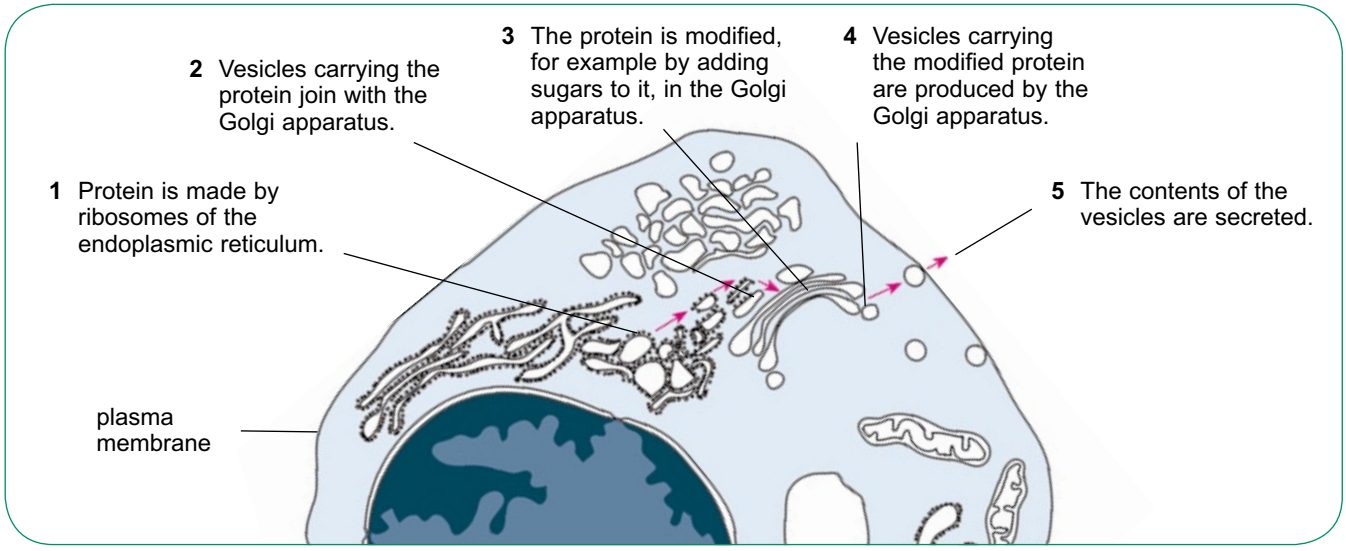

Figure 1.20 Function of the Golgi apparatus.

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Chloroplasts

Chloroplasts are found in some plant cells, but never in animal cells (Figure 1.21). They are the site of photosynthesis.

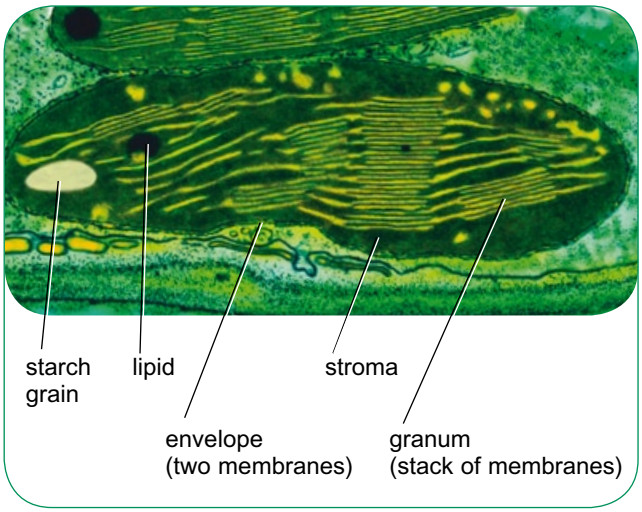

Figure 1.21 Transmission electron micrograph of a chloroplast (×27000).

A chloroplast has a double membrane, called an **envelope**, surrounding it. These membranes isolate the reactions that take place inside the chloroplast from the rest of the cell.

Inside the chloroplast, there are membranes called **grana** (singular: granum). In places, the grana form stacks called **thylakoids**. The grana contain chlorophyll, and this is where the light-dependent reactions of photosynthesis take place. In these reactions, light energy is captured by chlorophyll and used to split water molecules to provide hydrogen ions, which are then used to make ATP and a substance called reduced NADP. The ATP and reduced NADP are then used to make carbohydrates, using carbon dioxide from the air, in the light-independent reactions. The light-independent reactions take place in the 'background material' of the chloroplast, called the **stroma**.

Chloroplasts often contain **starch grains**. Starch is a carbohydrate that is used as an energy store in plants.

Mitochondria

Mitochondria are found in both plant and animal cells. Like chloroplasts, they are surrounded by a double membrane, also known as an envelope (Figure 1.22).

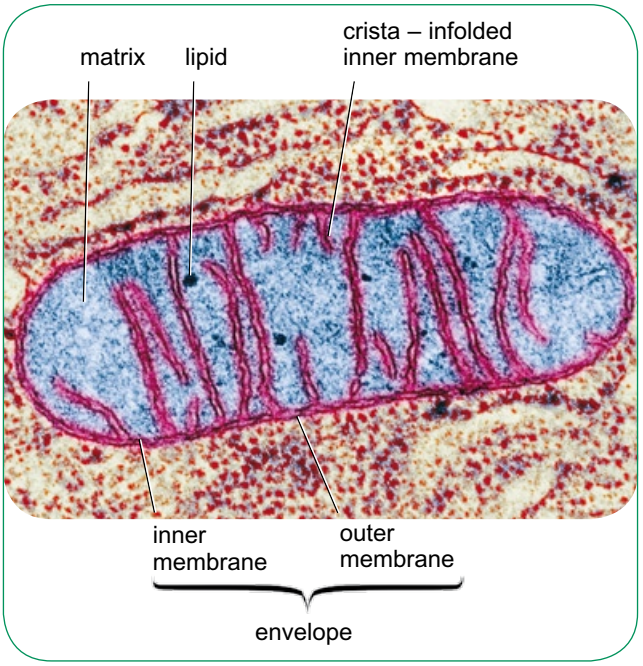

Figure 1.22 Transmission electron micrograph of a section through a mitochondrion (×46000).

Mitochondria are the site of **aerobic respiration** in a cell. Here, oxygen and energy-containing molecules produced from glucose are used to make **ATP**. ATP is the energy currency of a cell, necessary for every energy-using activity that it carries out. Each cell has to make its own ATP. Cells that use a lot of energy, such as muscle cells, therefore contain a lot of mitochondria.

The inner membrane of the mitochondrion is folded to form **cristae**. Here, ATP is made in a process that has many similarities with the production of ATP on the membranes inside a chloroplast. The 'background material' of the mitochondrion, called the **matrix**, is the site of the stages of aerobic respiration called the Krebs cycle.

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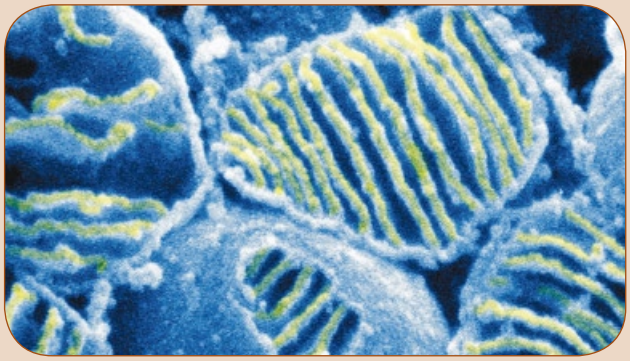
Faulty mitochondria

Mitochondria are unusual organelles. Like chloroplasts they have two membranes around them rather than just one, and they contain their own DNA. Mitochondria and chloroplasts have evolved from prokaryotic cells that 'invaded' eukaryotic cells early in their evolutionary history – perhaps 2 billion years ago – and made themselves invaluable by providing enzymes and pathways that help the cell to survive. They have become an integral part of their host cells.



Scanning electron micrograph of a group of mitochondria (× 60 000).

All the mitochondria in your cells have been produced from a few mitochondria that were in your mother's egg cell. The genes in mitochondria are passed down the maternal line. When a cell divides (Chapter 3), the mitochondria are shared out between the daughter cells.

The DNA in human mitochondria contains 37 different genes. These genes are not as well protected as those in the nucleus and are particularly prone to mutation. Some of these mutations are harmful, and mitochondria with mutant genes have been linked to a number of human diseases. However, mitochondria are not self-sufficient in DNA, and they rely on proteins that are produced following the code on the DNA in the nucleus. So faults in mitochondria are not necessarily caused by the mitochondria's own genes, but could be a result of a mutation in the nuclear DNA. This is borne out by the fact that more than 80% of diseases that are linked to faulty mitochondria do not follow a maternal inheritance pattern. This includes some cases of male infertility, caused by a lack of ATP generation in sperm cells, and also a tendency towards the development of type 2 (late onset) diabetes.

But about 1 in every 5000 people are thought to carry mutations in their mitochondrial DNA, and this can sometimes lead to very serious health problems, such as liver, kidney or brain damage. Often, a fetus that has inherited these faulty mitochondria from its mother does not survive and the mother has a miscarriage. Work is in progress to find methods of removing these faulty mitochondria from the mother's egg and replacing them with healthy mitochondria taken from a donor egg. The mother's nucleus would still be present in the egg, so the child would still be genetically hers – except for the genes in her mitochondria.

Licences to carry out such work in the UK are granted by the Human Fertilisation and Embryology Authority. The HFEA has a general ruling that embryos cannot be genetically altered in such a way that the altered genes would be passed on to their own offspring one day – they cannot pass along the 'germ line' from one person to their offspring. Initially, this ruling was thought to exclude the substitution of a mother's mitochondria with someone else's, because mitochondria contain genes. However, in 2006, the HFEA ruled that this would be allowable, and they have granted a licence for research work to be carried out on the technique. Professor John Burn, from the Newcastle Institute of Clinical Genetics, which is the first institution to receive such a licence, says: 'My belief is that what we are doing is changing a battery that doesn't work for one that does. The analogy is with a camera: changing the battery won't affect what's on the film, and changing the mitochondria won't affect the important DNA.'

16

Vacuole

A vacuole is a membrane-bound organelle that contains liquid. Mature plant cells often have large vacuoles that contain cell sap. The membrane surrounding the vacuole is known as the **tonoplast**. Cell sap contains a variety of substances in solution, especially sugars, pigments and also enzymes.

Plasma (cell surface) membrane

Every cell is surrounded by a **plasma membrane**, sometimes known as the **cell surface membrane**. This is a thin layer made up of lipid (fat) molecules and protein molecules. Its role is to control what enters the cell and what leaves it. You can read about the movement of substances through the plasma membrane in Chapter 2.

Centrioles

Centrioles are found in animal cells but not in plant cells. Centrioles make and organise tiny structures called **microtubules**, which are made of a protein called **tubulin** (Figure 1.23). During cell division, microtubules form the **spindle**, and are responsible for moving the chromosomes around in the cell, and pulling them to opposite ends of the cell. Plant cells also use microtubules during cell division, but they are not organised by centrioles.

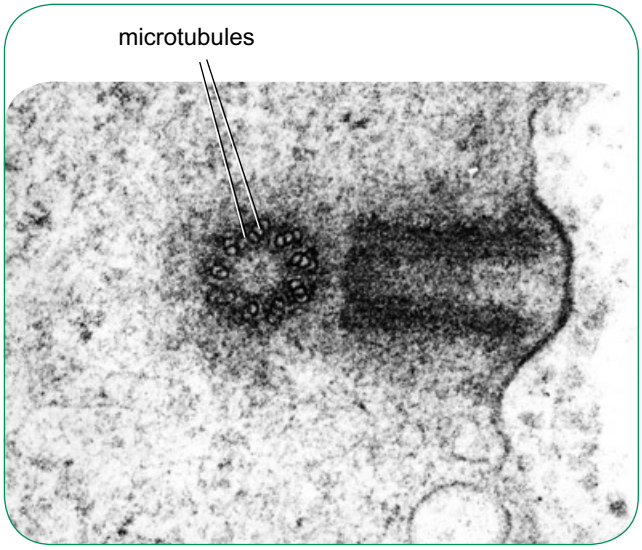


Figure 1.23 Transmission electron micrograph showing the two centrioles of an animal cell (at right angles to each other) (×126 000).

Cilia and flagella

Cilia and **flagella** (singular: cilium and flagellum) are long, thin extensions from the surface of a cell, which can produce movement. They are found in some animal cells, and rarely in plant cells – some primitive plants such as liverworts and mosses produce male gametes that swim using flagella.

Cilia and flagella have the same basic structure. The term 'cilia' is used for relatively short structures, usually found in large numbers, whereas 'flagella' are longer and normally found in ones or twos.

Cilia and flagella contain microtubules, always arranged in a 9 + 2 arrangement – that is, with two microtubules in the centre surrounded by a ring made up of nine pairs of microtubules (Figure 1.24 and Figure 1.25). Movement is produced by these microtubules sliding against each other. The movement causes the cilium or flagellum to bend and then straighten. Cilia in a group of ciliated cells usually all move in harmony with each other, looking like a field of wheat as wind sweeps over it.

The movement of cilia can move fluids over the surface of the cell. For example, in the lining of the bronchus, cilia sweep mucus up to the throat, where it is swallowed. Flagella, however, usually cause the cell to swim through a liquid.

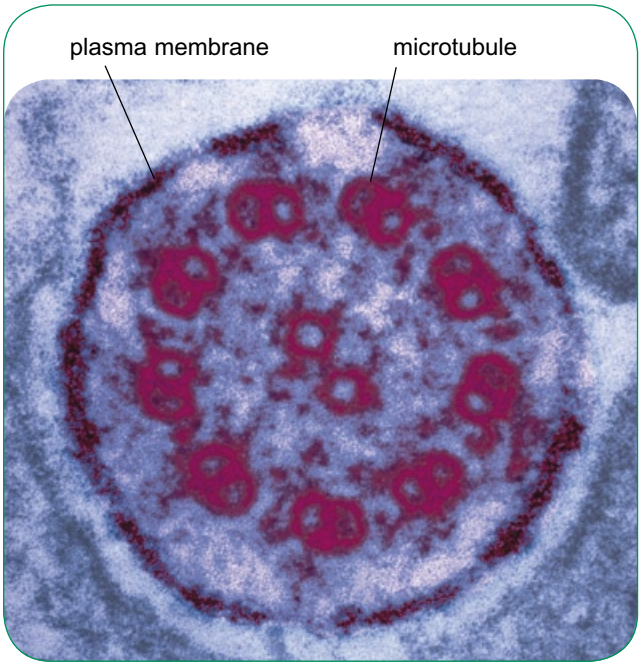


Figure 1.24 Transmission electron micrograph of a transverse section of a cilium or flagellum (×265 000).

17

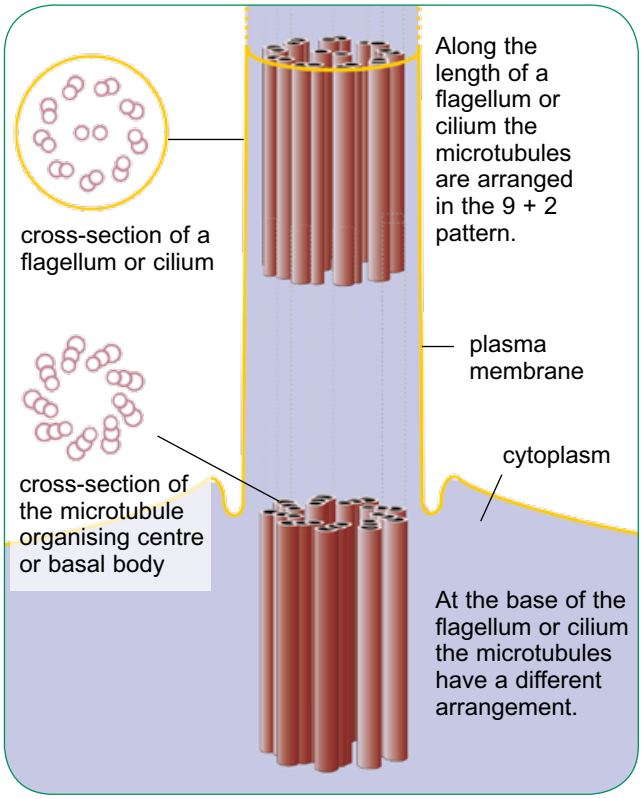


Figure 1.25 Cilia and flagella.

The cytoskeleton

All plant and animal cells contain a network of protein filaments, called **microfilaments**, that act as a 'skeleton' helping to support the cell and to determine its shape. Together with microtubules, these filaments make up the **cytoskeleton** (Figure 1.26).

The cytoskeleton provides mechanical strength for the cell, and also helps to direct movement of organelles within the cell. It provides 'tracks' along which organelles can be moved. The microtubules can act as 'motors', using energy from ATP to pull organelles along the tracks from one place to another. The cytoskeleton can also help the whole cell to move.

Extension

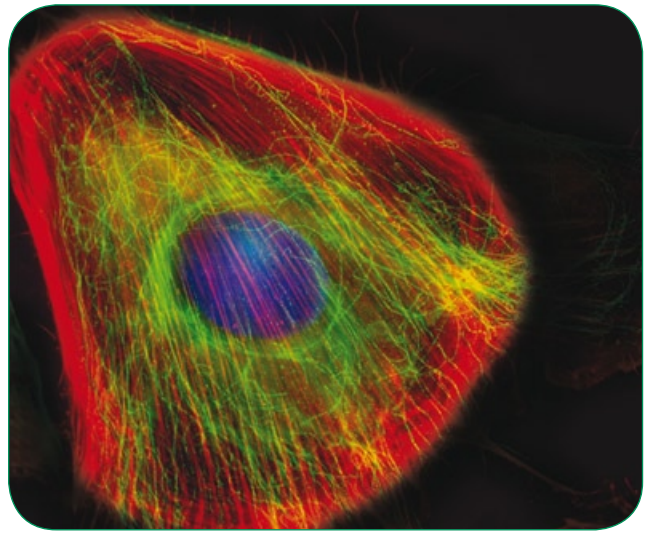


Figure 1.26 Light micrograph showing the cytoskeleton in a kidney cell. Microtubules are stained green, microfilaments red and the nucleus blue (× 500).

Cell walls

Plant cells are always surrounded by a **cell wall** (Figure 1.27 and Figure 1.28). This is not an organelle, because it is not inside the cell.

Plant cell walls are made of long strands of a carbohydrate called **cellulose**. The cellulose fibres are very strong, and are arranged in a criss-cross manner, held together by a matrix that contains **pectin**. This composite structure has tremendous resistance to stretching forces that might act on it – for example, if the cell has taken up a lot of water and is expanding. The cell wall holds firm, preventing the cell from bursting.

Pectin is also found in the **middle lamella** that cements one cell to another (Figure 1.28).

SAQ

8 Draw a table to compare the structures visible in an animal cell and a plant cell, when they are viewed through an electron microscope.

Hint

Answer

18

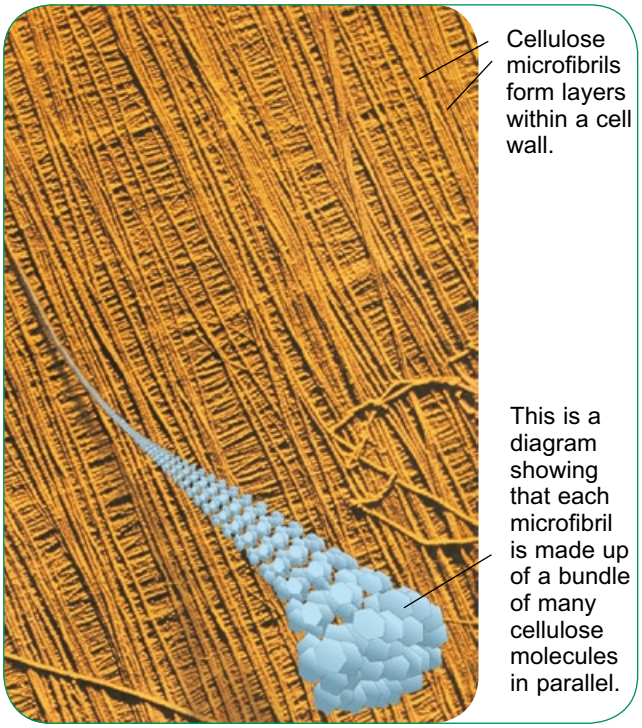


Figure 1.27 Scanning electron micrograph and diagram showing the structure of a plant cell wall (background electron micrograph ×600 000). Notice that the microfibrils lie in different directions in different layers, which greatly increases the mechanical strength of the cell wall.

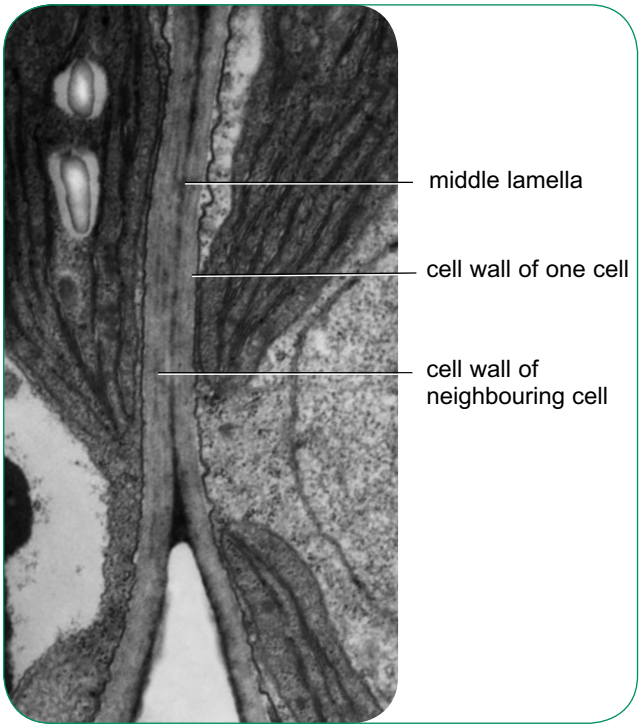


Figure 1.28 Transmission electron micrograph of plant cell walls. Where two plant cells lie next to each other, a structure called the middle lamella holds the adjacent walls firmly together (×18 000).

Prokaryotic cells

Prokaryotic means 'before nucleus'. Prokaryotes are single-celled organisms that do not have nuclei. Cells that do have nuclei are said to be **eukaryotic**.

The structure of a prokaryotic cell

Figure 1.29 shows the structure of a typical prokaryotic cell. The most obvious difference between this cell and a eukaryotic cell is the lack of a nucleus. The prokaryote's DNA lies free in the cytoplasm.

In eukaryotic cells, the DNA is organised into several chromosomes, in which a long strand of DNA is associated with proteins called **histones**. This is not the case in prokaryotes. The DNA is not usually associated with histones (although histones are present in Archaea), and it is circular rather than linear as in eukaryotes.

This arrangement of the DNA is so different that some people think we should not use the term 'chromosome' to describe it. However, it has now become common for scientists to talk about bacterial chromosomes, despite the fact that they are not the same as the chromosomes in eukaryotic cells.

Prokaryotes also lack complex membrane-bound organelles, such as mitochondria, chloroplasts and endoplasmic reticulum. They do have ribosomes, but these are smaller than in eukaryotic cells, and they are always free in the cytoplasm rather than attached to membranes.

Prokaryotes are surrounded by a cell wall, but its structure is not at all like that of plant cells. The prokaryote cell wall is made up of fibres of **peptidoglycan**. Like plant cell walls, this cell wall stops the cell bursting if it expands.

Table 1.2 summarises the differences and similarities between eukaryotic cells and prokaryotic cells.

19

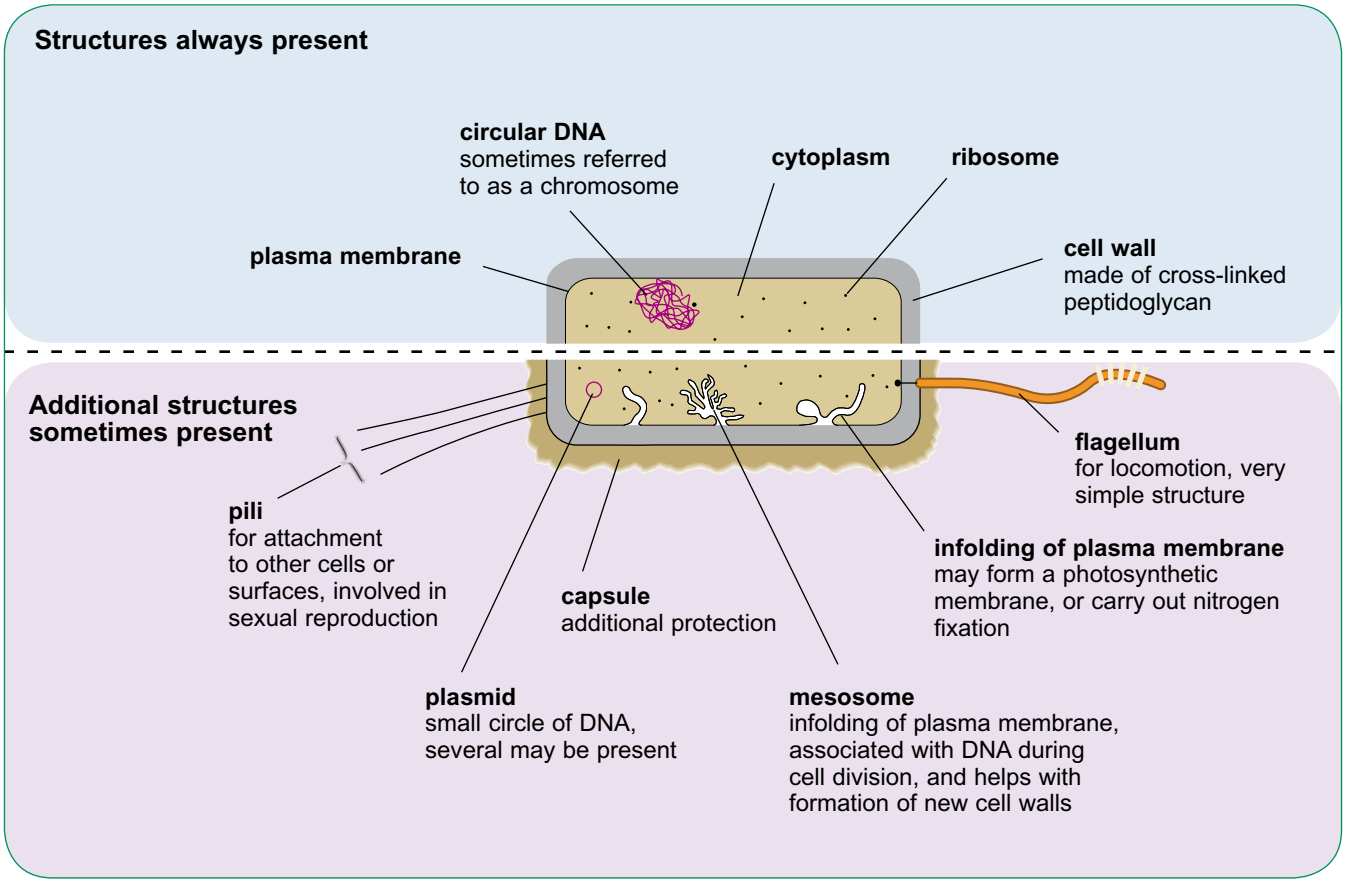


Figure 1.29 The structure of a typical prokaryotic cell.

Structure	Eukaryotic cell	Prokaryotic cell
nucleus	usually present, surrounded by a nuclear envelope and containing a nucleolus	no nucleus, and therefore no nuclear envelope or nucleolus
mitochondria	usually present	never present
chloroplasts	present in some plant cells	never present
endoplasmic reticulum	always present	never present
ribosomes	relatively large, about 30 nm in diameter	relatively small, about 20 nm in diameter
cytoskeleton	always present, made up of microtubules and microfilaments	no cytoskeleton
chromosomes	DNA arranged in several long strands, associated with histones	DNA circular, not associated with histones
cell wall	cellulose cell walls present in plant cells	cell wall always present, made of peptidoglycan
cilia and flagella	sometimes present	some have flagella, but these have a different structure from those in eukaryotic cells

Table 1.2 Comparison of the ultrastructure of eukaryotic and prokaryotic cells.

20

Summary

Glossary

- All living organisms are made of a cell or cells. Cells and their contents are usually measured in micrometres (μm). One micrometre is one thousandth of a millimetre.
- Light microscopes have much less resolving power than electron microscopes and so the images obtained from light microscopes can only be usefully magnified up to about 1400 times, compared with 300 000 times for an electron microscope.
- The greater resolving power of the electron microscope enables us to see the ultrastructure of a cell – that is, the small organelles that it contains, and their internal structure.
- The following formula can be used to calculate magnifications or the real sizes of objects being viewed:

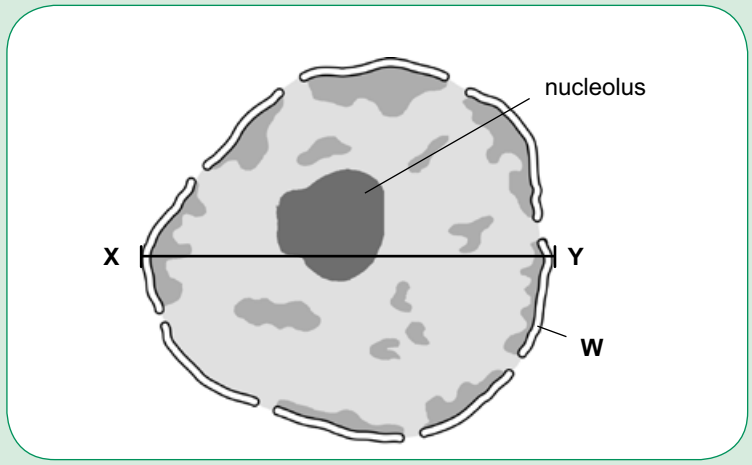
$$\text{magnification} = \frac{\text{size of image}}{\text{real size of object}}$$

- Specimens to be viewed using a microscope are often stained to make parts of them look darker, or different colours.
- Plant and animal cells are eukaryotic cells, with a nucleus surrounded by an envelope. The nucleus contains the DNA, in the form of chromosomes. All cells are surrounded by a partially permeable plasma membrane.
- Plant and animal cells contain ribosomes for protein synthesis, endoplasmic reticulum for the storage and transport of substances made in the cell, Golgi apparatus for processing and packaging proteins the cell has made, lysosomes containing digestive enzymes and mitochondria to produce ATP by aerobic respiration.
- Plant cells sometimes also contain chloroplasts, where photosynthesis takes place, and they may have a large vacuole containing cell sap. They are surrounded by a fully permeable cellulose cell wall.
- Animal cells contain a pair of centrioles, which organise the microtubules in the cell – for example, when forming the spindle during cell division. Animal cells may also have cilia or flagella, which contain microtubules in a 9 + 2 arrangement and can produce movement.
- Microtubules and microfilaments form the cytoskeleton, holding the cell in shape and helping to move organelles around inside the cell.
- Bacteria are prokaryotic cells, which do not have a nucleus. Their DNA is not associated with histones, and is present as a circular strand. Prokaryotic cells lack complex membrane-bound organelles such as mitochondria. They have smaller ribosomes than eukaryotic cells. They always have a cell wall, but this is made of peptidoglycan and not cellulose.

21

Questions

1 a The drawing shows an animal cell nucleus as seen using an electron microscope.



i Name the structure labelled W. [1]

ii The actual diameter of the nucleus, measured along the line XY, is 7 µm.
Calculate the magnification of the nucleus. Show your working. [2]

b Each part of a cell is specialised to carry out a particular function.

Below is a list of parts of a cell, labelled **A** to **F**. Each of the list of statements, numbered **1** to **6**, refers to one of these parts of the cell.

A nucleus	**1** where some lipids, including steroids, are made
B mitochondrion	**2** controls entry of substances into the cell
C plasma membrane	**3** controls the activities of the cell
D chloroplast	**4** where polypeptides are made
E smooth endoplasmic reticulum	**5** where photosynthesis takes place
F ribosomes	**6** where aerobic respiration takes place

Match a statement to part of the cell. For example, **3** matches with **A**. [5]

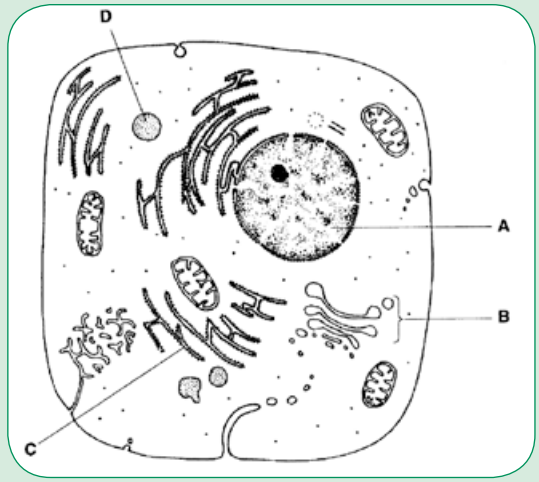
OCR Biology AS (2801) January 2003 [Total 8]

Answer

2 a The drawing shows an animal cell as seen under an electron microscope.

Complete the following table by:

- identifying the parts of the cell A to E
- naming the part of the cell responsible for the function stated. The first one has been done for you.



Function	Part of cell	Label
controls activities of the cell	nucleus	A
attaches to mRNA in protein synthesis		
produces secretory vesicles		
contains digestive enzymes		

[6]

b Outline the structure and functions of the cytoskeleton. [4]

OCR Biology AS (2801) January 2005 [Total 10]

Answer

continued

22

3 With reference to <u>both</u> light and electron microscopy, explain and distinguish between the terms *magnification* and *resolution*.

Hint

OCR Biology AS (2801) January 2002 [Total 4]

Answer

4 The table below compares the features of typical eukaryotic and prokaryotic cells. Copy and complete the table by placing one of the following, as appropriate, in each empty box: a tick (✓), a cross (✗) or the words 'sometimes present'

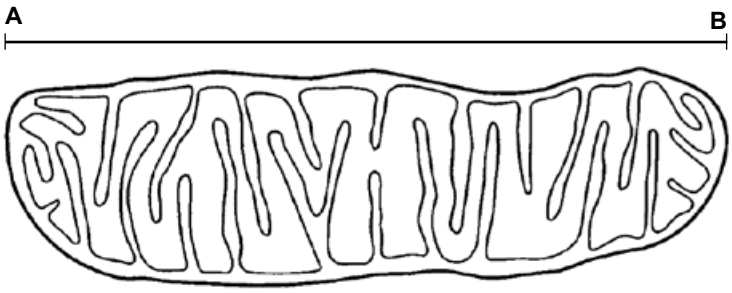
Feature	Eukaryotic cell	Prokaryotic cell
cell wall	sometimes present	✓
nuclear envelope	✓	
Golgi apparatus		✗
flagellum	sometimes present	
ribosomes		✓
carries out respiration	✓	
chloroplast	sometimes present	

OCR Biology AS (2801) January 2001 [Total 6]

Answer

5 a The diagram shows a drawing of an organelle from a ciliated cell as seen with an electron microscope.

Hint



i Name the organelle shown in the diagram. [1]

ii State the function of this organelle. [2]

iii State why ciliated cells contain relatively large numbers of these organelles. [1]

iv Calculate the actual length as shown by the line AB in the diagram.
Express your answer to the <u>nearest micrometre</u> (μm).
Show your working. [2]

b An image shown to the same magnification as the diagram above could be produced using a light microscope. Explain why such an image would be of little use when studying cells. [2]

OCR Biology AS (2801) January 2006 [Total 8]

Answer

23

Cell membranes

Background

e-Learning

Objectives

Every living cell is surrounded by a membrane. This is called the **plasma membrane**, or the **cell surface membrane**. The plasma membrane defines the limits of the cell. It separates the cell's contents from its external environment, and it controls what can pass from this environment into the cell, and from the cell into the external environment. It is partially permeable.

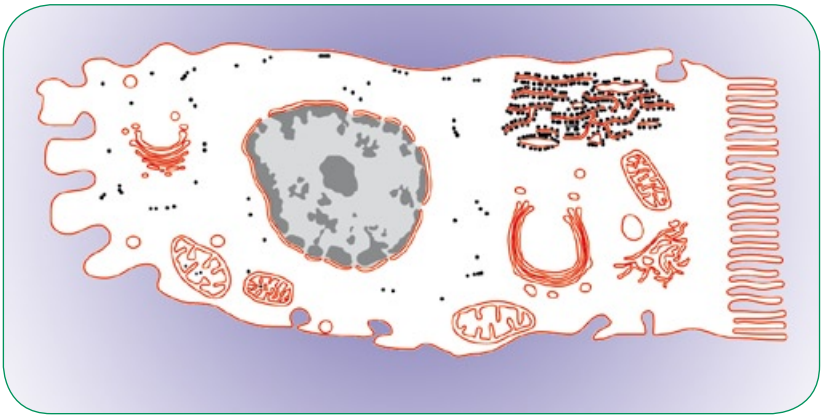


Figure 2.1 Membranes in an animal cell (shown in red).

Membranes are also found inside cells. Some organelles are surrounded by a single membrane – for example, lysosomes. The nucleus, mitochondria and chloroplasts each have two membranes around them, making up an **envelope**. Most eukaryotic cells also have an extensive network of membranes within their cytoplasm, forming the rough endoplasmic reticulum, the smooth endoplasmic reticulum and the Golgi apparatus (Figure 2.1). Like the plasma membrane, these membranes inside the cell are partially permeable, and therefore able to control what can pass through them. They separate what happens inside the organelle from what is happening in the rest of the cell.

Table 2.1 summarises the functions of membranes around and inside cells. You will find out more about some of these functions in this chapter.

Function	Example
Membranes are partially permeable, controlling what passes through them.	The plasma membrane allows small or uncharged particles to pass through it; protein channels and transporters control the passage of larger or charged particles.
Membranes produce different compartments inside cells.	Mitochondria are surrounded by two membranes, which isolate the reactions taking place inside from the reactions taking place in the cytoplasm.
Membranes are important in cell signalling.	A substance produced by one cell docks into a receptor in the plasma membrane of another, causing something to happen in the second cell.
Membranes can allow electrical signals to pass along them.	The membrane of the axon of a motor neurone transmits action potentials from the central nervous system to a muscle.
Membranes provide attachment sites for enzymes and other molecules involved in metabolism.	The inner membrane of a mitochondrion contains molecules needed for the production of ATP. The inner membrane of a chloroplast contains chlorophyll needed for photosynthesis.

Table 2.1 Functions of membranes.

24

Structure of cell membranes

All cell membranes have a similar structure. They are normally between 7 nm and 10 nm thick, which makes them invisible with a light microscope but visible using an electron microscope. They are formed from a double layer of molecules called phospholipids, in which many different kinds of **proteins** are situated.

Phospholipid bilayer

Phospholipid molecules have an unusual property. Their heads have a tiny charge, and this attracts them to water molecules. But their tails don't have a charge, and they are repelled from water molecules. We say that the heads of the phospholipids are **hydrophilic** ('water-loving') and the tails are **hydrophobic** ('water-hating') (Figure 2.2).

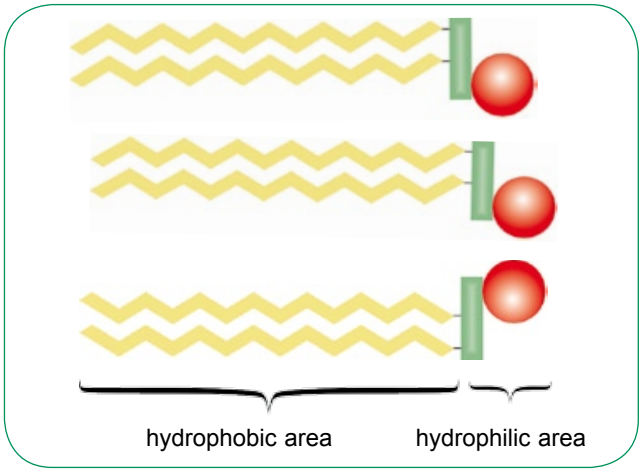


Figure 2.2 Phospholipid molecules.

The cytoplasm inside a cell contains a lot of water, and so does the fluid outside cells. (This is true whether the cell is the single cell of a unicellular organism, or one cell of many in the body of a multicellular organism.) The hydrophilic heads of phospholipid molecules are therefore drawn to these fluids, while the hydrophobic tails are repelled by them. This causes the phospholipids to arrange themselves in a double layer, with heads facing outwards and tails facing inwards. This is called a phospholipid bilayer (Figure 2.3).

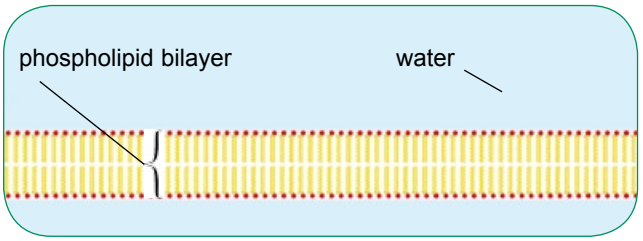


Figure 2.3 A phospholipid bilayer.

Other components of cell membranes

Membranes also contain another type of lipid. This is **cholesterol**. Cholesterol molecules lie alongside the phospholipids, helping to make up the bilayer.

There are also many different protein molecules in cell membranes. They are much larger than phospholipid molecules. Some of the protein molecules lie in the membrane, protruding from both sides. Others float in just the outer layer or the inner layer (Figure 2.4).

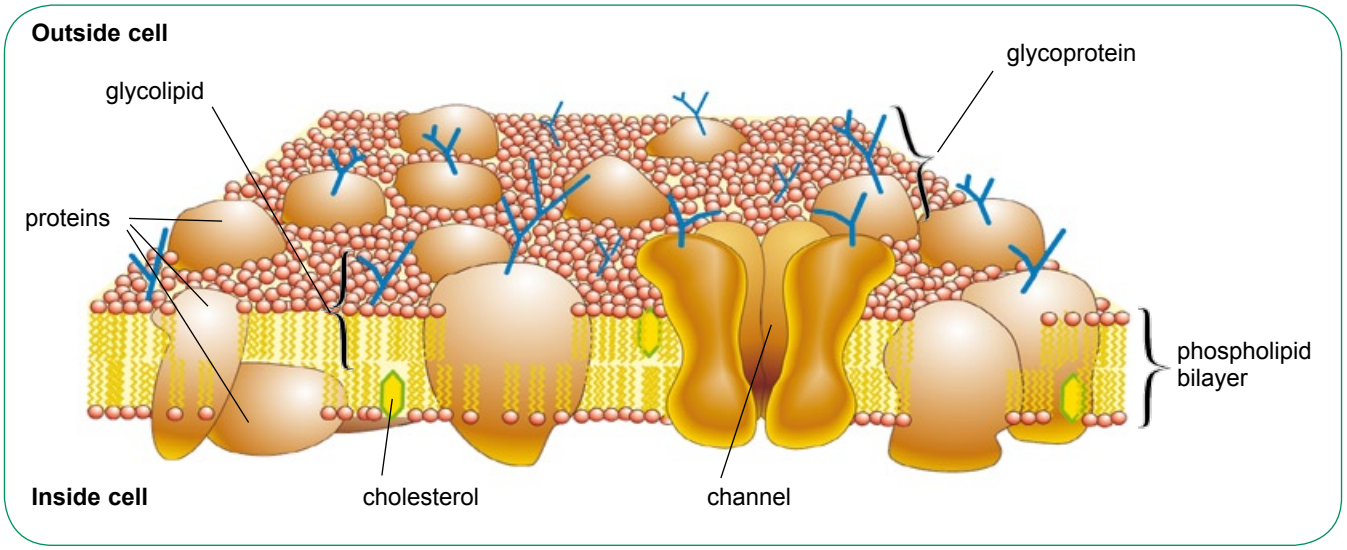


Figure 2.4 Part of a cell surface membrane.

25

Many of the lipid molecules and protein molecules have short strings of **sugar** molecules attached to them, forming **glycolipids** and **glycoproteins**.

Figure 2.4 shows the structure of a plasma (cell surface) membrane, including all of these components. This is called the **fluid mosaic model** of membrane structure. The term 'fluid' refers to the fact that the molecules in the membrane are in constant motion, moving around within their own layer (they don't normally swap sides). The term 'mosaic' refers to the way the membrane would look if viewed from above, with a mosaic pattern formed by the protein molecules that are scattered throughout.

Table 2.2 summarises the roles of the different components of cell membranes.

SAQ

1 What is the difference between the outer surface and the inner surface of a plasma membrane?

Answer

Cell signalling

A cell must stay in contact with its environment and with other cells in order to survive. Cells must be able to react to changes in their environment. In a multicellular organism, cells in one part of the body must be able to communicate with cells in other parts. A cell therefore needs to be able to pick up 'signals' at its surface to which it may need to respond.

Signals arrive at the plasma membrane from outside the cell as particular substances – for example, a hormone – or changes in electrical potential – as happens in nerve impulses. A receptor in the cell's plasma membrane picks up these signals, and brings about actions within the cell. This process is known as **cell signalling**.

You will meet several different examples of cell signalling as you continue through your Biology course, especially in the context of coordination by hormones and nerve impulses. Cell signalling has potential implications for medicine. For example, why do liver cells in some people not respond to insulin as they should? (This is the cause of type 2 diabetes.) Why do cancer cells not respond to signals that should stop them dividing? Answers to these questions may help to bring about cures or treatments for these and other diseases.

Component	Roles
phospholipid	• forms the bilayer which is the fundamental basis of the membrane in which all other components are embedded • provides a barrier to water-soluble (hydrophilic) substances, such as ions and molecules that carry a charge
cholesterol	• helps to maintain the fluidity of the membrane, preventing it from becoming too stiff when temperatures are low, or too fluid when temperatures are high
protein and glycoprotein	• form channels through which hydrophilic substances can pass; the channels can be opened and closed • act as transporters that can move substances across the membrane up their concentration gradients, with the use of energy from ATP • act as receptor sites, allowing specific molecules from outside the cell, such as hormones, to bind with them and then set up responses within the cell • act as recognition sites, because their precise structure may be specific to a particular type of cell or to a particular individual • act as enzymes

Table 2.2 Roles of the components of cell membranes.

26

Mechanisms of cell signalling

Figure 2.5 shows three different ways in which cell signalling can occur. In Figure 2.5a, the signal is a chemical that attaches to a protein or glycoprotein acting as an ion channel. When the chemical attaches to the receptor, it makes the channel open and let ions into the cell, bringing about a response.

Figure 2.5b shows a slightly more complex mechanism of cell signalling. Here, the receptor in the plasma membrane interacts with another molecule, a **G-protein**. When the signal molecule attaches to the receptor, the G-protein is activated. The G-protein then activates an enzyme, which brings about a reaction inside the cell.

Figure 2.5c shows a third type of signalling, this time involving a receptor that is also an enzyme. The receptor is made up of two parts. When the signal molecule arrives, it slots into both of these parts, connecting them to one another and forming them into an active enzyme. The enzyme then brings about reactions inside the cell.

Extension

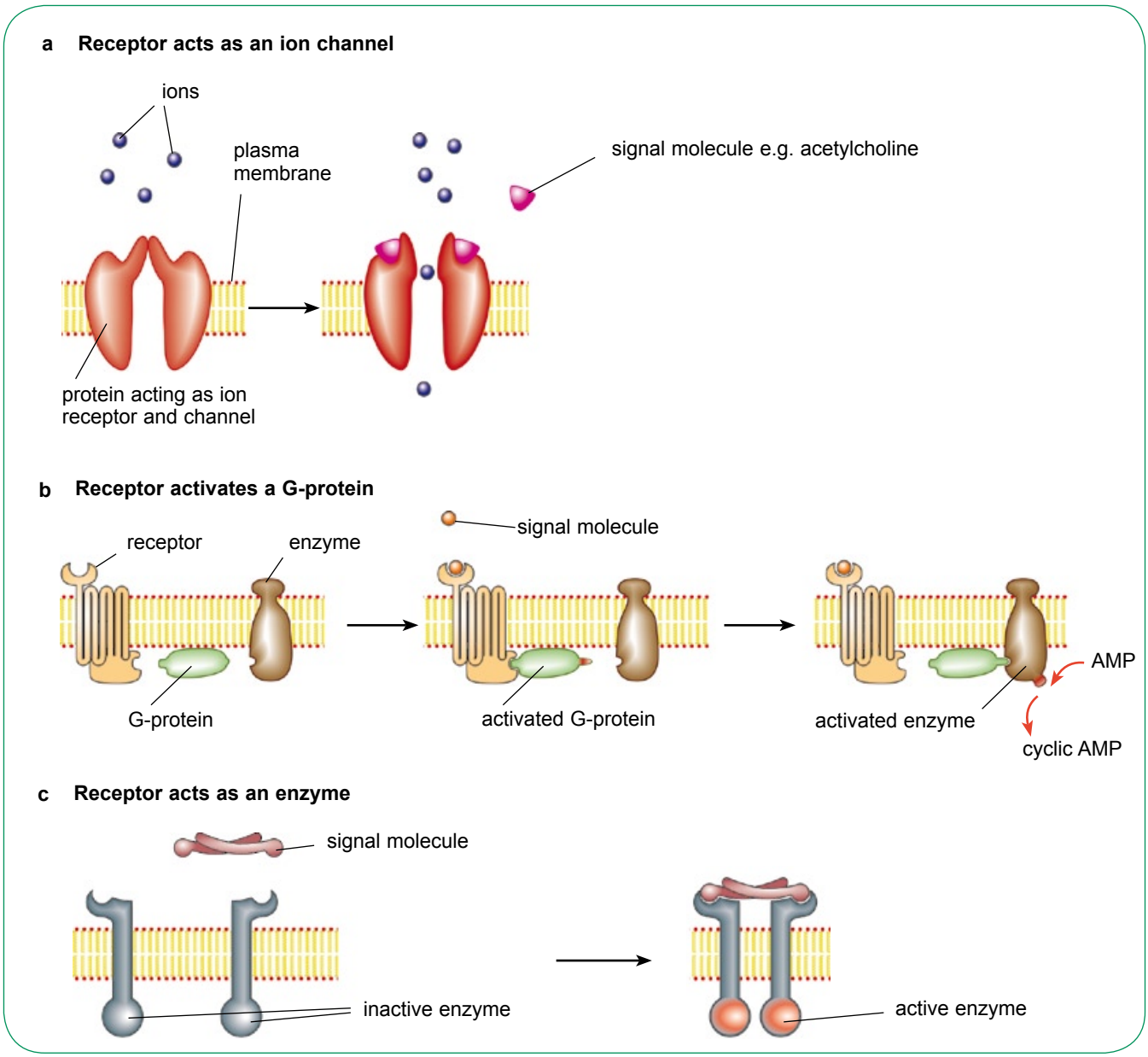


Figure 2.5 Mechanisms of cell signalling: **a** receptor acts as an ion channel; **b** receptor activates a G-protein; **c** receptor acts as an enzyme.

27

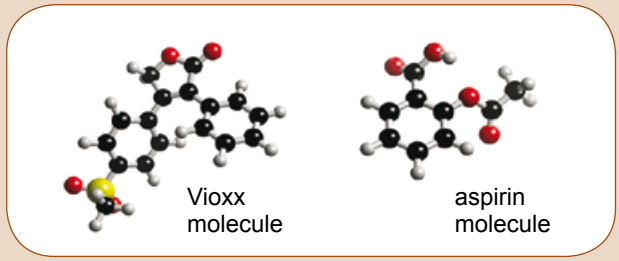
Aspirin and Vioxx

Aspirin seems to have become a wonder drug. Cheap and widely available, not only does it help to relieve pain, but people who are at risk of developing a blood clot in an artery or vein – perhaps because they have atherosclerosis, or are going on a long plane journey – are sometimes recommended to take half an aspirin tablet daily. This is because aspirin reduces the tendency of blood to clot.

Aspirin has these effects because it blocks some important cell-signalling pathways. One of these pathways involves chemicals called prostaglandins. Prostaglandins are made in cells in practically all the tissues in the body, especially after injury. They pass out of the cell and slot into receptors in the membranes of several different kinds of cells, activating G-proteins and bringing about various effects in those cells. For example, some nerve cells respond to prostaglandins by sending pain signals to the brain. Prostaglandins also cause inflammation, where blood capillaries become leaky and allow fluid and white blood cells into the damaged area.

Pain and inflammation in a damaged tissue are useful responses. The pain tells you to take care of that part of your body, and not to do any more damage to it. Inflammation brings white blood cells that can attack and destroy any invading bacteria that have managed to get into the wound. Swelling provides a cushion around the damaged area, helping to protect it while it heals.

But you don't always appreciate these responses of your body to damage! Inflammation has its harmful side, sometimes causing damage to healthy tissue. We would like to be free of pain and to be able to reduce the swelling caused by inflammation. Aspirin does both by stopping the production of prostaglandins. It acts by inhibiting an enzyme inside cells called COX-2, which produces prostaglandins from a lipid called arachidonic acid. With COX-2 out of action, prostaglandin production stops, and inflammation and pain are reduced.



Arachidonic acid is also the starting point for making a substance called thromboxane. Thromboxane stimulates platelets to stick together and form blood clots. Aspirin also inhibits the production of thromboxane, which is how it is able to reduce the risk of blood clots forming.

Unfortunately, aspirin also inhibits another enzyme called COX-1, and this enzyme helps to produce the protective layer of mucus that lines the stomach. So taking aspirin makes it more likely that the strong acid in the stomach could damage its walls. People with stomach ulcers are advised not to take aspirin.

As we learn more about the complex metabolic pathways that produce enzymes like COX-1 and COX-2, and about the cell-signalling mechanisms involving prostaglandins and other chemicals, it is becoming possible to produce new drugs that have more narrow-ranging effects than aspirin. One such drug, called Vioxx, was developed to inhibit COX-2 but not COX-1. The idea was that it would reduce pain and inflammation without affecting the stomach lining. The drug went through all the normal testing procedures without difficulty, and was widely prescribed for pain caused by arthritis. However, it was eventually realised that patients taking Vioxx were at an increased risk of developing heart disease. No-one knows quite why this happens. Although the increased risk was very small – 1.5% of people taking Vioxx developed heart problems, compared with 0.78% taking a placebo – it was enough to cause Vioxx to be withdrawn.

Now drug companies are trying to find out more about how COX-1 inhibitors affect cell signalling, hoping that they can find a Vioxx-like substance that will have no harmful side-effects.

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Movement across cell membranes

Many substances move into and out of cells through their plasma membranes. Some of these substances move passively – that is, the cell does not have to use energy to make them move. Passive processes include **diffusion**, **facilitated diffusion** and **osmosis**. Other substances are actively moved by the cell, which uses energy to make them move up their concentration gradients. This is called **active transport**.

Diffusion

Particles are constantly moving around randomly. They hit each other and bounce off in different directions. Gradually, this movement results in the particles spreading evenly throughout the space within which they can move. This is **diffusion**.

If there are initially more particles in one place than another, we say there is a **concentration gradient** for them. Diffusion is the net movement of molecules or ions down their concentration gradient – that is, from a place where they are in a high concentration to a place where they are in a lower concentration.

There are usually a large number of different kinds of particles bouncing around inside and outside a cell, on both sides of its plasma membrane. Some of these particles hit the plasma membrane. If they are small – like oxygen and carbon dioxide molecules – and do not have an electrical charge, they can easily slip through the phospholipid bilayer.

Oxygen enters a cell like this. Inside the cell, aerobic respiration constantly uses up oxygen, so the concentration of oxygen inside the cell is low. If there is more oxygen outside the cell, then there is a concentration gradient for oxygen. Oxygen molecules on both sides of the plasma membrane are moving freely around, and some of them hit the plasma membrane and pass through it. This happens in both directions, but because there are more oxygen molecules in a given volume *outside* the cell than *inside*, more of them will pass through the membrane from outside to inside rather than in the opposite direction. The overall effect is for oxygen to move from outside the cell, through the plasma membrane, into the cytoplasm.

Facilitated diffusion

Oxygen and carbon dioxide have small molecules with no electrical charge, and can easily pass through the phospholipid bilayer. However, many other molecules or ions may be too big, or too highly charged, to do this. For example, chloride ions, Cl^-, have an electrical charge and cannot pass through the phospholipid bilayer.

Cells therefore need to provide special pathways through the plasma membrane which will allow such substances to pass through. Such pathways are provided by **channel proteins**. These proteins lie in the membrane, stretching from one side to the other, forming a hydrophilic channel through which ions can pass. The ions pass through by diffusion, down their concentration gradient. This process is called **facilitated diffusion**. It is just like ordinary diffusion, except that the molecules or ions only get through the membrane if they happen to bump into a channel (Figure 2.6).

Each channel formed by a protein will allow only a specific ion or molecule to pass through. The protein can change its shape, making the channel either open or closed. As we have seen, this is used in cell signalling.

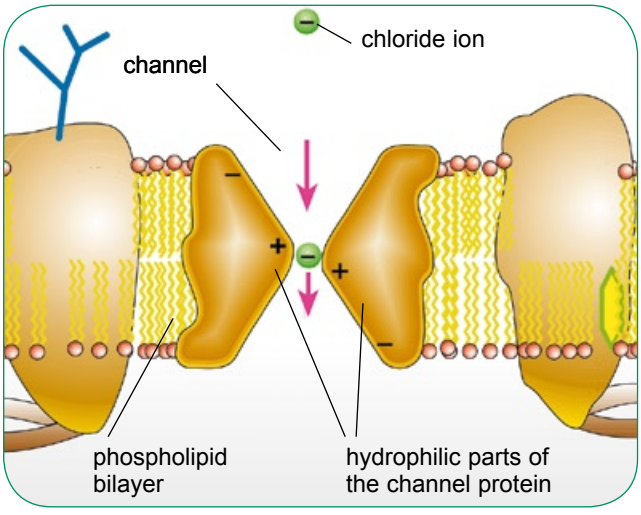

Figure 2.6 Facilitated diffusion.

SAQ

2 Explain under what circumstances carbon dioxide might diffuse into a palisade cell in a leaf, and how the process takes place.

Answer

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Osmosis

Water molecules, although they carry a charge (Chapter 7), are very small. They are therefore able to pass through the lipid bilayer by diffusion. This movement of water molecules, down their diffusion gradient, through a partially permeable membrane, is called **osmosis**.

It is not correct to use the term 'concentration' to describe how much water there is in something. Concentration refers to the amount of solute present. Instead, the term **water potential** is used. The symbol ψ (psi) can be used to mean water potential.

The water potential of a solution is a measure of how much water the solution contains in relation to other substances, and how much pressure is being applied to it. A solution containing a lot of water, and under pressure, is said to have a **high water potential**. A solution containing a lot of dissolved substances (solutes) and little water, and not under pressure, has a **low water potential**. You can think of water potential as being the tendency for water to leave a solution.

By definition, pure water at normal atmospheric pressure is given a water potential of 0. The more solute you dissolve in the water, the lower its water potential gets. Therefore, a solution of sugar has a water potential which is less than 0 – that is, it has a negative water potential.

Just as we don't normally talk about the 'concentration' of water, we don't normally use the term 'concentration gradient' either. Instead, we use the term **water potential gradient**. Water tends to move *down* a water potential gradient, from where there is a lot of water to where there is less of it (Figure 2.7). It diffuses out of a dilute solution (a lot of water – high water potential) and into a concentrated solution (a lot of solute – low water potential).

Why is this important? The cells in your body are surrounded by watery fluids. Blood cells, for example, float in blood plasma. Water can move freely through the plasma membrane of the blood cells, but most of the substances dissolved in the water cannot. If there is a water potential gradient between the contents of a cell and the blood plasma, then water will move either into or out of the cell. If a lot of water moves like this, the cell can be damaged.

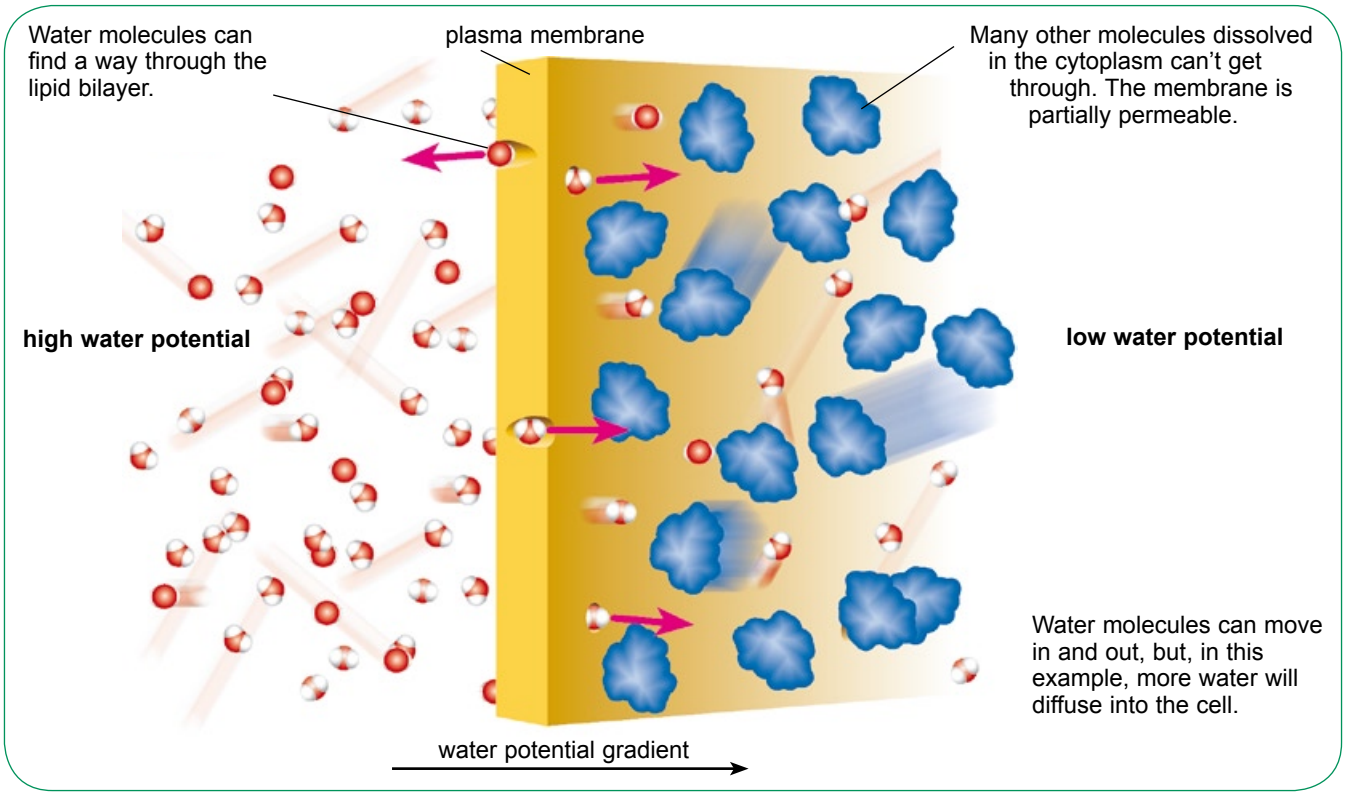

Figure 2.7 How osmosis occurs.

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Osmosis and animal cells

Figure 2.8 shows what happens when animal cells are placed in solutions with water potentials higher or lower than the water potential of the cytoplasm inside the cells. If the solution outside the cell has a higher water potential than the cytoplasm, then water enters the cell by osmosis. If the water potential gradient is very high, so much water may enter that the cell bursts.

If the water potential gradient is in the other direction, then water leaves the cell by osmosis. The cell may shrink, sometimes becoming 'star-shaped', described as being '**crenated**'. The concentration of the solutes in the cytoplasm increases, and this may adversely affect metabolic reactions taking place inside the cell.

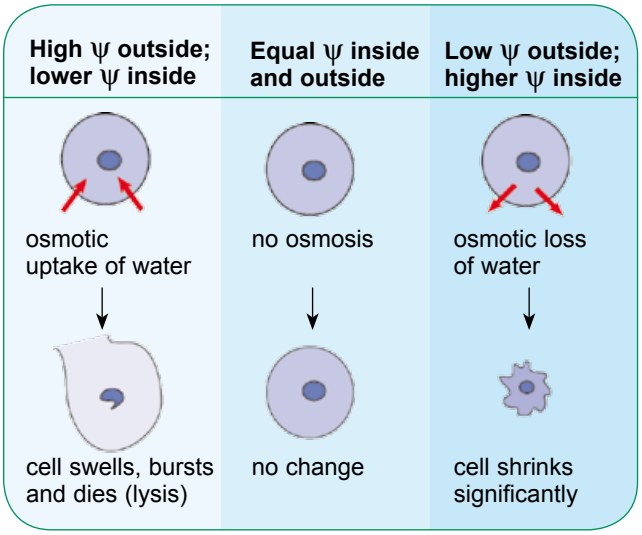

Figure 2.8 Osmosis and animal cells.

Osmosis and plant cells

Figure 2.9 shows what happens when plant cells are placed in solutions with water potentials higher or lower than the water potential of the cytoplasm in the cells.

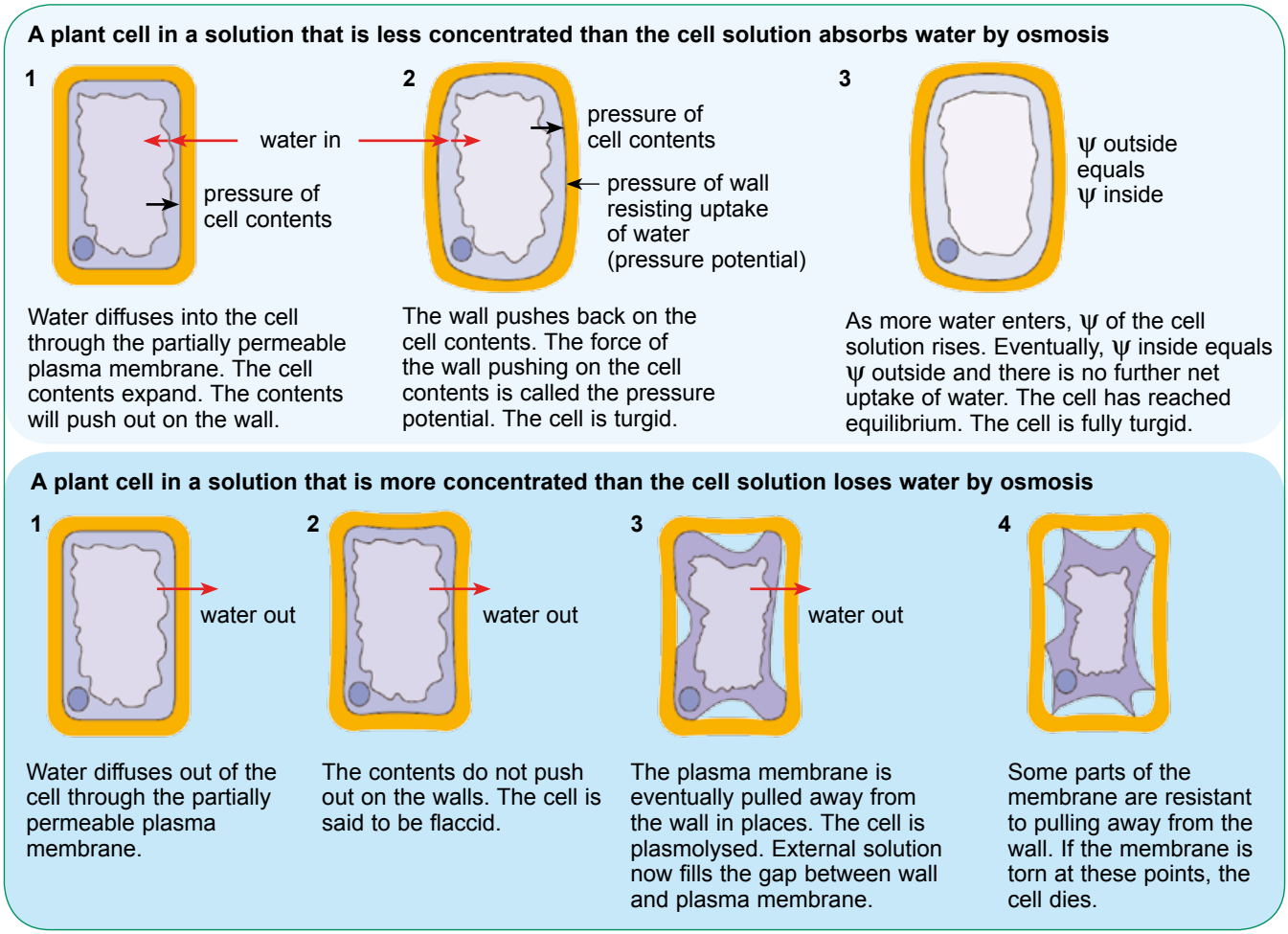

Figure 2.9 Osmosis and plant cells.

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Water moves into or out of the cell, down its water potential gradient, just as in an animal cell. The cell wall does not directly affect this movement, because it is fully permeable to water and to most of the solutes dissolved in it.

If the cell is put into water, then – just as in an animal cell – water enters by osmosis. But this time the cell does not burst. This is because, as it swells, it has to push out against the strong cell wall. The cell wall resists expansion of the cell, exerting a force called **pressure potential**. The cell becomes full and stiff, a state called turgor.

If a plant cell is put into a concentrated solution, then water leaves it by osmosis. The cell therefore shrinks. If a lot of water is lost, the contents no longer press outwards on the cell wall, and the cell loses its turgor. It is said to be **flaccid**.

The strong cell wall cannot cave in very much, so as the volume of the cell gets smaller and smaller, the plasma membrane may eventually pull away from the cell wall. The plasma membrane is often damaged in this process. A cell in this state is said to be **plasmolysed**. The cell usually dies.

Extension

Active transport

So far, we have looked at three ways in which substances can move down a concentration gradient (or a water potential gradient) from one side of the plasma membrane to the other. The cell does not have to do anything to make this happen, except perhaps to open a channel to allow facilitated diffusion to take place. These methods are all passive.

However, there are many instances where a cell needs to take up, or get rid of, substances whose concentration gradient is in the 'wrong' direction. This is usually the case with **sodium ions** and **potassium ions**. Most cells need to contain a higher concentration of potassium ions, and a lower concentration of sodium ions, than the concentration outside the cell. To achieve this, cells constantly pump sodium ions out and potassium ions in, up their concentration gradients. This requires energy input from the cell, so it is called **active transport** (Figure 2.10).

Active transport is carried out by **transporter proteins** in the plasma membrane, working in close association with ATP which supplies the energy. The ATP is used to change the shape of the transporter proteins. The shape

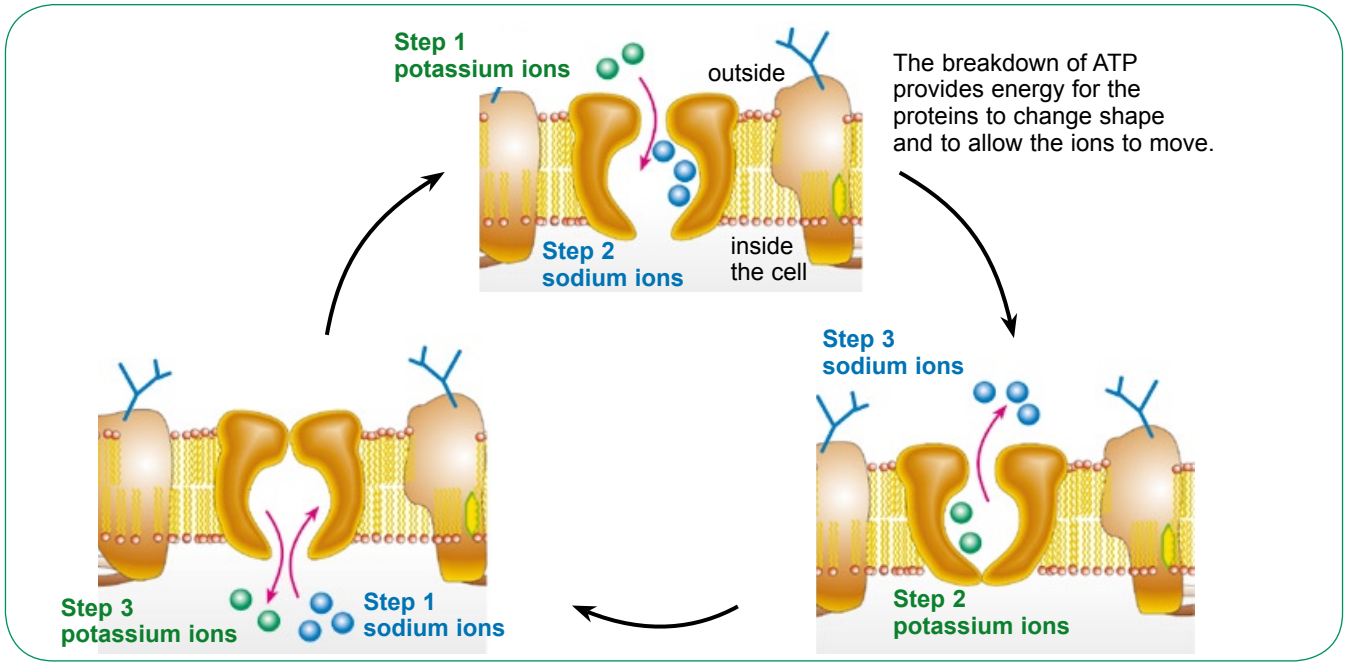

Figure 2.10 An example of active transport – the sodium–potassium pump. Start at step 1 for each ion in turn, and work your way round clockwise. Potassium ions are green and sodium ions are blue.

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change moves three sodium ions out of the cell and two potassium ions in. This is going on all the time in most of your cells, and is called the **sodium–potassium pump**. It is estimated that more than a third of the ATP produced in your cells by respiration is used as fuel for the sodium–potassium pump.

Exocytosis and endocytosis

All the mechanisms of movement across membranes that we have looked at so far involve individual ions or molecules moving. Cells can also move substances in bulk across the membrane.

Moving substances *out of* a cell in this way is called **exocytosis** (Figure 2.11). The substance to be released from the cell is contained in a tiny membrane-bound sac called a **vesicle**. The vesicle is moved to the plasma membrane along microtubules. The membrane around the vesicle fuses with the plasma membrane, emptying the vesicle's contents outside the cell.

Moving substances *into* a cell in this way is called **endocytosis**. A good example is the way that a phagocyte (a type of white blood cell) engulfs a bacterium. The cell puts out fingers of cytoplasm around the bacterium, which fuse with one another to form a complete ring around it. The bacterium is therefore enclosed in a vacuole, surrounded by a membrane. Enzymes can then be secreted into the vacuole to digest it.

Cells can also move bulk liquids into the cell by endocytosis. The process is the same – fingers of cytoplasm surround a small volume of liquid and form a vacuole around it.

Endocytosis and exocytosis are both active processes, requiring the cell to use energy to make them happen.

SAQ

3 Suggest what might be moved out of a cell in the pancreas by exocytosis.

Hint

Answer

How temperature affects membrane permeability

If you cut some pieces of beetroot, wash them and place them in water, the water will remain colourless. If, however, you heat the beetroot pieces, then some of their red colour comes out and the water goes red. Why does this happen?

The red colour in beetroot cells is caused by molecules of a red pigment. The pigment is held in by their cell membranes, which are not permeable to it. However, if you heat the cells, then their membranes become much more permeable. This happens because of the effects of a rise in temperature on the phospholipids and proteins in

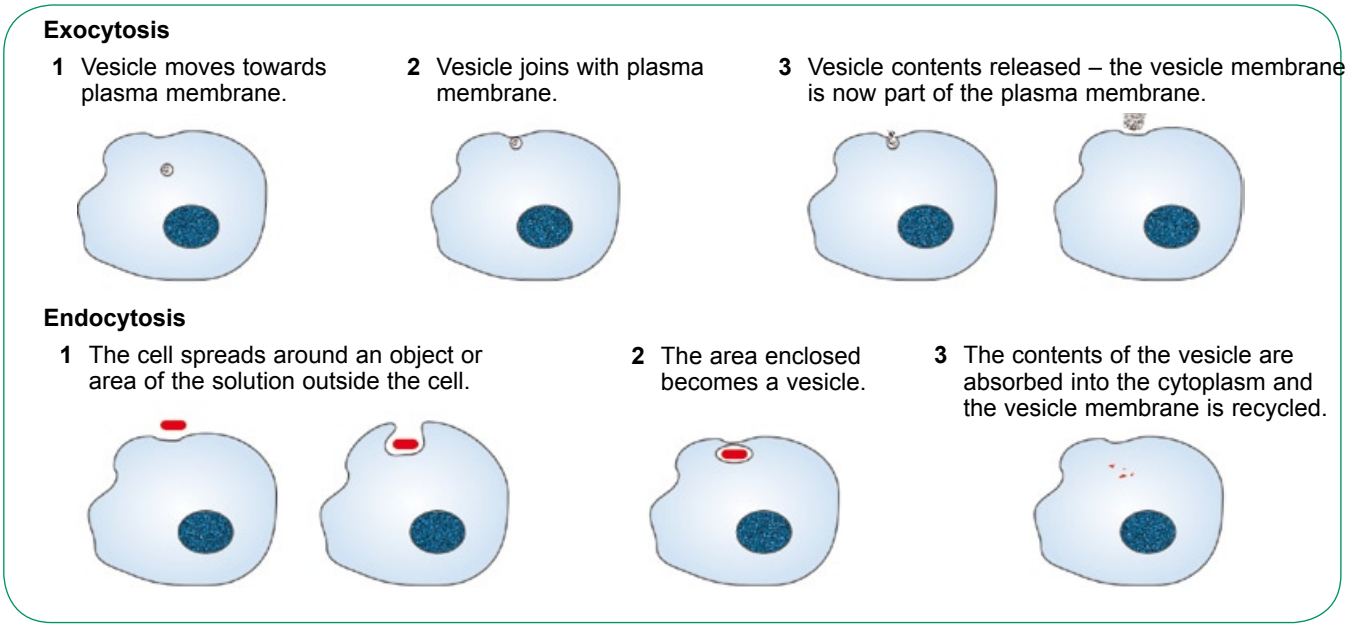

Figure 2.11 Exocytosis and endocytosis.

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the cell membranes.

As the phospholipid molecules get hotter, they vibrate more and more. They move much more than previously, leaving temporary gaps in the membrane through which the pigment molecules can pass.

The protein molecules, too, vibrate more and more as the temperature increases. They may vibrate so much that they begin to come apart and lose their shapes. This, too, leaves gaps in the cell membrane. Very low temperatures, on the other hand, *decrease* membrane permeability. The phospholipids vibrate much less, packing together tightly and only rarely providing pathways between themselves through which molecules might pass. Protein channels remain in place, but transporter proteins may not work very well, because the low temperatures make it difficult for the cell to provide ATP needed for active transport. Moreover, at low temperatures all molecules and ions will be moving around less, so few of them will hit the membrane and pass through it.

Extension

Summary

Glossary

- Every cell is surrounded by a selectively permeable plasma membrane, which controls what passes through it. The plasma membrane also has important roles in cell signalling.
- Many organelles are also surrounded by membranes; these membranes help to isolate the metabolic reactions inside the organelle from those outside it, and provide extra surface area for the attachment of enzymes and other molecules.
- Membranes are made of a phospholipid bilayer in which proteins are embedded. This is known as the fluid mosaic model. The membranes also contain cholesterol, glycolipids and glycoproteins, each of which has its own functions.
- Cells are able to send and receive signals – for example, in the form of molecules such as hormones. Such signals are received by the plasma membrane; the arrival of a signal may bring about a response in the cell.
- Substances that have small, uncharged molecules can diffuse passively through the phospholipid bilayer. Larger molecules and charged ions pass through channels formed by proteins. If they are diffusing passively down their concentration gradient, this is known as facilitated diffusion.
- Water molecules can move freely across most membranes, by diffusion, down their water potential gradient. This is known as osmosis.
- Cells placed in a solution that has a lower water potential than the cell contents lose water by osmosis, so their volume decreases. Animal cells may become crenated, whilst the cell membrane in plant cells may pull away from the cell wall as the cytoplasm shrinks.
- Cells placed in a solution that has a higher water potential than the cell contents gain water by osmosis, so their volume increases. Animal cells may burst, but plant cells do not because of the strong cell wall that surrounds them.
- Substances can also be moved across membranes against their concentration gradient, using energy in the form of ATP produced by the cell. This is called active transport, and takes place through carrier proteins in the membrane.
- Substances can be moved in bulk across a membrane by exocytosis or endocytosis.
- An increase in temperature increases the movement of the molecules in a membrane, increasing the membrane's permeability.

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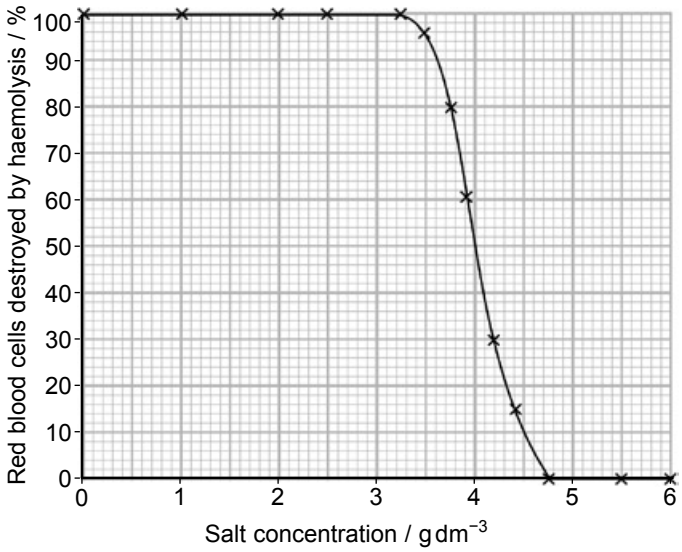
Questions

1 a Red blood cells of mammals respond to changes in the concentration of salts in the fluid that surrounds them. If they are placed in a solution that has a lower concentration of salts than blood plasma, they swell and may burst. This bursting is known as haemolysis.

Hint

Explain why red blood cells may burst when they are placed in a solution that has a lower concentration of salts than blood plasma. [3]

b An experiment was carried out in which red blood cells were placed in salt solutions of different concentrations. The percentage of cells which were destroyed by haemolysis was recorded. The results are shown in the graph.



The graph shows that the red blood cells do not all haemolyse at the same salt concentration.

i Using the graph, state the salt concentration at which the percentage of haemolysed red blood cells is equal to those that are not haemolysed.

ii Suggest why different red blood cells haemolyse at different salt concentrations.

c An experiment was carried out to investigate the uptake of potassium ions by carrot tissue. The experiment was carried out as follows:

- A carrot was cut into discs of uniform size.
- The discs were divided into four groups.
- Equal volumes of a solution containing potassium ions were added.

The temperature remained constant at 21 °C and the experiment was carried out for the same length of time in each case. The experiment was carried out in different oxygen concentrations.

The results are shown in the table.

oxygen concentration / arbitrary units	0	4	11	20
rate of uptake of potassium ions / arbitrary units	7	27	92	100

i Using the information given in the table, state the <u>main</u> process by which potassium ions enter the carrot cells. [1]

ii Give a reason for your answer to **i**. [1]

iii Suggest an explanation for the uptake of potassium ions in the absence of oxygen. [1]

OCR Biology AS (2801) June 2004 [Total 8]

Answer

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Chapter 3

Cell division and cellular organisation

Background

e-Learning

Objectives

The cell cycle

Like most animals, you began your life as a single cell. This cell was a **zygote** – a cell that forms when two gametes fuse. The zygote contained a set of chromosomes from your father and a set of chromosomes from your mother.

All the cells in your body have developed from this single original cell. Soon after it was formed, the zygote divided to form two cells, which then each divided to form a total of four cells. This division went on and on, eventually forming your body containing many millions of cells. Some cells continue to divide even in an adult.

The repetitive process of growing and dividing, growing and dividing is called the **cell cycle** (Figure 3.1). The cell cycle is made up of two main phases, **interphase** and **mitosis**.

Extension

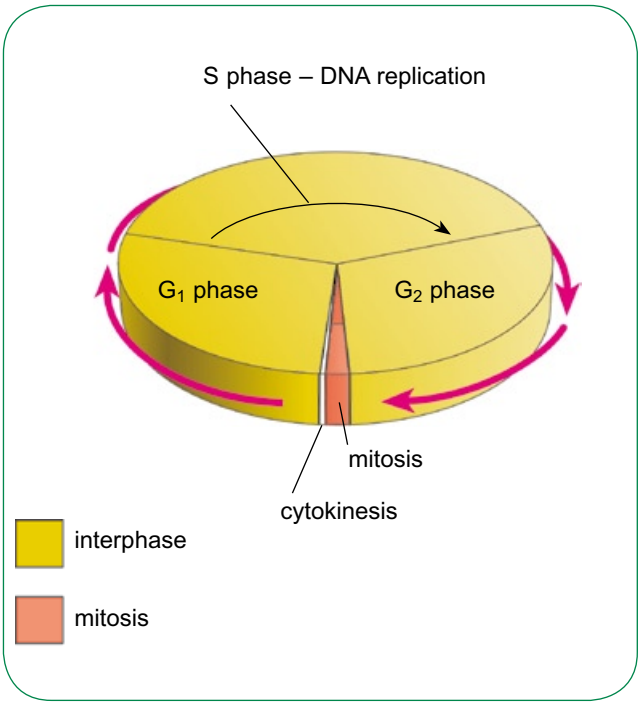

Figure 3.1 The cell cycle.

Interphase

In a cell in a human embryo, one complete cell cycle lasts about 24 hours. About 95% of this time is spent in **interphase**. During interphase, the cell is carrying out all the normal cell activities, such as respiration and protein synthesis. The DNA that makes up its chromosomes is duplicated – a perfect copy is made, so that the DNA can be divided up equally into the two new cells that will be made when the cell divides.

In a human cell, there are 46 **chromosomes**, each of which is made up of one enormously long molecule of DNA. Some time before the cell divides, each DNA molecule is copied. The pair of identical DNA molecules that are now contained in each chromosome remain attached to each other, at a point called the **centromere**. The two identical strands of DNA are called **chromatids** (Figure 3.2 and Figure 3.3).

It is very important that the new DNA molecules that are made are the same as the old ones. Even a small error – a **mutation** – could have harmful effects on the cell. Cells therefore run a 'checking' process on the new DNA. Special proteins work along the DNA molecules, checking for any errors and, where possible, correcting them.

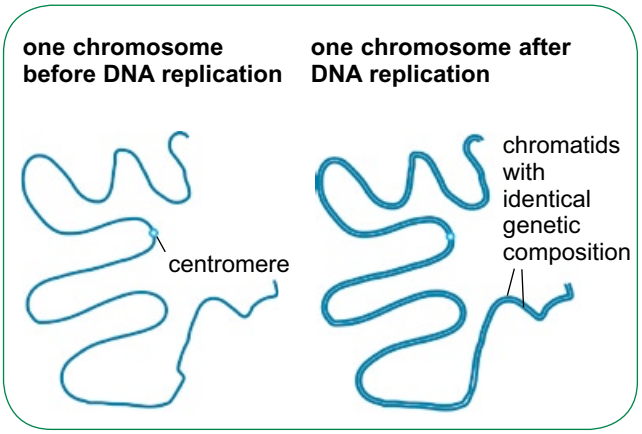

Figure 3.2 Chromosomes in interphase.

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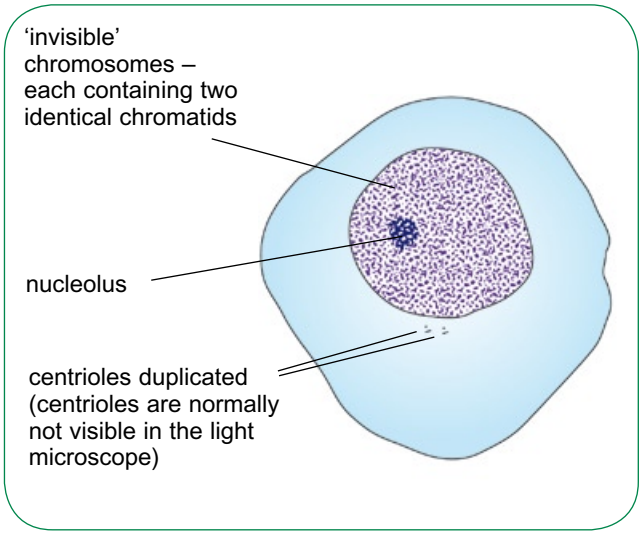

Figure 3.3 Late interphase.

Mitosis

The cell then moves into the next stage of the cell cycle, called **mitosis**. This is the stage during which the nucleus of the cell divides into two nuclei. During mitosis, the two chromatids which make up each chromosome break apart. One of them goes into one new nucleus and one into the other. In this way, the new cells will be genetically identical to each other and to the original parent cell.

Mitosis is made up of four stages: **prophase**, **metaphase**, **anaphase** and **telophase**. The four stages run into one another, without breaks between them.

Prophase

During prophase (Figure 3.4), the chromosomes become visible. Up to now, they have been lying in the nucleus as extremely long and thin threads, so thin that they cannot be seen at all with a light microscope. As prophase begins to get under way, the DNA molecules coil and supercoil, shortening and getting thicker until they eventually form threads that are thick enough to be visible if they are stained.

When the chromosomes appear, they can sometimes be seen to be made of two threads – the chromatids. The chromatids are held together at the centromere. The two chromatids of each chromosome contain identical molecules of DNA, formed in DNA replication during interphase.

As prophase proceeds, the nucleolus disappears. It is also at this stage that the **spindle** begins to form. The **centrioles** move away from each other to opposite ends of the cell. The centrioles organise the formation of the microtubules – long, thin tubes of protein (Figure 3.4).

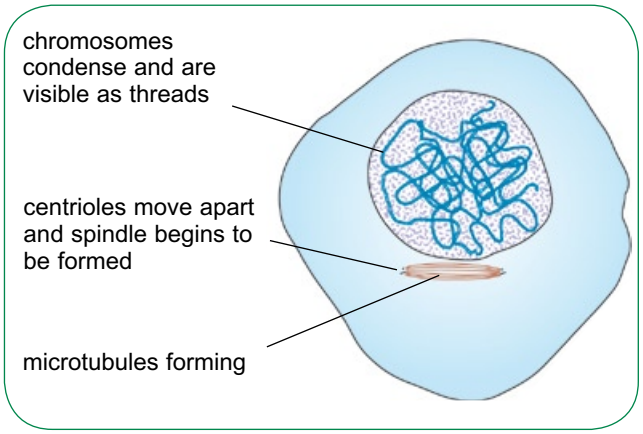

Figure 3.4 Prophase.

Metaphase

Now the nuclear membrane breaks down. Its loss means that the whole of the space in the cell is available for manoeuvring the chromosomes. By the time the nuclear membrane breaks down, many of the microtubules have attached themselves to the centromeres of the chromosomes. Each centromere is grabbed by one microtubule on either side. The microtubules pull in opposite directions on the centromeres, bringing the chromosomes to lie at the **equator** of the cell (Figure 3.5).

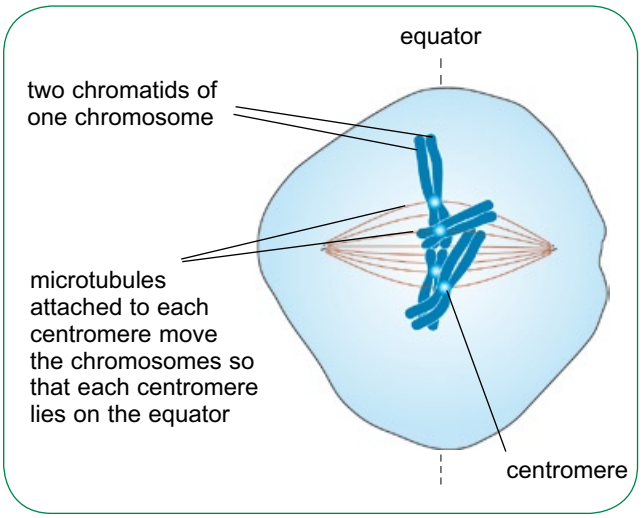

Figure 3.5 Metaphase.

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Anaphase

Now the centromeres split. The microtubules are still pulling on them, so the centromeres and the chromatids are pulled apart and moved to either end, or **pole**, of the cell (Figure 3.6).

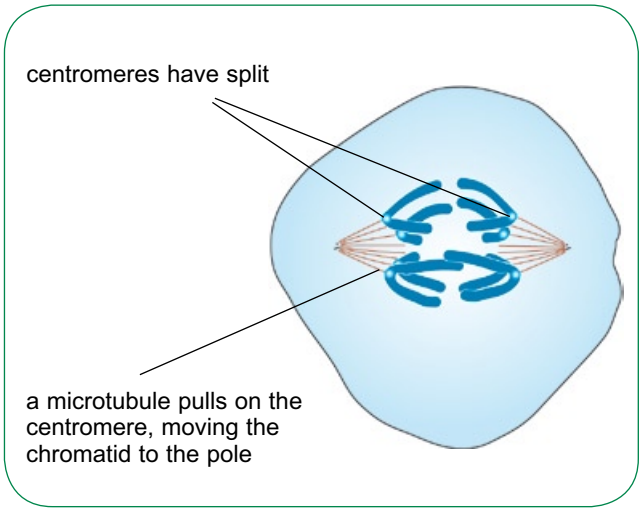

Figure 3.6 Anaphase.

Telophase

The two groups of chromatids have now arrived at the poles. Each group contains a complete set of chromatids, which we can now call chromosomes again. The microtubules making up the spindle fibres break down, so the spindle disappears. New nuclear envelopes form around each group of chromosomes. The chromosomes slowly uncoil and become thinner again, so they effectively disappear (Figure 3.7).

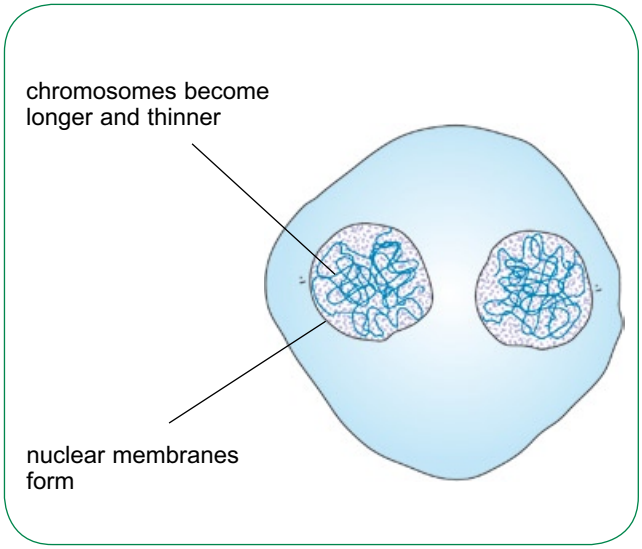

Figure 3.7 Telophase.

Cytokinesis

Usually, the cytoplasm now divides (Figure 3.8). This forms two new cells, each with a nucleus containing a complete set of chromosomes, and each with a centriole. The new cells are genetically identical to each other and to the original, parent cell.

A summary of mitosis and cytokinesis is shown in Figure 3.9, while Figure 3.10 shows micrographs of mitosis and cytokinesis taking place in plant cells.

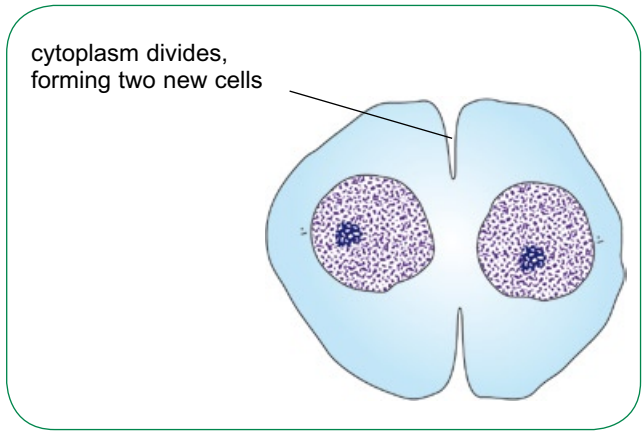

Figure 3.8 Cytokinesis.

SAQ

1 A student looked at a prepared slide of a group of cells in various stages of cell division. He identified the stage in 200 cells and counted up how many cells he could see in each stage. The table shows his results.

Stage	Number of cells
interphase	188
prophase	6
metaphase	3
anaphase	1
telophase	2

a How many cells were in a stage of mitosis?

b Explain what these data tell us about the relative lengths of time spent in each stage of the cell cycle in this group of cells.

Hint

Answer

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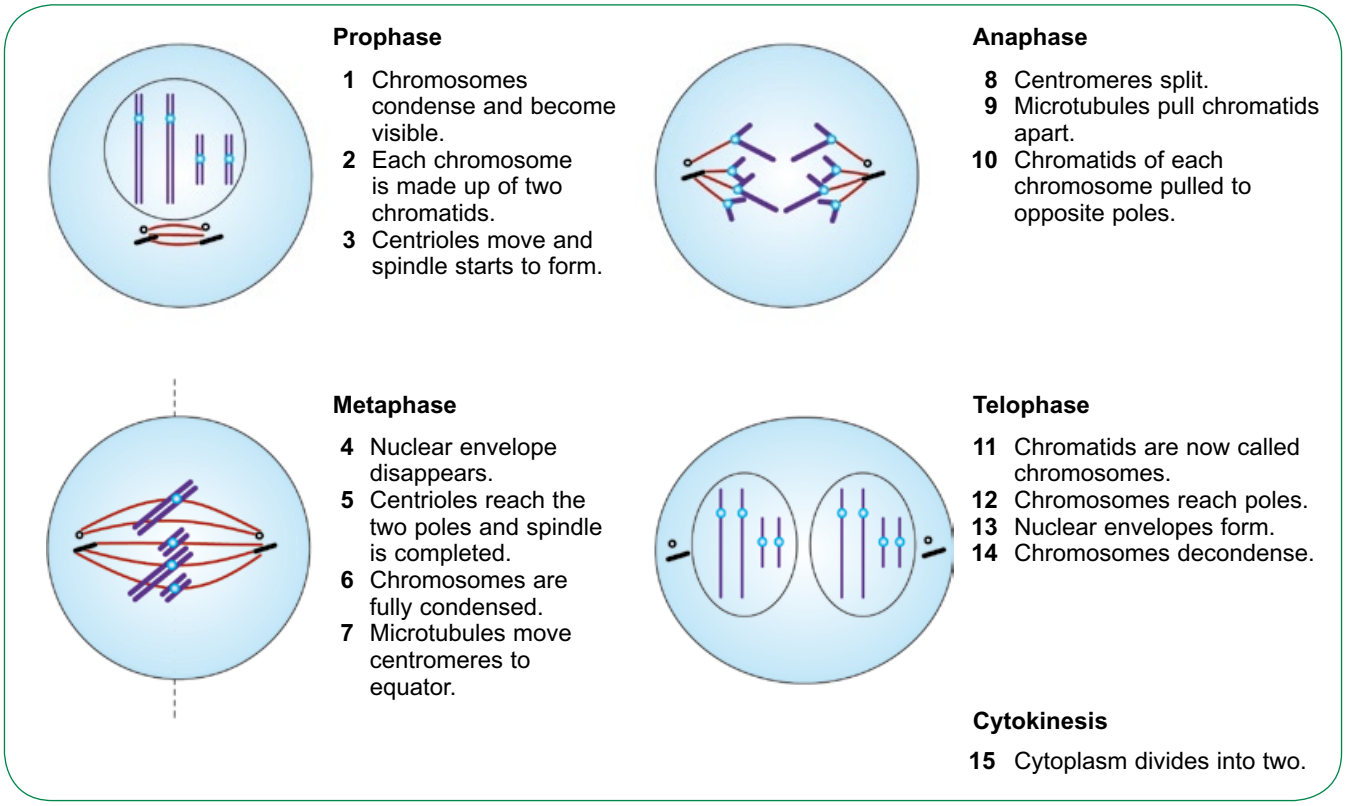

Figure 3.9 Summary of mitosis and cytokinesis.

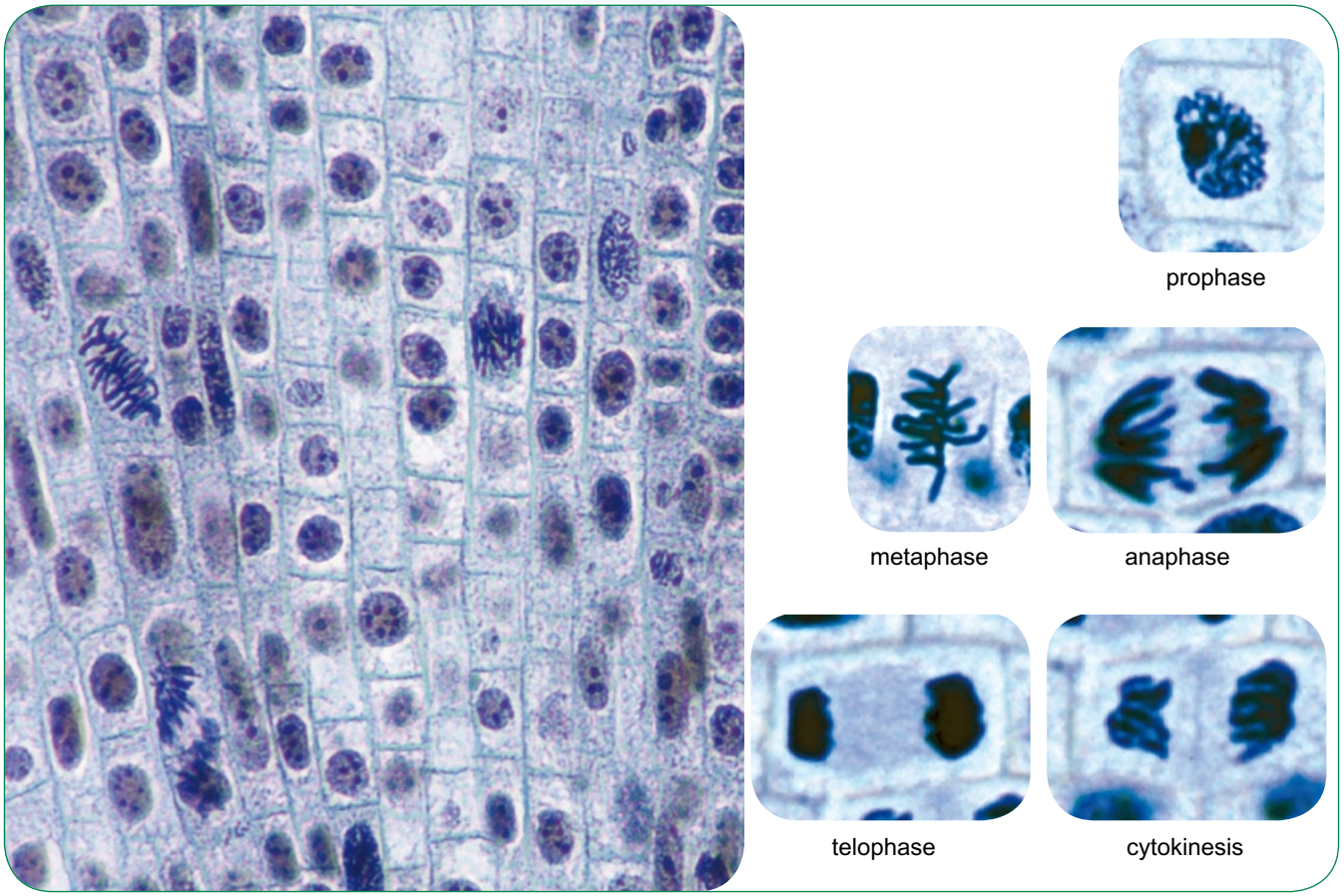

Figure 3.10 Stages of mitosis in an onion root tip (× 100 and × 230).

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The significance of mitosis

We have seen that mitosis produces new cells that are genetically identical to the parent cell. Each of these cells has the same number of chromosomes and identical DNA.

This is how cells divide when the body needs more of the same. Mitosis is the type of cell division that occurs in a developing embryo and throughout the growth of a human being.

Mitosis continues to occur in many parts of the body even when we are fully grown. For example, cells in the lining of the alimentary canal divide to provide new cells to replace those which get rubbed off as food moves past them. Mitosis also comes into play when part of the body is damaged and needs repair. For example, if you cut yourself, cells in the skin will produce new cells which spread across the wound to produce a new, protective layer of skin.

In some organisms, mitosis is used for reproduction. For example, strawberry plants grow runners which put down roots and produce new, genetically identical plants. This is **asexual** reproduction, which does not involve gametes or fertilisation. Some animals, for example *Hydra*, can also reproduce in this way.

Single-celled organisms can also reproduce by mitosis. The single-celled fungus, *Saccharomyces cerevisiae*, yeast, reproduces by budding. A new cell is formed from the old one by mitosis, and then breaks away (Figure 3.11).

Figure 3.11 Budding in yeast. The cell at the centre shows traces of two buds starting to form. A later stage of budding is seen with the large parent cell and smaller daughter cell at the left.

Differentiation

Your body contains about 10^{13} cells. They have all developed from the single cell with which you began your life – the zygote that was formed by the fusion of an egg cell and a sperm cell. The zygote divided to form a tiny ball of cells called a **blastocyst**, which continued to divide to form an embryo.

In multicellular organisms, there are usually many different kinds of cells. These cells have become specialised to carry out different functions. There is 'division of labour' amongst them.

The body is made up of 'teams' of cells, usually grouped together into **tissues**, which work together closely while each performing their own specialist functions. The specialisation of a cell to carry out a particular function is called **differentiation**.

Once a human cell has differentiated, it usually cannot change into another kind of cell. A heart muscle cell cannot change into a bone cell. A bone cell cannot change into a skin cell.

This is very different from the abilities of the cells in the blastocyst. These cells have the potential to become any of the many different kinds of cells within a human. They are **stem cells**. Stem cells differ from most human cells because:

- they are unspecialised
- they can divide repeatedly to make new cells
- they can differentiate into several kinds of specialised cells.

All the cells in a blastocyst are stem cells, and they can differentiate into any kind of specialised cell. They are therefore said to be '**totipotent**'. Even in an adult person, there are still some stem cells. So far, all the ones that have been found are only able to differentiate into a limited range of cells – for example, there are stem cells in bone marrow that can form white and red blood cells. But they cannot differentiate into neurones, or any other kind of cell.

There is much interest in stem cells, as they could cure many diseases. For example, Parkinson's disease is caused by the death of a particular group of cells in the brain. One day, it may be possible to use stem cells to replace these brain cells.

Extension

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Some specialised animal cells

Erythrocytes, otherwise known as red blood cells, transport oxygen in the blood. They have a very short life span. Every second, around 10 million old erythrocytes are destroyed in your spleen, and 10 million new ones are made. They are made from stem cells in the **bone marrow**, especially in the ribs, vertebrae, pelvic bones and skull. These stem cells also make **leucocytes**, the white blood cells. There are several types of these, including **neutrophils** – cells that attack and destroy invading microorganisms by phagocytosis.

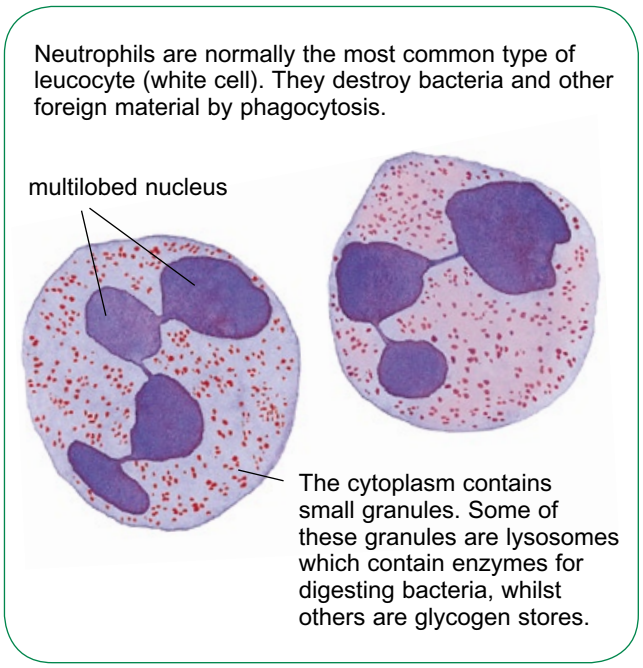

Figure 3.12 Neutrophils.

Figure 3.12 and Figure 3.13 show the structures of neutrophils and erythrocytes, and explain how their structures are adapted for their functions.

Spermatozoa, sperm for short, are the male gametes (Figure 3.14). They are made in the testes throughout a man's life. They are adapted to find and fertilise a female gamete.

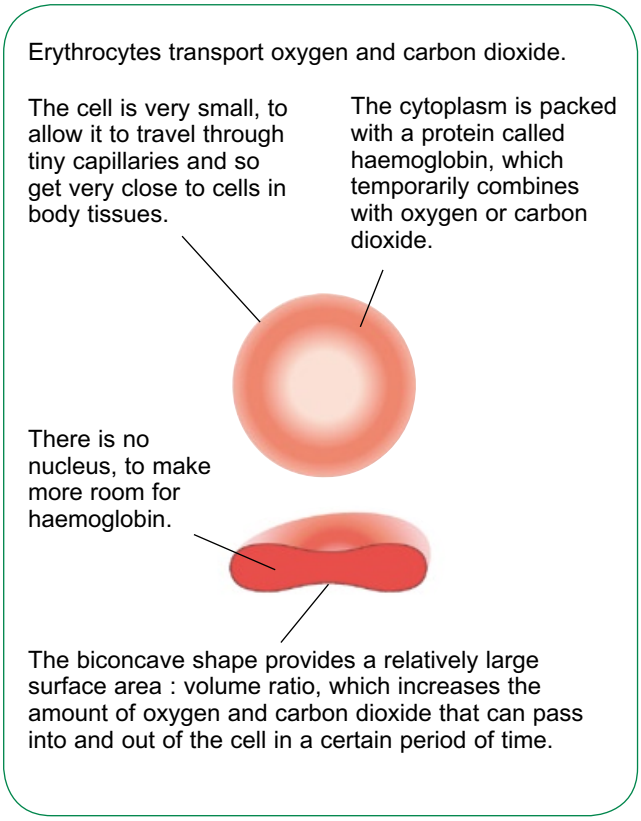

Figure 3.13 Erythrocytes.

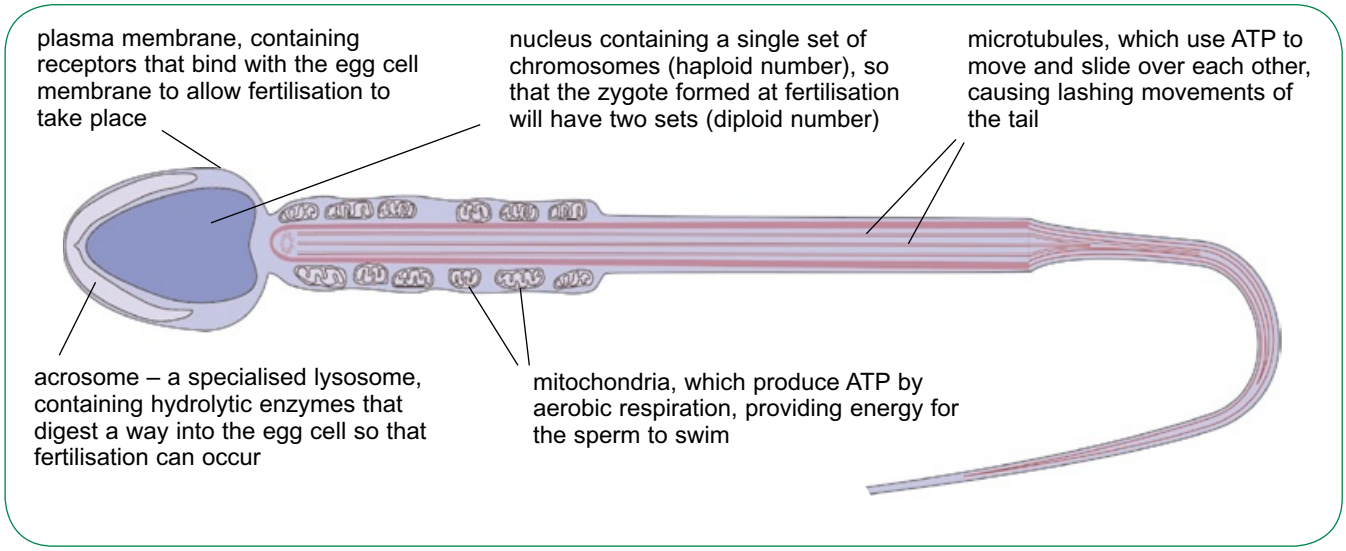

Figure 3.14 A spermatozoan.

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Some specialised plant cells

Plants do not have stem cells – most of their cells retain the ability to differentiate into other kinds of cells throughout their lives. However, there are several parts of a plant where cells are able to divide, and places where this occurs at a high rate are called **meristems**. The meristem just behind the root tip is a good place to find cells in various stages of mitosis, which you can prepare and stain as a 'root tip squash'.

There is another meristem that forms a ring of tissue in the stem, called **cambium**. These cells can divide to form **xylem vessels** on the inside of the ring and phloem sieve tubes on its outside, which help to form these two transport tissues. Figure 3.15 and Figure 3.16 show the structures and functions of these tissues and where they are found in a stem.

The cells that are often considered to be 'typical' plant cells are the **palisade cells** – the main type of photosynthetic cell found in plant leaves. They are, in fact, highly specialised, containing many chloroplasts in which photosynthesis takes place.

Root hair cells are found near the tips of roots. They are specialised epidermal cells – that is, cells that cover the outside of a plant organ. They have long, thin extensions that grow between the soil particles, providing a large surface area that is in contact with the layer of water that is usually present on and between these particles. The water contains various mineral ions in solution, which root hairs absorb. They have a short life, being easily broken as the root grows through the soil. Recently divided cells near the root tip differentiate to form new root hair cells (Chapter 6).

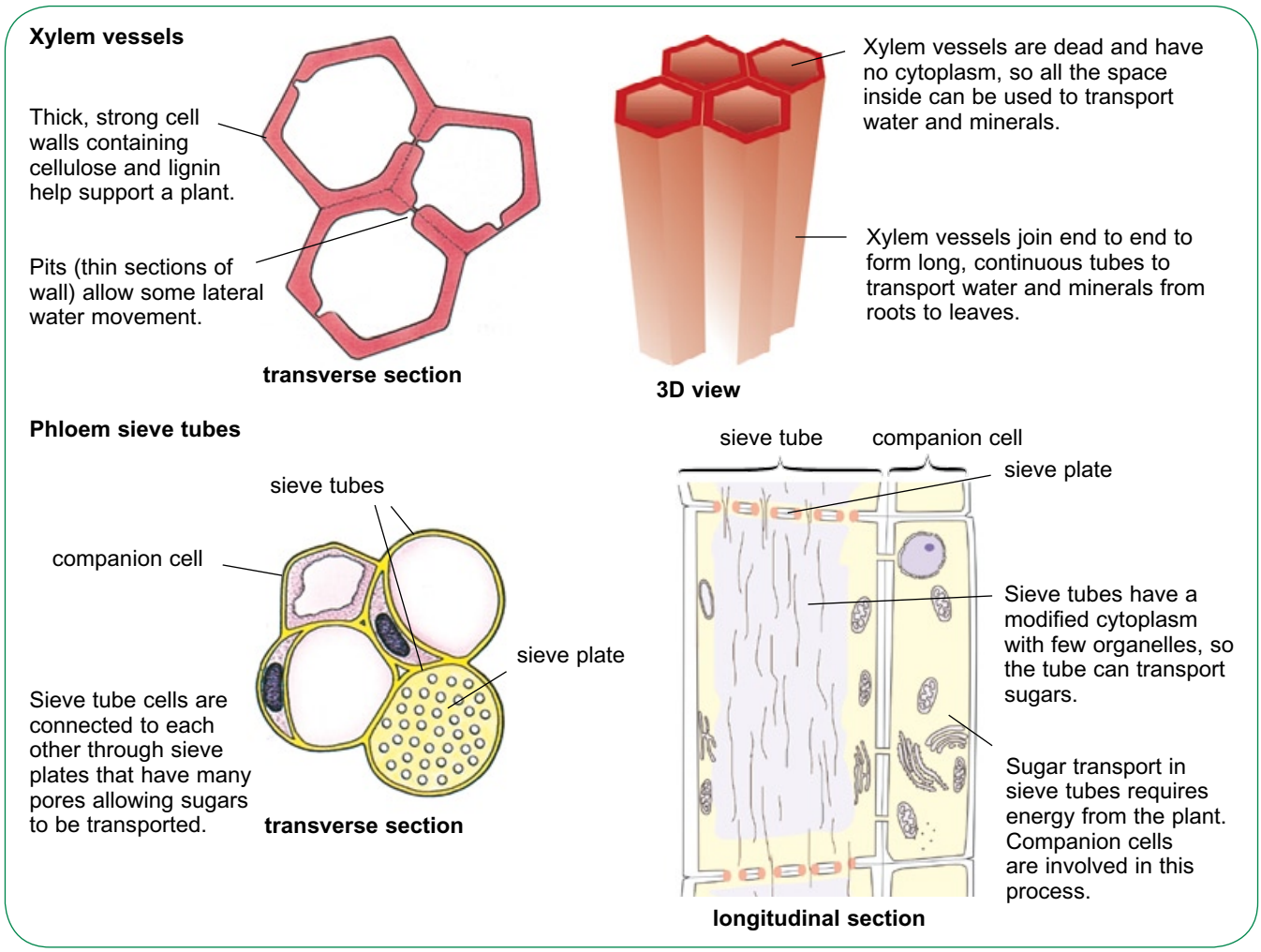

Figure 3.15 Xylem and phloem tissues. You can see micrographs of xylem tissue and phloem tissue in Chapter 6.

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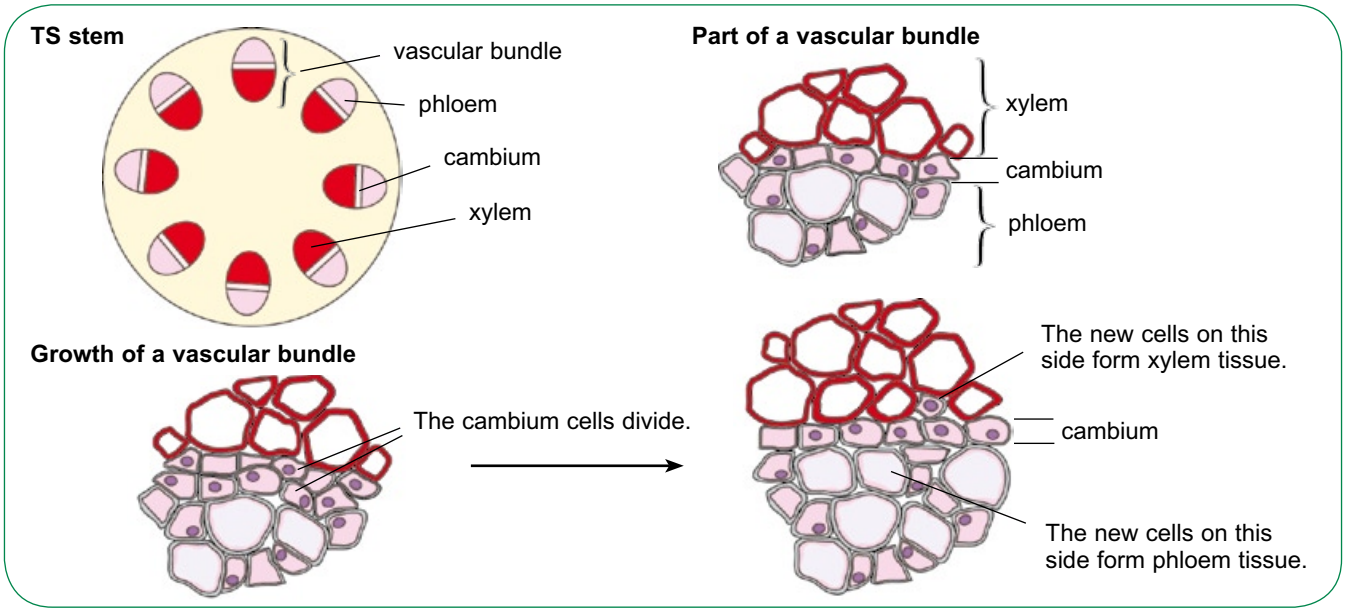

Figure 3.16 Cambium, xylem and phloem in a plant stem.

Dendrochronology

Each spring, as the weather warms up and there is more daylight, trees begin to grow after resting through the winter. Cells in the ring of cambium in the trunk divide, producing new phloem tissue on the outside of the ring, and new xylem tissue on the inside. This process continues throughout the summer, but the new cells produced later in the year are smaller than the ones produced during the period of maximum growth in spring.

The xylem tissue makes up the wood of the trunk. A slice across a tree trunk reveals rings in the wood, corresponding to the yearly growth cycle. The xylem tissue made in spring usually looks light in colour, because the vessels are larger. The summer xylem tissue forms a narrower, darker stripe.

The width of the stripes is determined by how well the tree grew that year, which depends on the weather conditions. In a dry year, the tree will grow less than in a wet year, so the ring for that year will be narrower. This will be true for all the trees growing in that place at that time.

Once the ring patterns of some samples of wood of known age have been analysed, then other samples of wood can be matched against them, looking for matching patterns of narrow and wide rings. This can be used to date the wood – a procedure known as 'dendrochronology'. Dendrochronologists have now built up enough data to establish patterns of growth going back to around 9000 years ago. These can be used to determine when a tree was felled to provide the wood that has been used to build an ancient ship or an old house, for example, as well as showing where the tree grew.

The *Mary Rose* contained wood from trees felled in southern England in 1510.

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Tissues, organs and organ systems

The millions of cells inside a multicellular organism such as yourself are not scattered randomly about. Cells that carry out the same function are usually grouped together, forming a tissue. Tissues may be further grouped into organs, and organs into systems. We can define these terms as follows:

- A **tissue** is a collection of cells, together with any intercellular ('between cells') secretion produced by them, that is specialised to perform one or more particular functions. The cells are often of the same type, such as palisade tissue in a plant leaf or squamous epithelium (page 46) in animals.
- An **organ** is a part of the body which forms a structural and functional unit and is composed of more than one tissue. A leaf is an example of a plant organ, and the brain is an example of an animal organ.
- A **system** is a collection of organs with particular functions, such as the excretory, reproductive, cardiovascular and digestive systems in humans.

Figure 3.17 shows the tissues in a leaf.

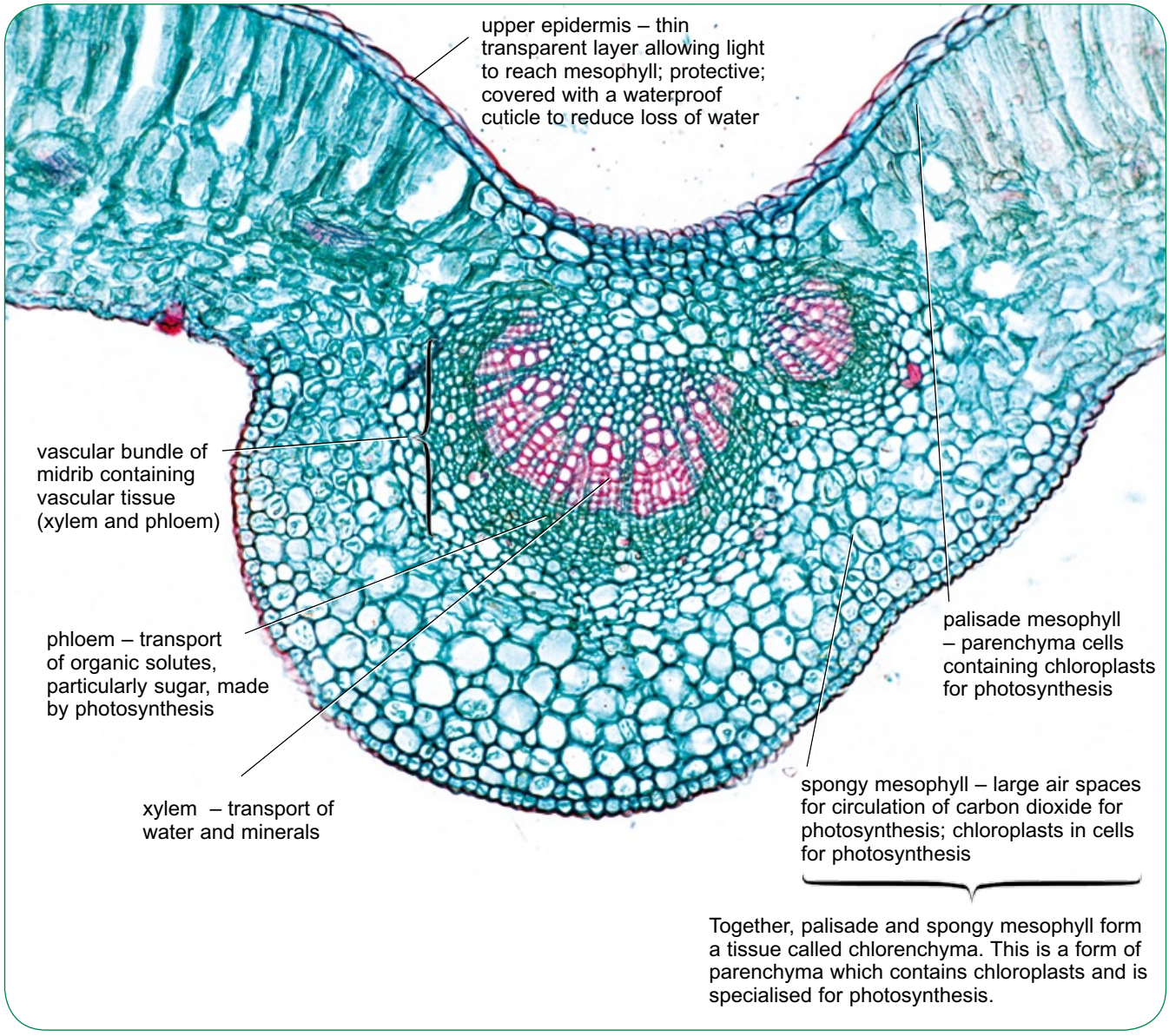

Figure 3.17 Transverse section through the midrib of a dicotyledonous leaf, *Ligustrum* (privet) (× 50).

44

Sponges

Sponges are believed to be amongst the very earliest multicellular animals to have appeared on Earth. The oldest fossil sponges that have so far been discovered are 600 million years old, and it is likely that sponges were around for some time before then.

Sponges are found in seas all over the world, and a few species live in fresh water. At first sight, sponges don't look like animals at all. They remain apparently motionless, generally fixed permanently to the sea bed or a coral reef. Under the microscope, however, they can be seen to have cells with no cell walls – a feature typical of animal cells.

Some of a sponge's cells have long flagella, which beat rhythmically, creating a water current that flows through the sponge's body, and from which the sponge's cells extract food material. The flagellated cells also have microvilli (tiny projections on the cell surface) to increase their surface area and therefore make food absorption more efficient. Other cells are tubular, providing pores through which the water current can circulate. Others secrete the protein collagen, and yet another type secrete little spicules of calcium carbonate or silica, which provide a skeleton for the sponge.

So, like most multicellular organisms, sponges have a range of different types of cells that are specialised for different functions. However, unlike all other groups of animals, sponges do not possess true tissues, organs or systems. The different cells are scattered throughout the sponge's body. This suggests that perhaps they were some of the earliest animals to evolve from the single-celled organisms that lived on Earth long ago.

Sponges have not been of great interest to humans in the past, except as a source of soft, rubbery absorbent material for washing – and even this function has now been almost entirely taken over by plastic sponges. But recently, sponges have become of great interest to pharmaceutical companies.

Unable to move, sponges cannot flee from other animals that eat them. Many of them have evolved a defence mechanism – they secrete toxic chemicals that deter predators, and also prevent other sponges from growing too close to them. Indeed, some other kinds of marine organisms, such as some species of crabs, carry sponges around on their bodies as a defence against predators.

Some of these chemicals show promise as drugs to fight human diseases. For example, a compound called halichondrin, derived from the sponge *Lissodendoryx*, is being developed as a possible anti-cancer drug. The sponge *Dysidea avara* produces a chemical called avarol, which could be used to treat psoriasis – a chronic condition in which red and scaly areas form on the skin. So far, we have only touched the tip of the iceberg, and there may be thousands of chemicals with pharmaceutical potential to be found in sponges.

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Some examples of animal tissues

Tissues that cover a surface in an animal are called **epithelial tissues**. The two examples shown in Figure 3.18 are only one cell thick, and so they are *simple* epithelia. The cells rest on a **basement membrane**, which, despite its name, is not a cell membrane at all. It is a network of collagen and glycoproteins that is secreted by the underlying cells, and that holds the epithelial cells in position.

Squamous epithelium covers many surfaces in the human body, including the inner lining of the cheeks, the inner surfaces of blood vessels, and the inner surfaces of the atria and ventricles in the heart. It also forms the walls of the alveoli in the lungs. The individual cells are smooth, flat and very thin. They fit closely together, providing a smooth, low-friction surface over which fluids can move easily. In the alveoli, the thinness of the cells allows rapid diffusion of gases between the alveoli and the blood (Chapter 4).

Ciliated epithelium is made up of cells that possess cilia. Sometimes these cells are shaped like cubes, making up *cuboidal* ciliated epithelium. This tissue lines the ends of the bronchioles in the lungs. Sometimes the cells are tall and narrow, making up *columnar* ciliated epithelium, found in the oviducts.

SAQ

2 Suggest the functions of the ciliated epithelium in:

a the bronchioles

b the oviducts.

Answer

Some examples of plant tissues

We have seen how xylem vessels and phloem sieve tubes are specialised for their functions of transporting substances within plants (Figure 3.15). These specialised cells form tissues within plant stems, roots and leaves. Their distribution and structures are also shown in Chapter 6.

Coordination

Division of labour within a multicellular organism means that every cell has its own set of functions in which it specialises. However, it is clearly essential that there is communication and cooperation between cells within a tissue, and between tissues, organs and systems in different parts of the body. Pulling the activities of all the different parts of the body together, so that they work with each other and do appropriate things at appropriate times, is essential if a multicellular organism is to survive.

As we have seen, this communication involves cell signalling. Much of it is done by means of molecules that are produced by one cell and that affect the behaviour of another. These include hormones. In animals, electrical signals, carried by neurones, are another method of communication. Even plants use electrical signals for communication in some circumstances – for example, in the closing of the leaf of a Venus fly trap around a fly that it has captured.

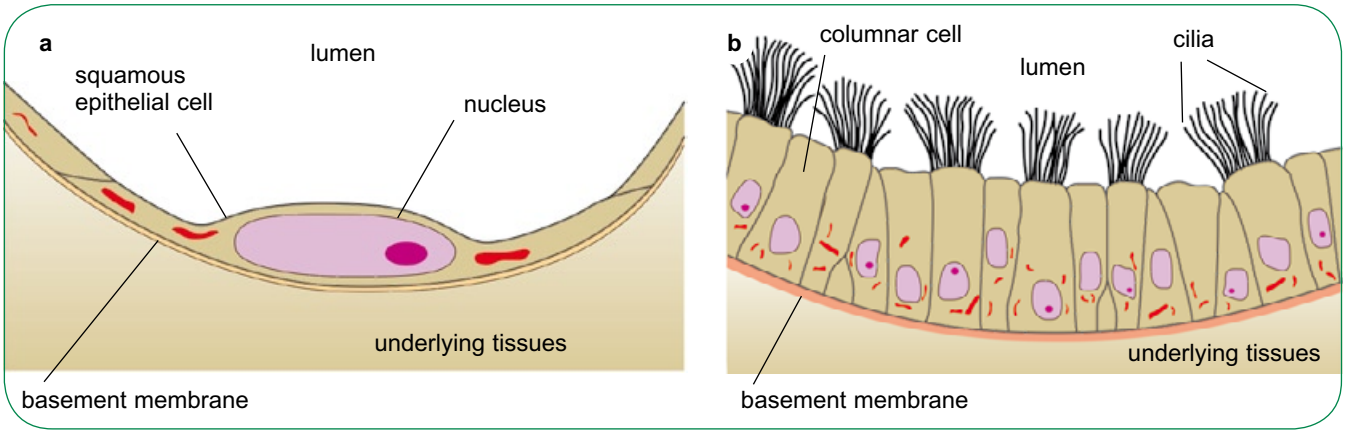

Figure 3.18 Some examples of epithelial tissues, as seen with a light microscope: **a** diagram of a section through squamous epithelium; **b** diagram of a section through ciliated columnar epithelium.

46

Another type of cell division

All of the specialised cells that are produced as an organism grows are formed by mitosis. As we have seen, this is the type of cell division that is used when the new cells are required to be genetically identical to the parent cell.

However, there is another type of cell division that is needed if an organism has a stage of sexual reproduction in its life cycle. This is called **meiosis**.

In the nucleus of each of your body cells, there are 46 chromosomes. These are actually two *sets* of chromosomes. One set of 23 came from your father, and the other set of 23 came from your mother.

We can see this if images of the chromosomes are 'cut and pasted' to arrange them in order. An arrangement like this is called a **karyotype** (Figure 3.19).

The chromosomes have been arranged and numbered by size, largest first. There are two of each kind, because there are two complete sets. Cells that have two complete sets of chromosomes are called **diploid cells**. The two chromosomes of a kind are said to be **homologous**. This means 'same position', and it refers to the fact that the chromosomes have genes for the same features in the same positions. However, these genes are unlikely to be identical on each chromosome. Most genes have several different varieties, called **alleles**, and some of the alleles on one of a pair of homologous chromosomes are very likely to differ from some of the alleles on the other.

When gametes are formed, a body cell divides by meiosis and produces new cells that have only *one* set of chromosomes. They are **haploid cells**. The new cells get just one chromosome of each homologous pair. They could get either one – the one that originally came from the father, or the one that came from the mother. So there are a very large number of different combinations of chromosomes that could end up in a gamete.

Gametes are therefore **genetically different** from each other. Moreover, any male gamete can fuse with any female gamete at fertilisation, so this offers even more possibilities for different mixtures of genes (Figure 3.20).

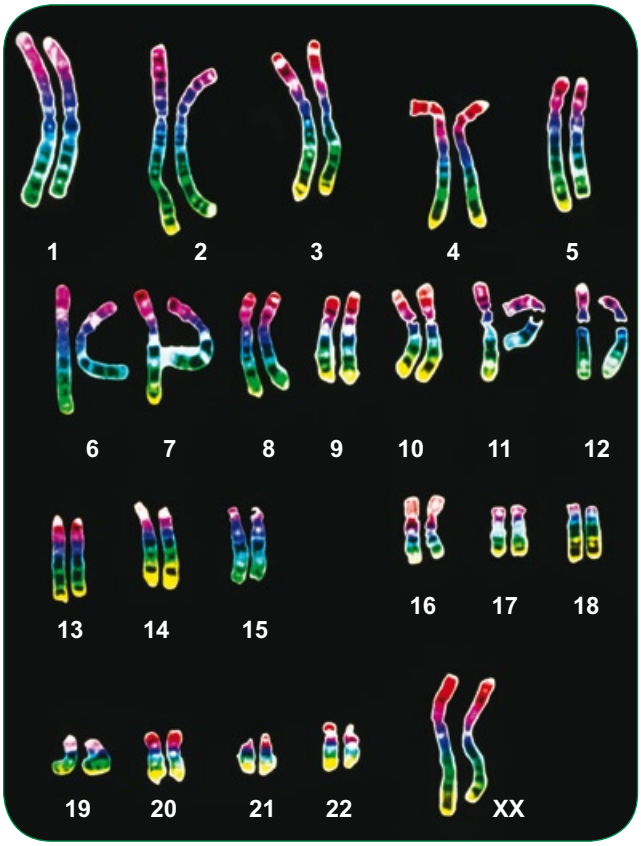

Figure 3.19 A karyotype (×2800).

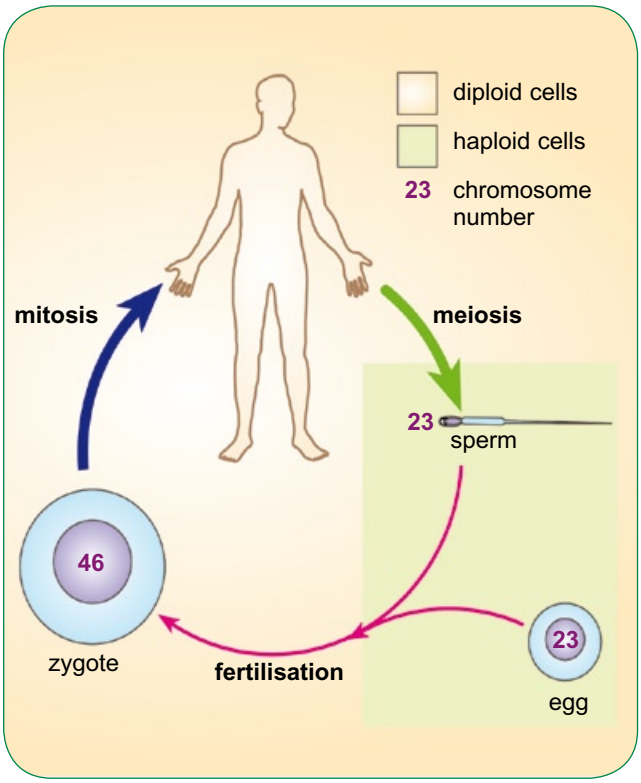

Figure 3.20 The human life cycle. Mitosis produces diploid body cells, and meiosis produces haploid gametes.

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Summary

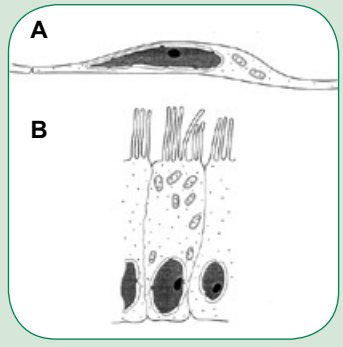
Glossary

- The cell cycle consists of interphase, mitosis and cytokinesis. Mitosis occupies only about 5% of the time, while the rest is used for the duplication and checking of DNA.
- In interphase, DNA replicates, so that each chromosome is made up of two identical chromatids joined at the centromere.
- During mitosis, the nuclear membrane breaks down, spindle fibres form, attach themselves to the condensed chromosomes and manoeuvre them to the equator of the cell. The centromeres then break, and the spindle fibres pull the separated chromatids to opposite ends of the cell. New nuclear membranes form around each group of chromatids. The phases of mitosis are prophase, metaphase, anaphase and telophase.
- During cytokinesis, the cytoplasm splits and two new cells are formed.
- Mitosis produces two daughter cells that are genetically identical to each other and to the parent cell. Mitosis is used for growth, repair and asexual reproduction.
- Multicellular organisms usually contain many types of cells, which have become differentiated to perform different functions. They are often grouped into tissues, containing cells that have the same function – for example, squamous and ciliated epithelium in animals, xylem and phloem in plants. Tissues are grouped into organs, and organs into organ systems.
- When an animal cell has become differentiated, it is normally unable to become any other type of cell. Some cells, however, called stem cells, retain the ability to divide and differentiate. Stem cells in a young embryo are able to differentiate into any kind of cell; in an adult, stem cells appear to have a limited range of specialised cells that they can form. For example, stem cells in bone marrow produce erythrocytes and leucocytes. In plants, cambium cells produce xylem vessels and phloem sieve tubes. These cells are highly adapted for their functions.
- Cells may divide by meiosis, which produces genetically different cells with half the number of chromosomes of the parent cell. Body cells are diploid, meaning that they have two complete sets of chromosomes. Matching, or homologous, chromosomes pair up in meiosis and are then shared out into the daughter cells. These are haploid, meaning that they have only one set of chromosomes.

Questions

1 a Explain what is meant by the term *tissue*. [2]

The diagram shows cells from two types of epithelial tissue, A and B, as seen under the electron microscope. The cells are not drawn to the same scale.



b i Name the types of epithelial tissue A and B. [2]

ii Explain why the cells of tissue B contain many more mitochondria than those in tissue A. [2]

c State <u>two</u> ways in which the cells of tissues A and B differ from prokaryotic cells. [2]

OCR Biology AS (2801) June 2002 [Total 8]

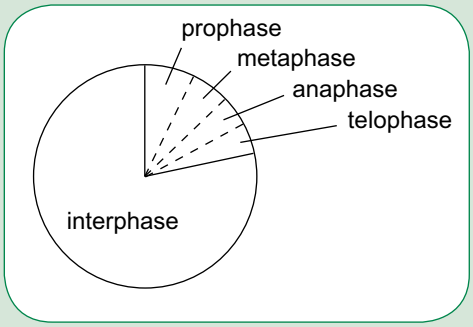
Answer

continued

48

2 a Describe the role of mitosis. [3]

The diagram shows the stages of the mitotic cell cycle.



b i Which processes must occur in a cell during interphase before mitosis can take place? [3]

ii In which direction, clockwise or anticlockwise, does the sequence shown in the diagram occur during the mitotic cell cycle? [1]

c Name the stage of mitosis shown in the diagram in which each of the following events occurs.

i Chromosomes split at centromeres. [1]

ii Chromosomes become visible. [1]

iii Nuclear envelope re-forms. [1]

iv Chromatids move to opposite poles of the cell. [1]

v Chromosomes line up along the equator of the spindle. [1]

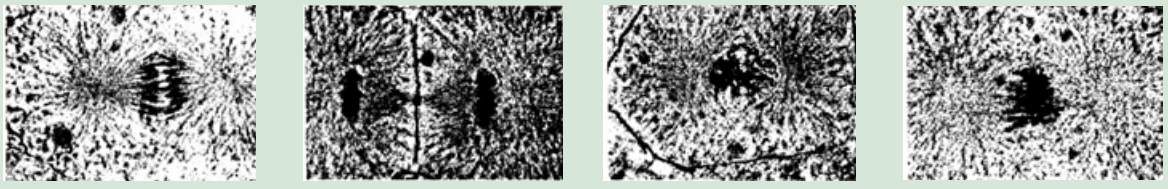
OCR Biology AS (2801) June 2004 [Total 12]

Answer

3 During the development of the embryo, cells divide by mitosis, grow and differentiate. The cells gradually become organised into tissues and organs.

a i State what is meant by the term *cell differentiation*. [2]

ii Describe the relationship between tissues and organs. [2]



A B C D

b The photographs show an animal cell at different stages of mitosis.

i Arrange the stages shown in the photographs in the correct order by writing their letters in sequence. [1]

ii Compare the genetic makeup of the daughter cells produced by mitosis with that of the original parent cell. [2]

OCR Human Biology AS (2857) January 2005 [Total 7]

Answer

49

Exchange

Background

e-Learning

Objectives

Exchange surfaces

All of the cells in your body need constant supplies of oxygen and nutrients, and need to get rid of waste materials, such as carbon dioxide, that are produced in their metabolic reactions. These substances are obtained from, or released to, the external environment, through your body's surface.

Cells and organisms have problems of scale to solve as they get bigger. As an organism gets bigger, both its surface area and its volume increase. However, its surface area does not increase as much as its volume (Figure 4.1). So a large organism such as yourself must find ways of increasing surface area, to provide enough surface to ensure that exchanges with your environment can take place rapidly enough to supply all of your cells with their needs.

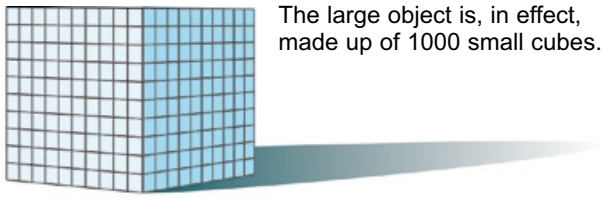
Cube with 1 cm sides

surface area of one small cube = 6 cm^2

volume of one small cube = 1 cm^3

surface area : volume ratio = $\frac{\text{surface area}}{\text{volume}}$ = 6

Cube with 10 cm sides



The large object is, in effect, made up of 1000 small cubes.

surface area of large object = 600 cm^2

volume of large object = 1000 cm^3

surface area : volume ratio = $\frac{\text{surface area}}{\text{volume}}$ = 0.6

The large object has much less surface area for each 'unit' of volume; it has a much lower surface area to volume ratio.

Figure 4.1 Size and surface area : volume ratio.

SAQ

1 Draw a table like this, with seven more empty rows in it.

Length of one side of a cube / cm	Total surface area / cm^2	Volume / cm^3	Surface area divided by volume
1	6	1	6
2	24	8	3

a Complete your table for cubes with sides up to 10 cm.

b Describe what happens to the surface area : volume ratio as the side length of the cube increases.

c Explain the relevance of this to living organisms.

Hint

Answer

50

Properties of exchange surfaces

In this chapter, we will look at how oxygen and carbon dioxide are exchanged with your environment, by diffusing across the gas exchange surface in your lungs. All exchange surfaces have features that help substances to move across them as quickly as possible, and in as large a quantity as possible (Figure 4.2).

For terrestrial (land-living) organisms, this can cause problems, because they run the risk of losing water vapour from their bodies across these exchange surfaces. There often has to be some kind of compromise between maximising the area and exposure of the exchange surface, and keeping water loss to an acceptable level.

The list below summarises the features of all exchange surfaces. Table 4.1 shows the ways in which these are achieved in the mammalian lung and in plant leaves.

- The exchange surface should have a *large surface area*. The larger the area across which a substance can diffuse, the more substance can cross the surface in a given time.
- The exchange surface should be *thin*. The shorter the distance across which a substance has to diffuse, the less time it takes.
- There must be a **diffusion gradient** across the exchange surface – in other words, the concentration of the substance on one side of the surface must be different from the concentration on the other, so that the substance diffuses down the gradient.
- In a terrestrial animal, the cells on the surface must be *protected from drying out*. If 'wet' cells are exposed to dry air, water vapour will diffuse out of them and into the air. If too much water is lost, the plasma membrane will lose its structure and the cells will die.

Figure 4.2 Aquatic animals, such as this axolotl, can have their gas exchange surfaces on the outside of their bodies.

SAQ

2 a The volume of an earthworm is about 0.005 dm^3. The surface area of its skin is about 0.40 dm^2. Calculate the surface area : volume ratio of an earthworm.

Hint

b The volume of a person's body is about 70 dm^3. The surface area of the skin is about 180 dm^2. Calculate the surface area : volume ratio of a person.

c The surface area of the gas exchange surface inside a person's lungs is about 7000 dm^2. What is the ratio of the area of gas exchange surface to the volume of the person's body?

d Use your answers to **a**, **b** and **c** to suggest why earthworms can use their skin for gas exchange, whereas humans need lungs.

Answer

51

Feature of exchange surface	Mammalian lungs	Plant leaves
Large surface area	Lungs contain millions of tiny alveoli.	Plants have highly branched shapes with many leaves, providing a relatively large surface area : volume ratio. Air spaces inside plant leaves ensure that many cell surfaces are exposed to air.
Thin	Alveolar walls and capillary walls are each only one cell thick.	Plant leaves are usually only a few cells thick; gases can reach most cells directly from the air. Stomata allow direct contact of the air spaces inside the leaf with the air outside it. Gases diffuse directly from air spaces into the cells that need them.
Diffusion gradient	Breathing movements replace oxygen-poor and carbon dioxide-rich air inside the lungs with atmospheric air. Blood flow through capillaries takes away oxygen-rich and carbon dioxide-poor blood and brings in blood low in oxygen and high in carbon dioxide.	In daylight, photosynthesis in palisade and spongy mesophyll cells uses carbon dioxide, lowering its concentration inside the leaf to below that in air. At night, respiration produces a diffusion gradient in the opposite direction. Oxygen diffuses in at night, and out during daylight.
Protection from drying out	The alveoli are tucked away deep inside the body, away from direct exposure to dry air. Cells secrete a watery fluid that covers the cells lining the alveoli, keeping them moist despite the loss of some water by evaporation into the air.	Stomata can close to prevent movement of gases, including water vapour, out of the leaf. A waxy cuticle covers the rest of the leaf, to reduce water loss from cells on the leaf surface.

Table 4.1 Gas exchange surfaces in mammals and plants.

SAQ

3 Emphysema is a disease that is frequently caused by smoking. In emphysema, the walls of the alveoli break down, creating larger and fewer spaces in the lungs.

In an investigation of the effects of smoking on lung surface area : volume ratios, samples of lung tissue of equal volume were taken from 10 normal lungs and 10 lungs from people with emphysema. The mean surface area of the samples from the normal lungs was 0.275 μm, and the mean surface area of the samples from lungs with emphysema was 0.170 μm.

a Explain how the breakdown of alveolar walls leads to a decrease in surface area : volume ratio of the gas exchange surface.

Hint

b Use the results of the study to explain why a person with emphysema has difficulty in getting enough oxygen into the blood.

Answer

52

The mammalian gas exchange system

Figure 4.3 shows the gross structure of the mammalian gas exchange system. The lungs are inside the **thorax** (chest), surrounded by a pair of **pleural membranes** that secrete **pleural fluid**. This provides an airtight, slippery covering that allows the lungs to inflate and deflate easily.

Air passes down into the lungs through the **trachea**, which branches into the left **bronchus** and right bronchus. Each bronchus branches repeatedly to form smaller tubes called **bronchioles**, which end in bunches of tiny sacs called **alveoli**. Each alveolus has a **blood capillary** very closely associated with it, and it is here that oxygen and carbon dioxide diffuse between the air inside the lungs and the blood inside the capillaries.

Lungs have no muscles, so movement is produced by muscles in the **diaphragm** – a sheet of tissue containing muscle, that separates the thorax from the abdomen – and the muscles between the **ribs**, which are called intercostal muscles. The rib cage also protects the lungs from damage, as well as protecting the heart, which is partly beneath the left lung.

Epithelial tissue in the airways

The tubes leading down to the lungs are lined by cells that are adapted to remove particles from the air before it reaches the lungs.

The cells making up the epithelial tissue that lines the trachea and bronchi are of two main types – **ciliated cells** and **goblet cells** (Figure 4.4). All of these cells sit on a **basement membrane** which contains fibres made from proteins that the cells beneath them have secreted.

Each cilium is about 3–4 µm long, and there are many of them on each ciliated cell. Each cilium contains microtubules which can slide past each other, causing the cilium to bend.

The numerous goblet cells in between the ciliated cells secrete **mucus**. Mucus contains substances called glycoproteins, whose molecules include very long chains of sugar molecules – it is these that make mucus so slimy and sticky. Mucus forms a complete protective covering over the epithelium. This not only stops the cells from drying out, but also traps particles from the air, preventing them from reaching the alveoli where they could cause damage.

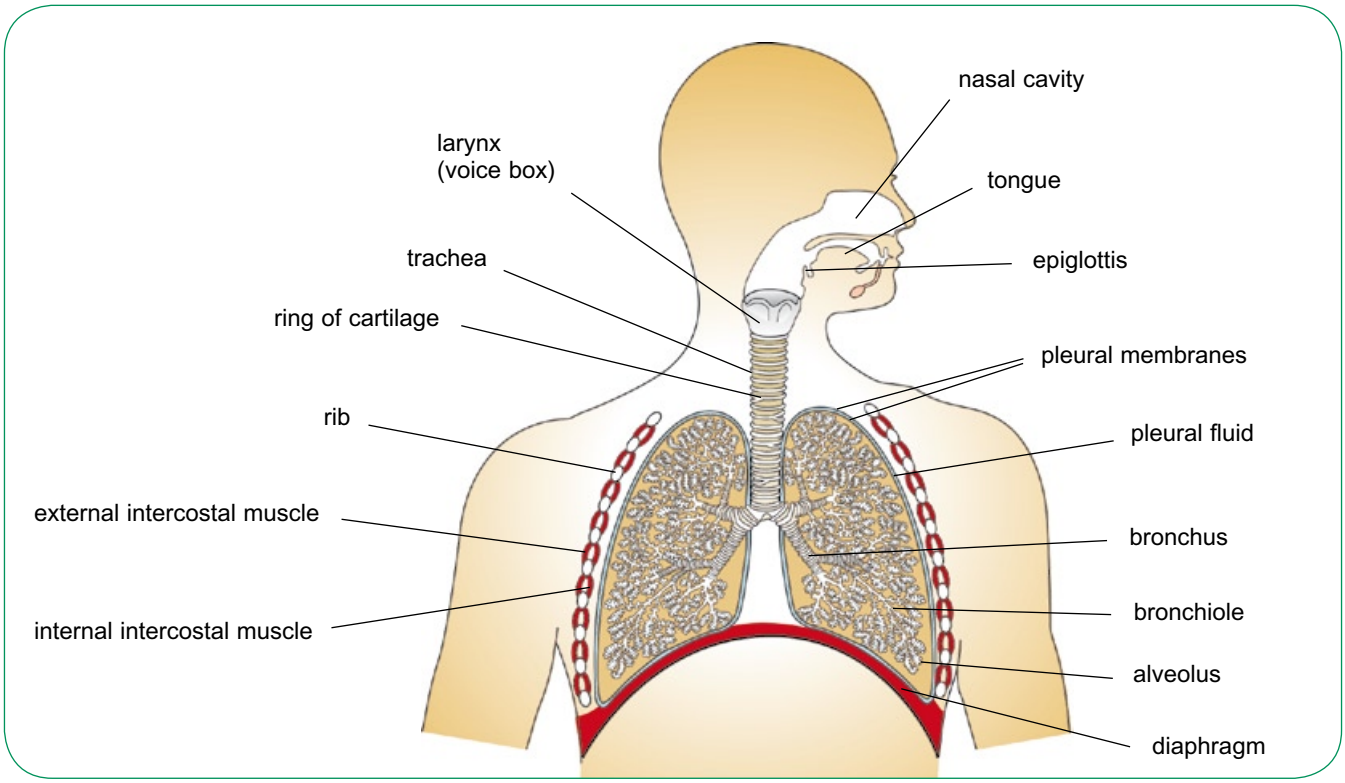


Figure 4.3 The mammalian gas exchange system.

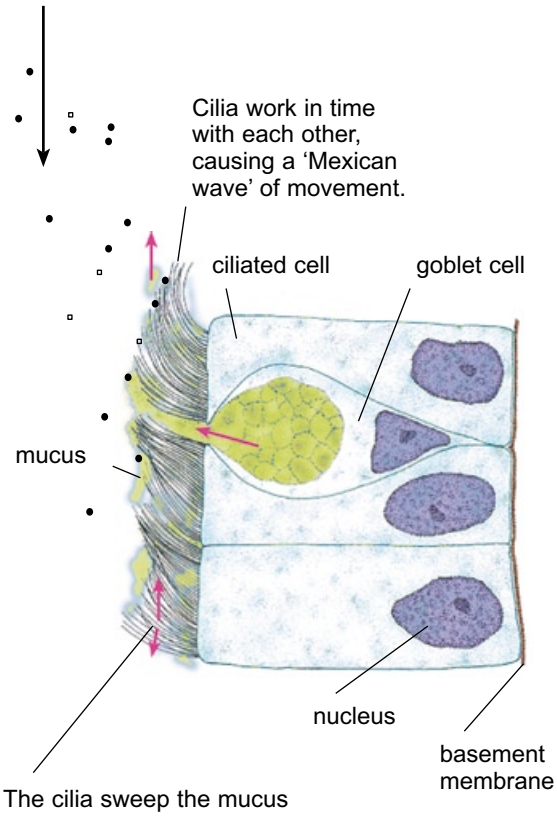


Figure 4.4 How the ciliated epithelium keeps the lungs clean.

SAQ

4 Ciliated cells have more mitochondria than many other types of cells. Goblet cells have a lot of rough endoplasmic reticulum and Golgi apparatus. Explain how these features relate to the functions of each of these types of cells.

Answer

Other tissues in the airways

The walls of the airways contain several other types of tissues, besides the ciliated epithelium that lines the trachea and bronchi. These tissues include cartilage, smooth muscle and elastic tissue (Figure 4.5 and Figure 4.6).

Cartilage is a tough tissue that helps to support the walls of the trachea and bronchi. The bronchioles do not contain cartilage. Like bone, cartilage is very strong, but it is more flexible than bone. Rings of cartilage in the walls of the trachea and bronchi help to hold these tubes open as the air pressure inside them changes during breathing. In the trachea, the cartilage is arranged in C-shaped rings. In the bronchi, it occurs in a more irregular pattern.

Smooth muscle is found in the walls of the trachea, bronchi and bronchioles. It is a type of muscle that contracts slowly and steadily and can remain contracted for long periods of time. It is **involuntary** muscle, meaning that you have no conscious control over its contraction. When the smooth muscle contracts, it narrows the airways. This is useful in changing the diameter of the small bronchioles – they can be made wider when

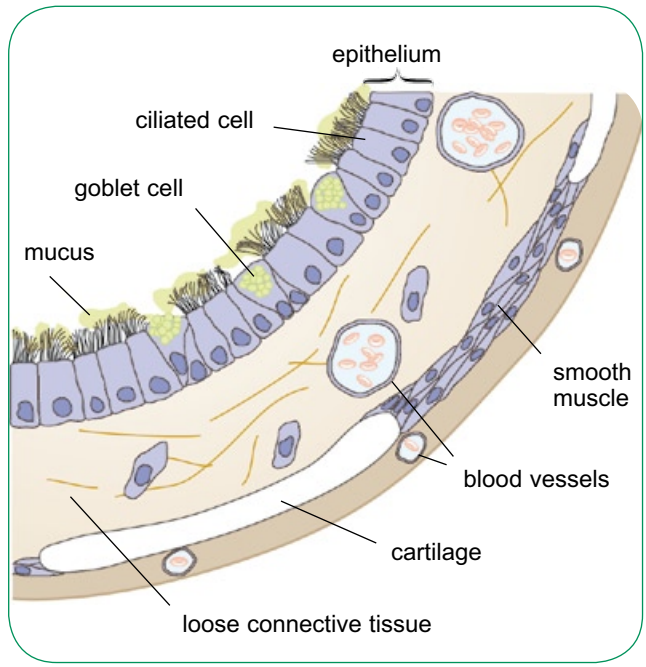


Figure 4.5 The histology of a bronchus wall.

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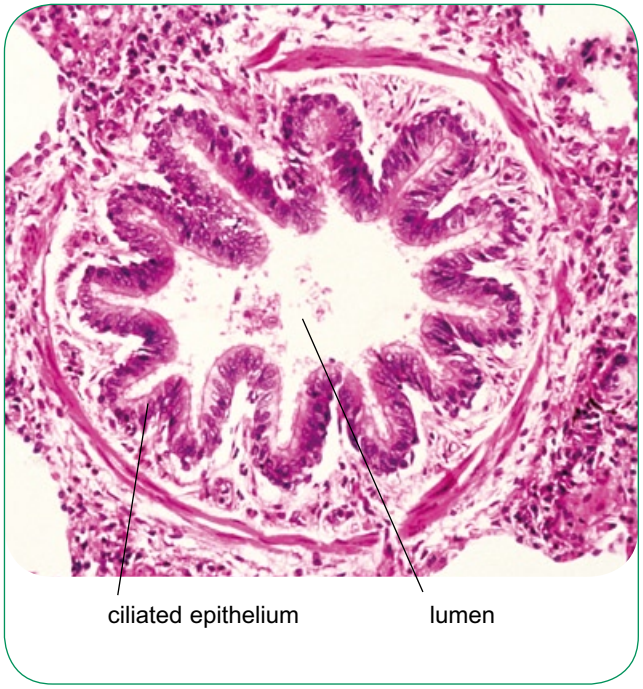


Figure 4.6 Photomicrograph of a bronchiole (×80).

a person is exercising and needs to get air into and out of the lungs more rapidly than normal. In people who suffer from asthma, the smooth muscle can contract in response to otherwise harmless substances in the air, or for other reasons, and this causes considerable breathing difficulties. Drugs called beta agonists can be inhaled to help make the muscles relax.

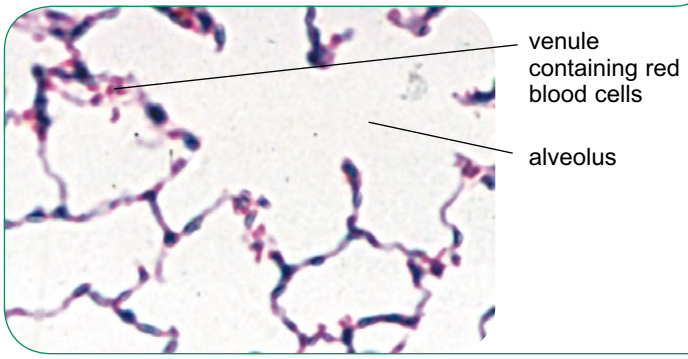
Elastic fibres are found in the walls of all of the airways, even the very smallest ones. They are especially important where they occur around the alveoli. During breathing in, the alveoli expand, stretching the elastic fibres. During breathing out, the fibres recoil, helping to decrease the volume inside the lungs and forcing air out.

Structure of alveoli

The alveoli, tucked deep inside the lungs, are the gas exchange surface. Here, atmospheric air is brought as close as possible to the blood, so that gases can diffuse quickly and easily between the two.

Figure 4.7 shows the structure of alveolar tissue. You can see that it is essentially made up of air spaces, divided by thin walls. The wall of each alveolus is a single layer of flattened cells, each cell being only about 5 µm thick. Blood capillaries, also with walls made up of single cells, are in close contact with them. The distance across which oxygen diffuses to pass from the alveolar air space into the blood inside a capillary is therefore very small.

In between the alveolar walls, elastic fibres provide strength and flexibility, so that the alveolar volume can easily increase during breathing in and decrease when you breathe out.



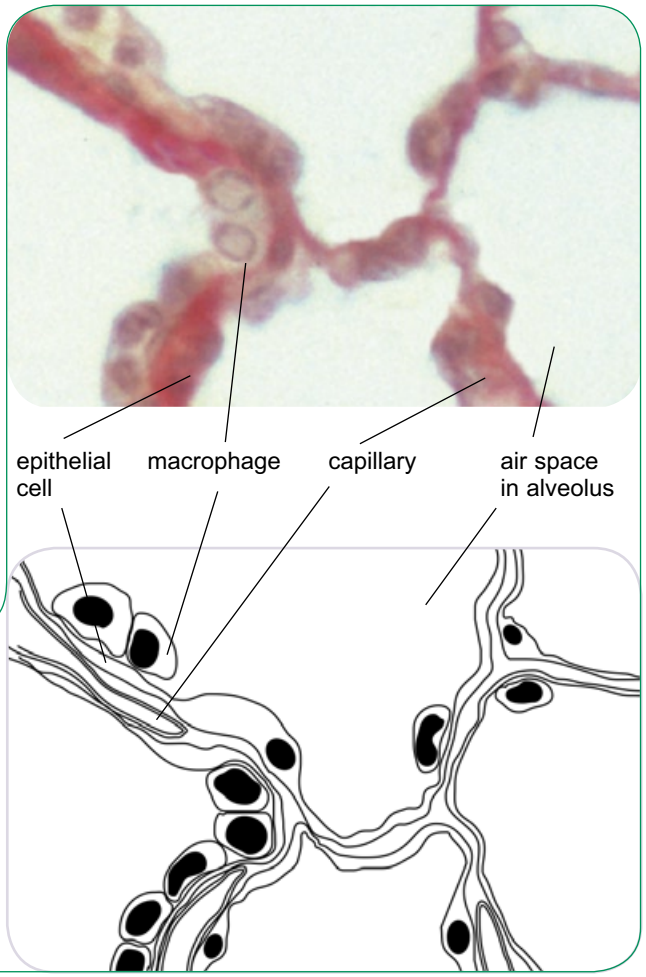


Figure 4.7 The structure of alveolar tissue.

55

Macrophages constantly patrol the alveolar surfaces. They scavenge for any harmful material that may have escaped the ciliated epithelium on the way into the lungs, such as bacteria, particulates from smoke, or dust particles. Macrophages are phagocytes, and will engulf and digest whatever they find. Some types of particles, however, cannot be digested, and they can cause serious harm. Asbestos fibres, for example, can accumulate in the lungs despite the best efforts of macrophages, and lead to serious disease (Figure 4.8).

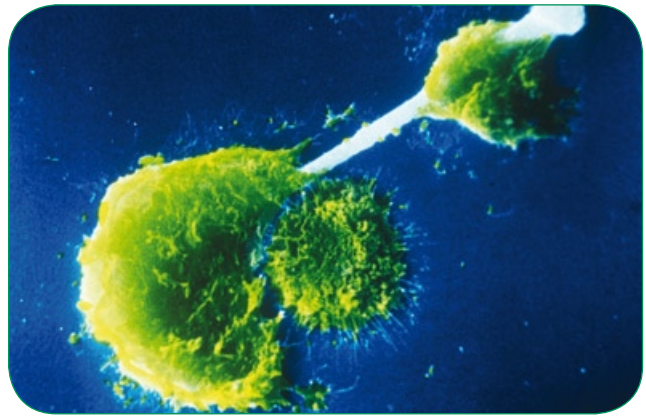


Figure 4.8 Two macrophages attempting to engulf an asbestos fibre. The fibres cannot be broken down and eventually puncture the macrophages. The contents of the macrophages leak out and they die.

Surfactant and respiratory distress syndrome

The inner surfaces of the alveoli are kept moist by the secretion of a watery fluid from the cells of the alveolar wall. Surface tension could easily cause the wet walls to stick together, making it difficult for the alveoli to expand when breathing in. To prevent this, the fluid contains a detergent-like substance called a **surfactant**, which reduces surface tension.

While a baby is still in the uterus, it does not use its lungs for gas exchange. Oxygen is supplied to its body through the umbilical cord, which contains two veins bringing blood from the placenta, where oxygen from the mother's blood diffuses into the baby's blood.

As the baby's lungs are not yet being used, there is no need for surfactant to be secreted, so this does not happen until fairly late in pregnancy. If a baby is born very prematurely, then its lungs may not be producing enough surfactant to stop the alveoli from sticking together. In this situation, the newborn baby may be unable to inflate its lungs when it tries to breathe. This condition is called respiratory distress syndrome of the newborn, often shortened to RDS. The more premature a baby, the greater the chance of RDS.

In a special baby unit at a hospital, a baby with RDS will be given extra oxygen, perhaps supplied under pressure to force the alveoli open. The baby may be placed inside a machine that rhythmically changes the air pressure around the baby's thorax, creating pressure gradients between the external air and the air in the lungs, which cause air to move in and out of the lungs. The baby may even be given surfactant through a tube leading to the lungs.

RDS usually gets worse before it gets better, and it may be several weeks before the baby can be taken off oxygen and out of the breathing machine. However, unless there are complications, there is a good chance that the baby will recover fully.

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The mechanism of breathing

As our gas exchange surface is tucked away deep inside the lungs, it is necessary to bring fresh supplies of air into contact with this surface. We do this by **breathing**. Breathing can be defined as making movements that move air into and out of the lungs.

The lungs have no muscles, so they cannot move by themselves. Breathing movements are caused by two sets of muscles – the **intercostal muscles** between the ribs and the **diaphragm muscles**. These are shown in Figure 4.9.

Contraction of the external intercostal muscles and of the muscles in the diaphragm increases the volume of the thoracic cavity. This lowers the pressure within the thoracic cavity to below the pressure of the air outside the body. Air therefore flows down the pressure gradient and into the thorax. The only way in is through the trachea and into the lungs, so air is drawn into the lungs. The lungs inflate.

To breathe out, these muscles all relax. The elastic fibres between the alveoli, which were stretched when the lungs expanded, go back to their normal length. As the volume of the thoracic cavity decreases, the pressure inside it increases. This forces air out of the lungs.

Figure 4.9 shows how these events take place.

Extension

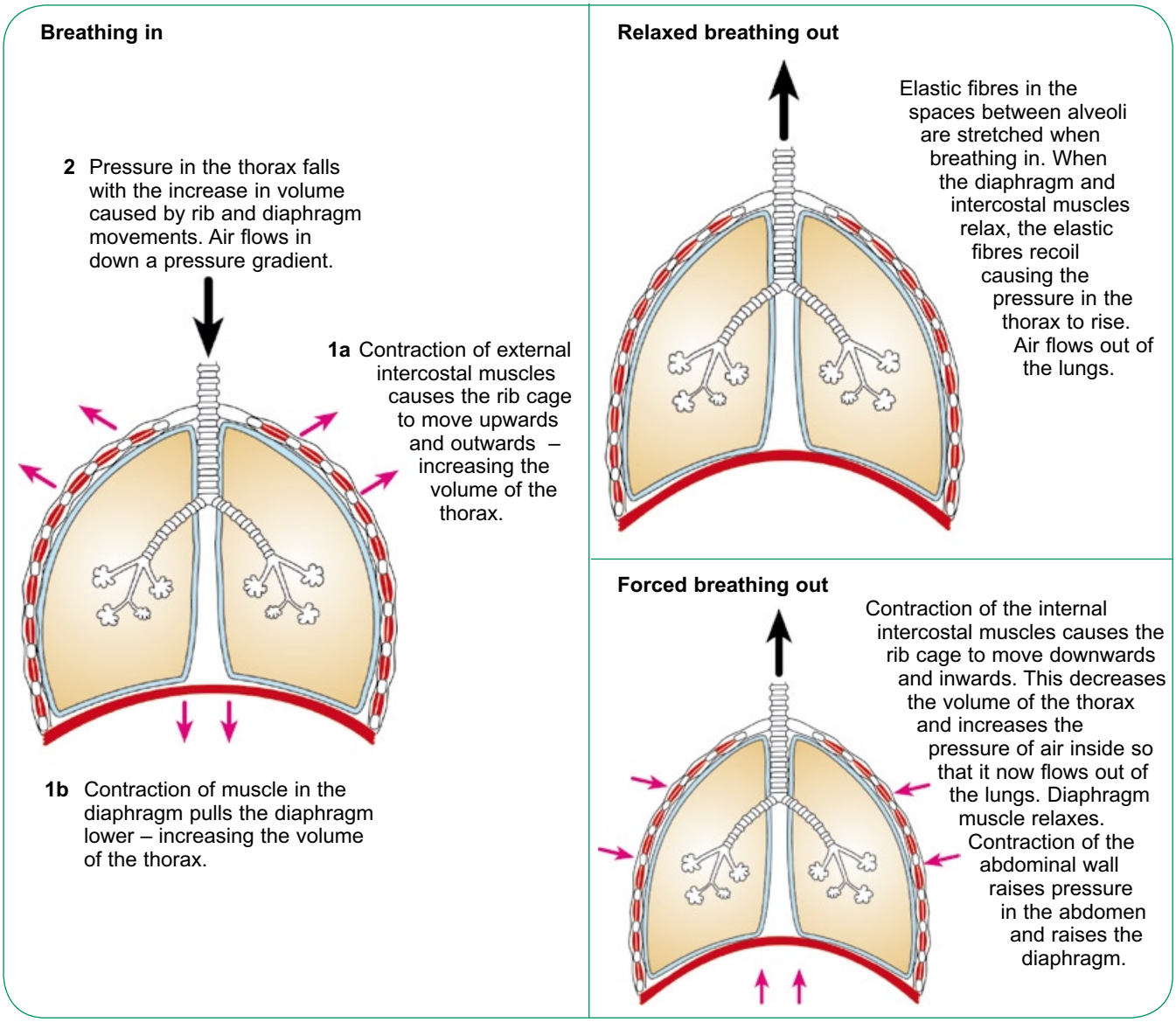

Figure 4.9 The mechanism of breathing.

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Measuring lung volumes

The volumes of air that are moved into and out of the lungs during breathing can provide useful information about the health of a person's lungs. These volumes can be measured using an instrument called a **spirometer** (Figure 4.10)

How a spirometer works

In the type of spirometer shown in Figure 4.10, a person breathes in and out into an enclosed air chamber. The air is trapped between the spirometer float and the water. As the person breathes in, the volume of air inside the chamber decreases, and the float drops down. As the person breathes out, the volume of air inside the chamber increases, and the float is pushed up.

The float is attached to a pen, which writes on paper attached to a revolving drum. The movement of the spirometer float is therefore recorded as a series of 'up and down' lines on the paper.

The air chamber can be filled with atmospheric air, or it can be filled with medical grade oxygen. The spirometer can be used with or without soda lime (see Figure 4.10). When soda lime is present, the air that the person breathes out passes through it, and all the carbon dioxide in the air is absorbed by the soda lime and does not go into the air chamber. This can be useful if the person is going to be breathing through the spirometer for a long period, to avoid them re-breathing air that has become quite rich in carbon dioxide. It can also be useful if you want to measure the volume of oxygen that has been consumed over a period of time (page 59).

Tidal volume and ventilation rate

Figure 4.11 shows a spirometer trace that was produced while a person breathed normally using a spirometer. Each time he breathed out, the pen went up, and each time he breathed in it went down. The chart shows four breaths in and five breaths out.

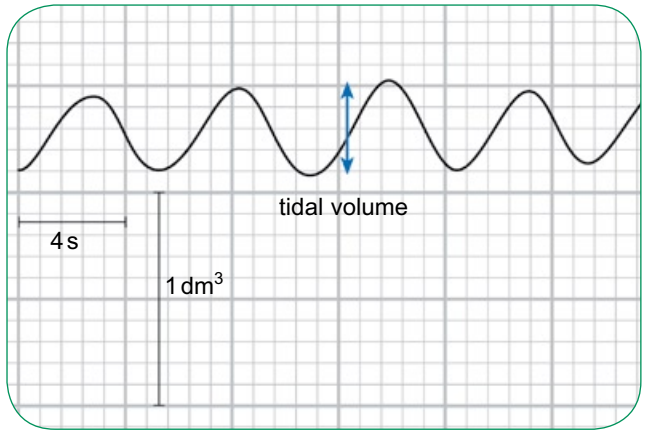

Figure 4.11 Tidal air movements.

The chart can be calibrated so that we know what volume of air is represented by a particular distance moved up or down by the pen. In this example, ten small squares on the vertical represent 1 dm^3 of air, and 5 small squares on the horizontal represent 4 s. You can think of the spirometer trace as a graph, with time on the *x*-axis and volume on the *y*-axis.

The chart can be used to measure the person's **tidal volume**. This is the volume of air that is breathed in and out with one breath. In this example, the tidal volume of the third breath is 0.4 dm^3.

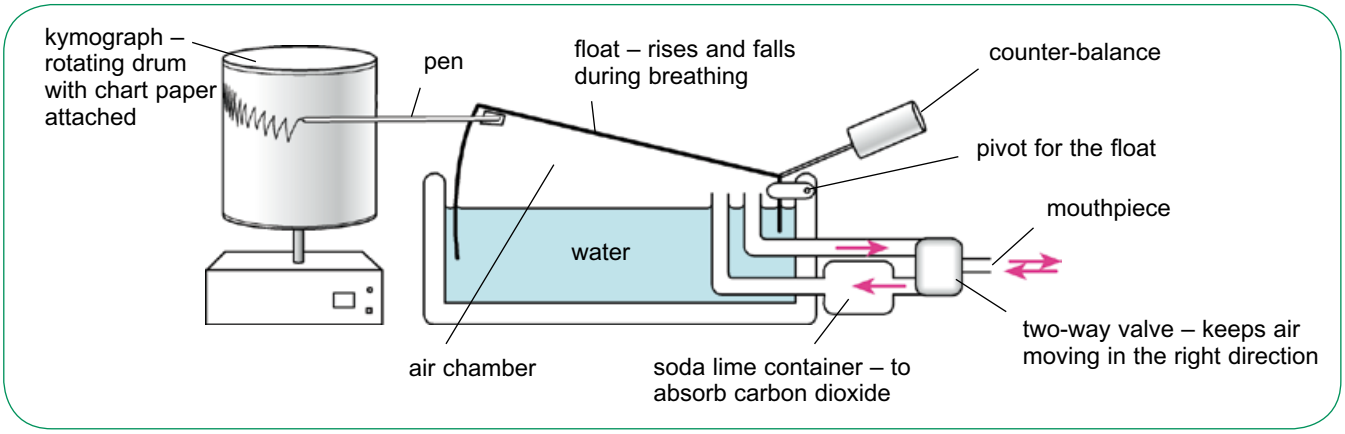

Figure 4.10 A spirometer.

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SAQ

5 Calculate the mean tidal volume shown in the spirometer trace in Figure 4.11.

Hint

Answer

We can also use the chart to work out the person's **breathing rate** – the number of breaths taken per minute. This can then be used to calculate the **ventilation rate**. This is the total volume of air breathed in or out in one minute. If you take 12 breaths per minute, and your mean tidal volume is 0.5 dm^3, then your ventilation rate is 12 breaths per minute × 0.5 dm^3 = 6 dm^3 per minute.

SAQ

6 Calculate the mean breathing rate, in breaths per minute, shown by the spirometer trace in Figure 4.11. Then use this value, and your answer to SAQ 5, to determine the ventilation rate.

Hint

Answer

Vital capacity

Your **vital capacity** is the very greatest volume of air you can move into and out of your lungs with one breath. It can be measured by breathing out every bit of air that you can from your lungs, and then taking your very largest breath in. The spirometer trace that is produced would look something like Figure 4.12.

When you breathe out deeply, you obviously move more air out of your lungs than during normal, relaxed breathing. This extra air breathed out is your **expiratory reserve volume**. The extra air you breathe *in* when you take a very deep breath is your **inspiratory reserve volume**. Your vital capacity is your tidal volume plus your expiratory reserve volume plus your inspiratory reserve volume.

SAQ

7 Use the spirometer trace in Figure 4.12 to find the person's vital capacity.

Answer

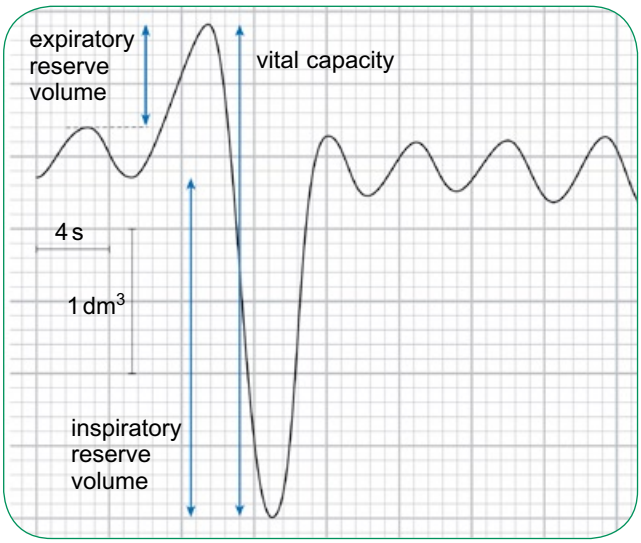


Figure 4.12 Vital capacity.

Measuring oxygen consumption

If the chamber of the spirometer is filled with oxygen, you can use it to measure how much oxygen you use over a period of time.

For this investigation, there must be soda lime in the container. Each time you breathe in, you take oxygen from the chamber and the float drops. When you breathe out, the unused oxygen in your expired air goes back into the air chamber, but the carbon dioxide in your expired air is absorbed by the soda lime. So the total volume of gas going back into the chamber is less than you took from it. With each breath, the volume of oxygen in the spirometer gets less and less, so the traces drawn by the pen go down and down. If we measure *how much* they go down over a period of time, this tells us the volume of oxygen that you have used.

Figure 4.13 shows the kind of spirometer trace you might get. The difference in the volume of air inside the spirometer chamber at the start of the session and at the end is 0.4 dm^3. This is the volume of oxygen that the subject used. The time taken for this volume of oxygen to be used was 24 seconds. So the rate of consumption of oxygen was 1 $dm^3 min^{-1}$.

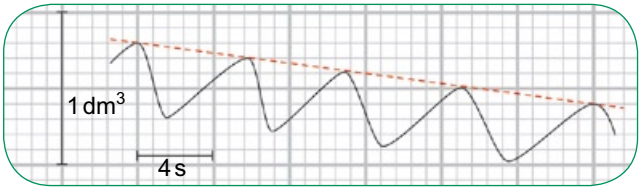
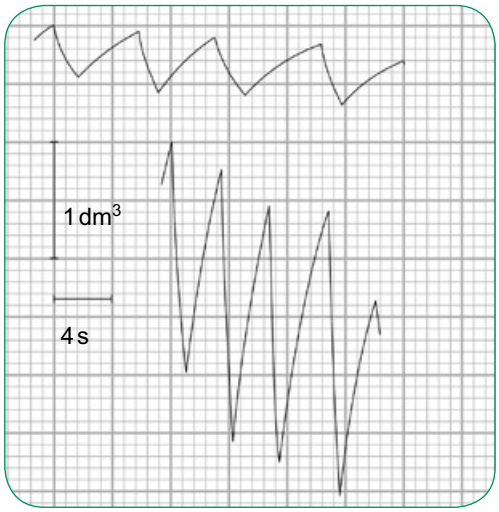


Figure 4.13 Measuring oxygen consumption.

59

SAQ

8 A spirometer's air chamber was filled with oxygen, and soda lime was used to absorb all the carbon dioxide in expired air. A subject breathed in and out of the spirometer while at rest. She then exercised vigorously for 5 minutes, and then breathed in and out of the spirometer again. The graph shows the spirometer trace.



a Calculate the breathing rate before exercise, and the breathing rate after exercise Show your working.

Hint

b Calculate the mean tidal volume before exercise, and the mean tidal volume after exercise. Show your working.

Hint

c Calculate the rate of oxygen consumption before exercise and the rate of oxygen consumption after exercise.

Hint

d You probably have some knowledge of aerobic respiration, anaerobic respiration and oxygen debt from your GCSE studies. Use this knowledge to try to explain the difference between the figures you have calculated for before and after exercise.

Answer

Summary

Glossary

- Multicellular organisms may need specialised exchange surfaces to increase the surface area : volume ratio. A good exchange surface should have a large surface area, be thin and be able to maintain a diffusion gradient. The cells on the surface must be protected from drying out.
- Alveoli in the human lung are very small, and there are large numbers of them, so providing a very large surface area. The distance between the air in the alveolus and the blood in the capillaries is very small. Breathing movements supply freshly inspired air to the alveoli, and blood flow brings deoxygenated blood to the alveolus and removes oxygenated blood, so maintaining diffusion gradients for oxygen and carbon dioxide.
- The airways leading to the lungs are lined with ciliated epithelium containing goblet cells that produce mucus. The mucus traps particles in the air and the cilia sweep the mucus upwards, away from the lungs.
- The walls of the trachea and bronchi contain cartilage, which supports them and prevents them from collapsing when air pressure inside them is low. Smooth muscle in the walls of the trachea, bronchi and bronchioles can contract to narrow the airway. Elastic fibres in the walls of all the airways, and in alveolar tissue, allow the lungs to inflate and deflate. This is especially important in ensuring that the alveoli deflate when breathing out.
- Air is moved into and out of the lungs by breathing movements. During breathing in, the external intercostal muscles and the muscles in the diaphragm contract. This increases the volume of the thoracic cavity, decreases the pressure within it and therefore causes air to flow in from outside, down a pressure gradient. During breathing out, these muscles relax, which decreases the volume of the thoracic cavity. Recoil of the elastic fibres in the lungs causes them to deflate, forcing air out of the body.

continued

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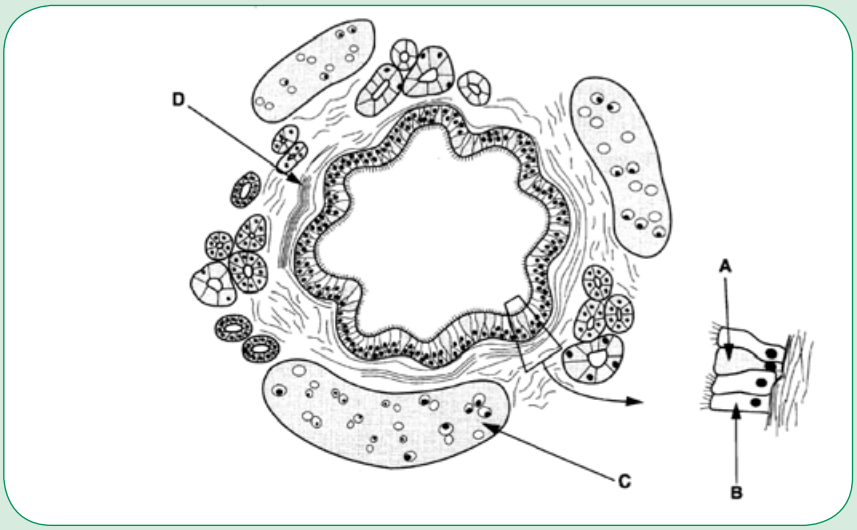
- Tidal volume is the volume of air moved in or out of the lungs in one breath. Vital capacity is the maximum volume of air that can be moved in or out of the lungs in one breath. These values can be measured using a spirometer.
- Oxygen uptake can be measured by recording the fall in volume of the air in a spirometer over several breaths.

Questions

1 The diagram shows a transverse section of a bronchus from the lung of a mammal.



a Name A to D. [4]

b Describe how the cells lining the bronchus protect the alveoli from damage. [4]

c There are elastic fibres between the cells lining the gaseous exchange surface in the alveoli. Describe the function of these fibres. [3]

d The table shows some measurements of a person's breathing. Ventilation rate is the volume of air breathed in during one minute.

tidal volume at rest	500 cm^3
vital capacity	4600 cm^3
breathing rate at rest	12 breaths per minute
ventilation rate during exercise	20 000 cm^3 min^{-1}

With reference to the table,

i calculate the ventilation rate at rest [1]

ii explain the meaning of the term *vital capacity* [2]

iii state how the person increased their ventilation rate even though their breathing rate remained constant. [1]

OCR Biology AS (2802) June 2001 [Total 15]

Answer

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Chapter 5

Transport in animals

e-Learning

Objectives

Types of transport system

Why do humans have a blood system? The answer is fairly obvious even to a non-scientist: our blood system transports substances such as nutrients and oxygen around the body. However, there are many organisms that either have much less complex transport systems or do not have any kind of transport system at all. Before looking in detail at the human transport system, we will consider why some organisms can manage without one.

A quick survey of some organisms that have very simple transport systems, or none at all, will provide an important clue. Table 5.1 lists six kinds of organisms, and gives a brief summary of the type of transport system that each has.

SAQ

1 Using the information in Table 5.1, suggest how important each of the following factors appears to be in determining whether or not an organism needs an efficient transport system. In each case, identify the information in the table which led you to your answer.

a size

b surface area : volume ratio

c level of activity

Answer

All living cells require a supply of nutrients, such as glucose. Most living cells also need a constant supply of oxygen. There will also be waste products, such as carbon dioxide, to be disposed of.

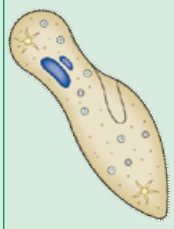
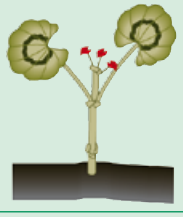
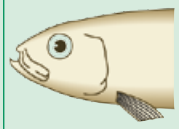
Type of organism	Single-celled	Cnidarians (jellyfish and sea anemones)	Insects	Green plants	Fish	Mammals
Size range	all microscopic	some microscopic, some up to 60 cm	less than 1 mm to 13 cm	1 mm to 150 m	12 mm to 10 m	35 mm to 34 m
Example	*Paramecium* 	sea anemone 	locust 	*Pelargonium* 	goldfish 	human 
Level of activity	move in search of food	jellyfish swim slowly; anemones are sedentary and move very slowly	move actively; many fly	no movement of whole plant; parts such as leaves may move slowly	move actively	move actively
Type of transport system	no specialised transport system	no specialised transport system	blood system with pumps	xylem and phloem make up transport system; no pump	blood system with pump	blood system with pump

Table 5.1 Different transport systems.

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Very small organisms, such as the single-celled protozoan *Paramecium*, can meet their requirements for the supply of nutrients and oxygen, and the removal of waste, by means of diffusion. The very small distances across which substances have to diffuse mean that the speed of supply or removal is sufficient for their needs. These tiny organisms have a large surface area : volume ratio, so there is a relatively large area of membrane across which gases can diffuse.

Even larger organisms, such as cnidarians, can manage by diffusion alone. A cnidarian's body is made up just two layers of cells, so every cell is within a very small distance of the water in which these organisms live, and with which they exchange materials. They, too, have relatively large surface area : volume ratios. Moreover, cnidarians are not very active animals, so their cells do not have large requirements for glucose or oxygen, nor do they produce large amounts of waste products. Diffusion, slow though it is, is quite adequate to supply their needs.

Larger, more active organisms, such as insects, fish and mammals, cannot rely on diffusion alone. Cells, often deep within their bodies, are metabolically very active, with requirements for rapid supplies of nutrients and oxygen, and with relatively large amounts of waste products to be removed. These organisms have well-organised transport systems, with pumps to keep fluids moving through them. Plants, although large, are less metabolically active than these groups of animals and, as you will see in Chapter 6, have evolved a very different type of transport system, with no obvious pump to keep fluids moving.

Open and closed circulatory systems

The human blood system, like that of all vertebrates, is a **closed circulatory system**. This means that the blood is always enclosed in vessels.

Insects, however, have an **open circulatory system** (Figure 5.1). Here, although the blood is pumped around the body by a heart and flows out of the heart in arteries, it is not then contained within vessels but fills the body cavity, which is called a **haemocoel** ('blood space').

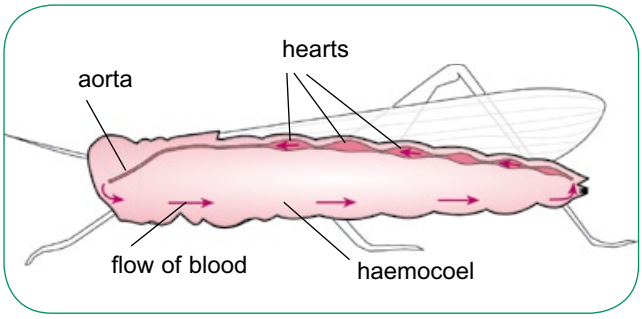

Figure 5.1 The transport system of an insect.

In insects, the blood does *not* transport oxygen around the body. Insects have a gas exchange system which is not at all like that of humans. Insects have an arrangement of tubes called **tracheae**, which penetrate deep into the body and carry air from the atmosphere directly to the tissues (Figure 5.2). The insect gas exchange surfaces are therefore very close to the cells that are using oxygen and making carbon dioxide, so diffusion is sufficient to satisfy their demands.

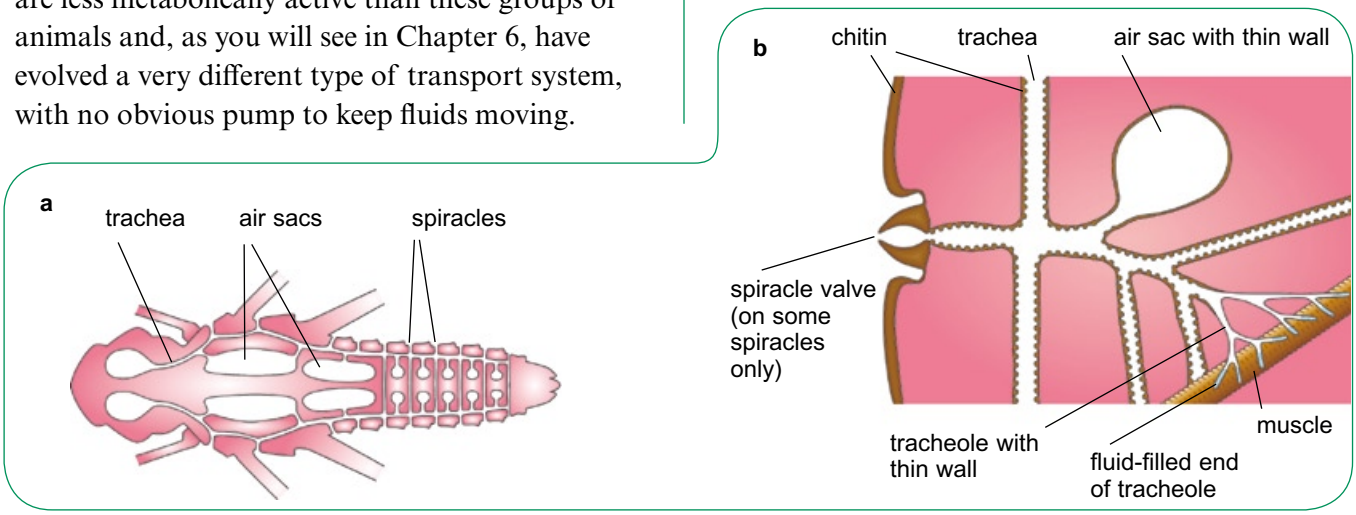

Figure 5.2 The gas exchange system of an insect: **a** dorsal view; **b** detail of parts of the gas exchange system.

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SAQ

2 To answer these questions, look at Figure 5.2.

a Explain how the insect gas exchange system provides a large surface area for gas exchange.

b Suggest why there are spirals of chitin (a tough, supporting material) around the tracheae. Hint

c Suggest why having valves on the spiracles is important for terrestrial insects. Hint

Answer

Single and double circulatory systems

The human circulation system is a **double circulatory system** (Figure 5.3). One part serves the lungs, and is called the **pulmonary circulation**. The other part serves the rest of the body, and is called the **systemic circulation**.

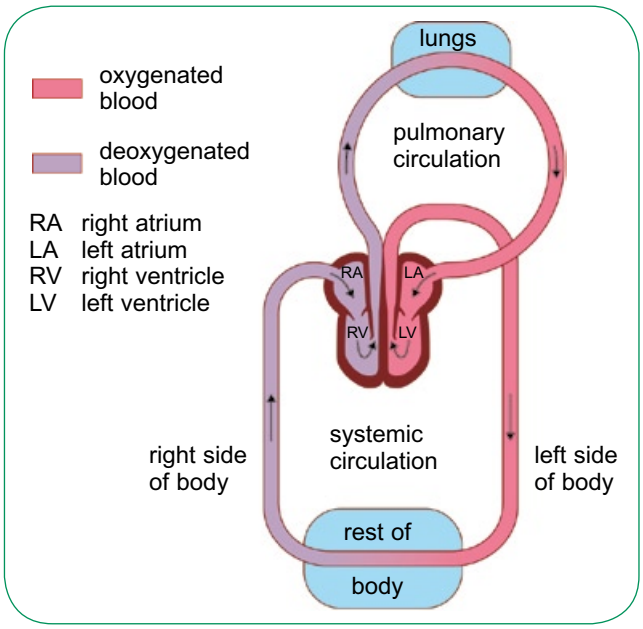


Figure 5.3 A double circulatory system. This is a general plan of the mammalian transport system.

SAQ

3 **a** Is the transport system shown in Figure 5.3 a closed system or an open system? Explain your answer.

b How many times does the blood pass through the heart on one journey round the body in a double circulatory system? Answer

Fish, however, have a **single circulatory system** (Figure 5.4). Here, the blood is pumped out of the heart to the gills (the equivalent of our lungs) where it picks up oxygen. But, instead of going back to the heart, the blood continues on around the rest of the body.

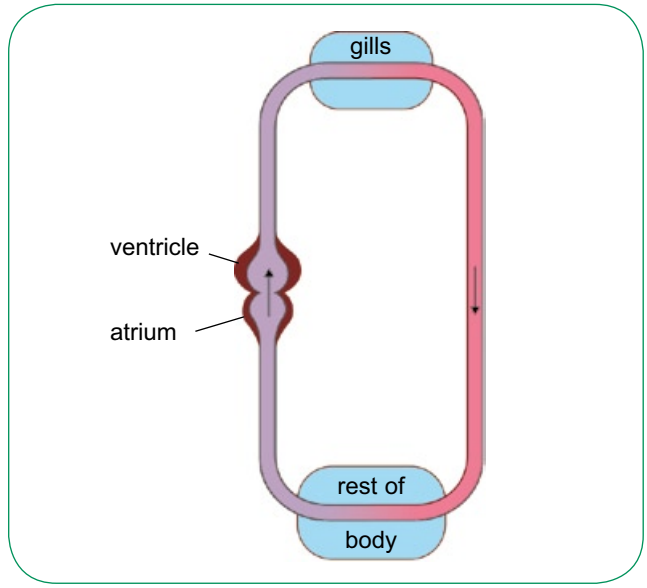


Figure 5.4 A single circulatory system in a fish.

This system is not as efficient as the mammalian system at getting oxygenated blood to the tissues. As blood from the heart reaches the gas exchange organs, it travels through many tiny capillaries, where it loses much of its pressure. In humans, the oxygenated blood returns to the heart, where the left ventricle pumps it out into the aorta. The oxygenated blood moves quickly out of the heart, and moves fast along the arteries, rapidly delivering oxygen to respiring tissues. In a fish, however, the blood from the gill capillaries is simply collected back up into vessels and carried on its way to the rest of the body, without being repressurised by the heart.

SAQ

4 State two differences between the circulatory systems of an insect and a fish. Answer

64

The mammalian heart

Structure of a human heart

The heart of an adult human has a mass of around 300 g and is about the size of your fist (Figure 5.5). It is a bag of muscle, filled with blood. Figure 5.6 shows the appearance of a human heart, looking at it from the front of the body.

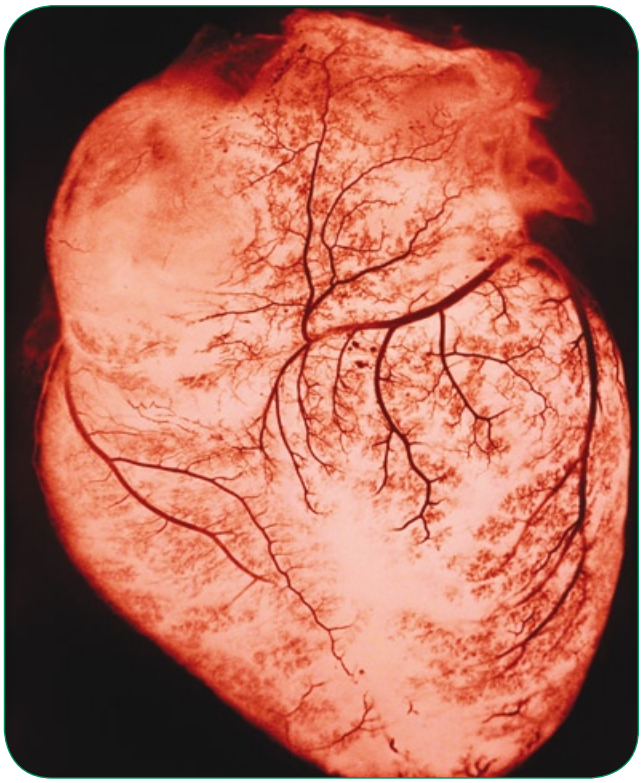


Figure 5.5 A human heart.

The muscle of which the heart is made is called cardiac muscle. This muscle is able to contract and relax rhythmically, 24 hours a day, throughout your life.

In Figure 5.6, you can see the blood vessels that carry blood into and out of the heart. The large, arching blood vessel is the largest artery, the **aorta**, with branches leading upwards towards the head and the main flow turning back downwards to the rest of the body. The other blood vessel leaving the heart is the **pulmonary artery**. This, too, branches very quickly after leaving the heart, into two arteries, one taking blood to the left lung and one to the right. Running vertically on the right-hand side of the heart are the two large veins, the **venae cavae** (singular: vena cava), one bringing blood downwards from the head and the other bringing it upwards from the rest of the body. The **pulmonary veins** bring blood back to the heart from the left and right lungs.

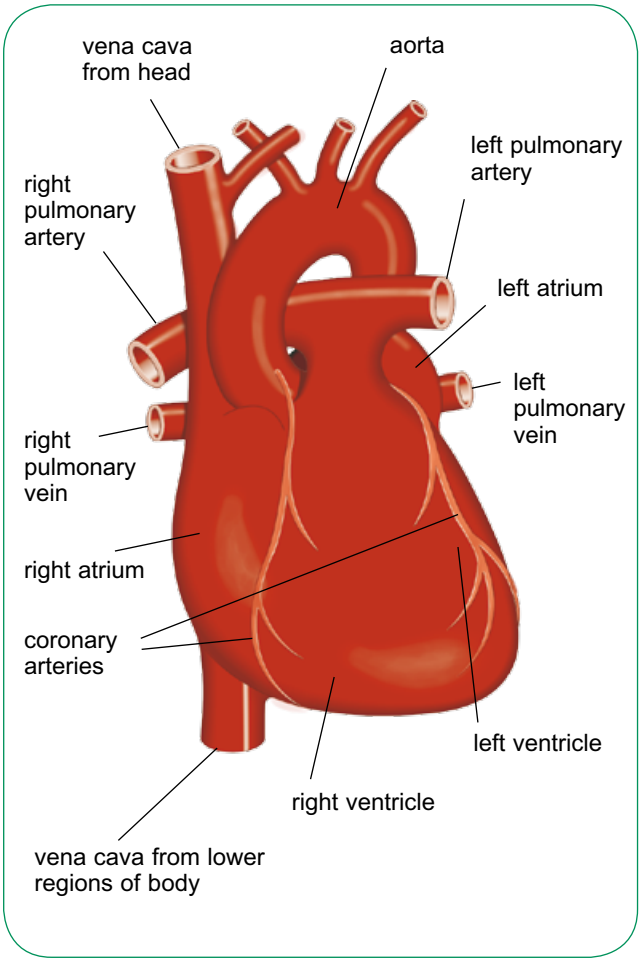


Figure 5.6 Diagram of the external structure of a human heart, seen from the front.

On the surface of the heart, the **coronary arteries** can be seen (Figures 5.5 and 5.6). These branch from the aorta and deliver oxygenated blood to the muscle of the walls of the heart.

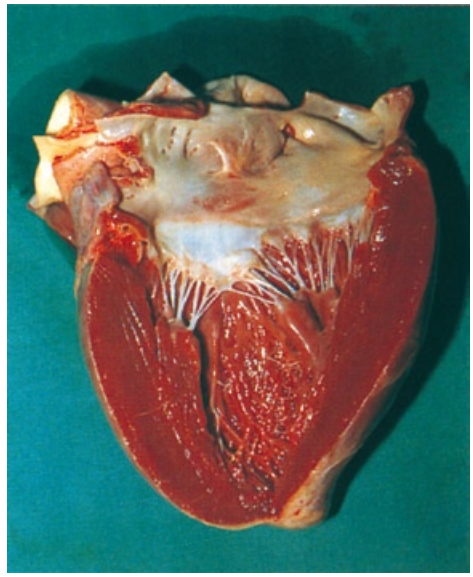
If the heart is cut open vertically (Figure 5.7), it can be seen to contain four chambers. The two chambers on the left of the heart are completely separated from those on the right by a wall of muscle called the **septum**. Blood cannot pass through this septum; the only way for blood to get from one side of the heart to the other is to leave the heart, circulate around either the lungs or the rest of the body, and then return to the heart.

The upper chamber on each side is called an **atrium**. The two atria receive blood from the veins. You can see from Figure 5.7 that blood from the venae cavae flows into the right atrium, while blood from the pulmonary veins flows into the left atrium.

The lower chambers are **ventricles**. Blood flows into the ventricles from the atria, and is then squeezed out into the arteries. Blood from the left ventricle flows into the aorta, while blood from the right ventricle flows into the pulmonary arteries.

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

a



b

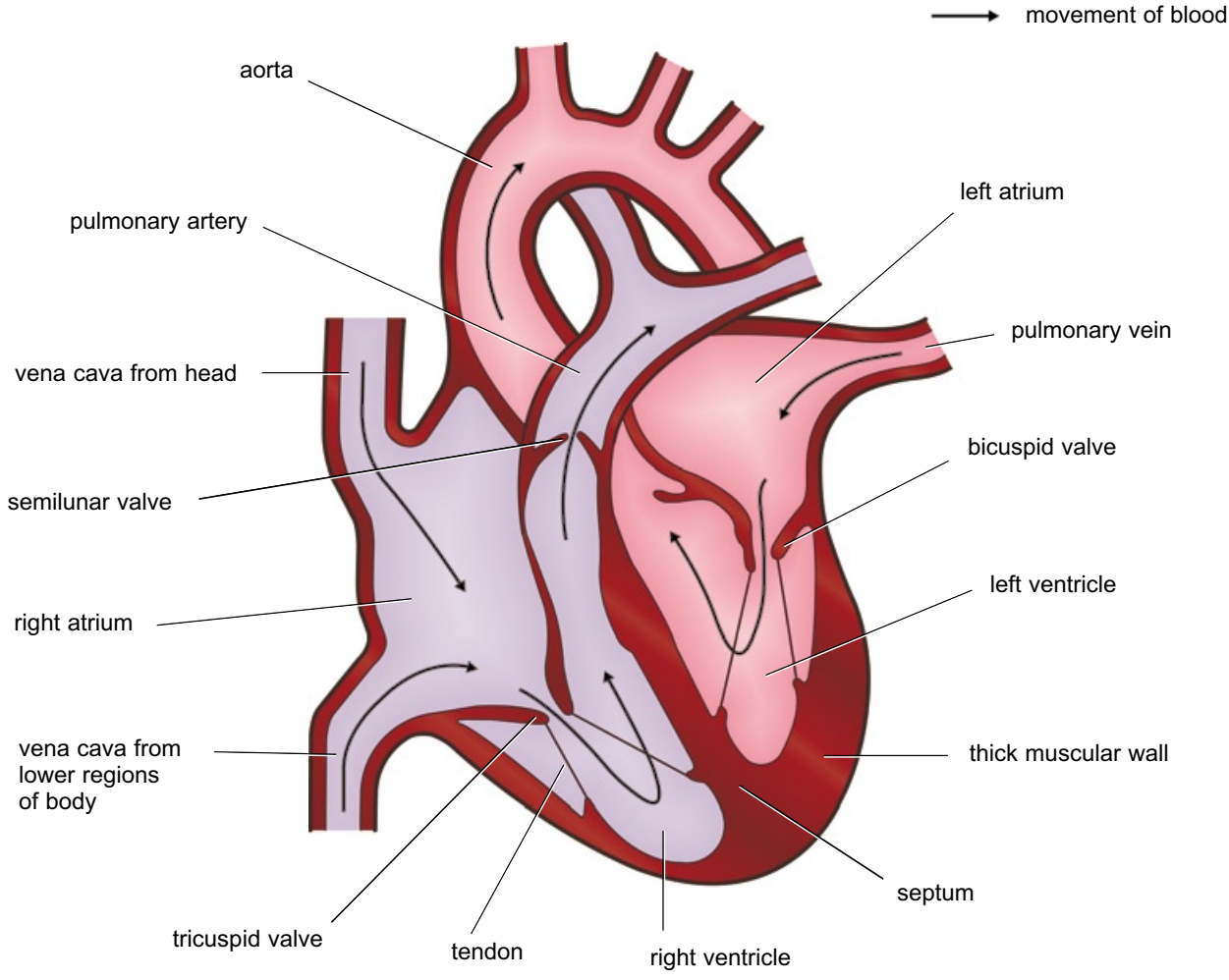


Figure 5.7 Vertical sections through a human heart: **a** the heart has been cut through the left atrium and ventricle only; **b** both sides of the heart are shown.

66

The cardiac cycle

Your heart beats around 70 times a minute at rest. The **cardiac cycle** is the sequence of events that makes up one heart beat.

As the cycle is continuous, a description of it could begin anywhere. We will begin with the time when the heart is filled with blood, and the muscle in the atrial walls contracts. This stage is called **atrial systole** (Figure 5.8). The pressure developed by this contraction is not very great, because the muscular walls of the atria are only thin, but it is enough to force the blood in the atria down through the atrio-ventricular valves into the ventricles. The blood from the atria does not go back into the pulmonary veins or the venae cavae, because these have semilunar valves to prevent backflow.

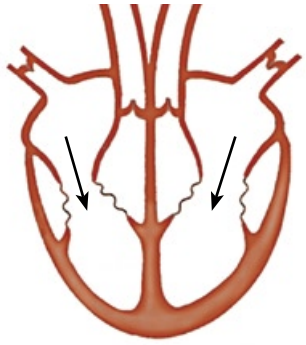
About 0.1 s after the atria contract, the ventricles contract. This is called **ventricular systole**. The thick, muscular walls of the ventricles squeeze inwards on the blood, increasing its pressure and pushing it out of the heart. As soon as the pressure in the ventricles becomes greater than that in the atria, this pressure difference forces the atrio-ventricular valves shut, preventing blood from going back into the atria. Instead, the blood rushes upwards into the aorta and pulmonary artery, pushing open the semilunar valves in these vessels as it does so.

Ventricular systole lasts for about 0.3 s. The muscle then relaxes, and the stage called **ventricular diastole** begins. The pressure in the ventricles drops. The high-pressure blood which has just been pushed into the arteries would flow back into the ventricles, but for the presence of the semilunar valves, which snap shut as the blood fills their cusps.

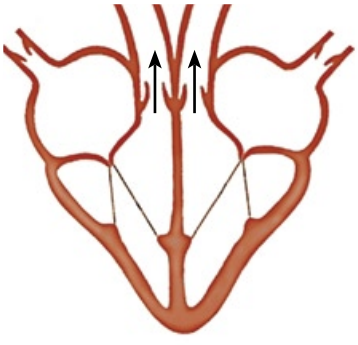
During diastole, as the whole of the heart muscle relaxes, blood from the veins flows into the two atria. The blood is at a very low pressure, but the thin walls of the atria are easily distended, providing very little resistance to the blood flow. Some of the blood flows down into the ventricles. The atrial muscle then begins to contract, pushing blood forcefully down into the ventricles, and the whole cycle begins again.

Figure 5.9 shows how the atrio-ventricular and semilunar valves work.

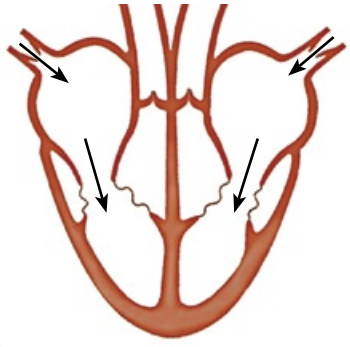
The walls of the ventricles are much thicker than the walls of the atria, because the ventricles need to develop much more force when they contract, to push the blood out of the heart and around the body. For the right ventricle, the force required is relatively small, as the blood goes only to the lungs, which are very close to the heart. The left ventricle has to develop sufficient force to push blood all around the rest of the body. So the muscular wall of the left ventricle needs to be thicker than that of the right ventricle.



1 **Atrial systole**. Both atria contract. Blood flows from the atria into the ventricles. Backflow of blood into the vein is prevented by closure of the valves in the veins.



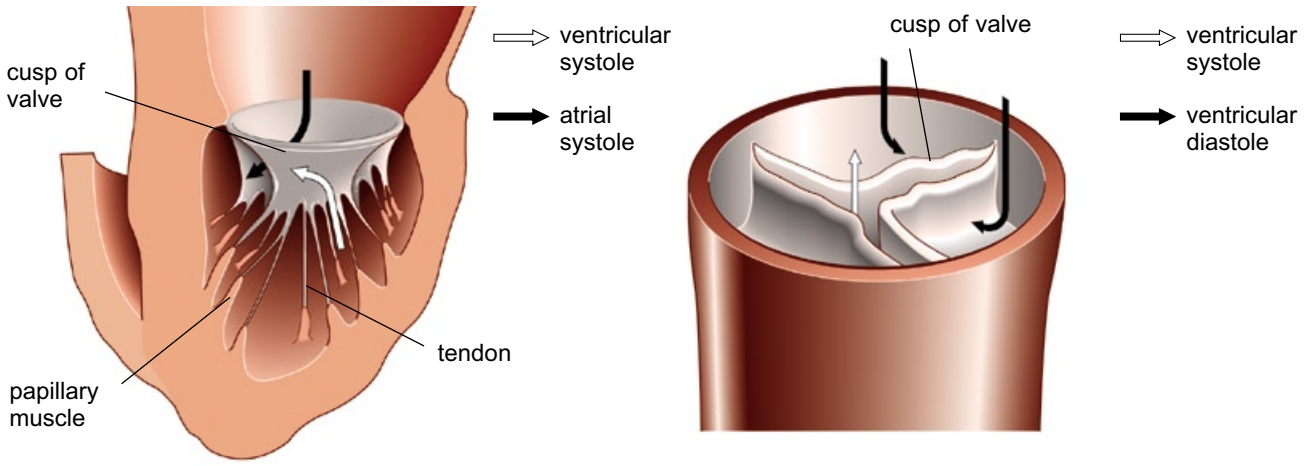
2 **Ventricular systole**. Both ventricles contract. The atrio-ventricular valves are pushed shut by the pressurised blood in the ventricles. The semilunar valves in the aorta and pulmonary artery are pushed open. Blood flows from the ventricles into the arteries.



3 **Ventricular diastole**. Atria and ventricles relax. The semilunar valves in the aorta and pulmonary artery are pushed shut. Blood flows from the veins through the atria and into the ventricles.

Figure 5.8 The cardiac cycle. Only three stages in this continuous process are shown.

67



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

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

Fig 5.9 How the heart valves function.

Drugs to help the heart

The heart rate is controlled by a patch of muscle in the heart called the **pacemaker**, or **sino-atrial node** (**SAN**).

Two nerves carry impulses from the brain to the SAN. One of these is the vagus nerve. It releases a transmitter substance called acetycholine next to the cells in the SAN. Acetylcholine slots into receptors in the plasma membranes of these cells, and makes the cells beat more *slowly*.

The other nerve, called the sympathetic nerve, releases a different chemical called noradrenalin. This has the opposite effect to acetylcholine, and makes the cells in the SAN beat more *rapidly*. The hormone adrenaline, released from the adrenal glands just above the kidneys when a person is frightened or excited, has the same effect.

There are several drugs that can be used to help a person who has problems with their rate of heartbeat. Two of these are digoxin and propranolol.

Digoxin inhibits a Na–K pump in the plasma membrane of the heart muscle cells. This pump usually keeps sodium concentration inside the cells at a low level. When the pump is slowed, sodium ions accumulate inside the cells. This also increases the concentration of calcium ions in them, which increases the force of muscle contraction.

Digoxin was discovered in foxgloves.

Propranolol has the opposite effect. It belongs to a class of drugs called beta blockers. They work by decreasing the effect of noradrenalin on the SAN, reducing the heart rate. Beta blockers are often given to people with angina, a pain in the chest that is a sign that the coronary arteries are not supplying enough oxygen to the heart muscle.

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SAQ

5 Figure 5.10 shows the pressure changes in the left atrium, left ventricle and aorta throughout two cardiac cycles. Make a copy of this diagram.

a i How long does one heart beat (one cardiac cycle) last?

ii What is the heart rate represented on this graph, in beats per minute?

b The contraction of the muscles in the ventricle wall causes the pressure inside the ventricle to rise. When the muscles relax, the pressure drops again. On your copy of the diagram, mark the following periods:

i the time when the ventricle is contracting (ventricular systole)

ii the time when the ventricle is relaxing (ventricular diastole).

c The contraction of muscles in the wall of the atrium raises the pressure inside the atrium. This pressure is also raised when blood flows into the atrium from the veins, while the atrial walls are relaxed. On your copy of the diagram, mark the following periods:

i the time when the atrium is contracting (atrial systole)

ii the time when the atrium is relaxing (atrial diastole).

d The atrio-ventricular valves open when the pressure of the blood in the atria is greater than that in the ventricles. They snap shut when the pressure of the blood in the ventricles is greater than that in the atria. On your diagram, mark the points at which these valves open and close.

e The opening and closing of the semilunar valves in the aorta depends, in a similar way, on the relative pressures in the aorta and ventricles. On your diagram, mark the points at which these valves open and close.

f The right ventricle has much less muscle in its walls than the left ventricle, and only develops about one-quarter of the pressure developed on the left side of the heart. On your diagram, draw a line to represent the probable pressure inside the right ventricle during the 1.3 s shown.

Answer

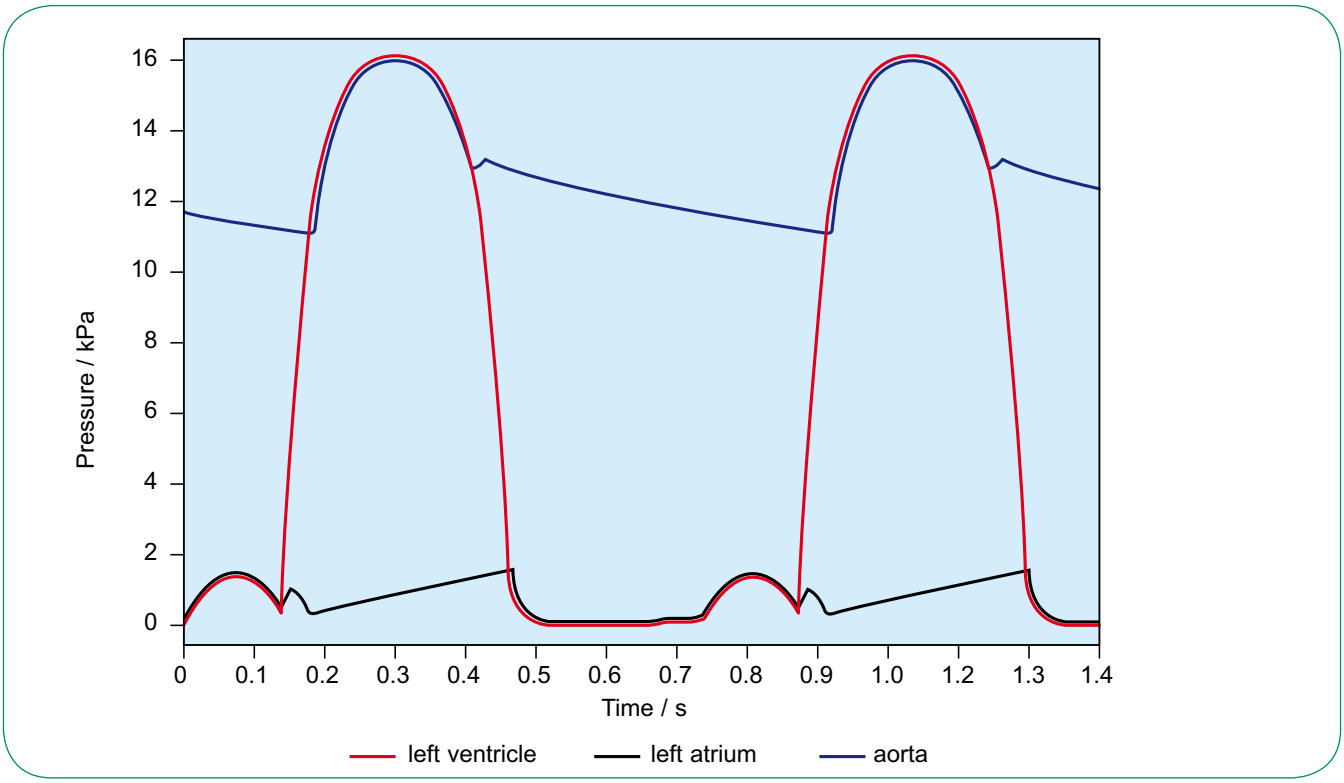

Figure 5.10 Pressure changes in the heart during the cardiac cycle.

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Control of the heart beat

Cardiac muscle differs from the muscle in all other areas of the body in that it is **myogenic**. This means that it automatically contracts and relaxes; it does not need to receive impulses from a nerve to make it contract. If cardiac muscle cells are cultured in a warm, oxygenated solution containing nutrients, they contract and relax rhythmically, all by themselves. Cardiac muscle cells joined together contract together, in unison.

However, the individual muscle cells in a heart cannot be allowed to contract at their own natural rhythms. If they did, parts of the heart would contract out of sequence with other parts; the cardiac cycle would become disordered and the heart would stop working as a pump. The heart has its own built-in controlling and coordinating system which prevents this happening.

The cardiac cycle is initiated in a small patch of muscle in the wall of the right atrium, called the **sino-atrial node** or **SAN** (Figure 5.11). It is often called the **pacemaker**. The muscle cells in the SAN set the pace and rhythm for all the other cardiac muscle cells. Their natural rhythm of contraction is slightly faster than the rest of the heart muscle. Each time they contract, they set up a wave of electrical activity, which spreads out rapidly over the whole of the atrial walls. The cardiac muscle in the atrial walls responds to this excitation wave by contracting, in the same rhythm as the SAN. Thus, all the muscle in both atria contracts almost simultaneously.

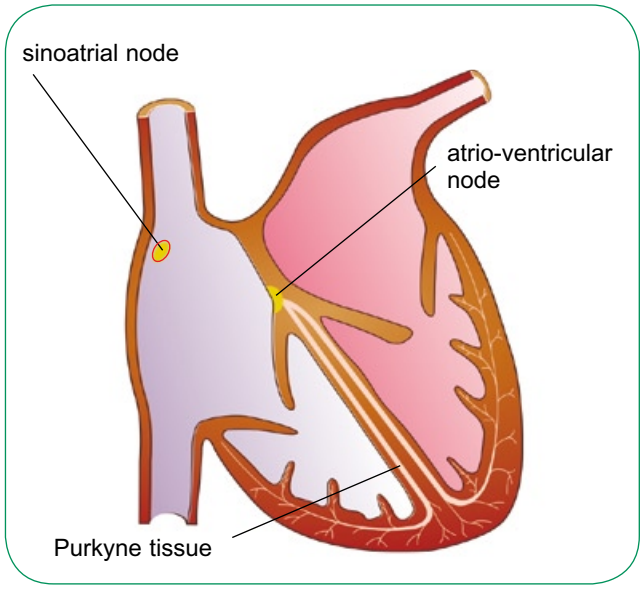

Figure 5.11 The sino-atrial node and atrio-ventricular node.

As we have seen, the muscles of the ventricles do not contract until *after* the muscles of the atria. (You can imagine what would happen if they all contracted at once.) This delay is caused by a feature of the heart that briefly delays the excitation wave in its passage from the atria to the ventricles.

There is a band of fibres between the atria and the ventricles which does not conduct the excitation wave. As the wave spreads out from the SAN, it cannot pass through these fibres. The only route is through a small patch of conducting fibres, known as the **atrio-ventricular node** or **AVN**. The AVN picks up the excitation wave as it spreads across the atria and, after a delay of about 0.1 s, passes it on to a bunch of conducting fibres, called the **Purkyne tissue**, which runs down the septum between the ventricles. This transmits the excitation wave very rapidly down to the base of the septum, from where it spreads outwards and upwards through the ventricle walls. As it does so, it causes the cardiac muscle in these walls to contract, from the bottom up, squeezing blood upwards and into the arteries (Figure 5.12).

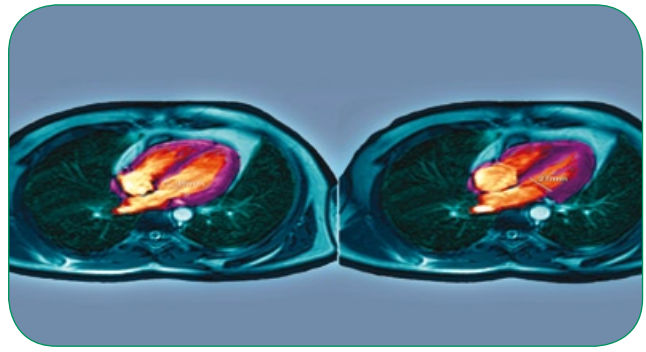

Figure 5.12 Two MRI scans of a man's chest cavity, showing his beating heart. The orange areas are the ventricles of the heart. In the left-hand image, the heart is in diastole. In the right-hand image, the ventricles are contracting – you can see that the volume inside them is less.

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Electrocardiograms

It is quite easy to detect and record the waves of electrical excitation as they travel through the heart muscle. Electrodes can be placed on the skin over opposite sides of the heart, and a recording is made of the electrical potentials. The result is essentially a graph of voltage against time. It is called an **electrocardiogram** or **ECG**. Figure 5.13 shows an ECG for a healthy heart.

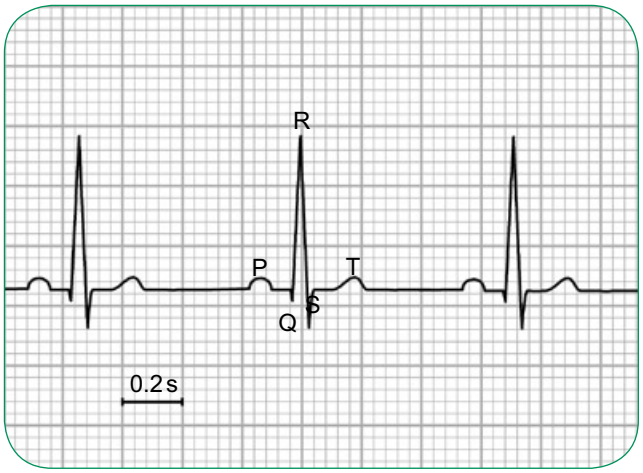


Figure 5.13 A normal ECG.

Figure 5.14 explains how the peaks and troughs of the ECG relate to the pressure changes we have already looked at. If you look very carefully, you can see that the ups and downs in the ECG happen just *before* the ups and downs in the pressure graph. For example, the P wave on the ECG comes before the pressure rise in the left atrium. This is because the ECG records the electrical impulses that are spreading over the heart, and these electrical impulses *cause* the contraction of the muscle in the heart walls. So the P wave in the ECG represents the wave of electrical activity spreading through the walls of the atria (Figure 5.15), which is quickly followed by the contraction of the atrial muscle and therefore the rise in pressure in the atria.

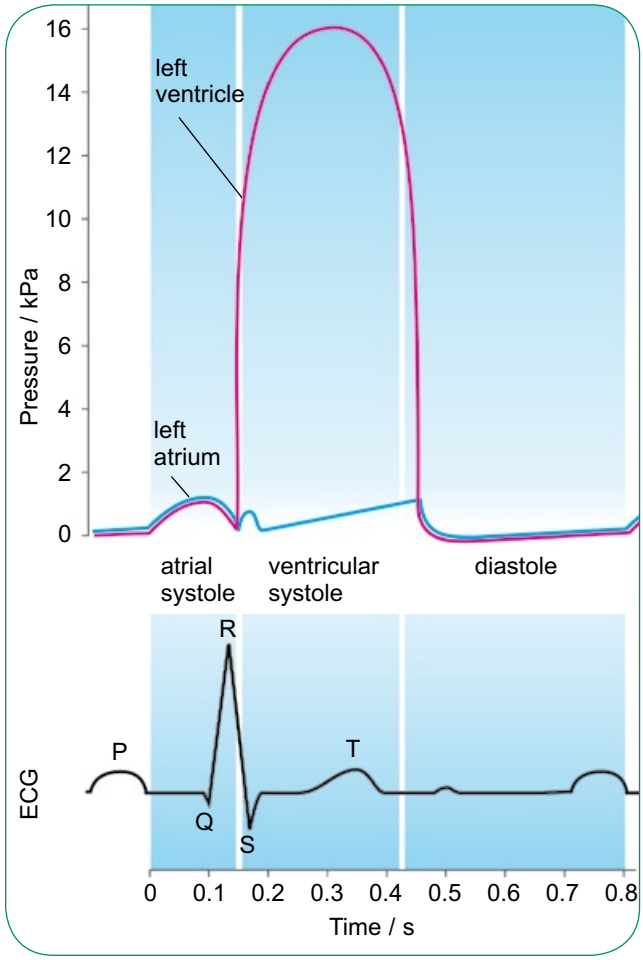
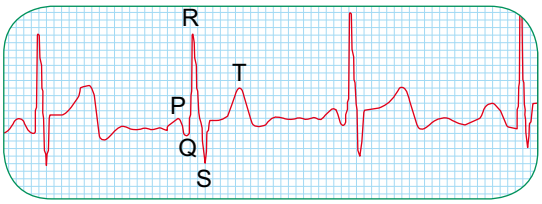


Figure 5.14 An ECG, and how it relates to the cardiac cycle.

SAQ

6 This diagram shows a normal ECG. The paper on which the ECG was recorded was running at a speed of 25 mm s^{-1}.



a Calculate the heart rate in beats per minute.

b The time interval between Q and T is called the **contraction time**.

i Suggest why it is given this name.

ii Calculate the contraction time from this ECG.

c The time interval between T and Q is called the **filling time**.

i Suggest why it is given this name.

ii Calculate the filling time from this ECG.

Answer

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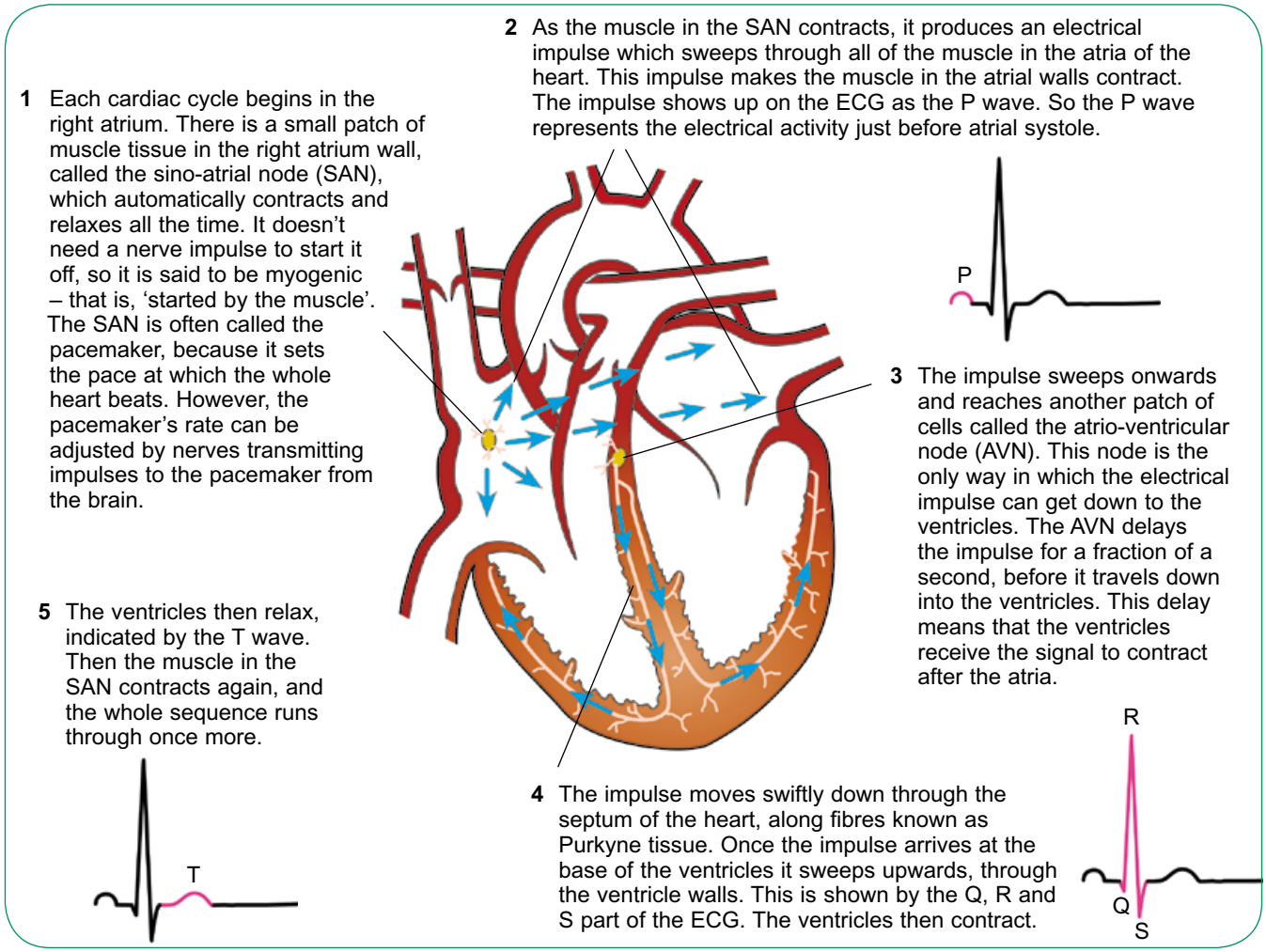

Figure 5.15 How electrical impulses move through the heart.

Figure 5.16 shows two examples of abnormal ECGs. The first shows ventricular fibrillation, in which the muscle in the ventricle walls just flutters. This could be because of serious damage to the heart muscle, which has caused it to stop beating – in other words, a heart attack or cardiac arrest. For any chance of survival, the person needs treatment with a defibrillator, which administers electric shocks, to try to get the heart muscle beating normally again.

The second ECG in Figure 5.16 shows a condition called heart block. There are many different kinds of heart block, a term which refers to problems with the movement of the electrical signals from one part of the heart to another. In this person, the signals are taking much longer than usual to pass from the atria to the ventricles, and you can see that the time interval between the P and R sections is longer than in Figure 5.13. This could be caused by damage to the Purkyne fibres.

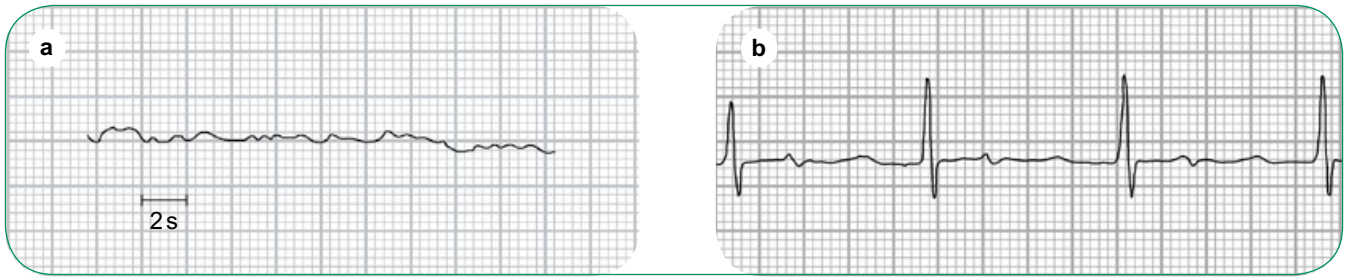

Figure 5.16 Two abnormal ECGs: **a** ventricular fibrillation; **b** heart block.

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Blood vessels

When blood first leaves the heart, it is travelling in vessels called **arteries**. Arteries always carry blood away from the heart. The largest arteries divide into smaller ones, and these continue to divide to form much smaller vessels called **arterioles**. These in turn divide into even smaller vessels called **capillaries**. Capillaries then join up with each other to form **venules** and these finally merge to form **veins**, which carry blood back to the heart. The structures of the walls of arteries, veins and capillaries are shown in Figure 5.17 and Figure 5.18.

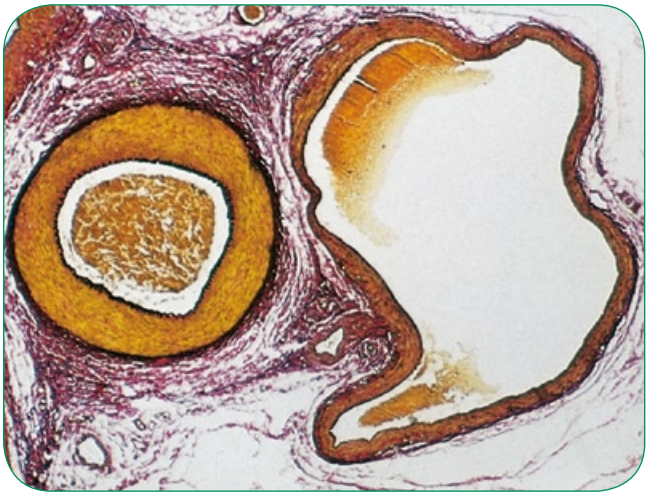

Figure 5.18 Micrograph of an artery and vein (×15).

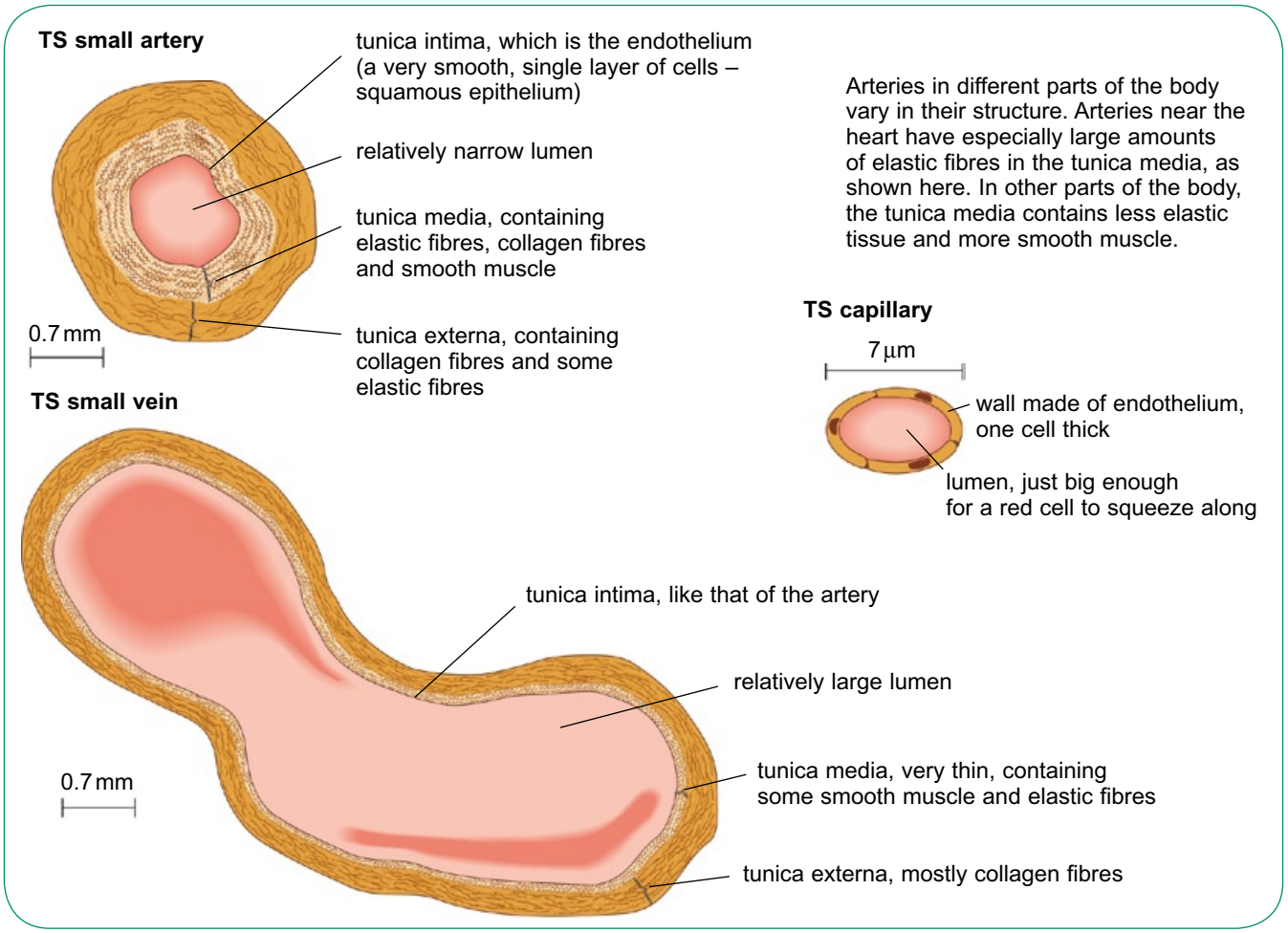

Figure 5.17 The tissues making up the walls of arteries, capillaries and veins.

Arteries

The function of arteries is to transport blood swiftly and at high pressure to the tissues.

Both arteries and veins have walls made up of three layers:

- an inner **endothelium** (lining tissue), made up of a layer of flat cells fitting together like jigsaw pieces; called squamous epithelium, this is very smooth, and so reduces friction as blood flows over its surface
- a middle layer called the **tunica media** ('middle coat') containing smooth muscle, collagen and elastic fibres
- an outer layer called the **tunica externa** ('outer coat') containing elastic fibres and collagen fibres.

The distinctive feature of an artery wall is its strength and elasticity. Blood leaving the heart is at a very high pressure. Blood pressure in the human aorta may be around 120 mm Hg, or 16 kPa. (Blood pressure is still measured in the old units of mm Hg even though kPa is the SI unit – mm Hg stands for 'millimetres of mercury' and refers to the distances which mercury is pushed up the arm of a U-tube when a sphygmomanometer is used; 1 mm Hg is equivalent to about 0.13 kPa.) To withstand the pressure surges, artery walls must be extremely strong and able to expand and recoil.

Arteries have the thickest walls of any blood vessel. The human aorta, the largest artery and the one where pressure is highest, has an overall diameter of 2.5 cm close to the heart, and a wall thickness of about 2 mm. Although 2 mm may not seem very great, the composition of the wall provides great strength and resilience. The tunica media, which is by far the thickest part of the wall, contains large numbers of elastic fibres. These allow the wall to stretch as pulses of blood surge through at high pressure as a result of the contraction of the ventricles. As the ventricles relax, the blood pressure drops, and the elastic artery walls recoil inwards.

Therefore, as blood at high pressure enters an artery, the artery becomes wider, which reduces the pressure slightly, so it is a little below what it would be if the wall could not expand. As blood at lower pressure enters an artery, the artery wall recoils inwards, giving the blood a small 'push' and raising the pressure a little. The overall effect is to 'even out' the flow of blood. However, the arteries are not entirely effective in achieving this: if you feel your pulse in your wrist, you can feel the artery, even at this distance from your heart, being stretched outwards with each surge of blood from the heart.

As arteries reach the tissue to which they are delivering blood, they branch into smaller vessels called **arterioles**. The walls of arterioles are similar to those of arteries, but they have a greater proportion of smooth muscle. This muscle can contract, narrowing the diameter of the arteriole and reducing blood flow through it. This helps to control the volume of blood flowing into a tissue at different times. For example, during exercise, arterioles that supply blood to muscles in your legs will be wide (dilated) as their walls relax, while those carrying blood to the gut wall will be narrow (constricted).

Extension

Capillaries

Arterioles branch to form the tiniest of all blood vessels, the capillaries (Figure 5.19). Their function is to take blood as close as possible to all cells, allowing rapid transfer of substances between the blood and the cells. Capillaries form a network throughout every tissue in the body except the cornea and cartilage. These networks are sometimes known as **capillary beds**. Although individual capillaries are very small, there are so many of them that their total cross-sectional area is considerably greater than that of the arteries.

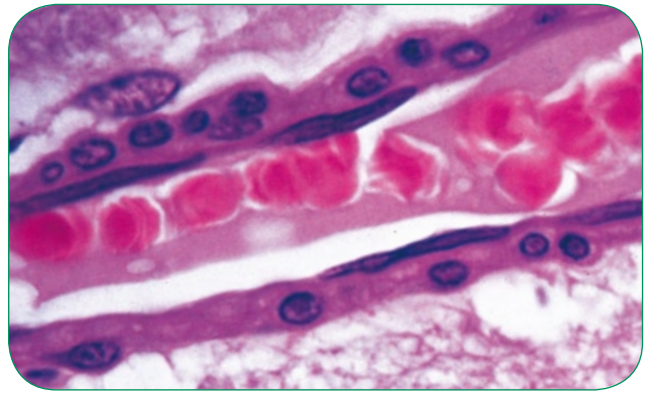

Figure 5.19 Micrograph of a blood capillary containing red blood cells (×900).

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Capillaries are often no more than 7 or 8 µm in diameter. This is about the same size as a red blood cell, so these can only pass through the capillaries in single file. This makes sure that every red blood cell, carrying its load of oxygen, is brought as close as possible to the cells in the surrounding tissues. This speeds up the transfer of oxygen to the cells and the removal of carbon dioxide. The gases move by diffusion, down their concentration gradients.

Capillaries have very thin walls, only one cell thick, which also speeds up transfer of materials between the blood and the tissues. Many substances pass across the endothelial cells in vesicles, by endocytosis and exocytosis (Chapter 2). The vesicles can even fuse to form tiny holes right through a cell. In most capillaries, there are also tiny gaps between the individual cells that form the endothelium, allowing easy transfer of substances dissolved in the plasma out of the capillary to the surrounding cells.

SAQ

7 Suggest why there are no blood capillaries in the cornea of the eye. Answer

Extension

Veins

As blood leaves a capillary bed, the capillaries join together to form **venules** and then **veins**. The function of veins is to return blood to the heart.

The blood which enters veins is at a much lower pressure than in arteries. In humans, a typical value for venous blood pressure is about 5 mm Hg or even less. Veins therefore have no need for thick, elastic walls. The walls are so thin that veins collapse when a section of tissue is cut to make a microscope slide. The walls have the same three layers as arteries, but the tunica media is much thinner with far fewer elastic fibres and muscle fibres.

The low blood pressure in veins creates a problem: how can this blood be returned to the heart? The problem is most obvious if you consider how blood can return upwards from your legs. Unaided, the blood in your leg veins would sink and accumulate in your feet. Many of the veins run within, or very close to, several leg muscles. Whenever you tense these muscles, they squeeze inwards on the veins, temporarily raising the pressure within them. This in itself would not help to push the blood back towards the heart – blood would just squidge up and down as you walked. To keep the blood flowing in the right direction, veins contain semilunar valves, formed from their endothelium (Figure 5.20). The valves allow blood to move towards the heart, but not away from it. When you contract your leg muscles, the blood in the veins is squeezed through the valves, but cannot drop back past them.

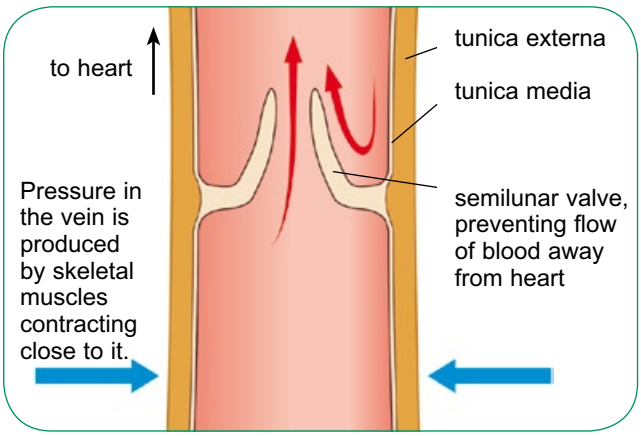

Figure 5.20 Longitudinal section through a small vein and a valve.

Table 5.2 summarises the differences between arteries, veins and capillaries, and Figure 5.21 shows how blood pressure changes as it travels on a complete journey from the heart, through the systemic circulatory system, back to the heart and finally through the pulmonary circulatiory system.

SAQ

8 Explain what causes each of the following: Hint

a Blood pressure oscillates (goes up and down) in the arteries.

b Blood pressure drops in the arterioles and in the capillaries.

c Blood pressure rises in the pulmonary artery, but not so high as in the aorta. Answer

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	Artery	Vein	Capillary
Elastic tissue in wall	Large amount, especially in arteries close to the heart. This allows the wall to stretch and recoil as high-pressure blood pulses through.	Small amount. Blood in veins is at low pressure, so there is no need for the walls to be elastic.	None.
Smooth muscle in wall	Relatively large amount in small arteries and arterioles. Contraction of this muscle reduces the size of the lumen, which can divert blood from one area to another.	Small amount. All blood in veins is travelling back to the heart, so there is no advantage in being able to divert it to different tissues.	None.
Thickness of wall	Relatively thick. Artery walls must be strong enough to withstand the high pressure of the blood flowing inside them.	Relatively thin. The blood in veins is at low pressure, so there is no need for a thick wall.	The wall is only one cell thick. Moreover, these cells are thin and flattened, so the wall is as thin as possible. This allows rapid transfer of substances by diffusion between the blood and tissue fluid.
Endothelium (inner lining)	Very smooth. This allows blood to flow freely and quickly. A rough wall would present more resistance to blood flow. Intact endothelium decreases the likelihood of a thrombus (blood clot) forming.	As arteries.	The wall of a capillary is made of endothelium only, with no other layers of tissue. The thin endothelium and pores speed up exchange of substances with the tissues.
Presence of valves	There are no valves in arteries, except those in the aorta and pulmonary artery as they leave the heart.	Veins have valves, which allow blood to flow towards the heart but not away from it. They are necessary because of the low pressure of blood in the veins.	There are no valves in capillaries.
Diameter of lumen	Relatively small compared with veins.	Relatively large. The wide lumen of a vein provides less resistance to blood flow than the narrow lumen of an artery, allowing blood at low pressure to move through easily.	Tiny. Many capillaries are only 8 µm wide. This brings the blood as close as possible to the cells in the tissues with which it is exchanging materials such as oxygen and carbon dioxide.

Table 5.2 Summary of blood vessel structure and function.

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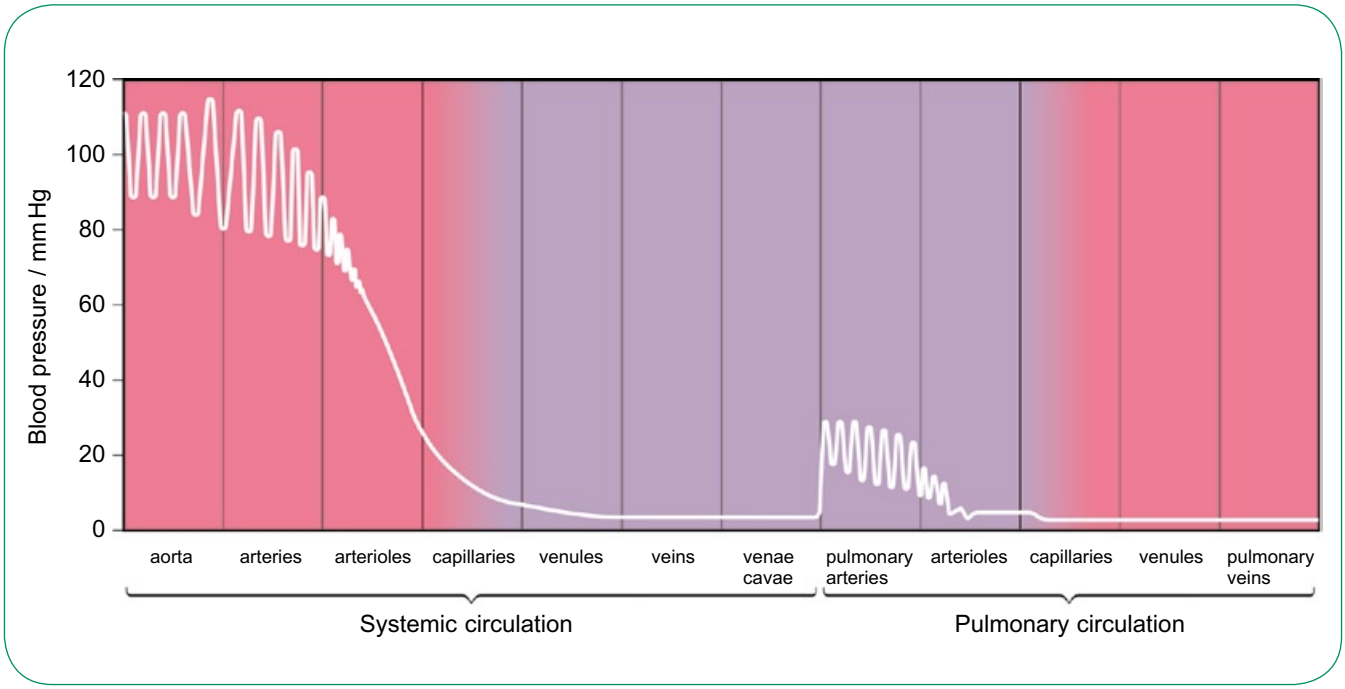

Figure 5.21 Blood pressure in different regions of the human circulatory system.

Blood plasma, tissue fluid and lymph

Blood is composed of cells floating in a pale yellow liquid called **plasma**. Blood plasma is mostly water, with a variety of substances dissolved in it. These solutes include nutrients, such as glucose, and waste products, such as urea, that are being transported from one place to another in the body. They also include protein molecules, called **plasma proteins**, that remain in the blood all the time.

How tissue fluid is formed

As blood flows through capillaries within tissues, some of the plasma leaks out through capillary walls and seeps into the spaces between the cells of the tissues. Almost one-sixth of your body consists of spaces between your cells. These spaces are filled with leaked plasma, which is known as **tissue fluid**.

Tissue fluid is very similar in composition to blood plasma. However, it contains far fewer protein molecules than plasma, as these are too large to escape easily through the tiny holes in the capillary endothelium.

Red blood cells are much too large to pass through, but some white blood cells can squeeze through and move freely around in the tissue fluid. Table 5.3 shows the sizes of the molecules of some of the substances in blood plasma, and the relative ease with which they pass from capillaries into tissue fluid.

Substance	Relative molecular mass	Permeability of capillary wall to this substance
water	18	1.00
sodium ions	23	0.96
urea	60	0.8
glucose	180	0.6
haemoglobin	68 000	0.1
albumin	69 000	0.000 01

Table 5.3 Relative permeability to different substances of capillaries in a muscle. The permeability to water is given a value of 1; the other values are given relative to this.

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SAQ

9 Use the information in Table 5.3 to answer these questions.

a How does the permeability to a substance of the capillary walls appear to depend on the relative molecular mass of that substance?

b In a respiring muscle, would you expect the net diffusion of glucose to be from the blood plasma to the muscle cells, or vice versa? Explain your answer.

c Albumin is the most abundant plasma protein. Suggest why it is important that capillary walls should be almost impermeable to albumin.

Answer

The amount of fluid which leaves the capillaries and forms tissue fluid is the result of two opposing pressures. Particularly at the arterial end of a capillary bed, the blood pressure inside a capillary is enough to push fluid out into the tissue. However, we have seen that water moves by osmosis from regions of low solute concentration (high water potential) to regions of high solute concentration (low water potential). Since tissue fluid lacks the high concentrations of proteins that are present in blood plasma, the imbalance leads to a water potential gradient, encouraging the movement of water back into the capillaries from the tissue fluid. The net result of these competing processes is that fluid tends to flow *out* of the capillaries into the tissue fluid at the arterial end of a capillary bed, and *into* the capillaries at the venous end. Overall, however, more fluid flows out than flows back in, so there is a net loss of fluid as blood passes through a capillary bed.

Tissue fluid is the immediate environment of each individual body cell. It is through tissue fluid that exchanges of materials between cells and the blood occur. Within our bodies, many processes take place to maintain the composition of tissue fluid at a constant level, to provide an optimum environment in which cells can work.

Lymph

About 90% of the fluid that leaks from capillaries eventually seeps back into them. The remaining 10% is collected up and returned to the blood system through a series of tubes called **lymph vessels** or **lymphatics**. These are tiny, blind-ending vessels, which are found in almost all tissues of the body. The end of one of these vessels is shown in Figure 5.22.

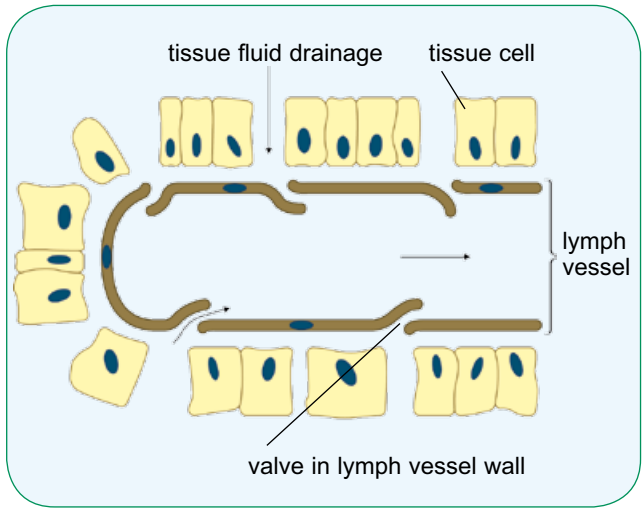

Figure 5.22 Drainage of tissue fluid into a lymph vessel.

Tissue fluid can flow into the lymphatics through tiny valves, which allow it to flow in but not out. These valves are wide enough to allow large protein molecules to pass through. This is very important, as such molecules are too big to get into blood capillaries, and so cannot be taken away by the blood. If your lymphatics did not take away the protein in the tissue fluid between your cells, you could die within 24 hours. If the rate of loss of fluid from blood plasma into the tissue fluid is not the same as the rate of removal of tissue fluid as lymph, then there can be a build-up of tissue fluid, called **oedema**.

SAQ

10 We have seen that capillary walls are not very permeable to plasma proteins. Suggest where the protein in tissue fluid has come from.

Answer

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The fluid inside lymphatics is called **lymph**. It is virtually identical to tissue fluid.

In some tissues, the lymph is rather different than in other tissues. For example, the tissue fluid and lymph in the liver have particularly high concentrations of protein. High concentrations of lipid are found in the lymph in the walls of the small intestine, where lipids are absorbed from digested food.

Lymphatics join up to form larger lymph vessels, which gradually transport lymph back up to the large veins which run just beneath the collarbone, the **subclavian veins** (Figure 5.23). Lymph is moved through lymphatics in the same way as blood in veins – there are valves to prevent backflow, and the contraction of surrounding muscles provides pressure. Lymph flow is very slow, and only about 100 cm^3 per hour flows through the largest lymph vessel, the thoracic duct, in a resting human. This is a big contrast with blood flow, which moves at about 80 cm^3 per second.

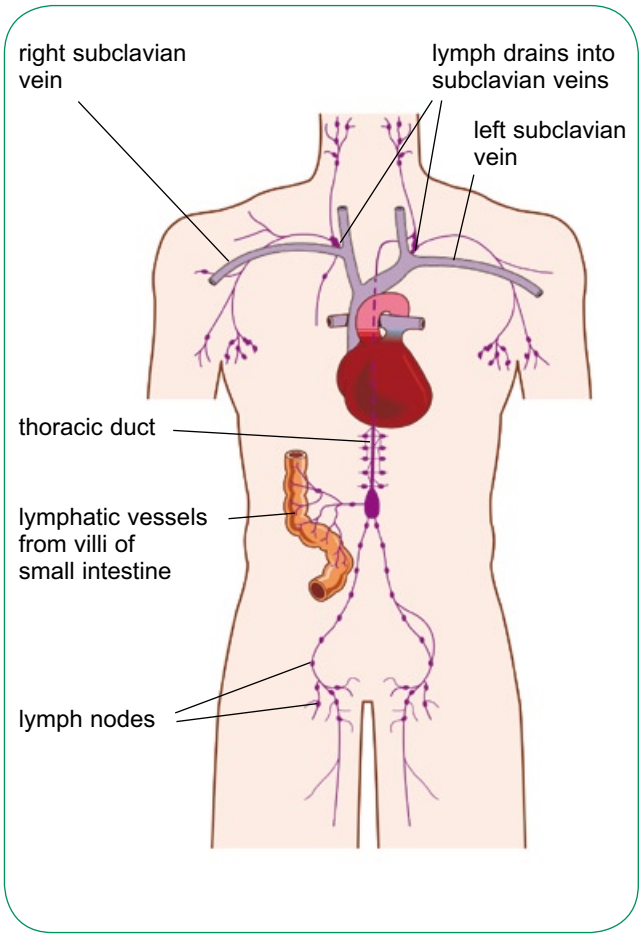

Figure 5.23 The human lymphatic system.

Blood

You have about 5 dm^3 of blood in your body, with a mass of about 5 kg. Suspended in the blood plasma, you have around 2.5×10^{13} red blood cells, 5×10^{11} white blood cells and 6×10^{12} platelets (Figure 5.24). In this chapter, we will look at the structure and functions of red blood cells, also known as **erythrocytes**.

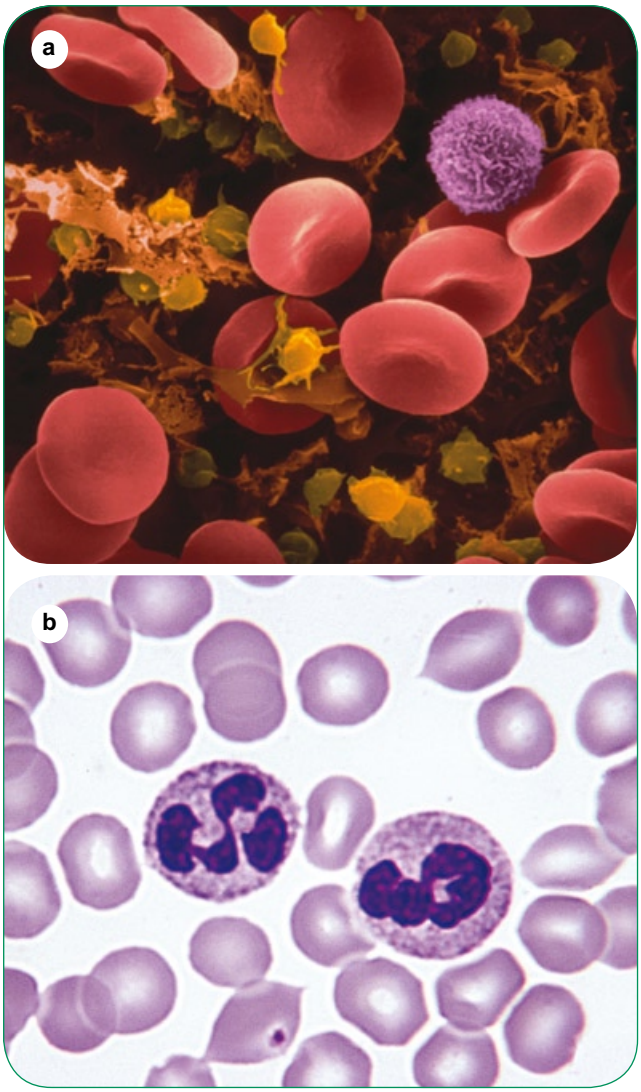

Figure 5.24 Micrographs of human blood. **a** This is a false-colour scanning electron micrograph. Red blood cells are coloured red. The purple sphere is a white blood cell. Platelets are coloured yellow (×900). **b** This photograph is taken with a normal light microscope. This blood has been stained so that the nuclei of the white cells are dark purple (×850).

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The structure of erythrocytes

Erythrocytes are small cells, with no nucleus (Figure 5.25). Their red colour is caused by the red pigment **haemoglobin**, Hb, a globular protein (Chapter 7). The main function of erythrocytes is to transport oxygen, and also carbon dioxide, between the lungs and respiring tissues.

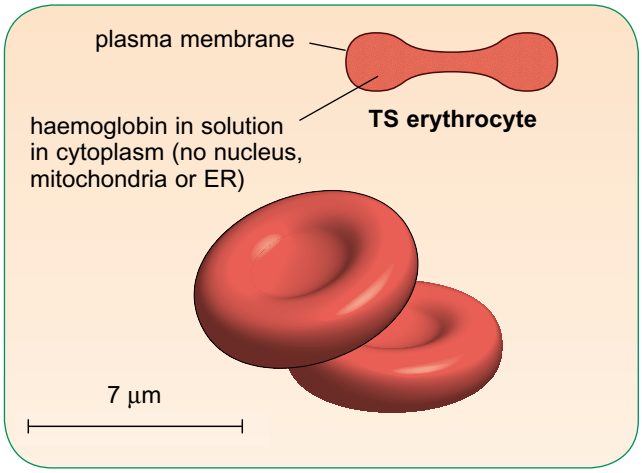

Figure 5.25 Erythrocytes.

Erythrocyte structure is unusual in three ways.

- Erythrocytes are very small. The diameter of a human red blood cell is about 7 µm, compared with the diameter of an 'average' liver cell of 40 µm. This small size means that all haemoglobin molecules within the cell are close to the cell's plasma membrane, and can therefore exchange oxygen easily with the fluid outside the cell. It also means that capillaries can be only 8 µm wide and still allow erythrocytes to squeeze through them, bringing oxygen as close as possible to the cells that require it.
- Erythrocytes are shaped like a biconcave disc. The 'dent' in each side of the cell, like its small size, increases its surface area : volume ratio. This means that oxygen can diffuse rapidly into and out of the cell.
- Erythrocytes have no nucleus, no mitochondria and no endoplasmic reticulum. This leaves more room for haemoglobin.

The role of haemoglobin

Oxygen is transported around the body in combination with haemoglobin. Each haemoglobin molecule can combine with eight oxygen atoms, forming **oxyhaemoglobin**. Haemoglobin combines with oxygen when oxygen is at a high concentration, and releases it in areas where it is at a low concentration. This means that it picks up oxygen at the lungs, and releases it in tissues.

SAQ

11 Which of these functions could be carried out in a red blood cell? Explain each answer.
a protein synthesis
b cell division
c lipid synthesis

Answer

12 In a healthy adult human, there are about 150 g of haemoglobin in each dm^3 of blood.
a 1 g of haemoglobin can combine with 1.3 cm^3 of oxygen at body temperature. How much oxygen can be carried in 1 dm^3 of blood?
b At body temperature, 0.025 cm^3 of oxygen can dissolve in 1 cm^3 of water. Assuming that blood plasma is mostly water, how much oxygen could be carried in 1 dm^3 of blood if we had no haemoglobin?

Answer

The haemoglobin dissociation curve

To investigate how haemoglobin behaves in different conditions, samples are extracted from the blood and then exposed to different concentrations, known as **partial pressures**, of oxygen. The amount of oxygen that combines with each sample of haemoglobin is then measured.

The maximum amount of oxygen with which a haemoglobin sample can possibly combine is given a value of 100%. A sample of haemoglobin that has combined with this maximum amount is said to be 100% saturated. At lower oxygen concentrations, less oxygen combines with the haemoglobin, and so it is less saturated. We can plot the percentage saturation of haemoglobin against the different partial pressures of oxygen. This gives us a curve known as a **dissociation curve** (Figure 5.26).

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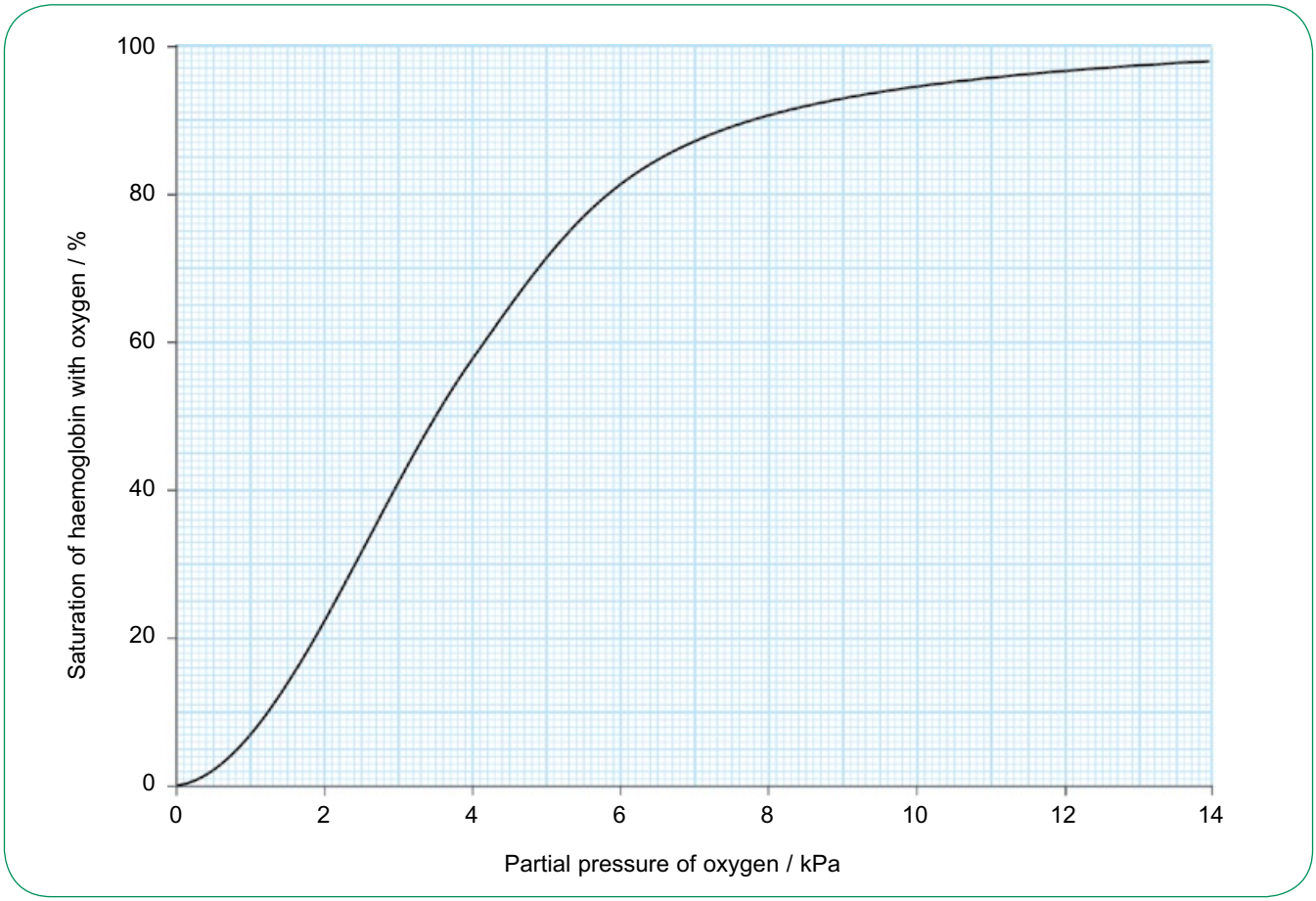

Figure 5.26 The haemoglobin dissociation curve.

You can see that, in general, the greater the partial pressure of oxygen, the greater the percentage saturation of the haemoglobin. This is what we would expect. The more oxygen there is, the more is taken up by the haemoglobin.

Think about the haemoglobin inside an erythrocyte in a capillary in the lungs. Here, where the partial pressure of oxygen is high, the haemoglobin will be 95–97% saturated with oxygen. In an actively respiring muscle, however, where the partial pressure of oxygen is much lower, the haemoglobin will be only about 20–25% saturated with oxygen. This means that the haemoglobin coming from the lungs loses a lot of its oxygen when it arrives at a muscle. The released oxygen diffuses out of the red blood cell and into the muscle, where it can be used in respiration.

Extension

SAQ

13 Use the dissociation curve in Figure 5.26 to answer these questions.

a i The partial pressure of oxygen in the alveoli of the lungs is about 12 kPa. What is the percentage saturation of haemoglobin in the lungs?

ii If 1 g of fully saturated haemoglobin is combined with 1.3 cm^3 of oxygen, how much oxygen will 1 g of haemoglobin in the capillaries in the lungs be combined with?

b i The partial pressure of oxygen in an actively respiring muscle is about 2 kPa. What is the percentage saturation of haemoglobin in the capillaries in this muscle?

ii How much oxygen will 1 g of haemoglobin in the capillaries of this muscle be combined with?

Answer

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Carbon dioxide transport

Carbon dioxide is constantly produced in respiring tissues, and is transported in the blood to the lungs, where it is excreted.

The carbon dioxide from the tissues diffuses into the blood plasma. Then, one of three things can happen to it (Figure 5.27).

- Some of it remains as carbon dioxide molecules, dissolved in the plasma. About 5% of the total carbon dioxide carried in the blood is in this form.
- Some of the carbon dioxide diffuses into the erythrocytes. In the cytoplasm of the erythrocytes, there is an enzyme called **carbonic anhydrase**. This enzyme catalyses the following reaction:

$$\underset{\text{carbon dioxide}}{CO_2} + \underset{\text{water}}{H_2O} \xrightarrow{\text{carbonic anhydrase}} \underset{\text{carbonic acid}}{H_2CO_3}$$

The carbonic acid then **dissociates** (splits):

$$\underset{\text{carbonic acid}}{H_2CO_3} \longrightarrow \underset{\text{hydrogen ion}}{H^+} + \underset{\text{hydrogencarbonate ion}}{HCO_3^-}$$

The hydrogen ions quickly combine with the haemoglobin molecules inside the erythrocyte. This forms **haemoglobinic acid**, which makes the haemoglobin release the oxygen that it is carrying. The hydrogencarbonate ions diffuse out of the erythrocyte and into the blood plasma. They remain here in solution, and are carried to the lungs. About 85% of carbon dioxide is transported like this.

- Some of the carbon dioxide that diffuses into the erythrocytes escapes the attentions of carbonic anhydrase. Instead, it combines directly with haemoglobin, forming a compound called **carbaminohaemoglobin**. About 10% of the carbon dioxide is transported in this form.

When blood reaches the lungs, all of these reactions go into reverse. Carbon dioxide diffuses out of the blood and into the air in the alveoli. This leaves the haemoglobin molecules free to combine with oxygen, ready to begin another circuit of the body.

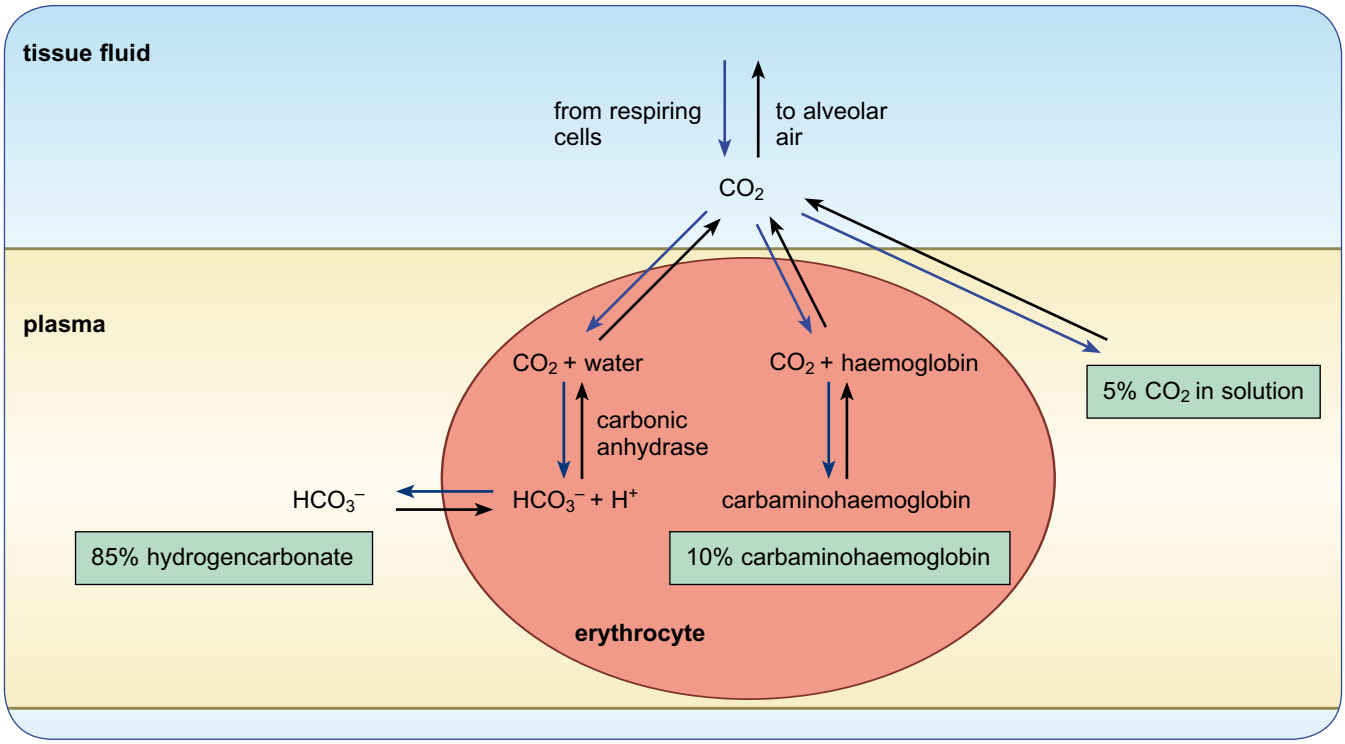

Figure 5.27 Carbon dioxide transport in the blood. The blood carries carbon dioxide partly as undissociated carbon dioxide in solution in the plasma, partly as hydrogencarbonate ions in solution in the plasma and partly combined with haemoglobin in the erythrocytes.

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The Bohr shift

We have seen that, when there is a lot of carbon dioxide around, the high concentration of carbon dioxide causes events in the erythrocyte that make the haemoglobin release some of its oxygen. This is called the **Bohr effect**, after Christian Bohr who discovered it in 1904. It is exactly what the body needs. High concentrations of carbon dioxide are found in respiring tissues, which need oxygen. These high carbon dioxide concentrations cause haemoglobin to release its oxygen even more readily than it would otherwise do.

If a dissociation curve is drawn for haemoglobin at high concentrations of carbon dioxide, the curve lies to the right of and below the 'standard' curve (Figure 5.28). We can say that a high carbon dioxide concentration lowers the affinity of haemoglobin for oxygen.

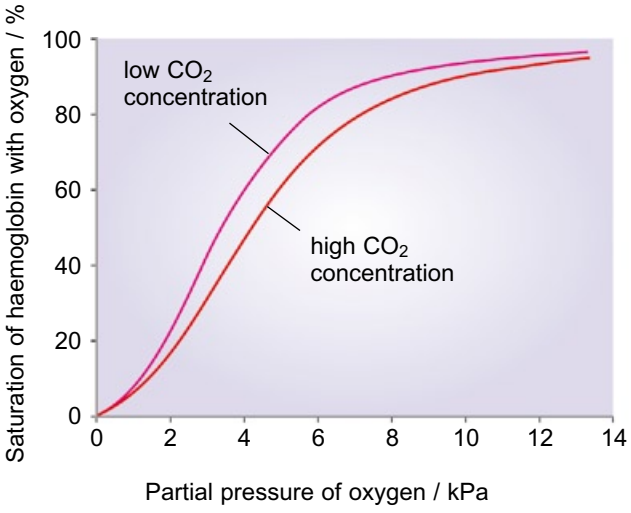
Fetal haemoglobin

A developing fetus obtains its oxygen not from its own lungs, but from its mother's blood. In the placenta, the mother's blood is brought very close to that of the fetus, allowing diffusion of various substances from the mother to the fetus and vice versa.

Oxygen arrives at the placenta in combination with haemoglobin, inside the mother's erythrocytes. The partial pressure of oxygen in the blood vessels in the placenta is relatively low, because the fetus is respiring. The mother's haemoglobin therefore releases some of its oxygen, which diffuses from her blood into the fetus's blood.

The partial pressure of oxygen in the fetus's blood is only a little lower than that in its mother's blood, which should mean that the diffusion of oxygen from mother to fetus is very slow. However, the haemoglobin of the fetus is not the same as its mother's. Fetal haemoglobin combines more readily with oxygen than adult haemoglobin does. Fetal haemoglobin is said to have a higher affinity for oxygen than adult haemoglobin.

The effect of changes in carbon dioxide concentration on haemoglobin saturation



The effect of changes in carbon dioxide concentration on oxygen transport

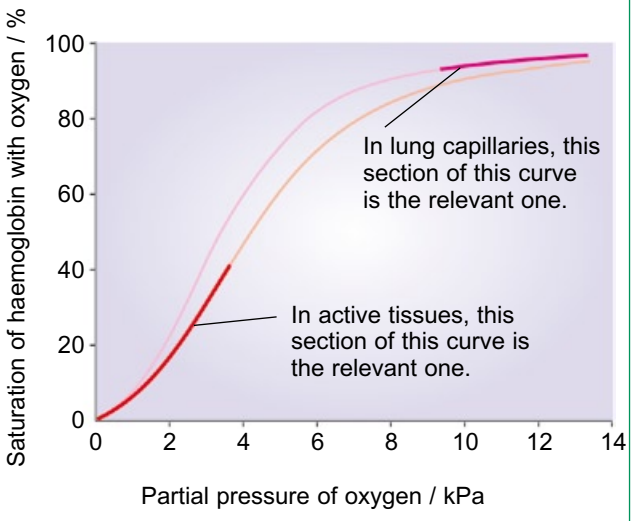


Figure 5.28 Dissociation curves for haemoglobin at two different partial pressures of carbon dioxide; the shift of the curve to the right when the haemoglobin is exposed to higher carbon dioxide concentration is called the Bohr effect.

A dissociation curve for fetal haemoglobin (Figure 5.29) shows that, at any partial pressure of oxygen, fetal haemoglobin is more saturated than adult haemoglobin. The curve lies *above* and to the left of the curve for adult haemoglobin. So, at any particular partial pressure of oxygen, fetal haemoglobin will take oxygen from adult haemoglobin.

Extension

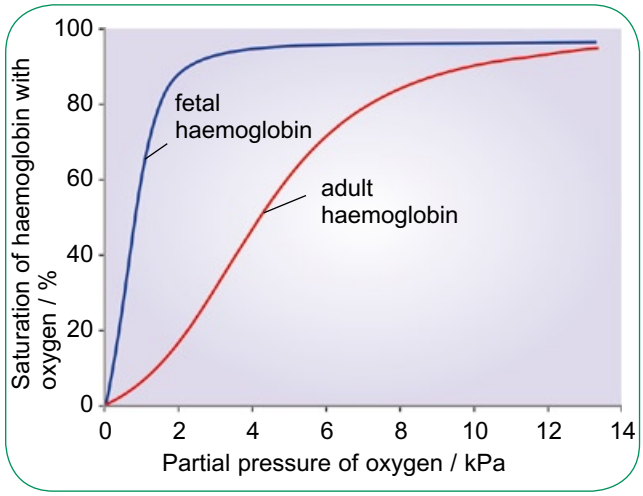


Figure 5.29 Dissociation curves for adult and fetal haemoglobin.

Blood doping

At the 1984 Olympic Games, held in Los Angeles, American cyclists won medals for the first time in 72 years. More surprisingly, no fewer than four of them won medals. It emerged that they had used a technique called 'blood doping' to enhance their performance.

Over the next few years many athletes used blood doping. Several months before competition, 1 dm^3 of blood was taken from the athlete and then frozen. As the athlete continued in his or her training, their blood volume would gradually return to normal. Then, a few hours before the competition, the red cells were thawed and transfused back into their body.

Blood doping was done because it raised the quantity of haemoglobin in the athlete's blood. This meant that the blood could carry more oxygen, so the muscles were able to carry out aerobic respiration more quickly. This especially helped athletes taking part in endurance sports, such as cycling and cross-country skiing.

By 1998, more sophisticated ways of achieving the same effect were being used. These involved a hormone called erythropoetin, or EPO for short. This hormone is produced by the kidneys and increases the rate of production of red blood cells. Some cyclists who took part in the Tour de France in 1998 had injected this hormone.

The use of blood doping is now officially banned. This is because it is seen as being unfair, and also because it can be very dangerous. Blood doping increases the risk of clots developing in blood vessels, and it is thought that several European cyclists died from this between 1987 and 1990. But still people continued to do it. In March 2002, at the Salt Lake City winter Olympics, a cleaner found discarded blood transfusion equipment at the house in which the Austrian skiing team had been staying. Investigations found that three of the skiers had received blood transfusions just before the competition.

Blood doping is very difficult to detect. However, tests are now available that can distinguish between the EPO that is naturally produced in the body and the EPO which can be bought and injected. Another test which is very useful is to measure the haemoglobin concentration in the blood. If this is well above normal, then blood doping is suspected.

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Summary

Glossary

- Large, multicellular, active organisms need transport systems to deliver oxygen, glucose and other substances to cells, and to remove their waste products, because their surface area : volume ratio is too low for direct diffusion.
- Mammals have a double circulatory system, in which blood is returned to the heart after passing the gas exchange surface. In the heart, its pressure is increased before moving through the systemic system. Fish have a single circulatory system, in which blood travels directly around the body after passing the gills.
- Vertebrates have a closed circulatory system, where blood is always within vessels. Insects have an open system, where blood fills the body cavity.
- The human heart has two atria and two ventricles. Blood enters the heart by the atria and leaves from the ventricles. A septum separates the right side (containing deoxygenated blood) from the left side (containing oxygenated blood). The ventricles have thicker walls than the atria, and the left ventricle has a thicker wall than the right. This is related to the pressure the muscles in the walls need to produce when they contract.
- Semilunar valves in the veins and in the entrances to the aorta and pulmonary artery, and atrio-ventricular valves, prevent backflow of blood.
- The heart is made of cardiac muscle, which is myogenic. The sino-atrial node (SAN) sets the pace for the contraction of muscle in the heart. Excitation waves spread from the SAN across the atria, causing their walls to contract. The AVN slows down the spread to the ventricles. The Purkyne fibres conduct the wave to the base of the ventricles, so these contract after the atria and from the bottom up. One complete cycle of contraction and relaxation is called the cardiac cycle.
- An electrocardiogram (ECG) shows the electrical activity of the heart.
- Arteries have thicker, more elastic walls than veins, to allow them to withstand the high pressure of pulsing blood. Veins have thinner walls and valves, to aid the flow of blood at low pressure back to the heart. Capillaries have leaky walls, only one cell thick, which allow rapid transfer of substances between tissues and the blood.
- Plasma leaks from capillaries to form tissue fluid. This is collected into lymphatics and returned to the blood at the subclavian veins.
- Erythrocytes carry oxygen in the form of oxyhaemoglobin. Haemoglobin combines with oxygen at high partial pressures of oxygen, and releases it when the partial pressure is low. When carbon dioxide is present, the affinity of haemoglobin for oxygen is lowered, and the dissociation curve lies to the right of and below the normal curve. This is called the Bohr shift.
- Carbon dioxide is carried in the blood as carbon dioxide molecules in solution in the plasma, as HCO_3^- ions in solution in the plasma, and as carbaminohaemoglobin in the erythrocytes. Carbonic anhydrase in the erythrocytes is responsible for the formation of the HCO_3^- ions.
- Fetal haemoglobin has a higher affinity for oxygen than adult haemoglobin, and its dissociation curve lies to the left of and above the curve for adult haemoglobin. This allows effective transfer of oxygen from mother to fetus across the placenta.

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Questions

1 Figure 1 and Figure 2 are diagrams to show how the internal structure of the heart and its associated circulatory system in a simplified form. Figure 1 represents the system for a mammal and Figure 2 that for a frog (an amphibian).
Both systems are described as closed systems. The mammalian system is also described as a complete double circulation but the frog as a partial double circulation.

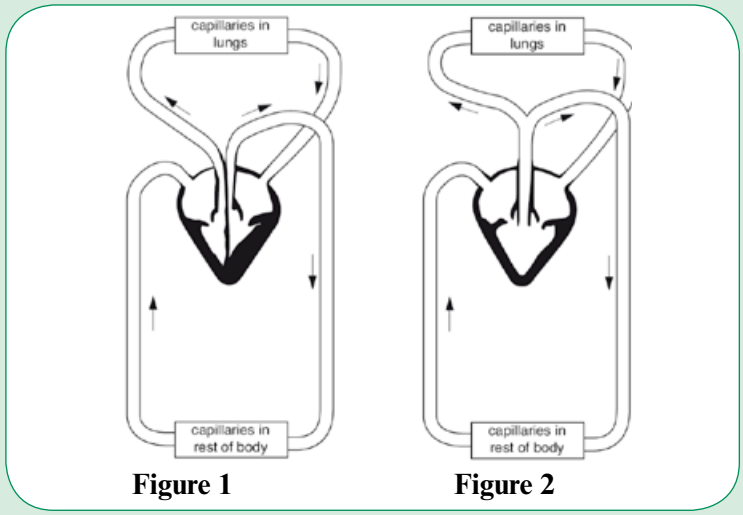

Figure 1 **Figure 2**

a State what is meant by a closed system. [1]

b Use the information in the two figures above to suggest why the mammalian system is called a complete double circulation whilst that of the frog is called a partial double circulation. [3]

Hint

c Suggest why the system shown for the frog may be less effective at supplying the body tissues with oxygen. [2]

OCR Biology AS (2803) June 2006 [Total 6]

Answer

2 The table contains information about various components of the mammalian circulatory system.

	Blood in aorta	Tissue fluid	Lymph	Blood in vena cava
red blood cells	many		none	many
white blood cells		some	some	many
glucose concentration	high	high		high
pressure	high	low	low	

a i Copy the table, and complete each of the empty boxes with the most appropriate word. [4]

Hint

ii Explain the differences recorded in the table for glucose and pressure. [4]

b The blood also contains hydrogencarbonate ions (HCO_3^-). Describe how these ions are formed in the blood. [3]

OCR Biology AS (2803) June 2006 [Total 11]

Answer

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Chapter 6

Transport in plants

Background

e-Learning

Objectives

Plant transport systems

Plant cells, like animal cells, need a regular supply of oxygen and nutrients. All plants are multicellular, and some of them are very large, so the problem of surface area : volume ratio applies to them just as it does to animals (Chapter 5). Most plants, however, have a much more branching shape than animals, and this provides a much larger surface area : volume ratio for exchange with their environment than in an animal of the same body mass.

The requirements of plants differ from those of animals in several ways, both in the nature of the nutrients and gases required and the rate at which these need to be supplied.

- **Carbon dioxide**: Photosynthesising plant cells need a supply of carbon dioxide during daylight. They obtain this from the air. Aquatic plants get carbon dioxide from the water that surrounds them.
- **Oxygen**: All living plant cells need oxygen for respiration. Cells that are actively photosynthesising produce more than enough oxygen for their needs. Cells that are not photosynthesising have to take in oxygen from their environment, but they do not respire at such a high rate as mammals and so they do not need such a rapid oxygen supply.
- **Organic nutrients**: Some plant cells make many of their own organic food materials, such as glucose, by photosynthesis. However, many plant cells do not photosynthesise and need to be supplied with organic nutrients from photosynthetic or storage cells.
- **Inorganic ions and water**: All plant cells require a range of inorganic ions and also water. These are taken up from the soil, by roots, and are transported to all areas of the plant.

The energy requirements of plant cells are, on average, far lower than those of cells in a mammal. This means that their rate of respiration and, therefore, their requirement for oxygen and glucose are considerably less than those of mammals. Plants can therefore manage with a much slower transport system.

One of the main requirements of the photosynthetic regions of a plant is sunlight. Plants have evolved thin, flat leaves which present a large surface area to the Sun. This also makes it easy for oxygen and carbon dioxide to diffuse into and out of the leaves, reaching and leaving every cell quickly enough so that there is no need for a transport system to carry gases.

As a result of these differences between the structures and requirements of a plant and a mammal, it is not surprising that they have evolved different transport systems. In fact, plants have *two* transport systems, one for carrying mainly water and inorganic ions from the roots to the parts above ground, and one for carrying substances made by photosynthesis from the leaves to other areas. In neither of these systems do fluids move as rapidly as blood does in a mammal, nor is there an obvious pump. Neither plant transport system carries oxygen or carbon dioxide, which travel to and from cells and the environment by diffusion alone.

SAQ

1 Explain why plants do not need a transport system to distribute oxygen or carbon dioxide.

Hint

Answer

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Water transport in plants

Figure 6.1 outlines the pathway taken by water as it is transported through a plant. Water from the soil enters a plant through its root hairs and then moves across the root into the xylem tissue in the centre. It then moves upwards in the xylem vessels through the root into the stem and finally into the leaves.

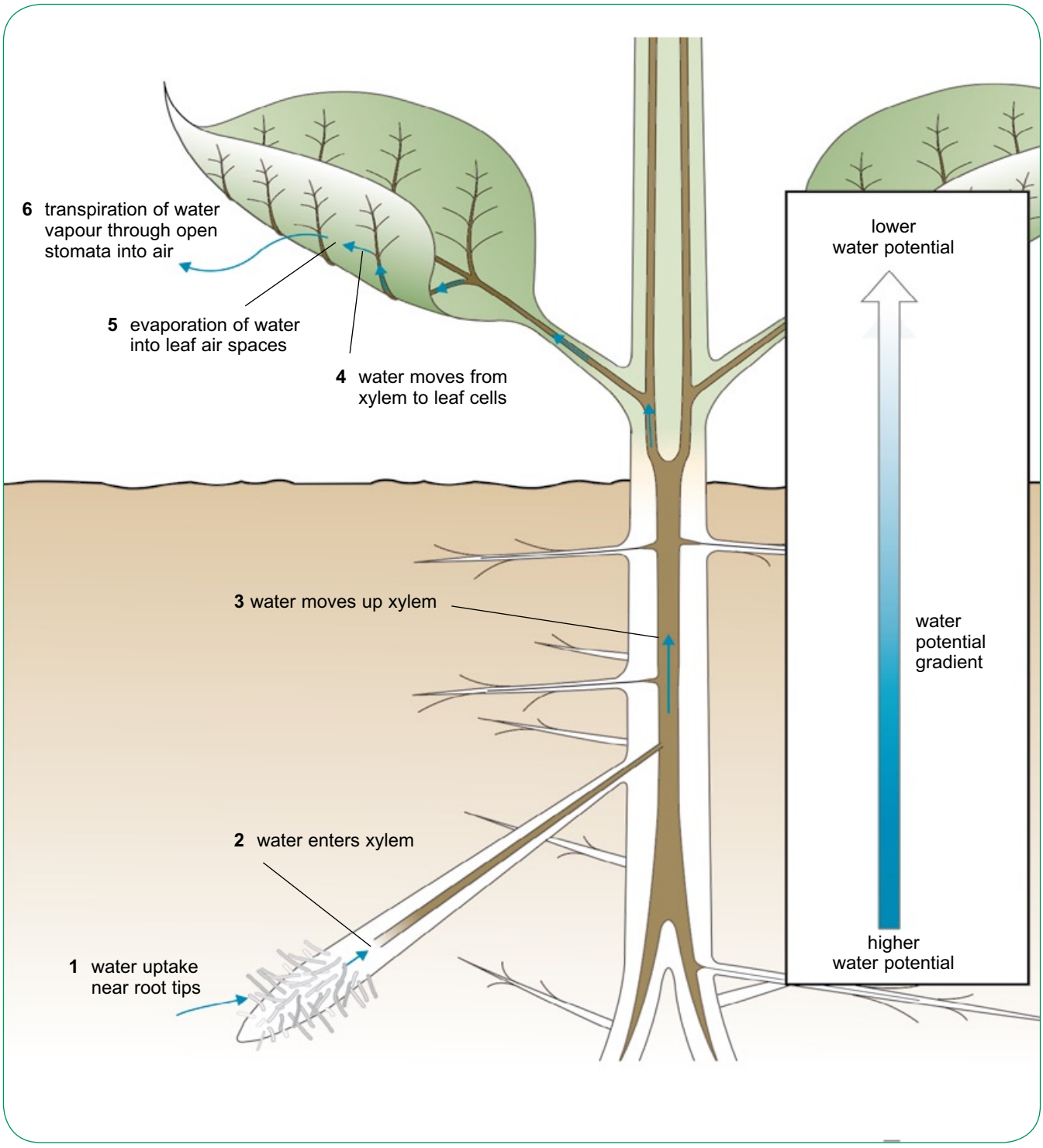

Figure 6.1 An overview of the movement of water through a plant; water moves down a water potential gradient from the soil to the air.

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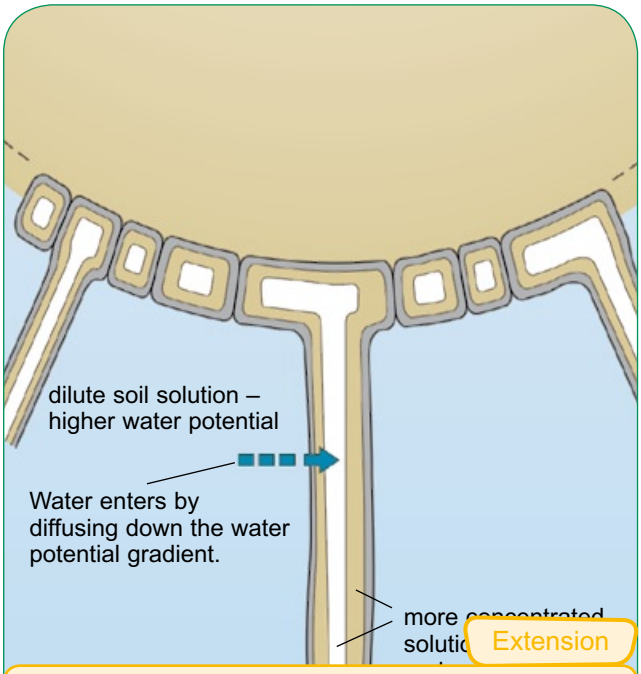
From soil into root hair

The roots of plants have very thin, single-celled extensions of some of the cells that make up the outer layer (epidermis) of the root. They are called **root hairs**, and they are a specialised exchange surface for the uptake of water and mineral ions.

Each root hair is only about 200–250 µm across, but this is large enough for them to be visible with the naked eye (Figure 6.2). There may be thousands of them on each tiny branch of a root, so together they provide an enormous surface area that is in contact with the soil surrounding the root.

Soil is made up of particles of minerals and humus. Between the soil particles there are air spaces. Unless the soil is very dry, there is a thin layer of water covering each soil particle. The root hairs make contact with this water, and absorb it by osmosis. The water moves into the root hair because there is a lower concentration of solutes in the soil than there is inside the root hair cell. The water potential outside the root hair is therefore higher than the water potential inside, so water moves passively down the water potential gradient into the cells (Figure 6.3).

Figure 6.2 A root of a young radish showing the root hairs.



Extension

Mycorrhizas

The roots of many plants are very closely associated with fungi. The fungi and the plant roots grow very closely together and help each other to survive. This is an example of symbiosis.

The fungal hyphae (long, thin threads) provide a huge surface area. They help the plant by absorbing mineral ions from the soil. Some plant species are unable to survive at all without their associated mycorrhizas. In return, the fungi receive organic nutrients that the plant has made.

Mycorrhizas frequently form connections between one plant and another – sometimes even between plants of different species. Substances from one plant can move to another, through the mycorrhizas.

The fungi that can be found growing in woodlands are the reproductive structures of some of the mycorrhizas growing beneath the soil.

If you would like to find out more about mycorrhizas, a good starting point is www.ffp.csiro.au/research/mycorrhiza/index.html.

Extension

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From root hair to xylem

Figure 6.4 and Figure 6.5 show the internal structure of a young root. Water that has been taken up by the root hairs travels across the **cortex** and into the centre of the root. It does this because the water potential inside the xylem vessels is lower than the water potential in the root hairs and the cells in between. Water moves passively down this water potential gradient, from the root hairs at the edge of the root to the xylem in the centre.

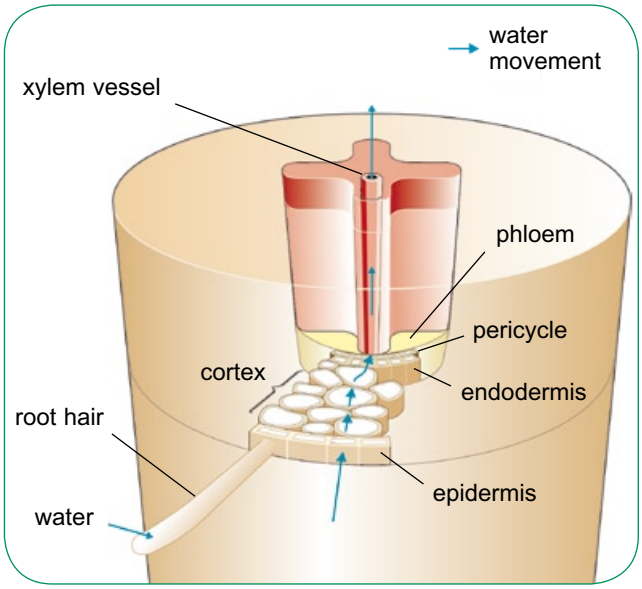


Figure 6.4 The pathway of water movement from root hair to xylem.

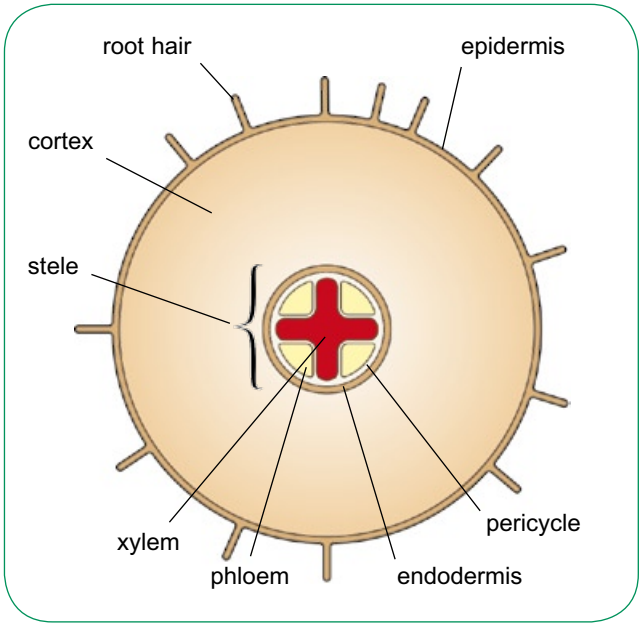


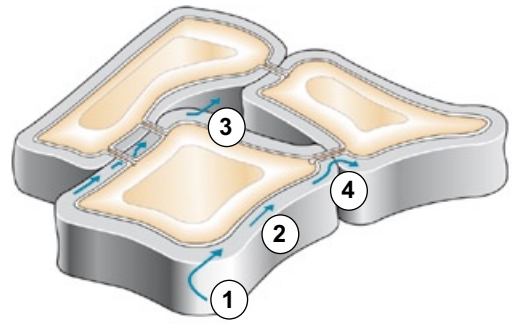
Figure 6.5 Transverse section of a young root to show the distribution of tissues.

The water takes two different routes through the cortex. The cells of the cortex, like all plant cells, are surrounded by cell walls made of many layers of cellulose fibres criss-crossing each other. Water soaks into these walls rather as it would soak into filter paper, and then seeps across the root from cell wall to cell wall, and through the spaces between the cells, without ever entering a cell. This route is called the **apoplast pathway** (Figure 6.6a).

Some water, however, enters the cells and moves from cell to cell by osmosis, or through strands of cytoplasm that make direct connections between adjacent cells, called **plasmodesmata** (Figure 6.6b). This is called the **symplast pathway**.

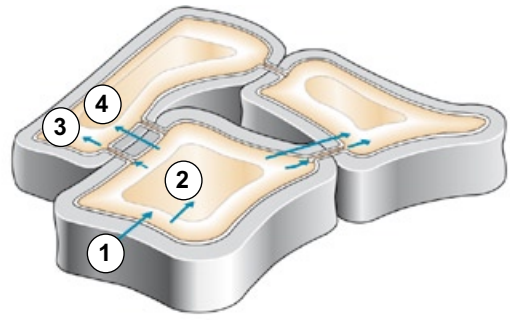
The relative importance of these two pathways depends on the species of plant and the environmental conditions.

a



1 Water enters the cell wall.
2 Water moves through the cell wall.
3 Water may move from cell wall to cell wall, across the intercellular spaces.
4 Water may move directly from cell wall to cell wall.

b



1 Water enters the cytoplasm across the partially permeable plasma membrane.
2 Water can move into the sap in the vacuole, through the tonoplast.
3 Water may move from cell to cell through the plasmodesmata.
4 Water may move from cell to cell through adjacent plasma membranes and cell walls.

Figure 6.6 How water moves across a root: **a** the apoplast pathway; **b** the symplast pathway.

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When the water reaches the **stele** (Figure 6.5), the apoplast pathway is barred. The cells in the outer layer of the stele, called the **endodermis**, have a thick, waterproof, waxy substance called **suberin** in their walls (Figure 6.7). This band of suberin, called the **Casparian strip**, forms an impenetrable barrier to water in the walls of the endodermis cells. The only way for the water to cross the endodermis is through the cytoplasm of these cells. This arrangement gives the plant control over what ions pass into its xylem vessels, as everything has to cross a plasma membrane on the way in.

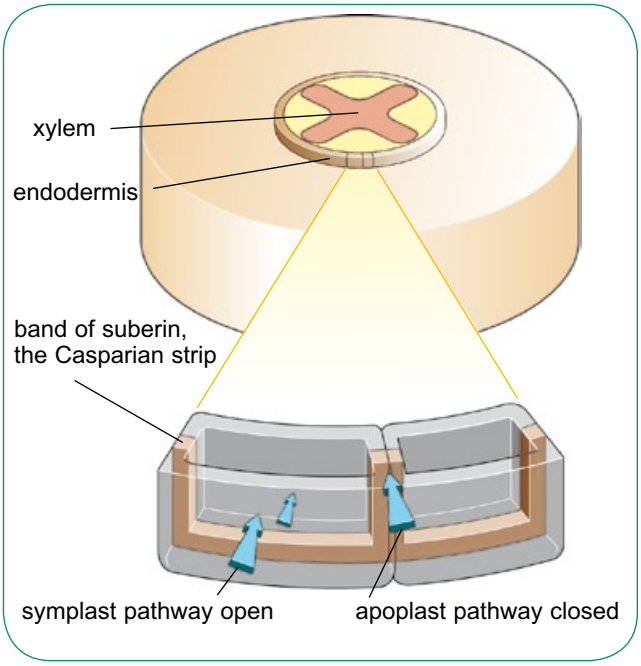

Figure 6.7 The Casparian strip.

Up through the xylem vessels

Water is carried from the roots all the way up to the top of the plant inside **xylem vessels**. In a large tree, the distance from the roots to the topmost leaf could be tens of metres. Yet there is no pump making the water move. What force causes water to travel up a plant?

To answer this question, we need to understand what is happening to the water in the leaves, because this is what drives the process. It is also important to know something about the structure of the xylem vessels, as this too helps to keep the water moving.

We have already looked briefly at the structure of xylem vessels, in Chapter 3. Xylem vessels are made up of many long, narrow cells called **xylem elements** stacked end to end. Xylem elements began as living cells, with cytoplasm, nucleus and cellulose cell walls. However, they then differentiated into extremely specialised structures – and died. Xylem elements contain no living material, and are just the empty shells of the cells from which they developed.

Figure 6.8 and Figure 6.9 show the structure of xylem vessels. Each xylem element has a wall made of cellulose and a substance called **lignin**. Lignin is a very strong, waterproof material. It is important not only in keeping water inside the xylem vessels, but also in helping to support the plant. The wood of tree trunks and branches is made of xylem vessels.

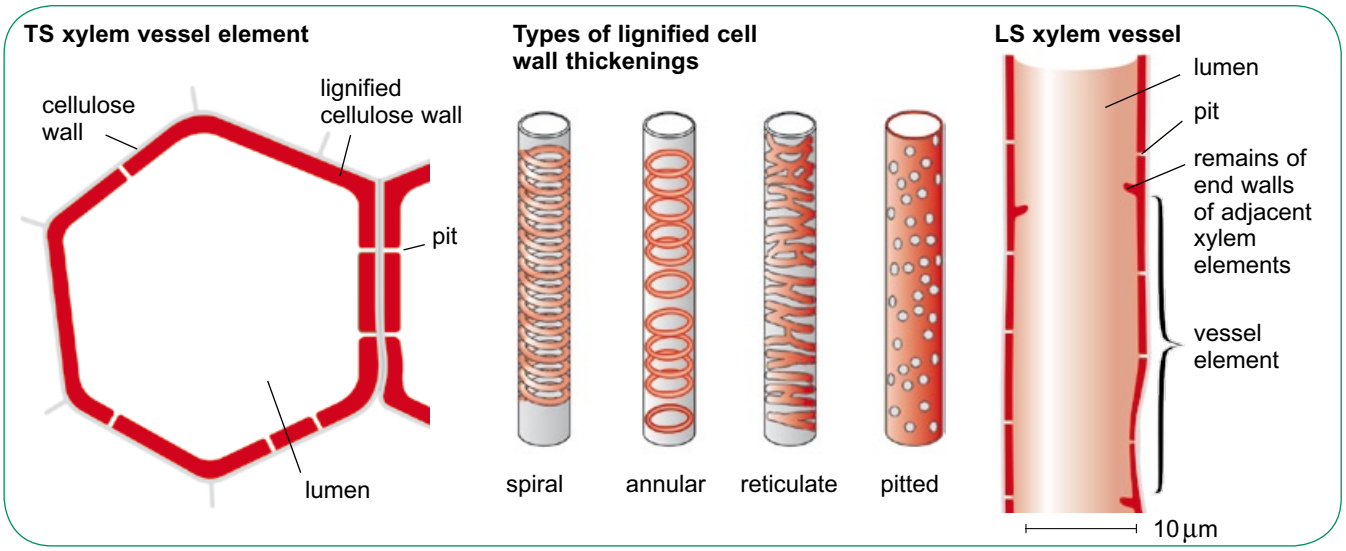

Figure 6.8 The structure of xylem vessels.

91

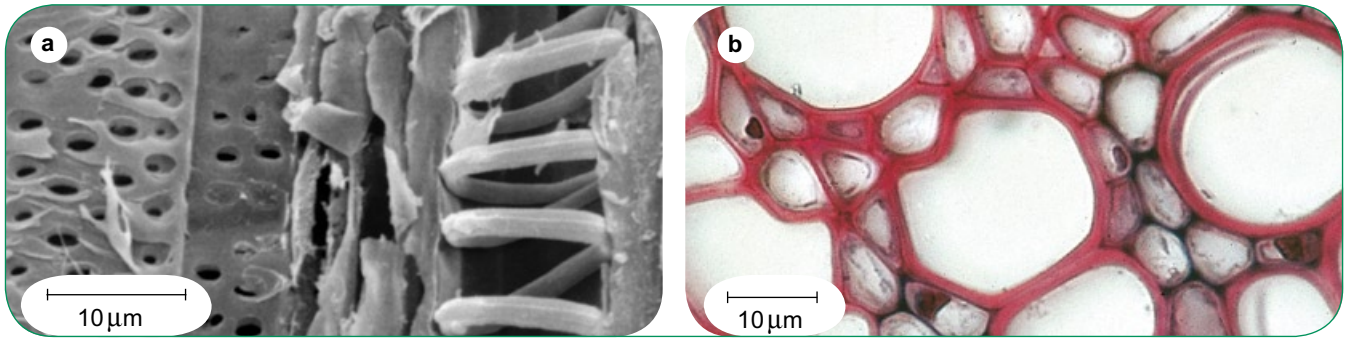

Figure 6.9 **a** Scanning electron micrograph of a longitudinal section through part of a buttercup stem, showing xylem vessels. The young vessel on the right has a spiral band of lignin around it, while those on the left are older and have more extensive coverings of lignin with many pits.

b Light micrograph of a transverse section of xylem vessels. They have been stained so that the lignin appears red. The xylem vessels are the large empty cells. You can also see smaller parenchyma cells between them; these do not have lignified walls, and each contains a nucleus and cytoplasm.

The end walls of the xylem elements usually disappear completely, so that the stack of elements makes up a continuous tube, like a drainpipe, reaching all the way from the roots, through the stem (Figure 6.10) and up to the very top of the plant. There are usually several xylem vessels side by side. Water can move sideways between them, and out of the xylem vessel into the surrounding cells, though **pits** in their walls. These are small gaps where no lignin has been deposited, leaving just the cellulose cell wall, through which water can easily move.

You can think of xylem vessels as being like a group of drinking straws. To pull water up a straw, you put your mouth over the top and suck. 'Sucking' means reducing the pressure. Because you have reduced the pressure at the top of the straw, there is a pressure gradient from the bottom of the straw to the top. The liquid moves down this pressure gradient, from the relatively high pressure at the bottom to the relatively low pressure at the top.

The liquid moves up the straw, and up through xylem vessels, by **mass flow**. Mass flow is the way that water moves in a river, or up a drinking straw, or out of a tap. A whole body of water flows along together. This is very different from diffusion or osmosis, which rely on the random movements of individual molecules.

The column of water in the xylem vessels holds together because individual water molecules are attracted to each other. This attraction is called **cohesion**, and you will find out why it exists in Chapter 7. The water molecules are also attracted to the sides of the xylem vessels, and this is known as **adhesion**. This gives them a tendency to 'crawl' up the inner surface of the vessel. Cohesion and adhesion help the whole column of water to flow up the xylem vessel without breaking. Xylem

SAQ

3 Use the scale bar in Figure 6.9b to calculate the width of the lumen (space) inside the xylem vessels that are shown in transverse section.

Hint

Answer

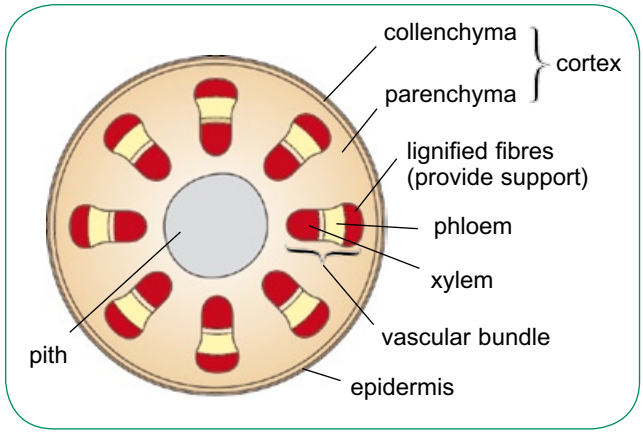

Figure 6.10 Transverse section through a young stem to show the distribution of tissues.

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vessels are very narrow – usually somewhere between 0.01 mm and 0.2 mm in diameter – and this means that more of the water is in contact with the sides of the vessel than would be the case if the vessels were wider. Adhesive forces are therefore relatively high. So, to move water up xylem vessels, there needs to be a pressure gradient. Something must lower the pressure at the top. The process that does this is **transpiration**.

From leaf to atmosphere – transpiration

Figure 6.11 shows the structure of a leaf. The cells in the **spongy mesophyll** layers are not tightly packed, and there are many spaces around them filled with air. The water in the cells seeps into the walls, so these cell walls are always wet. Some of this water evaporates into the air spaces, so that the air inside a leaf is usually saturated with water vapour.

These air spaces are in direct contact with the air outside the leaf, through small pores called **stomata**. If the air outside the leaf contains less water vapour than inside it, then there is a water potential gradient from the air spaces inside the leaf to the outside. Water vapour therefore diffuses out through the stomata. This is called transpiration (Figure 6.12).

As water evaporates from the cell walls of the mesophyll cells, water moves into them to replace it. This water comes from the xylem vessels in the leaf. This removal of water from the top of the xylem vessels reduces its pressure. The water pressure at the top of the xylem vessel is therefore less than the water pressure at the bottom, so water flows up the vessel – just like water up a drinking straw. Cohesion between the water molecules keeps them moving together without the column breaking, all the way up to the top of even the tallest trees.

The continuous movement of water from the roots, up through the xylem, into the leaves and then out into the atmosphere is known as the **transpiration stream**. The plant does not have to provide any energy at all to make it happen. The driving force is supplied by the difference in water potential between the air and the soil. The water moves down a water potential gradient.

SAQ

4 Explain how each of these features adapts xylem vessels for their function of transporting water from roots to leaves.

a total lack of cell contents
b no end walls in individual xylem elements
c a diameter of between 0.01 mm and 0.2 mm
d lignified walls
e pits

Answer

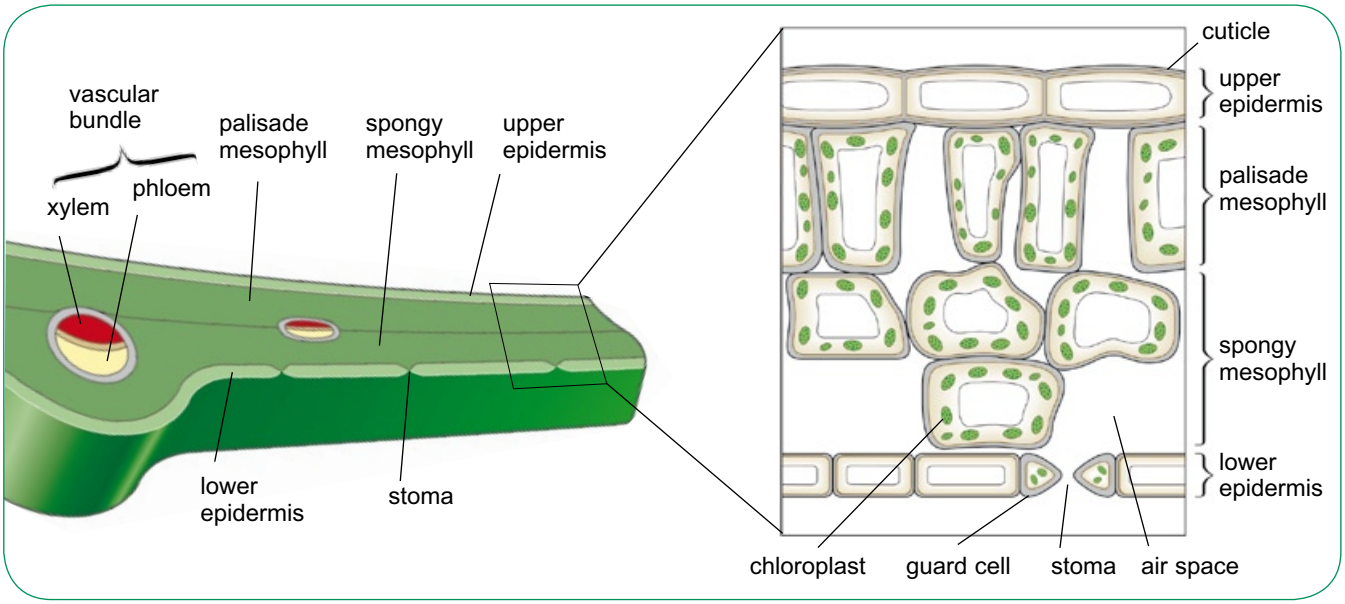

Figure 6.11 The structure of a leaf; water enters the leaf as liquid water in the xylem vessels, and diffuses out as water vapour through the stomata.

93

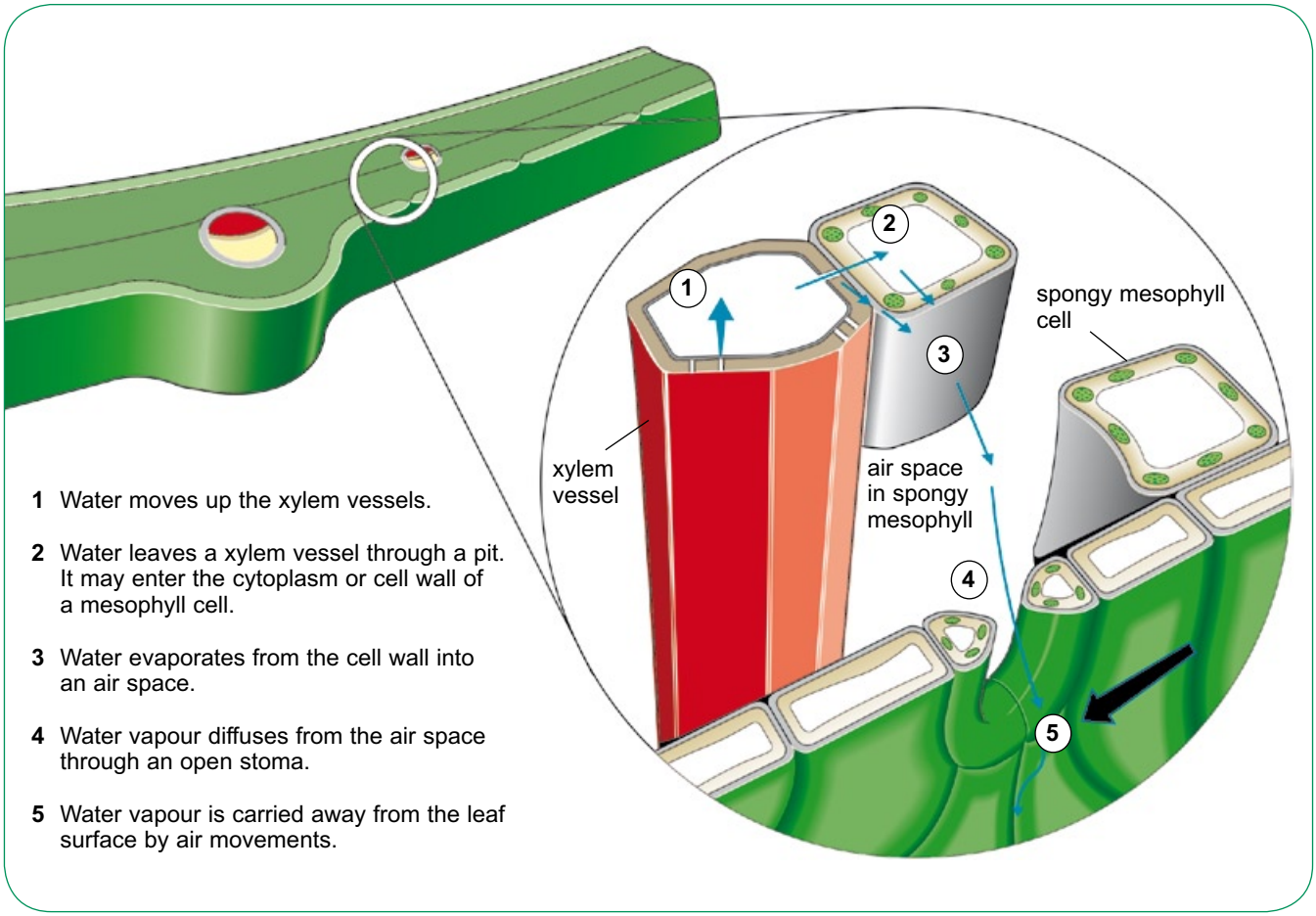

Figure 6.12 Water movement through a leaf.

Factors affecting transpiration

Anything that increases the water potential gradient between the air spaces in the leaf and the air outside, or that speeds up the movement of the water molecules, will increase the rate of transpiration.

- **Humidity**: Humidity is a measure of how much water vapour is held in the air. In conditions of low humidity – that is, when the air is dry – there is a steep water potential gradient between the leaf and the air. Transpiration rates are therefore greater in low humidity than in high humidity.
- **Temperature**: An increase in temperature causes an increase in the kinetic energy of water molecules. This increases the rate of evaporation of water from the cell walls into the air spaces, and also the rate of diffusion of the water vapour out of the leaf. An increase in temperature therefore increases the rate of transpiration.
- **Light intensity**: Light does not normally have any direct effect on the rate of transpiration during the daytime. However, many plants close their stomata at night, when it is dark and they are unable to photosynthesise and so do not need to use carbon dioxide from the air.
  In especially dry conditions, the plant may close its stomata even when light levels are ideal for photosynthesis, to avoid losing too much water from its leaves. There is often a compromise to be reached between allowing in enough carbon dioxide for photosynthesis, and not letting out too much water vapour.

In hot conditions, the evaporation of water from the plant's leaves can have a very useful cooling effect, in a similar manner to the evaporation of sweat from your skin.

Extension

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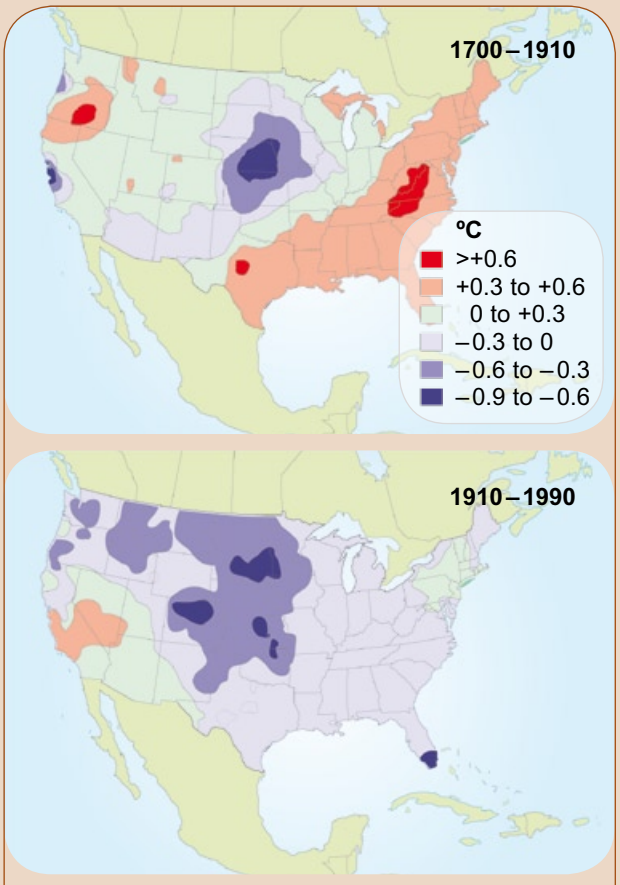
Transpiration and climate

Most of us are aware that cutting down rainforests reduces photosynthesis, increasing the amount of carbon dioxide in the air and contributing to global warming. But fewer people realise how transpiration can affect climate.

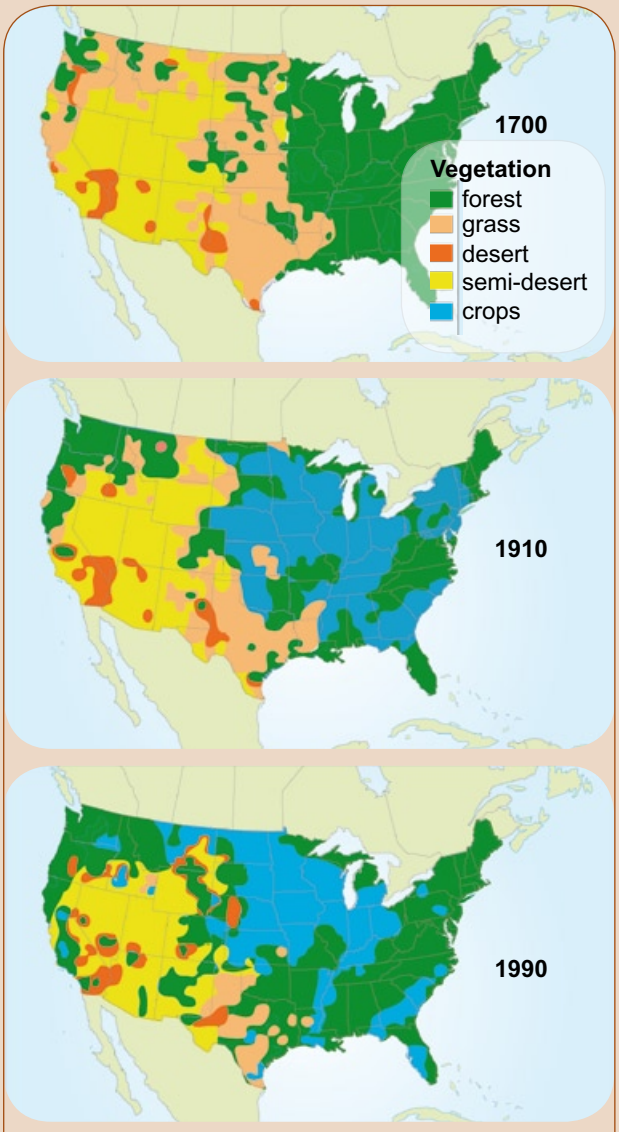
Aerial photographs, historical records and data and computer models from NASA have been used to look at the effects of changes in land cover on climate in the USA. In the mid-west, the natural vegetation was grassland, but as this has been replaced by agricultural land, the average temperature in those regions has dropped by almost 1 °C. This is because grass does not transpire as much as crops. The extra transpiration from the crop plants increases the humidity of the air and has a cooling effect.



Change in average surface air temperature in July between 1700 and 1910, and between 1910 and 1990.

In contrast, when forest is removed to grow crops, as has happened on the east coast of the USA, the reverse effect is seen. Forest trees transpire much more than most crop plants, and so the air above the farmland often contains less water vapour than the air above a forest. As forest has been replaced by farmland, the climate in these regions has become warmer.

There have also been effects on local rainfall – slightly more rainfall where there are forests, compared to areas where forest has been replaced by crops. But these are much less marked than the temperature changes.



Vegetation in 1700, 1910 and 1990.

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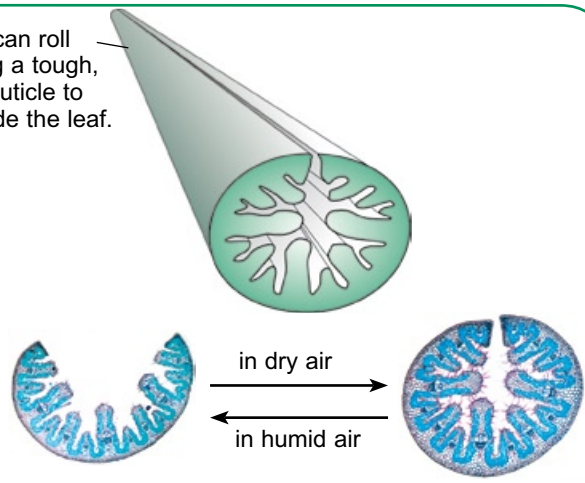
Xerophytes

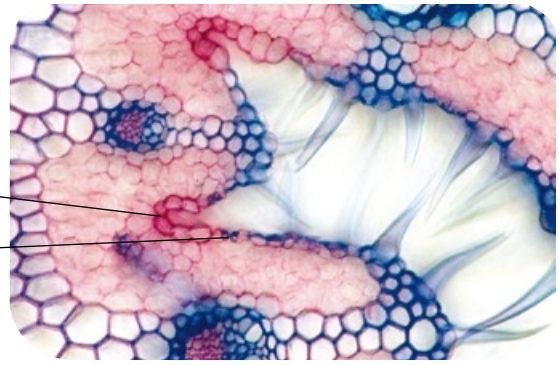
A **xerophyte** is a plant that is adapted to live in dry conditions. Plants that live in hot deserts are xerophytes, but some very cold places can also be dry. Moreover, plants cannot absorb water from the soil when the water is frozen.

Xerophytes generally have adaptations that help them to obtain more water, and other adaptations that help them to reduce the rate at which they lose water vapour from their leaves.

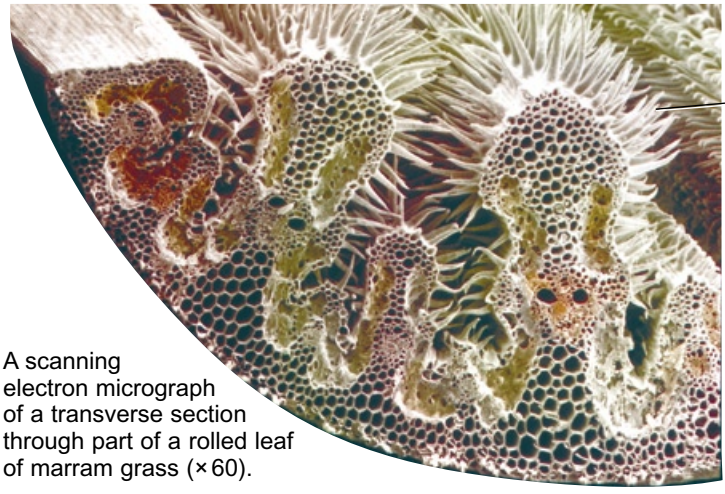
Figure 6.13 and Figure 6.14 shows some examples of xerophytes and their adaptations.

Marram grass is one of the few plants that can thrive in mobile sand dunes, surviving the very dry conditions that are found there.





A light micrograph of a transverse section through a marram grass leaf (×200).



A scanning electron micrograph of a transverse section through part of a rolled leaf of marram grass (×60).

Hairs help to keep the humid air trapped inside a rolled leaf. When the leaf is unrolled, the hairs again help to trap a layer of moist air close to the leaf surface, reducing air movement and increasing the thickness of the layer of still, humid air at the surface. Water vapour diffuses through this layer before it can be carried away in air movements. The thicker the layer, the more slowly water is lost by transpiration.

Figure 6.13 The adaptations of marram grass, *Ammophila arenaria*, for dry conditions.

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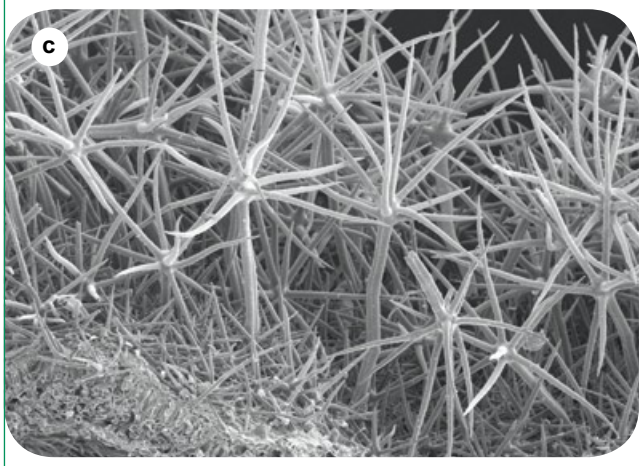
Opuntia is a cactus with flattened, photosynthetic stems that store water. The leaves are reduced to spines, which reduces the surface area from which transpiration can take place and protects the plant from being eaten by animals.

False-colour SEM of a needle from a Sitka spruce (× 1500), a large tree from Canada and Alaska. Its leaves are in the form of needles, greatly reducing the surface area available for water loss. Its leaves are covered in a layer of waterproof wax and have sunken stomata, as shown here.



TS SEM of *Phlomis italica* leaf showing its 'trichomes' (× 20). These are tiny hair-like structures that act as a physical barrier to the loss of water, like the marram grass hairs. Phlomis is a small shrub that lives in dry habitats in the Mediterranean regions of Europe and North Africa.

The cardon, *Euphorbia canariensis*, grows in dry areas of Tenerife. It has swollen, succulent stems that store water and photosynthesise. The stems are coated with wax, which cuts down water loss. The leaves are extremely small.

Figure 6.14 Some adaptations shown by xerophytes.

SAQ

5 Use the information in Figure 6.13 and Figure 6.14, and any other information you can find, to construct a table describing and explaining features of xerophytes. You could use a table like the one below. Try to find at least six different features.

Hint

Feature	How it helps the plant to conserve water

Answer

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Comparing rates of transpiration

It is not easy to measure the rate at which water vapour is leaving a plant's leaves. This makes it very difficult to investigate directly how different factors, such as temperature or wind speed, affect the rate of transpiration. However, it *is* relatively easy to measure the rate at which a plant stem takes up water. A very high proportion of the water taken up by a stem is lost in transpiration. As the rate at which transpiration is happening directly affects the rate of water uptake, this measurement can give a very good approximation of the rate of transpiration.

The apparatus used for this is called a **potometer** (Figure 6.15). It is essential that everything in the potometer is completely watertight and airtight, so that no leakage of water occurs and so that no air bubbles break the continuous water column. To achieve this, it helps if you can insert the plant stem into the apparatus with everything submerged in water, so that air bubbles cannot enter the xylem when you cut the stem. It also helps to cut the end of the stem with a slanting cut, as air bubbles are less likely to get trapped against it.

Potometers can be simpler than the one in Figure 6.15. You can manage without the reservoir (though this does mean it takes more time and effort to refill the potometer) and the tubing can be straight rather than bent. In other words, you can manage with just a straight piece of glass tubing.

As water evaporates from the leaves, more water is drawn into the xylem vessels that are exposed at the cut end of the stem. Water is drawn along the capillary tubing. If you record the position of the meniscus at set time intervals, you can plot a graph of distance moved against time. If you expose the plant to different conditions, you can compare the rate of water uptake.

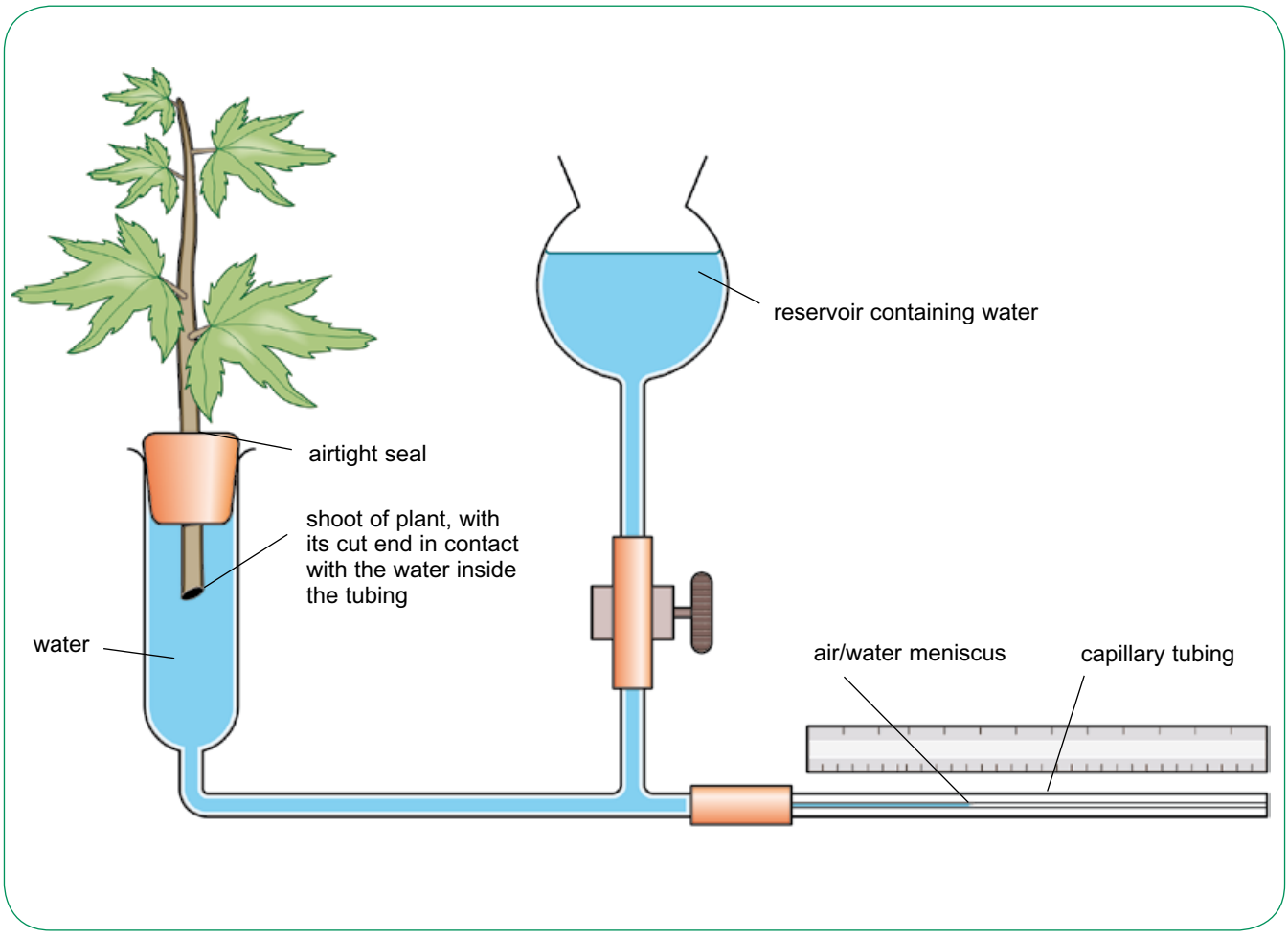

Figure 6.15 A potometer.

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Translocation

Translocation is the term used to describe the transport of soluble organic substances within a plant. These are substances that the plant itself has made – such as sugars, which are made by photosynthesis in the leaves. These substances are sometimes called **assimilates**. The main substance transported in phloem is sucrose.

Assimilates are transported in **sieve elements**. Sieve elements are found in **phloem tissue**, together with several other types of cells including **companion cells**. Sieve elements and companion cells work closely together to achieve translocation.

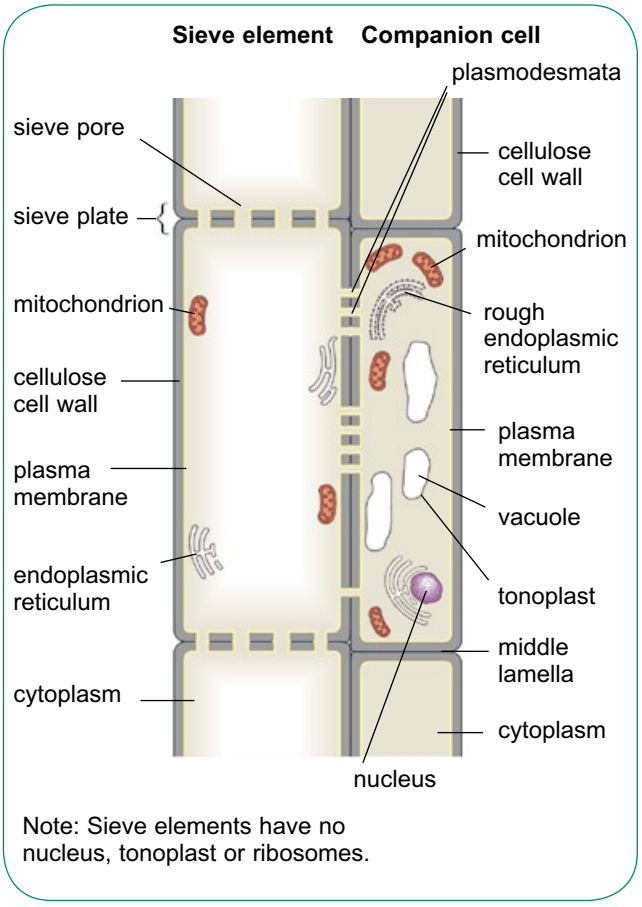

Figure 6.16 A phloem sieve element and its companion cell.

Extension

Sieve elements

Figure 6.16 shows the structure of a sieve tube and its accompanying companion cell. A sieve tube is made up of many elongated sieve elements, joined end to end vertically to form a continuous column. Each sieve element is a living cell. They are very narrow, often between 10 and 15 µm in diameter. Like a 'normal' plant cell, a sieve element has a cellulose cell wall, a plasma membrane and cytoplasm containing endoplasmic reticulum and mitochondria. However, the amount of cytoplasm is very small and only forms a thin layer lining the inside of the wall of the cell. There is no nucleus, nor are there any ribosomes.

Perhaps the most striking feature of sieve elements is their end walls. Where the end walls of two sieve elements meet, a **sieve plate** is formed. This is made up of the walls of both elements, perforated by large pores. These pores are easily visible with a good light microscope. When sieve plates are viewed using an electron microscope, strands of fibrous protein can sometimes be seen passing through these pores from one sieve element to another (Figure 6.17). However, these strands are produced by the sieve element in response to the damage caused when the tissue is cut during preparation of the specimen for viewing. In living phloem, the protein strands are not present, and so the pores are open and present little barrier to the free flow of liquid through them.

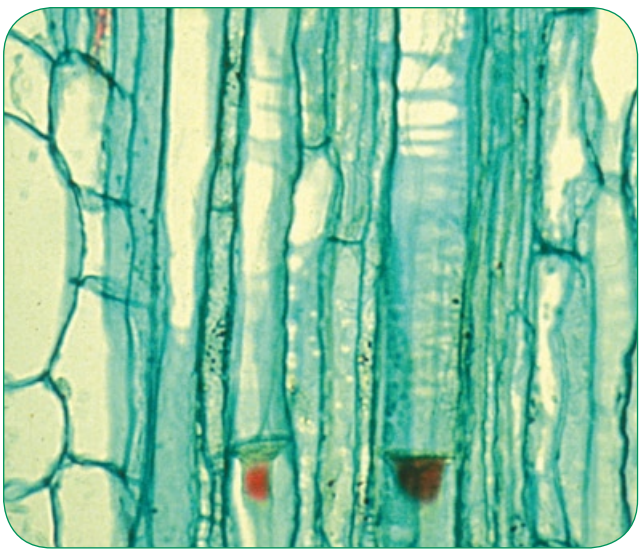

Figure 6.17 Photomicrograph showing phloem sieve elements (×600).

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Companion cells

Each sieve element has at least one companion cell lying close beside it. Companion cells have the structure of a 'normal' plant cell, with a cellulose cell wall, a plasma membrane, cytoplasm, a vacuole and a nucleus. However, the number of mitochondria and ribosomes is rather larger than usual, and the cells are metabolically very active. Also, the vacuole remains small and does not form a large central vacuole.

Companion cells are very closely associated with the neighbouring sieve elements. Many plasmodesmata (strands of cytoplasm) pass through their cell walls, providing a direct pathway between the cytoplasm of the companion cell and the cytoplasm of the sieve element.

The contents of sieve tubes

The liquid inside phloem sieve tubes is called **phloem sap**, or just sap. Table 6.1 shows the composition of the sap of the castor oil plant, *Ricinus communis*.

Solute	Concentration in mol dm^{-3}
sucrose	250
potassium ions, K^+	80
amino acids	40
chloride ions, Cl^-	15
phosphate ions, PO_4^{3-}	10
magnesium ions, Mg^{2+}	5
sodium ions, Na^+	2
nitrate ions, NO_3^-	0
plant growth substances (e.g. auxin)	small traces

Table 6.1 Composition of sap in *Ricinus communis*.

SAQ

6 Which of the substances in Table 6.1 are synthesised by the plant?

Answer

It is not easy to collect enough phloem sap to analyse its contents. When phloem tissue is cut, the sieve elements respond by rapidly blocking the sieve pores. The pores are blocked first by plugs of phloem protein, and then, within hours, by a carbohydrate called **callose**. However, castor oil plants are unusual in that their phloem sap does continue to flow for a while, making it relatively easy to collect.

Aphids are a good way of collecting sap. Aphids, such as greenfly, feed by inserting their tubular mouthparts, called stylets, into the phloem of plant stems and leaves (Figure 6.18). Phloem sap flows through the stylet into the aphid. If the stylet is cut near the aphid's head, the sap continues to flow. It seems that the small diameter of the stylet does not allow sap to flow out rapidly enough to switch on the plant's phloem 'clotting' mechanism.

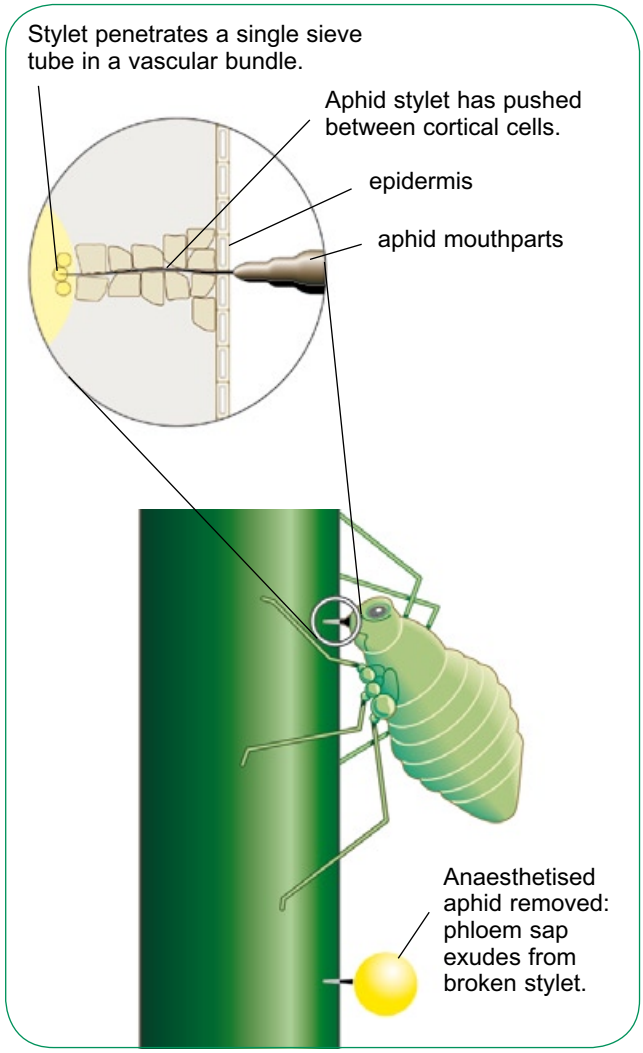

Figure 6.18 Using an aphid to collect phloem sap.

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How translocation occurs

Phloem sap, like the contents of xylem vessels, moves by mass flow. However, whereas in xylem vessels differences in pressure are produced by a water potential gradient between soil and air, requiring no energy input from the plant, this is not so in phloem transport. To create the pressure differences needed for mass flow in phloem, the plant has to use its own energy. Phloem transport is therefore an *active* process, in contrast to the *passive* transport in xylem.

The pressure difference is produced by **active loading** of sucrose into the sieve elements at the place from which sucrose is to be transported. This is typically in a photosynthesising leaf. As sucrose is loaded into the sieve element, this decreases the water potential in the sap inside it. Therefore, water follows the sucrose into the sieve element, moving down a water potential gradient by osmosis.

At another point along the sieve tube, sucrose may be removed by other cells. Root cells, for example, may use sucrose delivered by phloem. Sucrose will often be at a relatively low concentration in these cells, because they are using it up. So sucrose simply diffuses out of the phloem and into the root cell, and water follows by osmosis.

So, in the leaf, water moves into the sieve tube. In the root, it moves out of it. This creates a pressure difference, with the pressure at the 'leaf' end of the phloem sieve tube being greater than that at the 'root' end. The pressure difference causes the liquid inside the tube to flow from the high pressure area to the lower one, by mass flow.

Any area of a plant from which sucrose is loaded into the phloem is called a **source**. An area that takes sucrose out of the phloem is called a **sink** (Figure 6.19).

Sinks can be anywhere in the plant, both above and below the photosynthesising leaves. So sap flows both upwards and downwards. This contrasts with the situation in xylem, where flow is always upwards. Within any one phloem sieve tube, however, the flow is all in one direction.

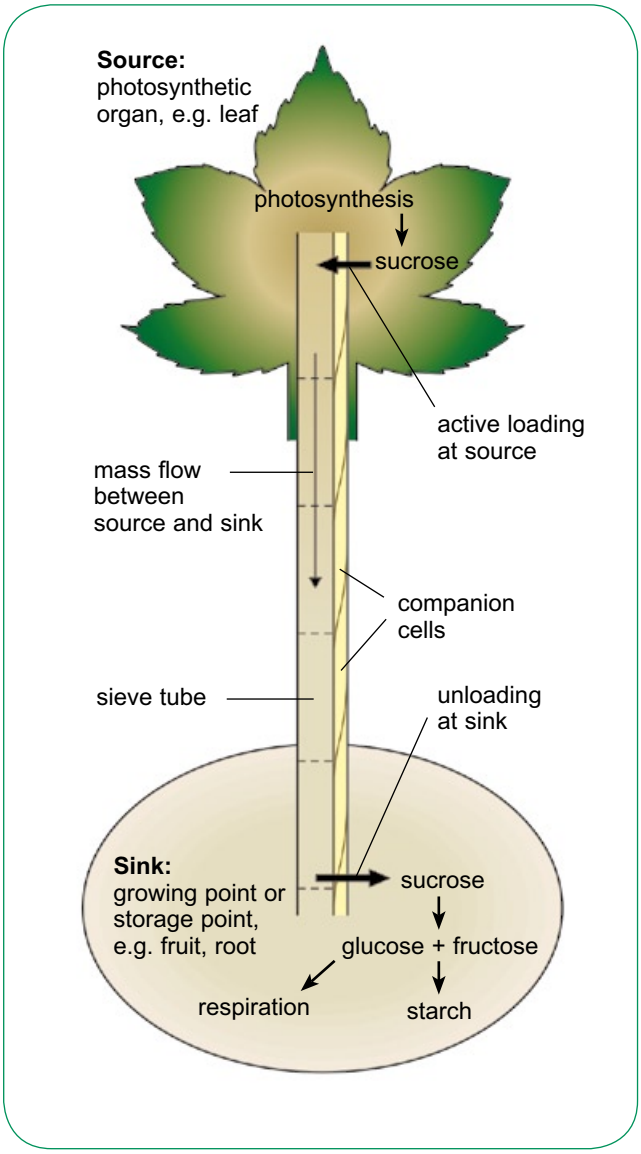

Figure 6.19 Sources, sinks and mass flow in phloem.

SAQ

7 Which of the following are sources, and which are sinks?

a a nectary in a flower — Hint

b a developing fruit — Hint

c the storage tissue of a potato tuber when the potato is just starting to sprout — Hint

d a growing potato tuber — Answer

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Loading sucrose into phloem

In leaf mesophyll cells, photosynthesis produces sugars. Some of these are converted into sucrose, which can be transported in the phloem to other parts of the plant.

Sucrose is soluble, so it dissolves in the water in the cell. It can move out of a mesophyll cell and across the leaf, by either the apoplast or symplast pathway.

Sucrose is loaded into companion cells by active transport (Figure 6.20). This is done in a rather roundabout way. First, hydrogen ions are pumped out of the cell by active transport, using ATP as the energy source. This creates a large excess of hydrogen ions outside the cell. They can move back into the cell down their concentration gradient, through a protein that acts as a carrier for both hydrogen ions and sucrose at the same time. The sucrose molecules are carried through this co-transporter into the companion cell, against the concentration gradient for sucrose. The sucrose molecules can then move from the companion cell into the sieve tube, through the plasmodesmata that connect them.

Unloading sucrose from phloem

Unloading occurs in any tissue that requires sucrose. It is likely that the sucrose moves out of the phloem and into the tissue by facilitated diffusion. Once in the tissue, the sucrose is converted into something else by enzymes. This decreases its concentration and therefore maintains a concentration gradient from the phloem into the tissue. One such enzyme is invertase, which converts sucrose to glucose and fructose.

SAQ

8 Draw a table and use it to compare the structure of xylem vessels and phloem sieve tubes. You could include cell structure (walls, diameter, cell contents and so on), substances transported and methods of transport.

Answer

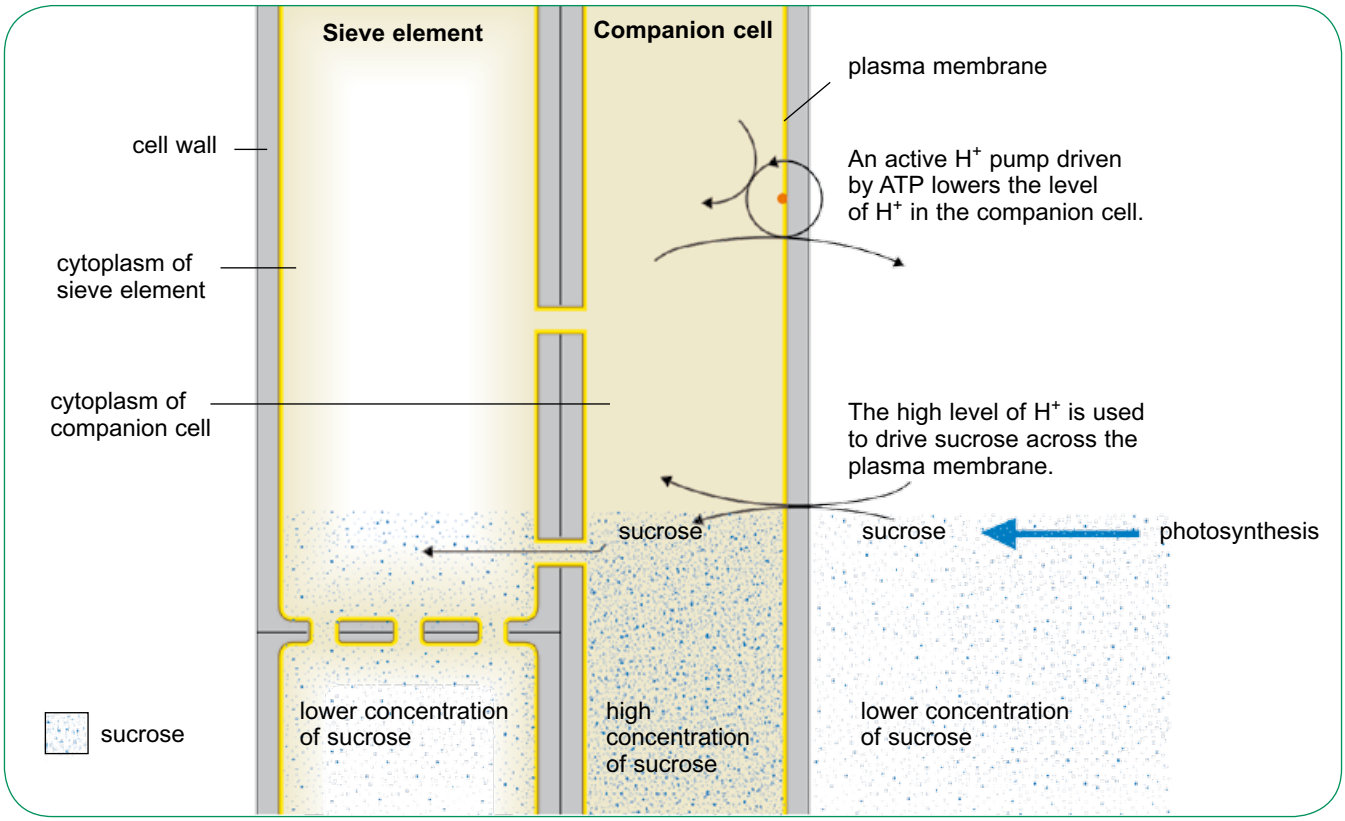

Figure 6.20 The method by which sucrose is loaded into phloem.

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Evidence for the mechanism of phloem transport

Until the late 1970s and 1980s, there was considerable argument about whether or not phloem sap did or did not move by mass flow, in the way we have described. The stumbling block was the presence of the sieve pores and phloem protein, as it was felt that these must have some important role. Several hypotheses were put forward, which tried to provide a role for the phloem protein. It is now known that the phloem protein is not present in living, active phloem tissue, and so there is no need to provide it with a role when explaining the mechanism of phloem transport.

There is now a lot of evidence that phloem transport does occur by mass flow. The rate of transport in phloem is about 10000 times faster than it would be if substances were moving by diffusion rather than by mass flow. The actual rates of transport measured match closely with those calculated from measured pressure differences at source and sink, assuming that the pores in the sieve plates are open and unobstructed.

Experimental work has investigated the sucrose–hydrogen co-transporter in plant cells, and it is understood how this works. There is also plenty of circumstantial evidence that this takes place, for example:

- phloem sap always has a relatively high pH, often around 8; this is what you would expect if hydrogen ions are being actively transported *out* of the neighbouring companion cell
- there is a difference in electrical potential across the plasma membrane of companion cells, which is more negative inside than outside; this could be caused by the greater concentration of positively charged hydrogen ions outside the cell than inside.

Summary

Glossary

- Plants are large, but have branching shapes, which increase the surface area : volume ratio. They have a relatively low metabolic rate compared to animals, and so can use diffusion to supply oxygen and carbon dioxide to their cells.
- Water is transported through a plant in xylem vessels. The water moves passively, down a water potential gradient from the soil to the air.
- Water moves into the root hairs by osmosis, and crosses the root cortex by the apoplast pathway (between the cells) or the symplast pathway (through the cells).
- The Casparian strip bars the apoplast pathway when the water arrives at the endodermis, so water has to pass through the cytoplasm of the endodermal cells and then into the xylem vessels.
- Xylem vessels are stacks of dead, empty xylem elements. These have no end walls, and their side walls are impregnated with lignin. Adhesion of water molecules to their walls and cohesion of water molecules to each other help the water column inside xylem vessels to move upwards by mass flow without breaking.
- Transpiration in the leaves provides the driving force for water movement through the plant. Water evaporates from the wet cell walls of cells inside the leaf, and then diffuses out through stomata into the air. Water moves from xylem vessels in the leaf into the leaf cells, by osmosis. This lowers the pressure at the top of the xylem so that water moves up the xylem by mass flow, down a pressure gradient.
- Transpiration is increased by high temperatures and high wind speeds, and is decreased by high humidity. A potometer can be used to compare rates of transpiration.

continued

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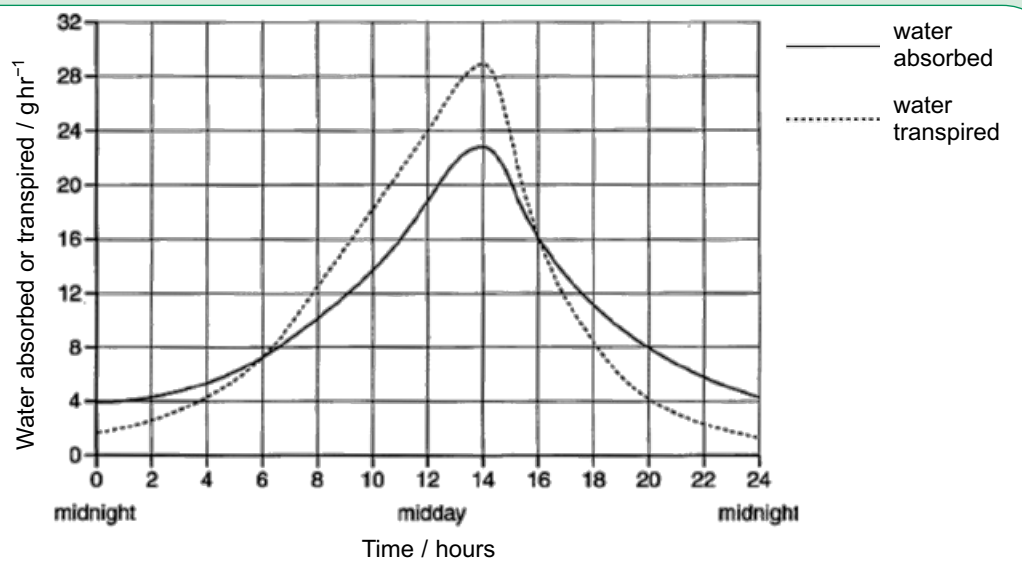
- Xerophytes are plants that are adapted to live in dry conditions. They have structures and mechanisms that help them to obtain as much water as possible, to store water and to limit the loss of water from their leaves.
- Substances that the plant has made, such as sucrose, are transported in phloem tubes. These are made up of sieve elements, which are living cells with perforated end walls. Sieve elements have no nucleus.
- Companion cells are closely associated with phloem sieve elements. Some of them actively load sucrose into a phloem sieve element, which reduces its water potential. Water therefore moves into the sieve element by osmosis. At the other end of the phloem tube, sucrose is removed by cells that are using it. This makes the pressure at the one end of the tube less than that at the other, so the liquid inside the tube flows from the high pressure area to the low pressure area by mass flow.
- A place where sucrose is loaded into the phloem is called a source. A place where sucrose is removed from it is called a sink.

Questions

1 The diagram shows the results of an investigation to compare rates of transpiration and water absorption by a plant during a hot day in summer. There was no shortage of soil water available to the plant throughout the investigation, which was carried out over 24 hours starting at midnight.



a i Define the term *transpiration*. [2]

ii Using the diagram, describe how the rate of transpiration varied over the 24 hour period and compare it with the rate of water absorption. [4]

iii Calculate the percentage of the 24 hour day in which the rate of water absorption exceeds the rate of transpiration.
Show your working and give your answer to the nearest whole number. [2]

b Explain how transpiration results in the movement of water up a plant stem. [4]

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Hint

Answer

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