Cambridge A2 Level Biology

Code (9700)

Chapter 14 and Chapter 15

Homeostasis and Coordination

Chapter 14 – Homeostasis

To function efficiently, organisms have control systems to keep internal conditions near constant, a feature known as homeostasis.

Some of the physiological factors controlled in homeostasis in mammals are:

■ core body temperature

■ metabolic wastes, particularly carbon dioxide and urea

■ blood pH

■ blood glucose concentration

■ water potential of the blood

■ the concentrations in the blood of the respiratory gases, oxygen and carbon dioxide.

Internal environment

The internal environment of an organism refers to all the conditions inside the body

Many features of the tissue fluid influence how well the cell functions. Three features of tissue fluid that influence cell activities are:

■ temperature – low temperatures slow down metabolic reactions; at high temperatures proteins, including enzymes, are denatured and cannot function

■ water potential – if the water potential decreases, water may move out of cells by osmosis, causing metabolic reactions in the cell to slow or stop; if the water potential increases, water may enter the cell causing it to swell and maybe burst

■ concentration of glucose – glucose is the fuel for respiration, so lack of it causes respiration to slow or stop, depriving the cell of an energy source; too much glucose may cause water to move out of the cell by osmosis, again disturbing the metabolism of the cell.

Homeostatic control

Most control mechanisms in living organisms use a negative feedback control loop (Figure 14.2) to maintain homeostatic balance. This involves a receptor (or sensor) and an effector.

These receptors send information about the changes they detect through the nervous system to a **central control** in the brain or spinal cord. This sensory information is known as the **input.**

The central control instructs an effector to carry out an action, which is called the **output**. These actions are sometimes called **corrective actions** as their effect is to correct (or reverse) the change

This mechanism to keep changes in the factor within narrow limits is known as **negative feedback**

The homeostatic mechanisms in mammals require information to be transferred between different parts of the body. There are two coordination systems in mammals that do this: the nervous system and the endocrine system.

■ In the nervous system, information in the form of electrical impulses is transmitted along nerve cells (neurones).

■ The endocrine system uses chemical messengers called hormones that travel in the blood, in a form of long-distance cell signalling.

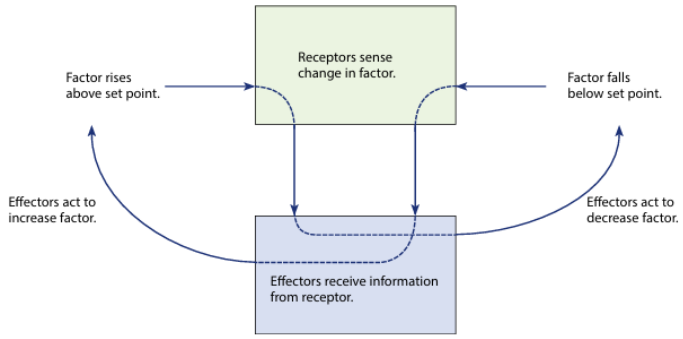


Figure 14.2 A negative feedback control loop.

The control of body temperature

Thermoregulation is the control of body temperature. This involves both coordination systems – nervous and endocrine.

Most other animals, with the exception of birds, rely on external sources of heat and are often relatively inactive when it is cold.

The hypothalamus has thermoreceptor cells that continually monitor the temperature of the blood flowing through it. The temperature it monitors is the **core temperature** – the temperature inside the body that remains very close to the set point, which is 37 °C in humans.

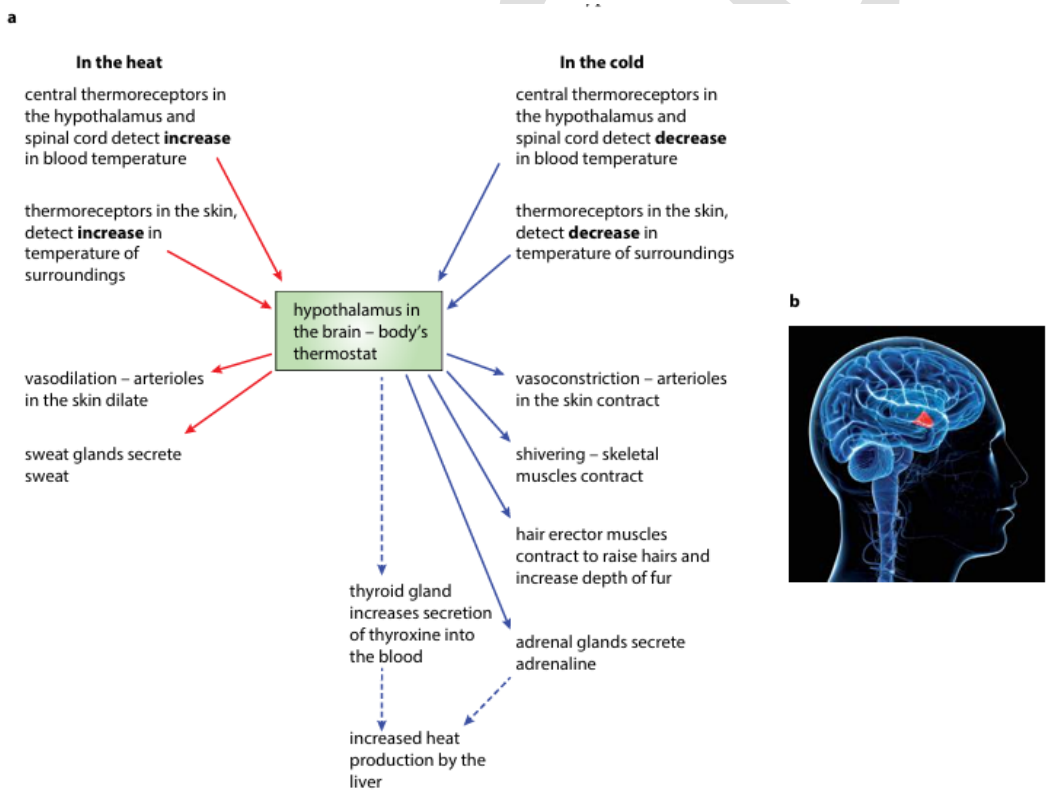


Figure 14.3 **a** A summary diagram to show the central role of the hypothalamus in thermoregulation when it is hot and when it is cold. The hypothalamus communicates with other regions of the body by using nerves (solid lines) and hormones (dashed lines). **b** The position of the hypothalamus, shown in red, in the brain.

If the core temperature decreases, or if the temperature receptors in the skin detect a decrease in the temperature of the surroundings, the hypothalamus sends impulses that activate the following physiological responses.

■ Vasoconstriction – muscles in the walls of arterioles that supply blood to capillaries near the skin surface contract. This narrows the lumens of the arterioles and reduces the supply of blood to the capillaries so that less heat is lost from the blood.

■ Shivering – the involuntary contraction of skeletal muscles generates heat which is absorbed by the blood and carried around the rest of the body.

■ Raising body hairs – muscles at the base of hairs in the skin contract to increase the depth of fur so trapping air close to the skin. Air is a poor conductor of heat and therefore a good insulator. This is not much use in humans, but is highly effective for most mammals.

■ Decreasing the production of sweat – this reduces the loss of heat by evaporation from the skin surface.

■ Increasing the secretion of adrenaline – this hormone from the adrenal gland increases the rate of heat production in the liver.

When an increase in environmental temperature is detected by skin receptors or the central thermoreceptors, the hypothalamus increases the loss of heat from the body and reduces heat production.

■ ■ Vasodilation – the muscles in the arterioles in the skin relax, allowing more blood to flow through the capillaries so that heat is lost to the surroundings.

■ ■ Lowering body hairs – muscles attached to the hairs relax so they lie flat, reducing the depth of fur and the layer of insulation.

■ ■ Increasing sweat production – sweat glands increase the production of sweat which evaporates on the surface of the skin so removing heat from the body

Excretion

Many of the metabolic reactions occurring within the body produce unwanted substances. Some of these are toxic (poisonous). The removal of these unwanted products of metabolism is known as **excretion**. Many excretory products are formed in humans, but two are made in much greater quantities than others. These are carbon dioxide and urea.

Urea is produced in the **liver**. The kidneys remove urea from the blood and excrete it, dissolved in water, as **urine**.

Deamination

If more protein is eaten than is needed, the excess cannot be stored in the body. It would be wasteful, however, simply to get rid of all the excess, because the amino acids provide useful energy.

We also produce small quantities of other nitrogenous excretory products, mainly creatinine and uric acid. A substance called **creatine** is made in the liver, from certain amino acids.

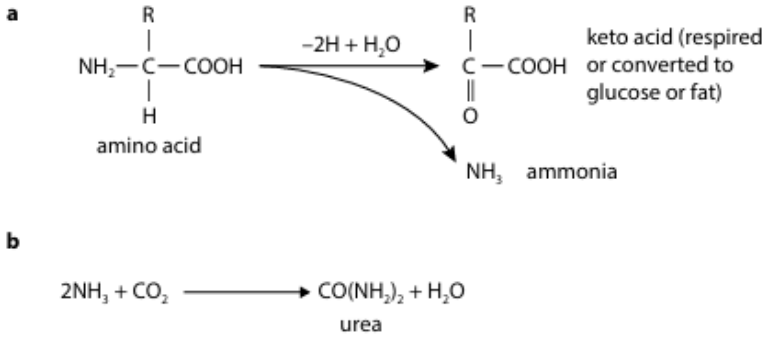


Figure 14.4 **a** Deamination and **b** urea formation.

The structure of the kidney

Figure 14.5 shows the position of the kidneys in the body, together with their associated structures. Each kidney receives blood from a **renal artery** and returns blood via a **renal vein.**

The whole kidney is covered by a fairly tough **capsule**, beneath which lies the **cortex**. The central area is made up of the **medulla**. Where the ureter joins, there is an area called the **pelvis**.

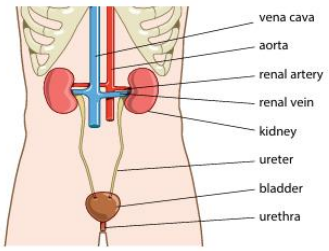


Figure 14.5 Position of the kidneys and associated structures in the human body.

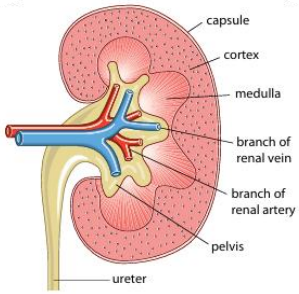


Figure 14.6 A kidney cut in half vertically.

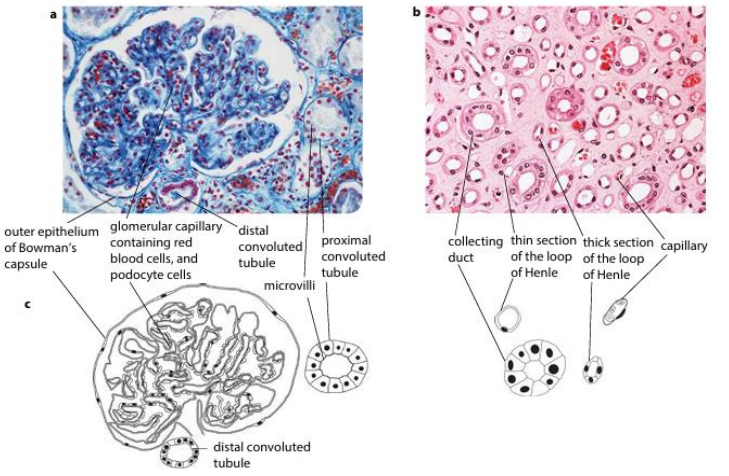


Figure 14.7 **a** Photomicrograph of a section through the cortex of the kidney showing a glomerulus and Bowman's capsule surrounded by proximal and distal convoluted tubules (×150); **b** photomicrograph of a section through the medulla of a kidney (×300); **c** interpretive drawings.

From the capsule, the tube runs towards the centre of the kidney, first forming a twisted region called the **proximal convoluted tubule**, and then a long hairpin loop in the medulla, the loop of Henle. The tubule then runs back upwards into the cortex, where it forms another twisted region called the **distal convoluted tubule**, before finally joining a collecting duct that leads down through the medulla and into the pelvis of the kidney.

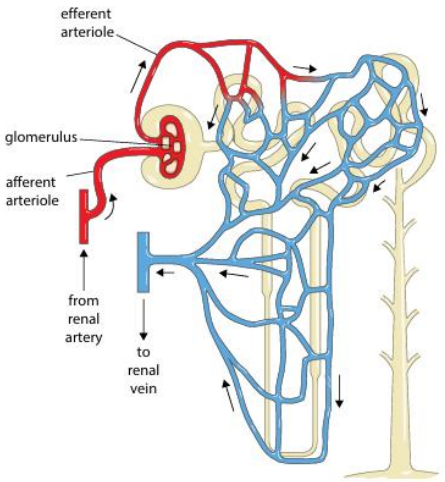


Figure 14.9 The blood supply associated with a nephron.

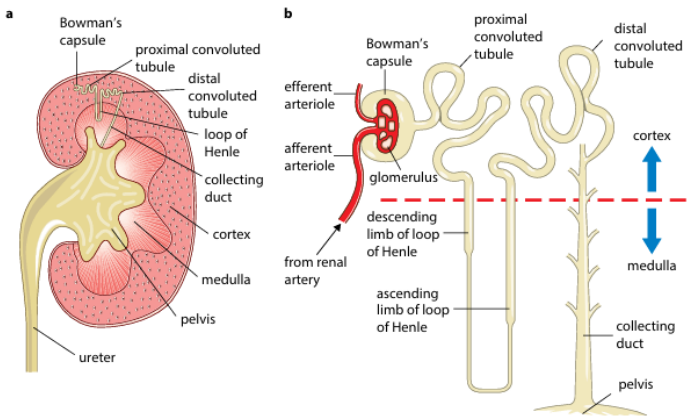


Figure 14.8 **a** Section through the kidney to show the position of a nephron; **b** a nephron.

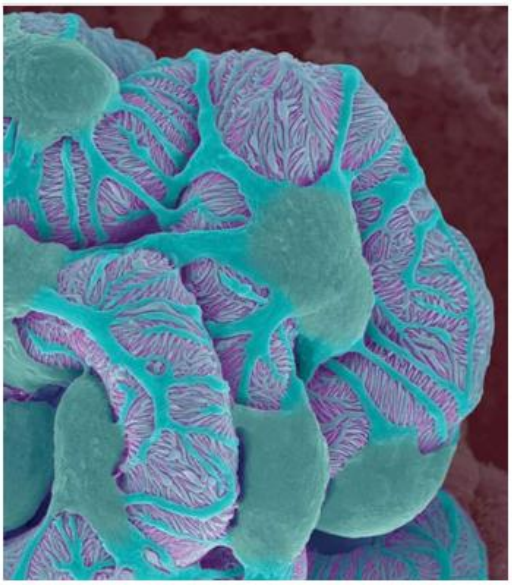


Figure 14.11 A false-colour scanning electron micrograph of podocytes (×3900). The podocytes are the blue-green cells with their extensions wrapped around the blood capillary, which is purple.

Ultrafiltration

Figure 14.10 shows a section through part of a glomerulus and Bowman's capsul. Next comes the **basement membrane**, which is made up of a network of collagen and glycoproteins. The second cell layer is formed from **epithelial cells**, which make up the inner lining of the Bowman's capsule.

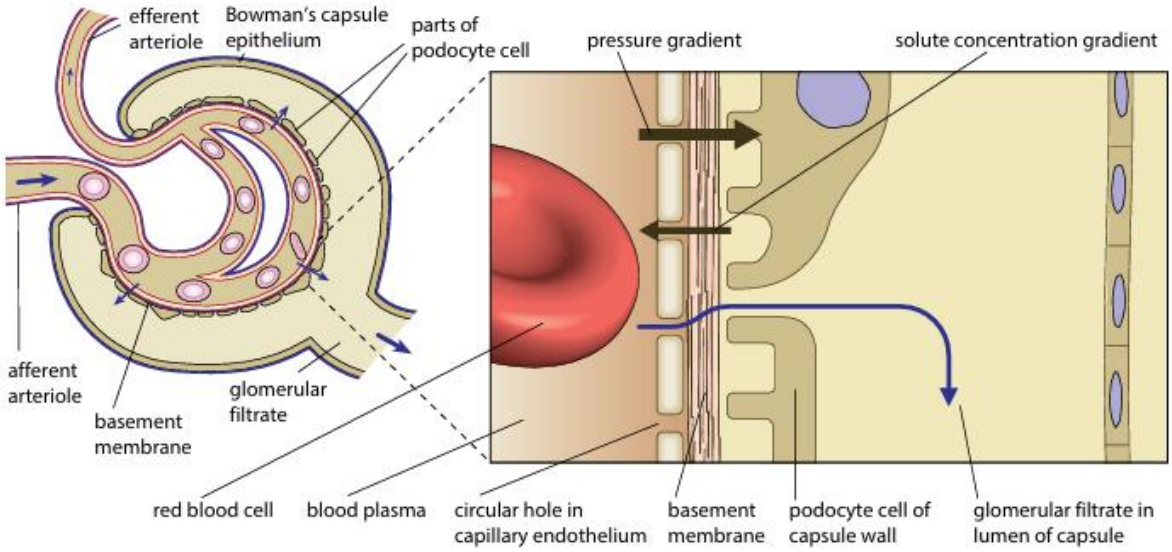


Figure 14.10 Detail of the endothelium of a glomerular capillary and Bowman's capsule. The arrows show how the net effect of higher pressure in the capillary and lower solute concentration in the Bowman's capsule is that fluid moves out of the capillary and into the lumen of the capsule. The basement membrane acts as a molecular filter.

his basement membrane therefore acts as a filter. Blood cells, both red and white, are also too large to pass through this barrier, and so remain in the blood. Table 14.1 shows the relative concentrations of substances in the blood and in the glomerular filtrate. You will see that glomerular filtrate is identical to blood plasma except that there are almost no plasma proteins in it.

Factors affecting glomerular filtration rate

The rate at which the fluid filters from the blood in the glomerular capillaries into the Bowman's capsule is called the glomerular filtration rate.

Overall, though, the effect of differences in pressure outweighs the effect of the differences in solute concentration. Overall, the water potential of the blood plasma in the glomerulus is higher than the water potential of the filtrate in the capsule. So water continues to move down the water potential gradient from the blood into the capsule.

Substance	Concentration in blood plasma / g dm^{-3}	Concentration in glomerular filtrate / g dm^{3}
water	900	900
proteins	80.0	0.05
amino acids	0.5	0.5
glucose	1.0	1.0
urea	0.3	0.3
uric acid	0.04	0.04
creatinine	0.01	0.01
inorganic ions (mainly Na^+, K^+ and Cl^-)	7.2	7.2

Table 14.1 Concentrations of substances in the blood and in the glomerular filtrate.

Reabsorption in the proximal convoluted tubule

Many of the substances in the glomerular filtrate need to be kept in the body, so they are reabsorbed into the blood as the fluid passes along the nephron. As only certain substances are reabsorbed, the process is called selective reabsorption.

The lining of this part of the nephron is made of a single layer of cuboidal epithelial cells. T hese cells are adapted for their function of reabsorption by having:

■ ■ microvilli to increase the surface area of the inner surface facing the lumen

■ ■ tight junctions that hold adjacent cells together so that f luid cannot pass between the cells (all substances that are reabsorbed must go through the cells)

■ ■ many mitochondria to provide energy for sodium potassium (Na+–K+) pump proteins in the outer membranes of the cells

■ ■ co-transporter proteins in the membrane facing the lumen.

All of the **glucose** in the glomerular filtrate is transported out of the proximal convoluted tubule and into the blood. Normally, no glucose is left in the filtrate, so no glucose is present in urine. Similarly, amino acids, **vitamins**, and many **sodium and chloride** ions (Cl–) are reabsorbed in the proximal convoluted tubule.

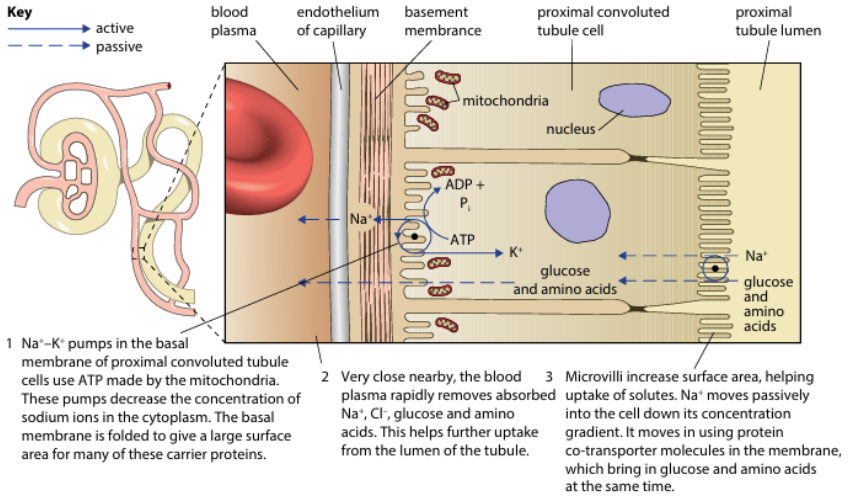


Figure 14.12 Reabsorption in the proximal convoluted tubule.

Reabsorption in the loop of Henle and collecting duct

About one-third of our nephrons have long loops of Henle. These dip down into the medulla. The function of these long loops is to create a very high concentration of sodium and chloride ions in the tissue fluid in the medulla.

The first part of the loop is the **descending limb,** and the second part is the **ascending limb.**

This decreases the water potential in the tissue fluid and increases the water potential of the fluid inside the ascending limb

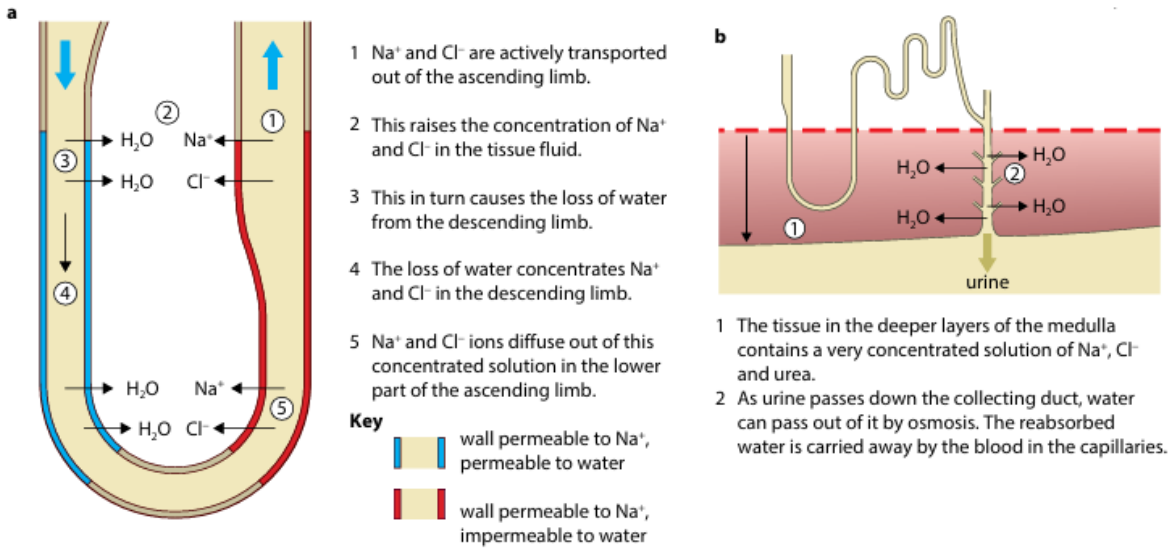


Figure 14.13 How the loop of Henle allows the production of concentrated urine. **a** The counter-current mechanism in the loop of Henle builds up high concentrations of sodium ions and chloride ions in the tissue fluid of the medulla. **b** Water can pass out of the fluid in the collecting duct by osmosis, as the surrounding tissue fluid has a lower water potential.

In Figure 14.13b you can see that the fluid continues round through the distal convoluted tubule into the **collecting duct**, which runs down into the medulla again. It therefore passes once again through the regions where the solute concentration of the tissue fluid is very high and the water potential very low.

Reabsorption in the distal convoluted tubule and collecting duct

The first part of the distal convoluted tubule functions in the same way as the ascending limb of the loop of Henle.

The rate at which these two ions are moved into and out of the fluid in the nephron can be varied, and helps to regulate the concentration of these ions in the blood.

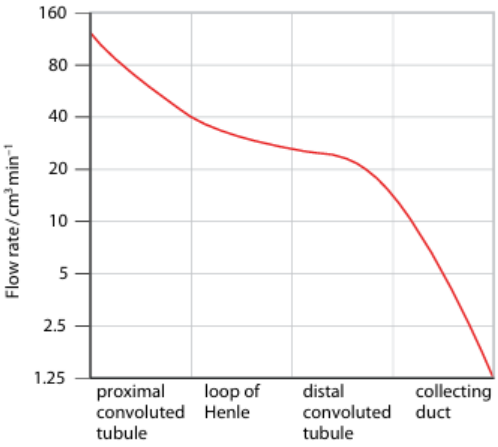


Figure 14.14 Flow rates in different parts of a nephron.

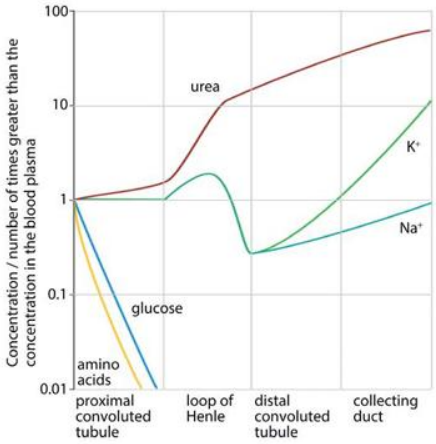


Figure 14.15 Relative concentrations of five substances in different parts of a nephron.

Control of water content

Osmoreceptors, the hypothalamus and ADH

Osmoregulation is the control of the water potential of body fluids. This regulation is an important part of **homeostasis** and involves the hypothalamus, posterior pituitary gland and the kidneys.

When these cells detect a **decrease** in the water potential of the blood below the set point, nerve impulses are sent along the neurones to where they terminate in the posterior pituitary gland (Figure 14.16).

These impulses stimulate the release of **antidiuretic hormone (ADH),** which is a peptide hormone made of nine amino acids

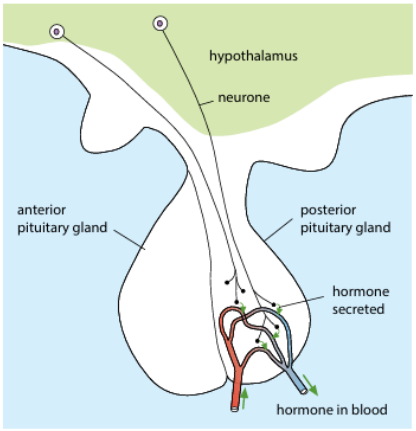


Figure 14.16 ADH is produced by neurones in the hypothalamus and is released into the blood where the neurones terminate in the posterior pituitary gland.

How ADH affects the kidneys

You have seen that water is reabsorbed by osmosis from the fluid in the nephron as the fluid passes through the collecting ducts. The cells of the collecting duct are the target cells for ADH.

What happens when you have more than enough water in the body – for example, after enjoying a large volume of your favourite drink? When there is an **increase** in the water potential of the blood, the osmoreceptors in the hypothalamus are no longer stimulated and the neurons in the posterior pituitary gland stop secreting ADH.

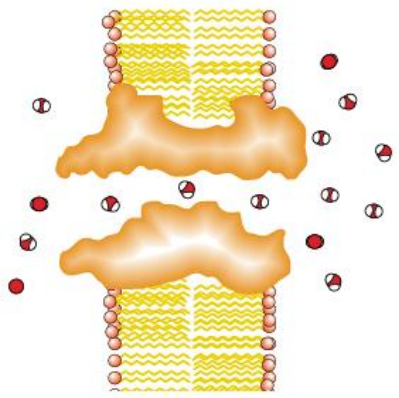


Figure 14.19 Aquaporin protein channels allow water to diffuse through membranes such as those in the cells that line collecting ducts.

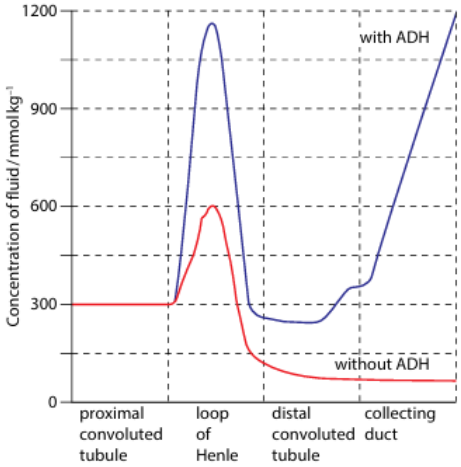


Figure 14.20 The concentration of fluid in different regions of a nephron, with and without the presence of ADH.

The control of blood glucose

Carbohydrate is transported through the human bloodstream in the form of glucose in solution in the blood plasma

The homeostatic control of blood glucose concentration is carried out by two hormones secreted by endocrine tissue in the pancreas. This tissue consists of groups of cells, known as the islets of Langerhans, which are scattered throughout the pancreas. The word islet means a small island, as you might find in a river. The islets contain two types of cells:

■ ■ α cells secrete glucagon

■ ■ β cells secrete insulin.

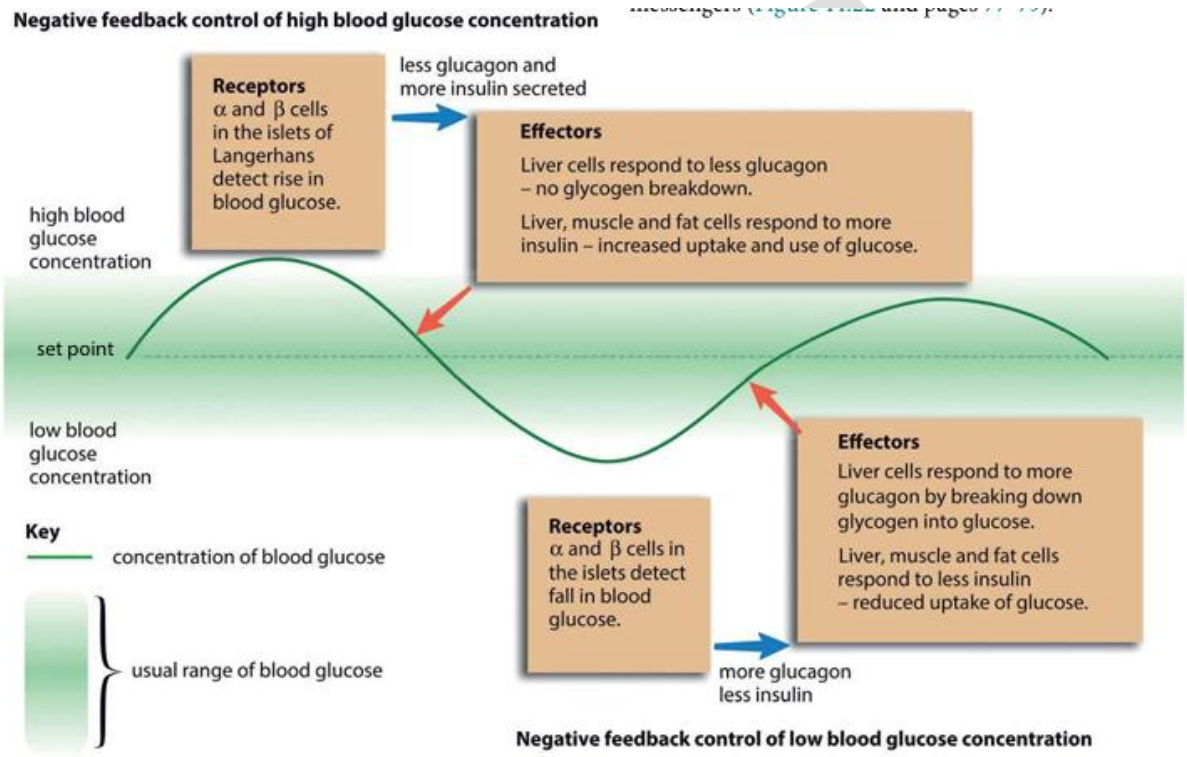


Figure 14.21 The control mechanism for the concentration of glucose in the blood.

Insulin activates glucokinase and phosphofructokinase enzymes, trapping glucose inside cells. It also adds glucose molecules to glycogen, increasing the size of glycogen granules.

Glucagon and insulin work in a negative feedback system, causing blood glucose concentrations to fluctuate due to time delays between changes and corrective actions. This results in oscillation, where blood glucose concentrations fluctuate slightly above or below the required level.

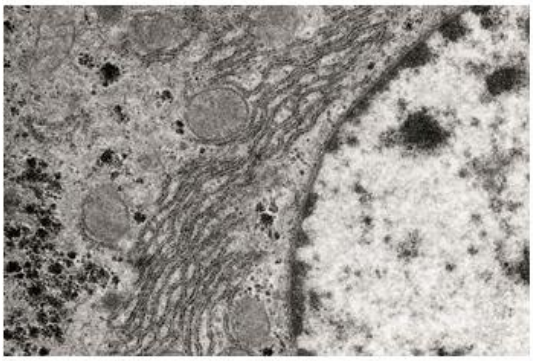


Figure 14.23 Transmission electron micrograph of part of a liver cell (×22 000). The dark spots are glycogen granules in the cytoplasm. Mitocondria can also be seen.

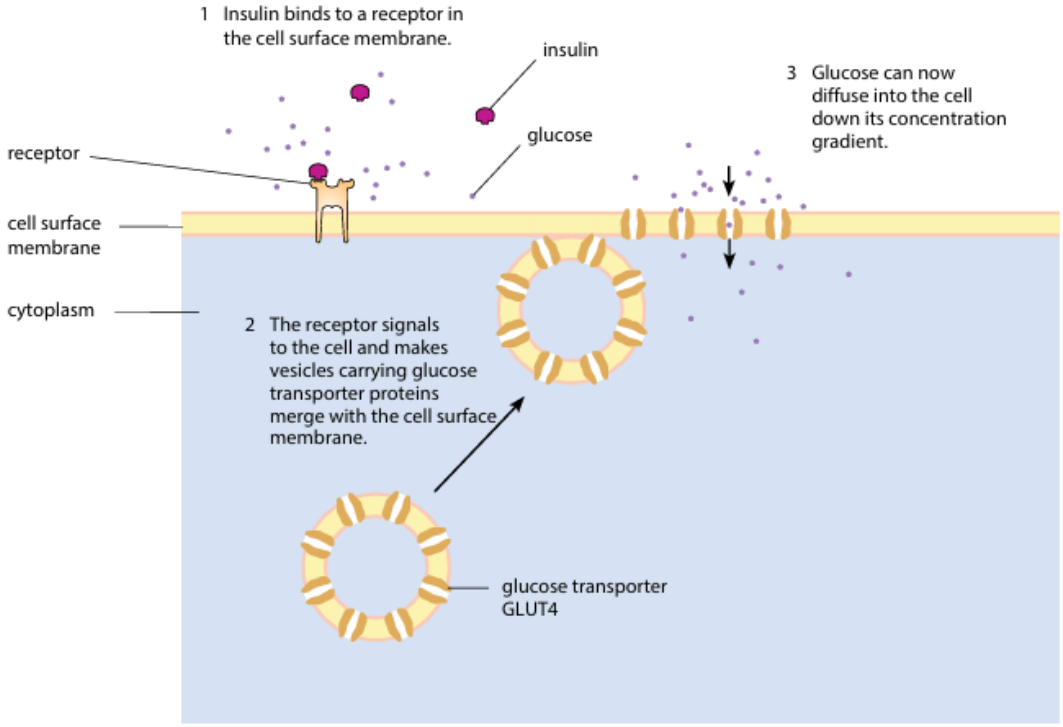


Figure 14.22 Insulin increases the permeability of muscle cells to glucose by stimulating the movement of vesicles with GLUT4 to the cell surface membrane.

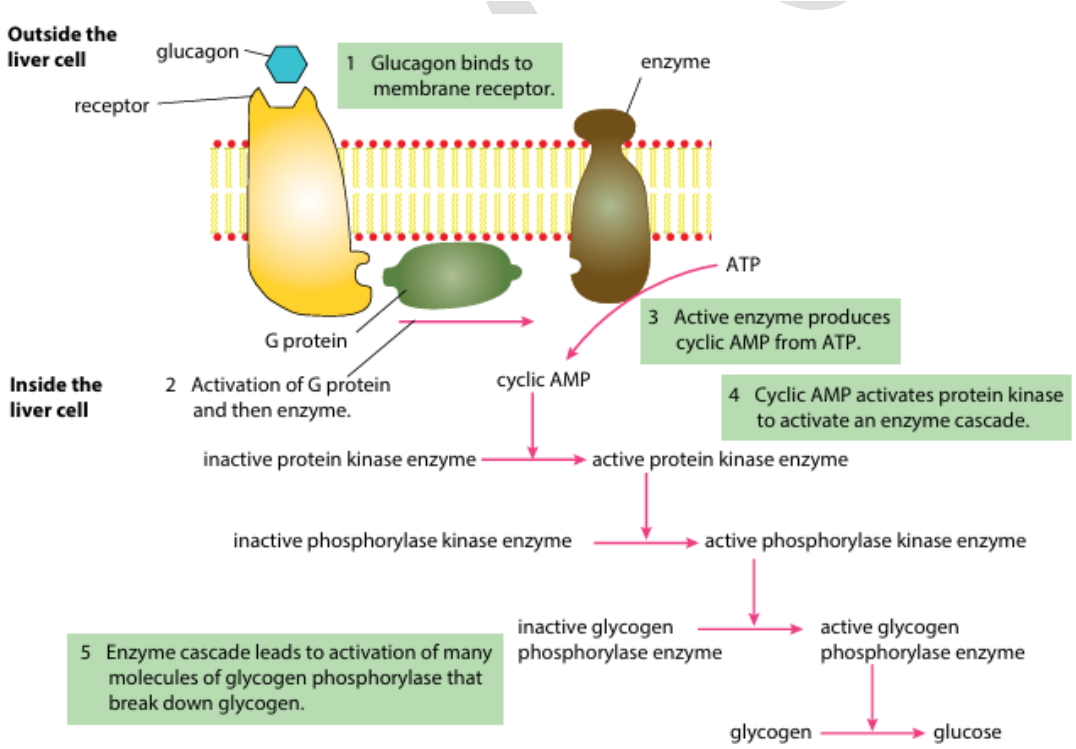


Figure 14.24 Glucagon stimulates the activation of glycogen phosphorylase enzymes in liver cells through the action of cyclic AMP.

Diabetes mellitus

There are two forms of sugar diabetes. **In insulin dependent** diabetes, which is also known as **type 1 diabetes**, the pancreas seems to be incapable of secreting sufficient insulin

The second form of diabetes is called **non-insulin dependent diabetes or type 2 diabetes**. In this form of diabetes, the pancreas does secrete insulin, but the liver and muscle cells do not respond properly to it.

Figure 14.26 A nurse teaches a girl with type 1 diabetes to inject insulin. The girl may have to receive injections of insulin throughout her life.

Urine analysis

It is much easier to collect a urine sample from someone than a blood sample. Simple tests on urine can give early indications of health problems, which can then be investigated more thoroughly.

Dip sticks and biosensors

Dip sticks (also known as test strips) can be used to test urine for a range of different factors including pH, glucose, ketones and protein. Dip sticks for detecting glucose contain the enzymes glucose oxidase and **peroxidase**.

A biosensor like the one in Figure 14.28 allows people with diabetes to check their blood to see how well they are controlling their glucose concentration.

The current is detected by an electrode, amplified and read by the meter which produces a reading for blood glucose concentration within seconds. The more glucose that is present, the greater the current and the greater the reading from the biosensor.

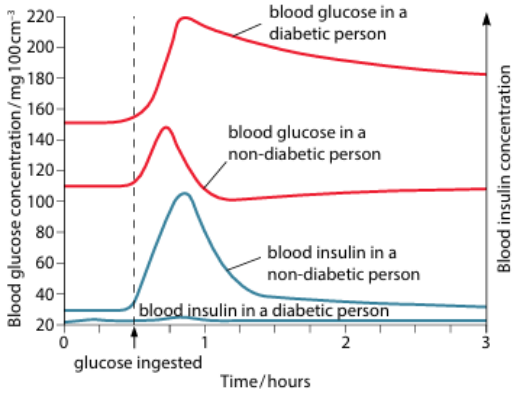


Figure 14.25 Concentrations of blood glucose and insulin following intake of glucose in a person with normal control of blood glucose and a person with type 1 diabetes.

Homeostasis in plants

It is as important for plants to maintain a constant internal environment as it is for animals. For example, mesophyll cells in leaves require a constant supply of carbon dioxide if they are to make best use of light energy for photosynthesis.

Stomata show daily rhythms of opening and closing. Even when kept in constant light or constant dark, these rhythms persist (Figure 14.30).

Stomata respond to changes in environmental conditions. Th ey open in response to:

■ ■ increasing light intensity

■ ■ low carbon dioxide concentrations in the air spaces within the leaf.

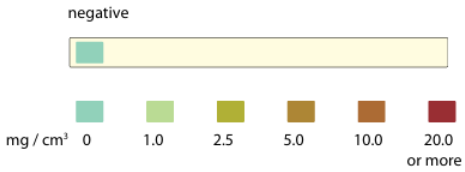


Figure 14.27 A dip stick can be used to test for the presence of glucose in urine. These dip sticks are used by people with diabetes to check whether their urine contains any glucose.

Figure 14.28 Biosensors use biological materials, such as enzymes, to measure the concentration of molecules such as glucose. This glucose biosensor is used to check the glucose concentration in a sample of blood. The meter shows a reading in the normal range.

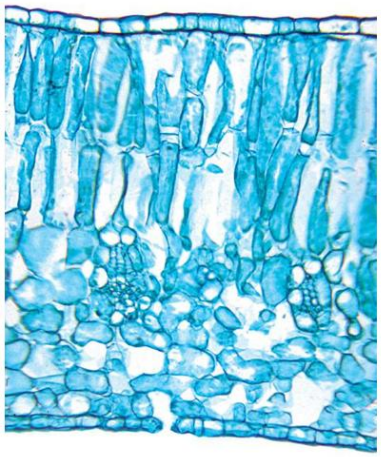


Figure 14.29 Photomicrograph of a TS of *Helianthus* leaf (×100). An open stoma is visible in the lower epidermis.

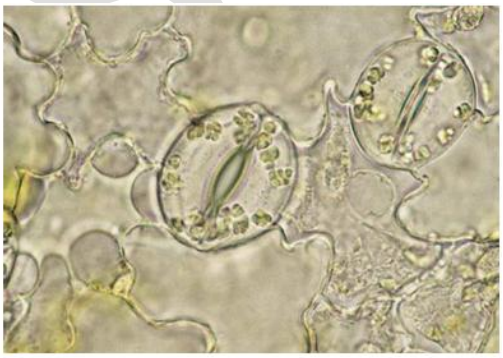


Figure 14.31 Photomicrograph of two stomata and guard cells in a lower epidermis of a leaf of *Tradescantia* (×870).

Stomata close in response to:

- darkness
- high carbon dioxide concentrations in the air spaces in the leaf
- low humidity
- high temperature
- water stress, when the supply of water from the roots is limited and/or there are high rates of transpiration.

Opening and closing of stomata

Guard cells in stomatal pore walls open and close when they gain water, becoming turgid and flaccid. Water enters cells through osmosis, with a decrease in water potential needed. Transporter proteins in cell surface membranes transport hydrogen ions out of guard cells, causing channel proteins to open, allowing potassium ions to enter. This lowers solute potential and water potential, increasing the turgor of guard cells and opening the stoma. Guard cells have unevenly thickened walls, with cellulose microfibrils arranged as hoops to ensure cell length increases. This curved shape opens the pore between the two cells.

Abscisic acid and stomatal closure

One role of ABA is to coordinate the responses to stress; hence it is known as a **stress hormone**. If a plant is subjected to difficult environmental conditions, such as very high temperatures or much reduced water supplies, then it responds by secreting ABA. In a plant in drought conditions, the concentration of ABA in the leaves can rise to 40 times that which would normally be present.

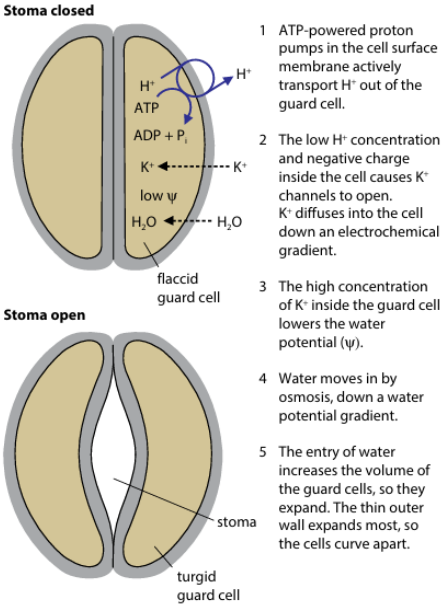


Figure 14.32 How a stoma is opened. Guard cells do not have plasmodesmata, so all exchanges of water and ions must occur across the cell surface membranes through the pump and channel proteins.

Chapter 15: Coordination

In animals, including mammals, there are two types of information transfer that are used to coordinate the body's activities:

■ ■ nerves that transmit information in the form of electrical impulses

■ ■ chemical messengers called hormones that travel in the blood.

Nervous communication

The mammalian nervous system is made up of the brain and spinal cord, which form the central nervous system (CNS), and the cranial and spinal nerves, which form the peripheral nervous system (PNS) (Figure 15.2)

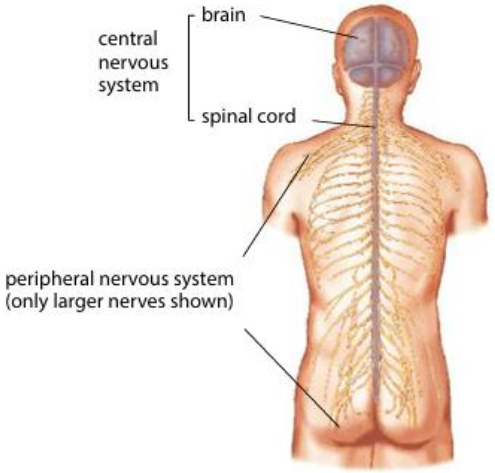


Figure 15.2 The human nervous system.

Neurones

There are three types of neurone (Figure 15.3), each with a different function:

■ ■ sensory neurones transmit impulses from receptors to the CNS

■ ■ intermediate neurones (also known as relay or connector neurones) transmit impulses from sensory neurones to motor neurones

■ ■ motor neurones transmit impulses from the CNS to effectors.

Thin cytoplasmic processes extend from the cell body. Some are very short and often have many branches – these are dendrites.

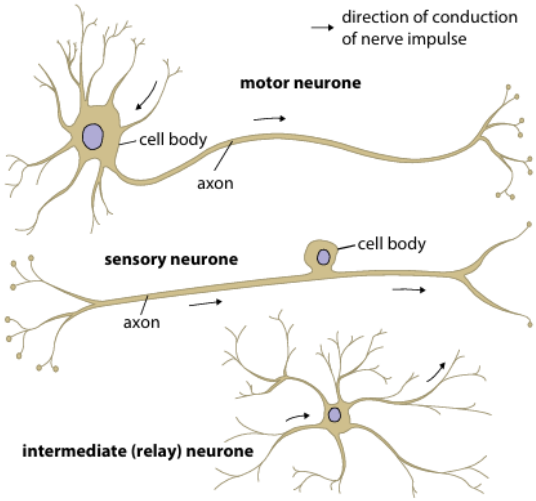


Figure 15.3 Motor, sensory and intermediate neurones.

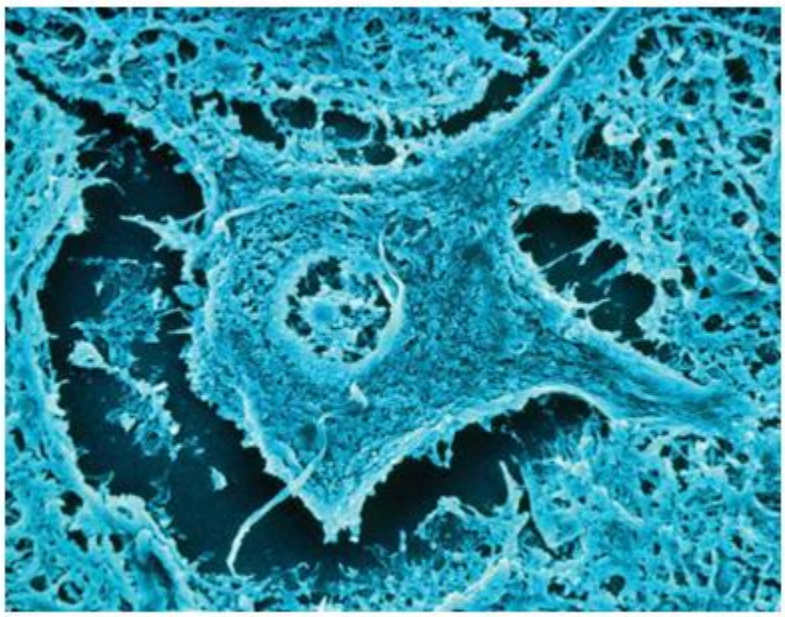


Figure 15.5 An electron micrograph of the cell body of a motor neurone within the spinal cord (×1000).

This enclosing sheath, called the myelin sheath, is made largely of lipid, together with some proteins. The sheath affects the speed of conduction of the nerve impulse (page 337).

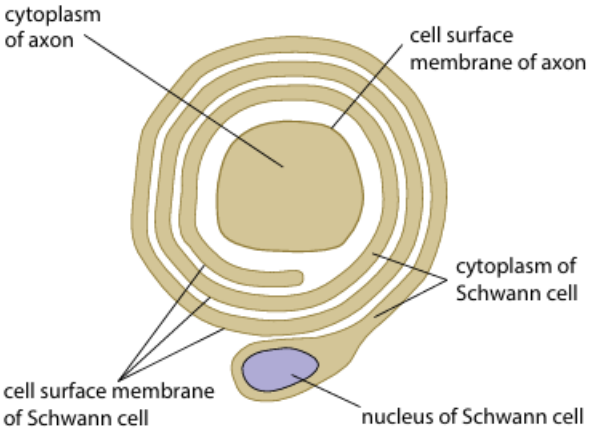


Figure 15.7 Transverse section of the axon of a myelinated neurone.

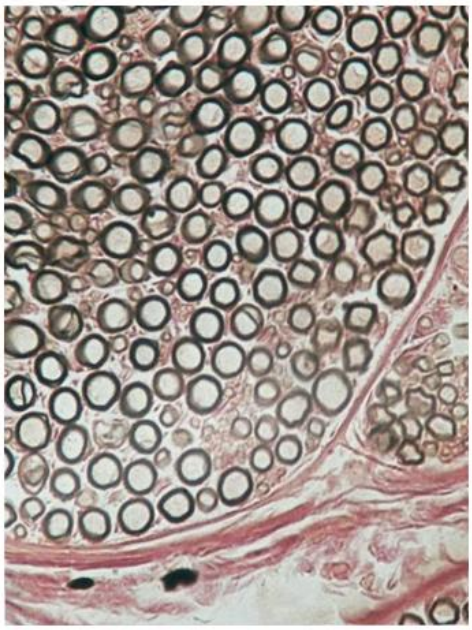


Figure 15.6 A photomicrograph of a transverse section (TS) of a nerve (×500). The circles are axons of sensory and motor neurones in cross-section. Some of these are myelinated (the ones with dark lines around) and some are not. Each group of axons is surrounded by a perineurium (red lines). Several such groups make a complete nerve.

A reflex arc

The spinal reflex arc is a pathway where impulses are transmitted from a receptor to an effector without involving conscious brain regions. It involves sensory, intermediate, and motor neurons working together. The impulse is passed from neurone to neurone within the spinal cord, and then to other neurons in the brain. This process occurs simultaneously with impulses traveling along the motor neurone to the effector. This reflex action is a fast, automatic response to a stimulus, useful for responding to danger signals.

Transmission of nerve impulses

Neurones transmit electrical impulses. These impulses travel very rapidly along the cell surface membrane from one end of the cell to the other, and are not a flow of electrons like an electric current.

Resting potential

Some axons in some organisms such as squids and earthworms are very wide; it is possible to insert tiny electrodes into their cytoplasm to measure the changes in electrical charge. Figure 15.9 shows just part of an unmyelinated axon.

The difference between these potentials, called the potential difference, is often between −60 mV and −70 mV. In other words, the electrical potential of the inside of the axon is between 60 and 70 mV lower than the outside. This difference is the resting potential.

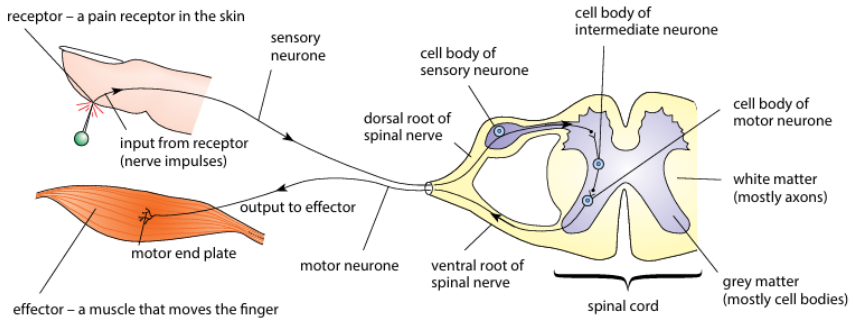


Figure 15.8 A reflex arc. The spinal cord is shown in transverse section.

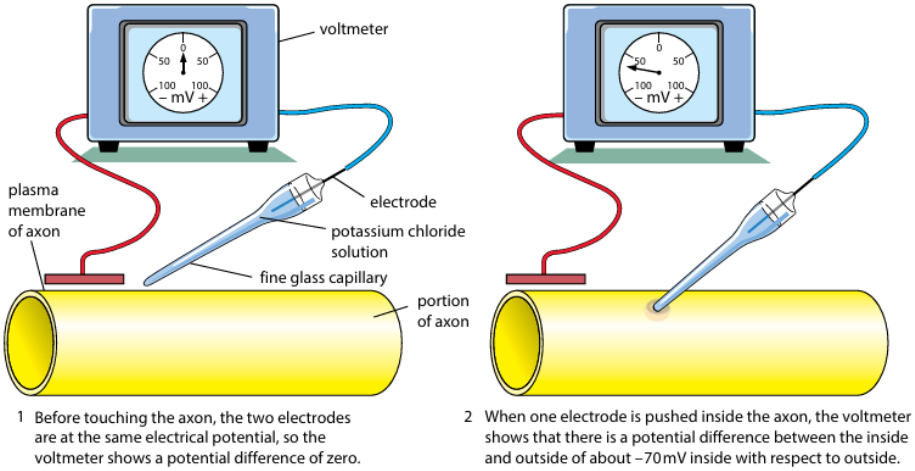


Figure 15.9 Measuring the resting potential of an axon.

There is a steep concentration gradient, and also the inside of the membrane is negatively charged, which attracts positively charged ions. A 'double' gradient like this is known as an electrochemical gradient.

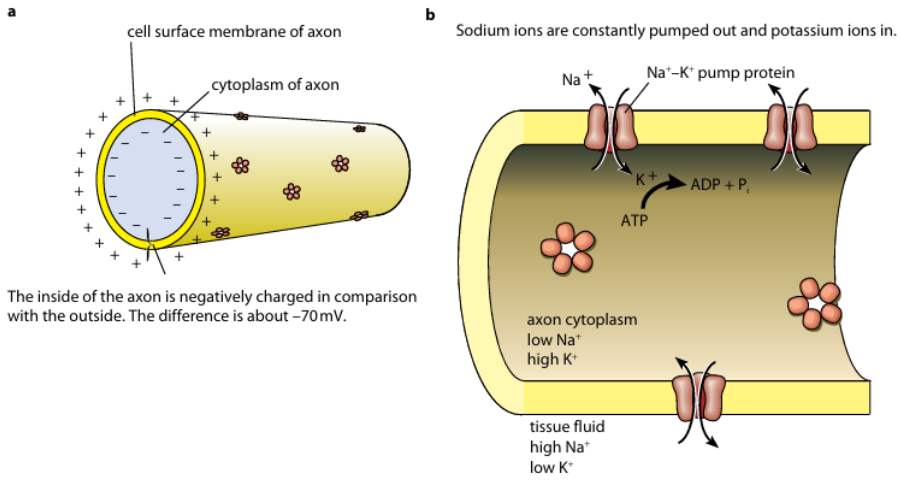


Figure 15.10 **a** At rest, an axon has negative electrical potential inside. **b** The sodium–potassium pump maintains the resting potential by keeping more sodium ions outside than there are potassium ions inside.

Action potentials

A small electric current can stimulate an axon, causing a sudden change in potential difference across the cell surface membrane. This action potential is caused by changes in the permeability of the cell surface membrane to sodium and potassium ions. Voltage-gated channels allow sodium ions to pass through, and when the membrane is at its resting potential, these channels are closed. The electric current stimulates the axon, causing the opening of voltage-gated channels, which allow sodium ions to pass through. This depolarization triggers more channels to open, leading to more depolarization.

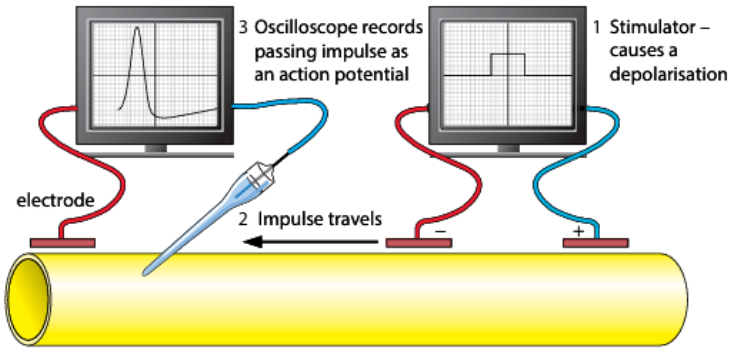


Figure 15.11 Recording of an action potential.

Action potentials are only generated if the potential difference reaches a value between −60 mV and −50 mV. This value is the **threshold potential**. If it is less than this, then an action potential does not occur.

Transmission of action potentials

Figure 15.12 shows what happens at one particular point in an axon membrane. However, the function of a neurone is to transmit information **along** itself.

In the body, action potentials begin at one end and 'new' action potentials are generated **ahead** and not behind.

There are several consequences of there being refractory periods.

■ ■ Action potentials are discrete events; they do not merge into one another.

■ ■ There is a minimum time between action potentials occurring at any one place on a neurone.

■ ■ The length of the refractory period determines the maximum frequency at which impulses are transmitted along neurones.

How action potentials carry information

What is different about the action potentials resulting from a strong and a weak stimulus is their **frequency.**

The brain can therefore interpret the frequency of action potentials arriving along the axon of a sensory neurone, and the **number** of neurones carrying action potentials, to get information about the

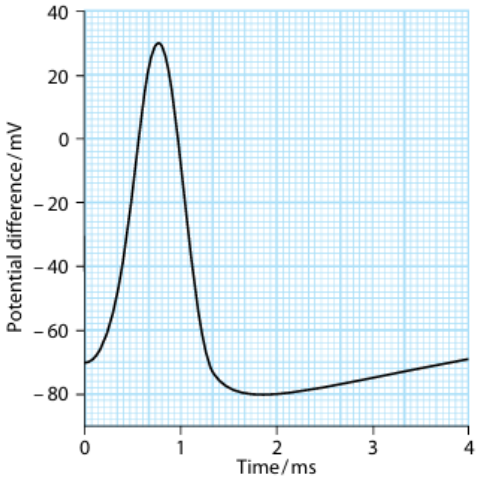


Figure 15.12 An action potential.

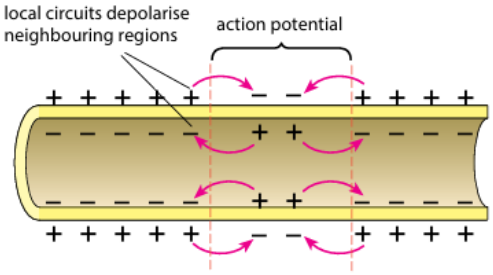


Figure 15.13 How local circuits cause an action potential to move along an axon.

strength of the stimulus being detected. The **nature** of the stimulus, whether it is light, heat, touch or so on, is deduced from the **position** of the sensory neurone bringing the information.

Speed of conduction

Unmyelinated neurones have slow conduction speeds, while myelinated human neurons can travel up to 100 ms−1. Myelin insulates the axon membrane, preventing sodium and potassium ions from flowing through. Action potentials can only occur at Ranvier nodes, where channel and pump proteins are concentrated. Saltatory conduction increases the speed of transmission by up to 50 times in myelinated axons. Diameter also affects transmission speed, with thick axons transmitting impulses faster.

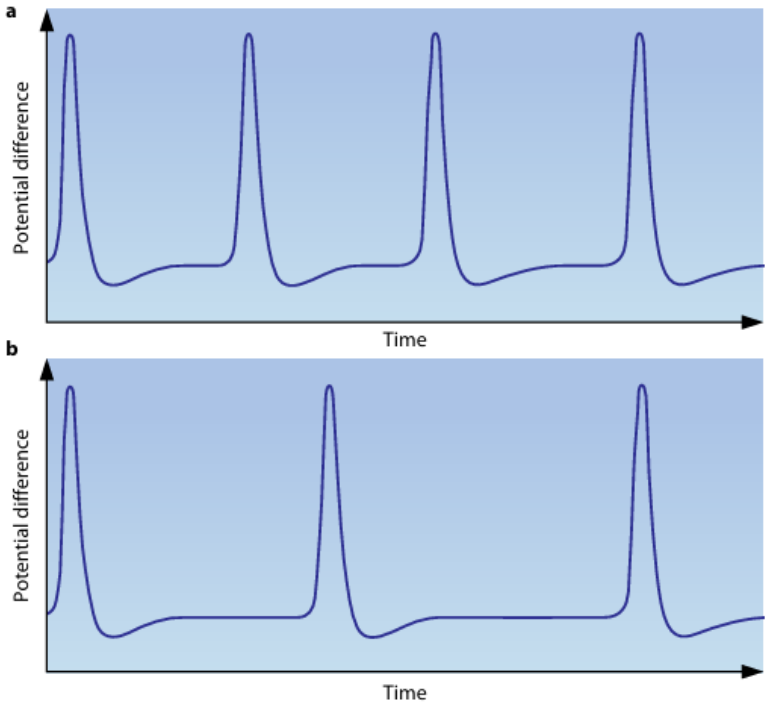


Figure 15.14 Action potentials resulting from **a** a strong stimulus and **b** a weak stimulus. Note that the size of each action potential remains the same, only its frequency changes.
a A high frequency of impulses is produced when a receptor is given a strong stimulus. This high frequency carries the message 'strong stimulus'.
b A lower frequency of impulses is produced when a receptor is given a weaker stimulus. This lower frequency carries the message 'weak stimulus'.

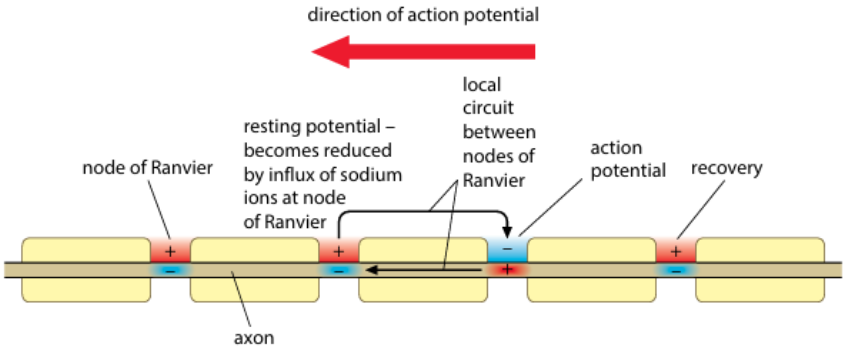


Figure 15.15 Transmission of an action potential in a myelinated axon. The myelin sheath acts as an insulator, preventing differences in potential across the parts of the axon membrane surrounded by the sheath. Potential differences can only occur at the nodes of Ranvier. The action potential therefore 'jumps' from one node to the next, travelling much more swiftly than in an unmyelinated axon.

What starts off an action potential?

In the description of the generation of an action potential on page 335, the initial stimulus was a small electric current. In normal life, however, action potentials are generated by a wide variety of stimuli, such as light, pressure (touch), sound, temperature or chemicals.

The tongue is composed of small bumps or papillae with taste buds, each with 50-100 receptor cells sensitive to chemicals in liquids or food. These receptors are covered with receptor proteins, each detecting different chemicals. Tastes are sweet, sour, salt, bitter, and umami. Chemoreceptors detect salt through sodium ions, which diffuse through selective channel proteins, leading to increased positive charge and receptor potential.

Threshold levels in receptors rarely stay constant all the time. With continued stimulation, they often increase so that it requires a greater stimulus before receptors send impulses along sensory neurones.

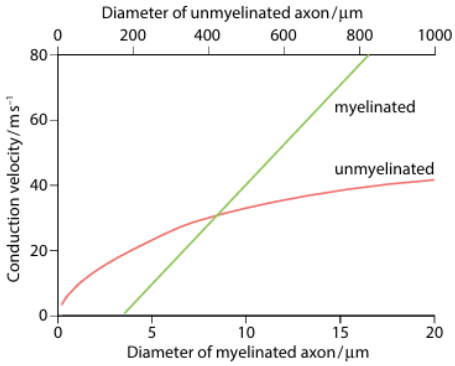


Figure 15.16 Speed of transmission in myelinated and unmyelinated axons of different diameters.

Receptor	Sense	Form in which energy is received
rod or cone cells in retina	sight	light
taste buds on tongue	taste	chemical potential
olfactory cells in nose	smell	chemical potential
Pacinian corpuscles in skin	pressure	movement and pressure
Meissner's corpuscles in skin	touch	movement and pressure
Ruffini's endings in skin	temperature	heat
proprioceptors (stretch receptors) in muscles	placement of limbs	mechanical displacement – stretching
hair cells in semicircular canals in ear	balance	movement
hair cells in cochlea	hearing	sound

Table 15.1 Some examples of energy conversions by receptors. Each type of receptor converts a particular form of energy into electrical energy – that is, a nerve impulse. All of the receptors in the table except for stretch receptors respond to external stimuli. Stretch receptors respond to changes inside the muscles. There are many receptors that respond to other internal stimuli.

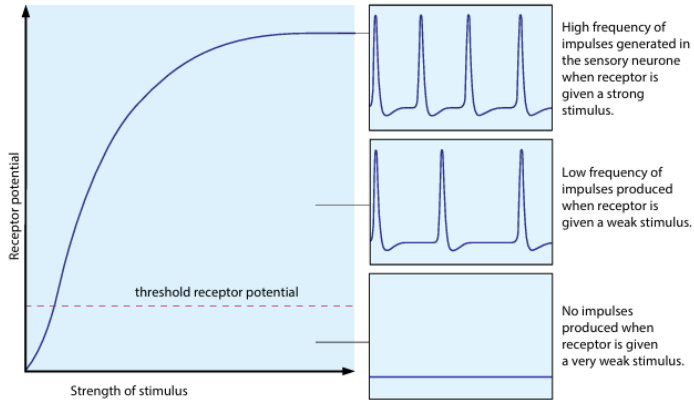


Figure 15.19 As the strength of a stimulus increases, the receptor potential also increases. If the receptor potential reaches the threshold, then impulses are sent along the sensory neurone at low frequency. Increasing the strength of the stimulus above the threshold increases the frequency of the impulses; it does not change their amplitude.

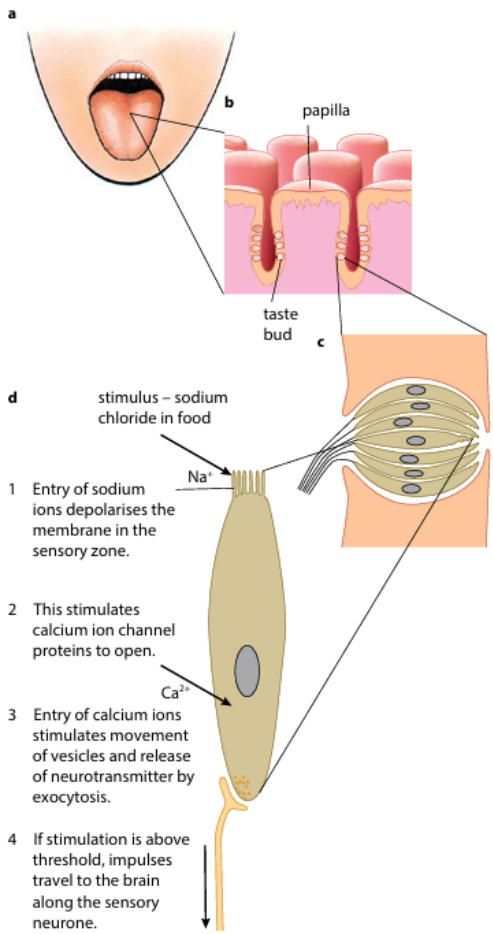


Figure 15.18 **a** Taste buds are in papillae that are distributed across the tongue. **b** A cross section through a papilla showing the distribution of taste buds. **c** A taste bud. **d** Details of one chemoreceptor cell.

Synapses

Where two neurones meet, they do not quite touch. There is a very small gap, about 20 nm wide, between them. This gap is called the synaptic clef.

The mechanism of synaptic transmission Impulses cannot 'jump' across the type of synapse shown in Figure 15.20. Instead, molecules of a transmitter substance, or neurotransmitter, are released to stimulate the next neurone. This is an outline of the sequence of events that occurs.

■ ■ An action potential occurs at the cell surface membrane of the first neurone, or presynaptic neurone.

■ ■ The action potential causes the release of molecules of transmitter substance into the cleft.

■ ■ The molecules of transmitter substance diffuse across the cleft and bind temporarily to receptors on the postsynaptic neurone.

■ ■ The postsynaptic neurone responds to all the impulses arriving at any one time by depolarising; if the overall depolarisation is above its threshold, then it will send impulses.

Let us look at these processes in more detail. The cytoplasm of the presynaptic neurone contains vesicles of transmitter substance (Figure 15.21). More than 40 different transmitter substances are known; noradrenaline and acetylcholine (ACh) are found throughout the nervous system, whereas others such as **dopamine, glutamic acid** and gamma-aminobutyric acid (GABA) occur only in the brain.

In the part of the membrane of the presynaptic neurone that is next to the synaptic cleft, the arrival of the action potential also causes **calcium ion voltage-gated** channels to open (Figure 15.22)

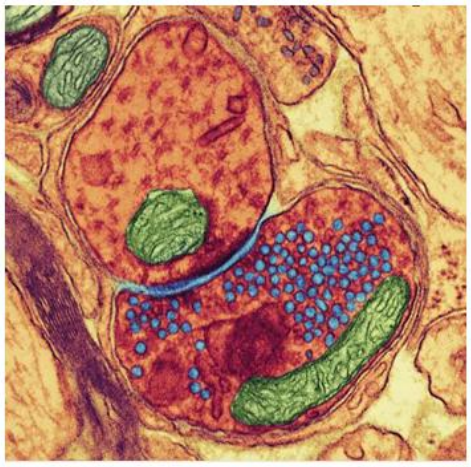


Figure 15.21 False-colour transmission electron micrograph of a synapse (×52 000). The presynaptic neurone (at the bottom) has mitochondria (shown in green) and numerous vesicles (blue), which contain the transmitter substance.

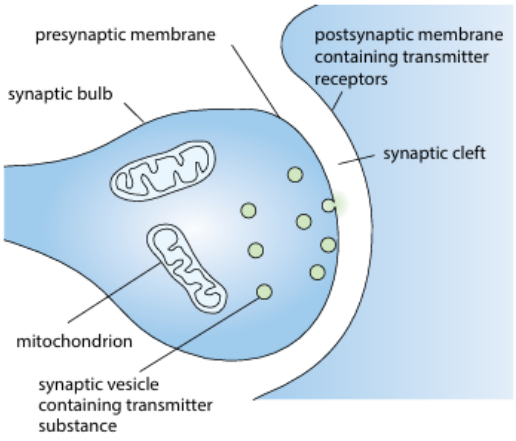


Figure 15.20 A synapse.

The cell surface membrane of the postsynaptic neurone contains **receptor** proteins

Research on synapses primarily focuses on synapses between motor neurons and muscles, not between two neurones. These synapses function similarly, producing an action potential in the muscle fiber, potentially causing contraction.

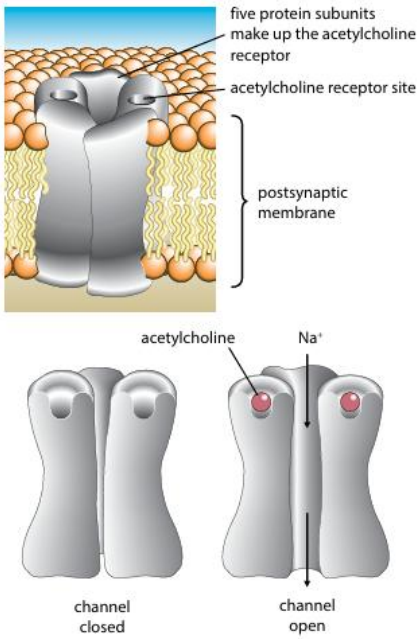


Figure 15.23 Detail of how the acetylcholine receptor works. The receptor is made of five protein subunits spanning the membrane arranged to form a cylinder. Two of these subunits contain acetylcholine receptor sites. When acetylcholine molecules bind with both of these receptor sites, the proteins change shape, opening the channel between the units. Parts of the protein molecules around this channel contain negatively charged amino acids, which attract positively charged sodium ions so they pass through the channel.

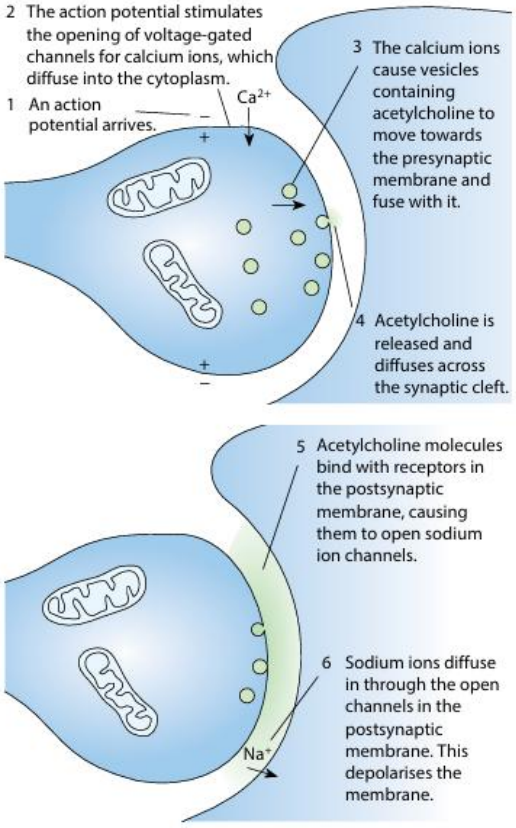


Figure 15.22 Synaptic transmission.

The roles of synapses

Synapses slow down the rate of transmission of a nerve impulse that has to travel along two or more neurones.

So why have synapses?

■ ■ Synapses ensure one-way transmission. Impulses can only pass in one direction at synapses. This is because neurotransmitter is released on one side and its receptors are on the other. There is no way that chemical transmission can occur in the opposite direction.

■ ■ Synapses allow integration of impulses. Each sensory neurone has many branches at the end of its axon that form synapses with many relay (intermediate) neurones. The cell body of each motor neurone is covered with the terminations of many relay neurones.

■ ■ Synapses allow the interconnection of nerve pathways. Synapses allow a wider range of behaviour than could be generated in a nervous system in which neurones were directly 'wired up' to each other. They do this by allowing the interconnection of many nerve pathways.

This happens in two ways: – individual sensory and relay neurones have axons that branch to form synapses with many different neurones; this means that information from one neurone can spread out throughout the body to reach many relay neurones and many effectors as happens when we respond to dangerous situations

– there are many neurones that terminate on each relay and motor neurone as they have many dendrites to give a large surface area for many synapses; this allows one neurone to integrate the information coming from many different parts of the body – something that is essential for decision-making in the brain

■ Synapses are involved in memory and learning. Despite much research, little is yet known about how memory operates. However, there is much evidence that it involves synapses.

Muscle contraction

This section discusses muscle contraction, specifically striated muscle, which is neurogenic and contracts when stimulated by motor neurones. Smooth muscle, found in organs like the gas exchange system, alimentary canal, and arteries, also contracts when stretched by blood pressure without the need for input from the nervous system. Smooth muscle has no striations and does not form smooth linings in tubular structures like trachea and arteries. The structures and functions of these three types of muscle tissue are compared in Table 15.2.

	Type of muscle		
	striated	**cardiac**	**smooth**
Appearance in the light microscope	stripes (striations) at regular intervals	stripes (striations) at regular intervals	no striations
Cell structure	multinucleate (syncytium)	uninucleate cells joined by intercalated discs (Figure 8.23, page 173)	uninucleate cells
Shape of cells	long, unbranched cylinder	cells are shorter with branches that connect to adjacent cells	long, unbranched cells that taper at either end
Organisation of contractile proteins inside the cell	organised into parallel bundles of myofibrils	organised into parallel bundles of myofibrils	contractile proteins not organised into myofibrils
Distribution in the body	muscles attached to the skeleton	heart	tubular structures e.g. blood vessels (arteries, arterioles and veins), airways, gut, Fallopian tubes (oviducts), uterus
Control	neurogenic	myogenic	neurogenic

Table 15.2 Mammals have three types of muscle tissue: striated, cardiac and smooth.

The structure of striated muscle

A muscle such as a biceps is made up of thousands of muscle fibres (Figure 15.25). Each muscle fibre is a very specialised 'cell' with a highly organised arrangement of contractile proteins in the cytoplasm, surrounded by a cell surface membrane. Some biologists prefer not to call it a cell, because it contains many nuclei.

The cell surface membrane is the sarcolemma, the cytoplasm is sarcoplasm and the endoplasmic reticulum is sarcoplasmic reticulum (SR). The cell surface membrane has many deep infoldings into the interior of the muscle fibre, called transverse system tubules or T-tubules for short (Figure 15.26)

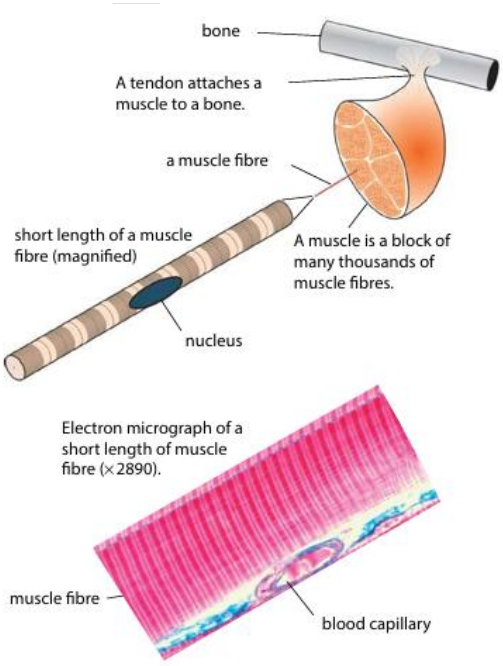


Figure 15.25 The structure of a muscle. As each muscle is composed of several tissues (striated muscle tissue, blood, nerves and connective tissue) it is an example of an organ.

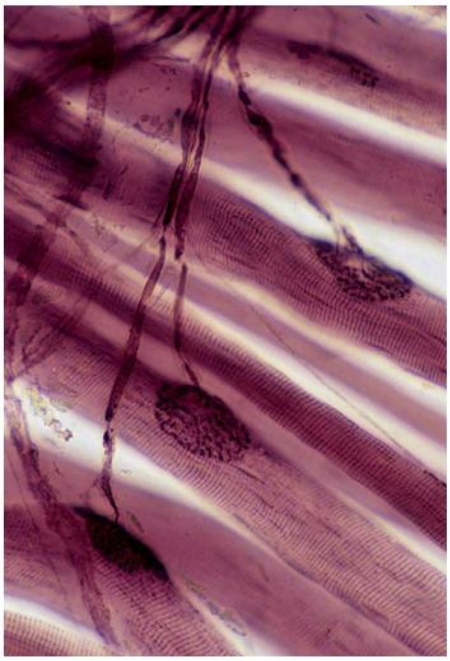


Figure 15.24 Photomicrograph of neuromuscular junctions (×200). The red tissue is muscle fibres, whereas the axons show as dark lines. The axons terminate in a number of branches on the surface of the muscle fibre, forming motor end plates. Action potentials are passed from the axon to the muscle, across a synaptic cleft, at these end plates.

Muscle fibres have distinctive stripes, produced by a regular arrangement of myofibrils in the sarcoplasm. These stripes are arranged in a pattern, with parallel groups of thick filaments and thin ones. The darker parts of the stripes, called A bands, correspond to thick myosin filaments, while the lighter parts, I bands, have no thick filaments. The darkest parts are formed by the overlap of thick and thin filaments. The Z line connects actin and myosin filaments, while the Z disc separates sarcomeres.

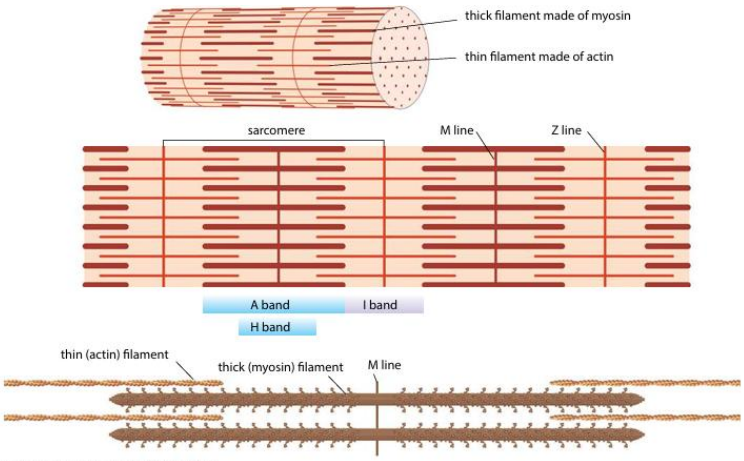


Figure 15.27 The structure of a myofibril.

Structure of thick and thin filaments

Thick filaments are composed of many molecules of myosin, which is a fibrous protein with a globular head. The fibrous portion helps to anchor the molecule into the thick filament. Within the thick filament, many myosin molecules all lie together in a bundle with their globular heads all pointing away from the M line.

How muscles contract

Muscles cause movement by contracting. The sarcomeres in each myofibril get shorter as the Z discs are pulled closer together. Figure 15.28 shows how this happens. It is known as the sliding filament model of muscle contraction. T he energy for the movement comes from ATP molecules that are attached to the myosin heads. Each myosin head is an ATPase.

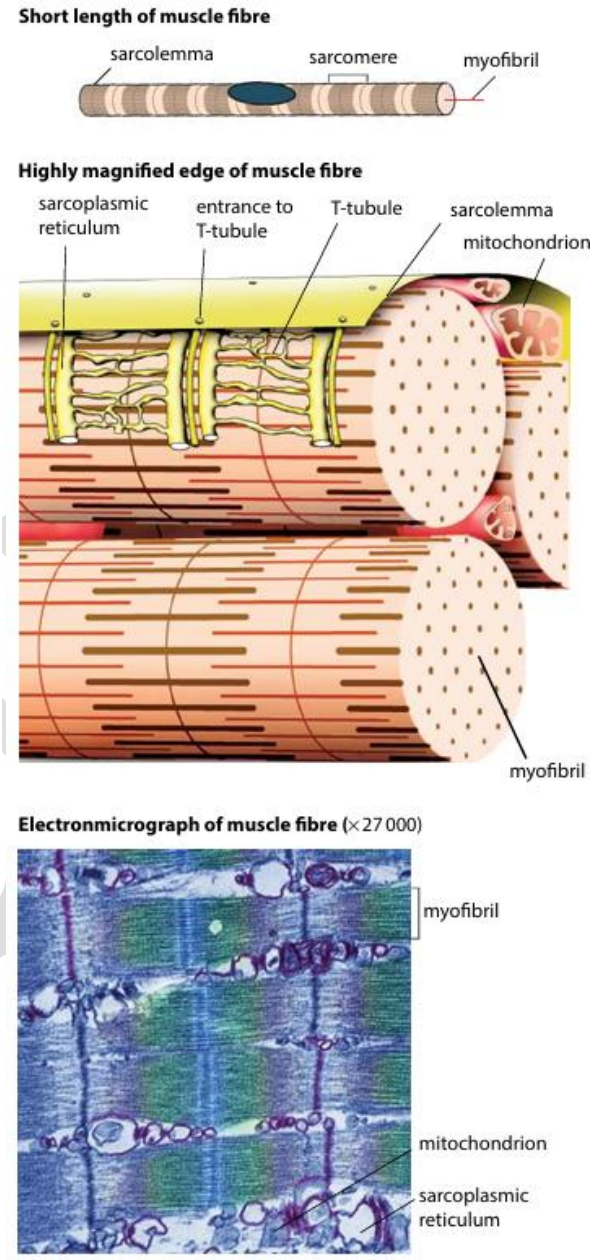


Figure 15.26 Ultrastructure of part of a muscle fibre.

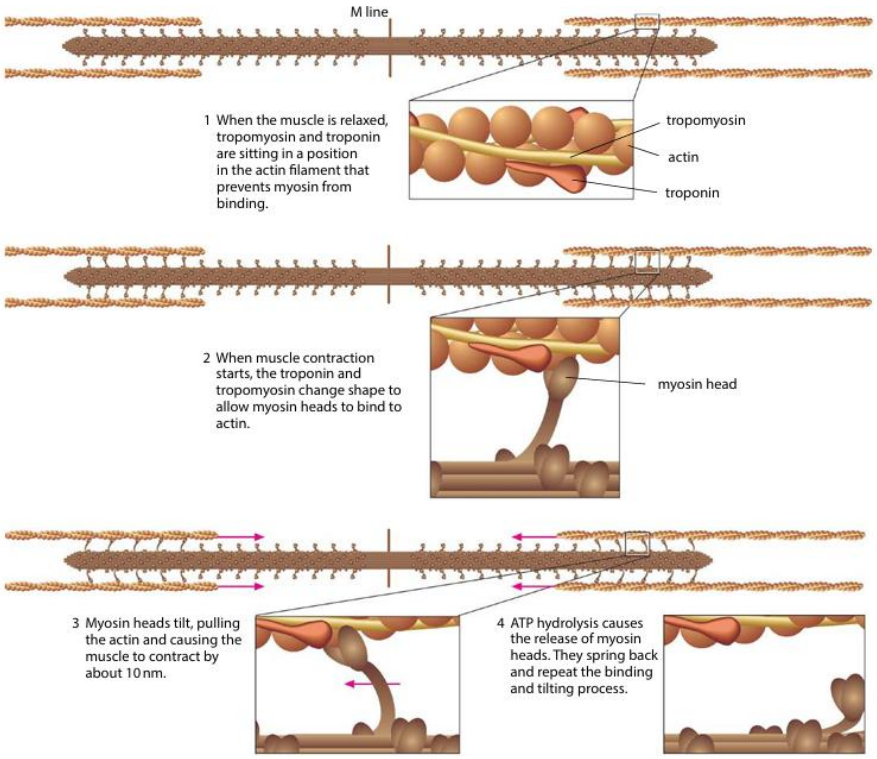


Figure 15.28 The sliding filament model of muscle contraction.

Stimulating muscle to contract

Skeletal muscle contracts when it receives an impulse from a neurone. An impulse moves along the axon of a motor neurone and arrives at the presynaptic membrane (Figure 15.29)

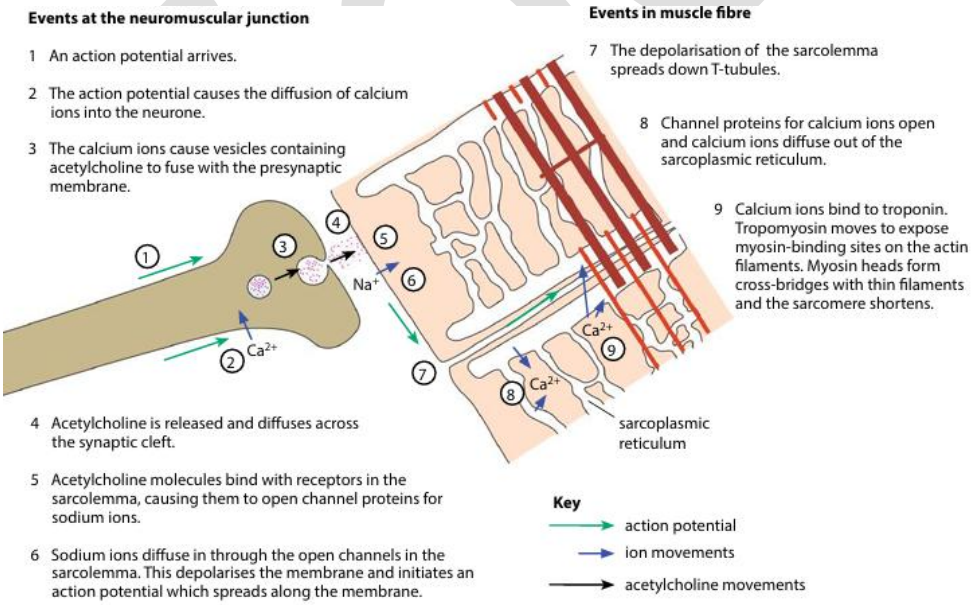


Figure 15.29 The sequence of events that follows the arrival of an impulse at a motor end plate.

Providing ATP for muscle contraction

A contracting muscle uses a lot of ATP. The very small quantity of ATP in the muscle fibres in a resting muscle is used up rapidly once the muscle starts to contract. More ATP is produced by respiration – both aerobic respiration inside the mitochondria and, when that cannot supply ATP fast enough, also by lactic fermentation in the sarcoplasm (Figure 15.30).

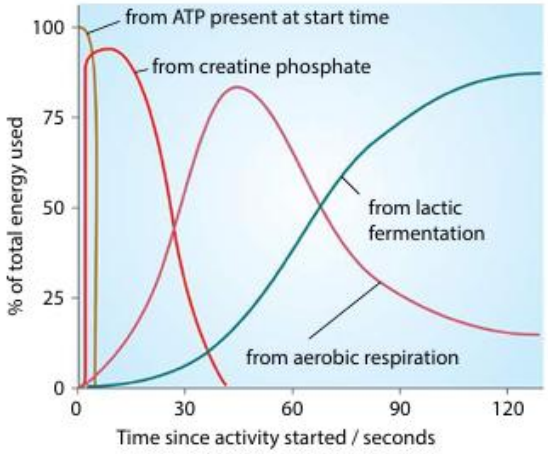


Figure 15.30 Energy sources used in muscle at high power output.

Hormonal communication

The nervous system's fast control is expensive due to energy needed for pumping sodium and potassium ions, protein synthesis, and maintaining neurones and Schwann cells. A cheaper alternative is using hormones secreted in small quantities and dispersed in the blood. Hormones like adrenaline, insulin, glucagon, and ADH are made in endocrine glands, which are ductless glands without ducts. Hormones are cell signaling molecules, with water-soluble peptides binding to receptors on target cells, and lipid-soluble steroid hormones binding to receptor molecules inside the cytoplasm or nucleus, activating processes like transcription.

Hormonal control of the human menstrual cycle

After puberty in women, the ovaries and the uterus go through a series of changes that recur approximately every 28 days – the menstrual cycle. Figure 15.31

The menstrual cycle is regulated by glycoprotein hormones released by the anterior pituitary gland and ovaries. These hormones control follicle activity, releasing oestrogen and progesterone during the monthly ovarian cycle. Menstruation starts with the onset of menstruation, which lasts four to eight days. During menstruation, the anterior pituitary gland secretes LH and FSH, increasing their concentrations. Oestrogen stimulates the endometrium to grow, thicken, and develop blood capillaries.

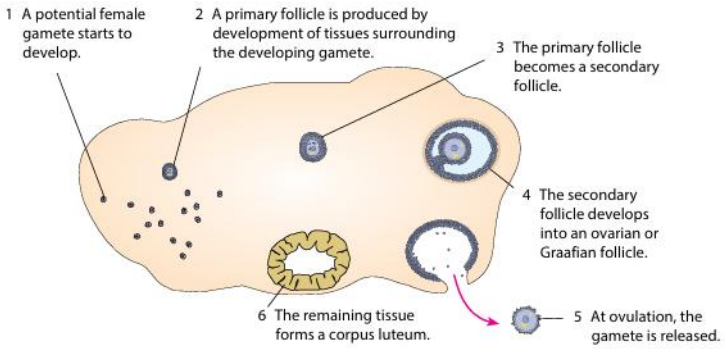


Figure 15.31 The ovary, showing the stages leading up to and following ovulation.

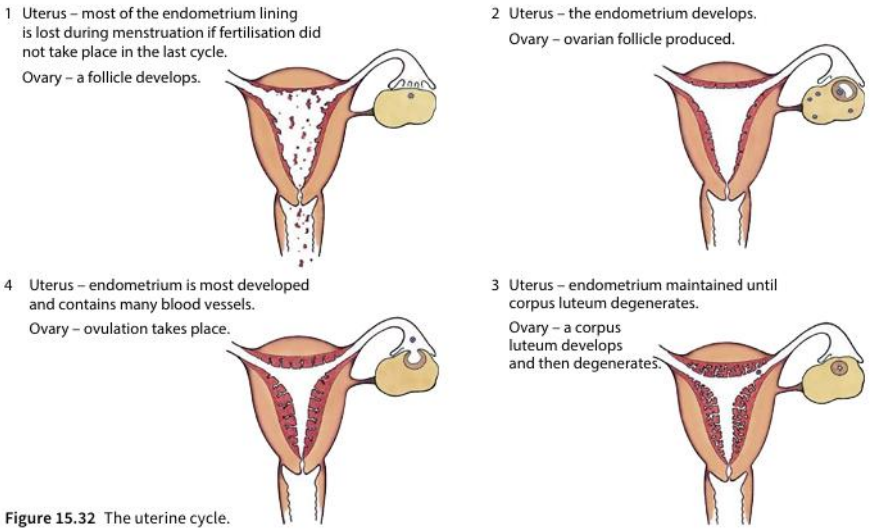


Figure 15.32 The uterine cycle.

Birth control

'Birth control' means taking control over if and when a couple have a child. It may involve contraception, which means preventing fertilisation when sexual intercourse takes place. There are also several methods of birth control that do not prevent conception, but rather prevent the tiny embryo from implanting into the lining of the uterus.

The menstrual cycle is regulated by glycoprotein hormones released by the anterior pituitary gland and ovaries. These hormones control follicle activity, releasing oestrogen and progesterone during the monthly ovarian cycle. Menstruation starts with the onset of menstruation, which lasts four to eight days. During menstruation, the anterior pituitary gland secretes LH and FSH, increasing their concentrations. Oestrogen stimulates the endometrium to grow, thicken, and develop blood capillaries.

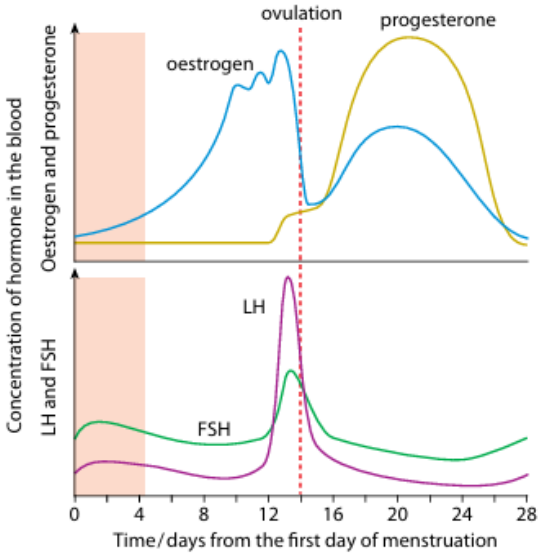


Figure 15.33 Changes in the concentrations of hormones in the blood during the menstrual cycle.

The morning-after pill

This form of birth control is intended to be taken after a woman has had unprotected sexual intercourse and thinks that she might be pregnant. It might be taken by a woman who forgot to take her oral contraceptive pill, or if a condom broke, or by someone who was raped, as well as by a woman who simply did not take any precautions to prevent pregnancy

Control and coordination in plants

Plants, like animals, have communication systems that allow coordination between different parts of their bodies. They too must respond to changes in their external and internal environments, as we saw in Chapter 14. Most plant responses involve changing some aspect of their growth to respond to factors such as gravity, light and water availability.

Electrical communication in plants

Plant cells have electrochemical gradients across their cell surface membranes in the same way as in animal cells. They also have resting potentials. As in animals, plant action potentials are triggered when the membrane is depolarized

The Venus fly trap is a carnivorous plant that obtains nitrogen compounds by trapping and digesting small animals, primarily insects. Charles Darwin described it as one of the most wonderful plants in the world. The specialized leaf has two lobes with red insides and three stiff sensory hairs that respond to being deflected. The insect's touch triggers action potentials that travel fast across the leaf, causing the trap to fold over and trap the insect. The trap takes less than 0.3 seconds to close and trap the insect. The lobes of the leaf bulge upwards when the trap is open, and the trap snaps shut.

Figure 15.35 The leaves of the Venus fly trap, *Dionaea muscipula*, have a group of stiff, sensitive hairs in their centres. When these are touched, the leaves respond by closing, trapping whatever was crawling over them. Digestive juices are then secreted, and the soluble products absorbed into the leaf cells.

Chemical communication in plants

Chemicals known as plant hormones or plant growth regulators are responsible for most communication within plants. Unlike animal hormones, plant growth regulators are not produced in specialised cells within glands, but in a variety of tissues. Here we consider two types of plant growth regulator:

■ ■ auxins, which influence many aspects of growth including elongation growth which determines the overall length of roots and shoots

■ ■ gibberellins, which are involved in seed germination and controlling stem elongation.

Abscisic acid (ABA) is another plant hormone, which controls the response of plants to environmental stresses such as shortage of water (Chapter 14, page 323).

Auxins and elongation growth

Plants make several chemicals known as auxins, of which the principal one is IAA (indole 3-acetic acid, Figure 15.36).

Growth in plants occurs at meristems, such as those at shoot tips and root tips (Chapter 5). Growth occurs in three stages: cell division by mitosis, cell elongation by absorption of water, and cell differentiation. Auxin is involved in controlling growth by elongation (Figure 15.37).

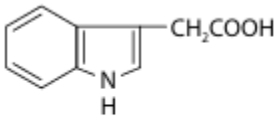


Figure 15.36 The molecular structure of indole 3-acetic acid, IAA.

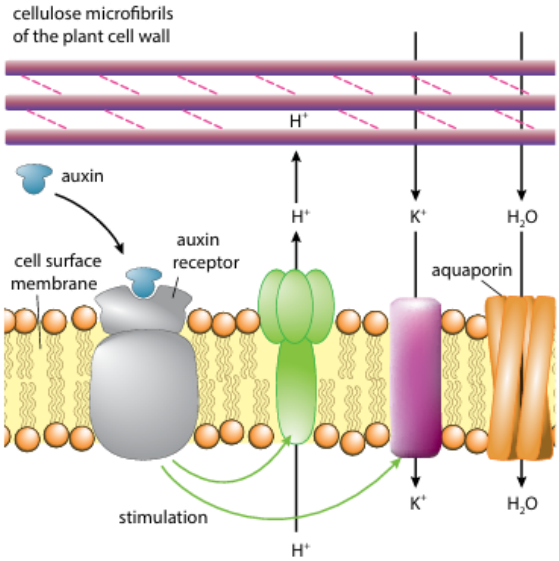


Figure 15.37 The binding of auxin to its receptor is thought to activate a membrane protein, which stimulates the pumping of protons out of the cell into the cell wall where they lower the pH and break bonds. Potassium ion channels are also stimulated to open leading to an increase in potassium ion concentration in the cytoplasm. This decreases the water potential so water enters through aquaporins.

Gibberellins

Gibberellins are plant growth regulators that are synthesised in most parts of plants. They are present in especially high concentrations in young leaves and in seeds, and are also found in stems, where they have an important role in determining their growth

Gibberellins and stem elongation

The height of some plants is partly controlled by their genes. For example, tallness in pea plants is affected by a gene with two alleles; if the dominant allele, Le, is present, the plants can grow tall, but plants homozygous for the recessive allele, le, always remain short.

Gibberellins and seed germination

Gibberellins play a crucial role in seed germination, allowing seeds like wheat and barley to survive in adverse conditions. The seed contains an embryo surrounded by endosperm and a protein-rich aleurone layer. Water absorption stimulates the embryo to produce gibberellins, which diffuse to the aleurone layer and stimulate cell synthesis of amylase. Amylase mobilizes energy reserves by hydrolyzing starch molecules, converting them to maltose molecules, which are transported to the embryo for energy.

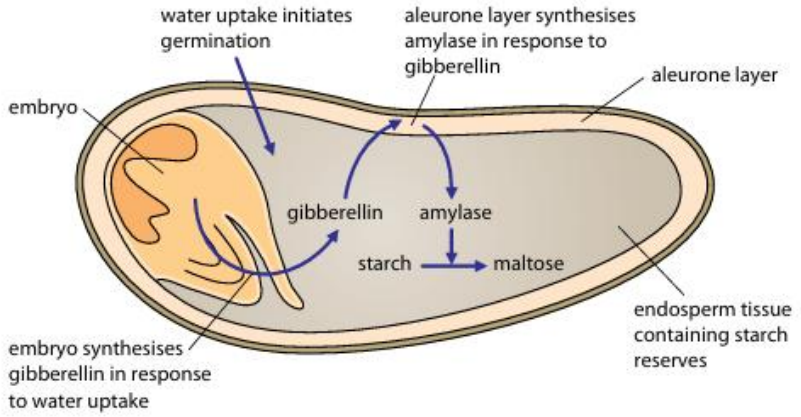


Figure 15.38 Longitudinal section through a barley seed, showing how secretion of gibberellins by the embryo results in the mobilisation of starch reserves during germination.

Revision questions

1. Read through the following passage on homeostasis and then answer the questions. Homeostasis is the regulation of the internal environment within narrow limits. This gives the organism a degree of independence from the external environment. The regulation is carried out by negative and positive feedback mechanisms which when not required are damped. All living organisms possess some powers of homeostasis but homeostasis is best developed in birds and mammals.

(a)(i) What do you understand by the term 'internal environment'?

(ii) Distinguish negative feedback control from positive feedback control.

(iii)Give one example of negative feedback control and one example of positive feedback control in mammals.

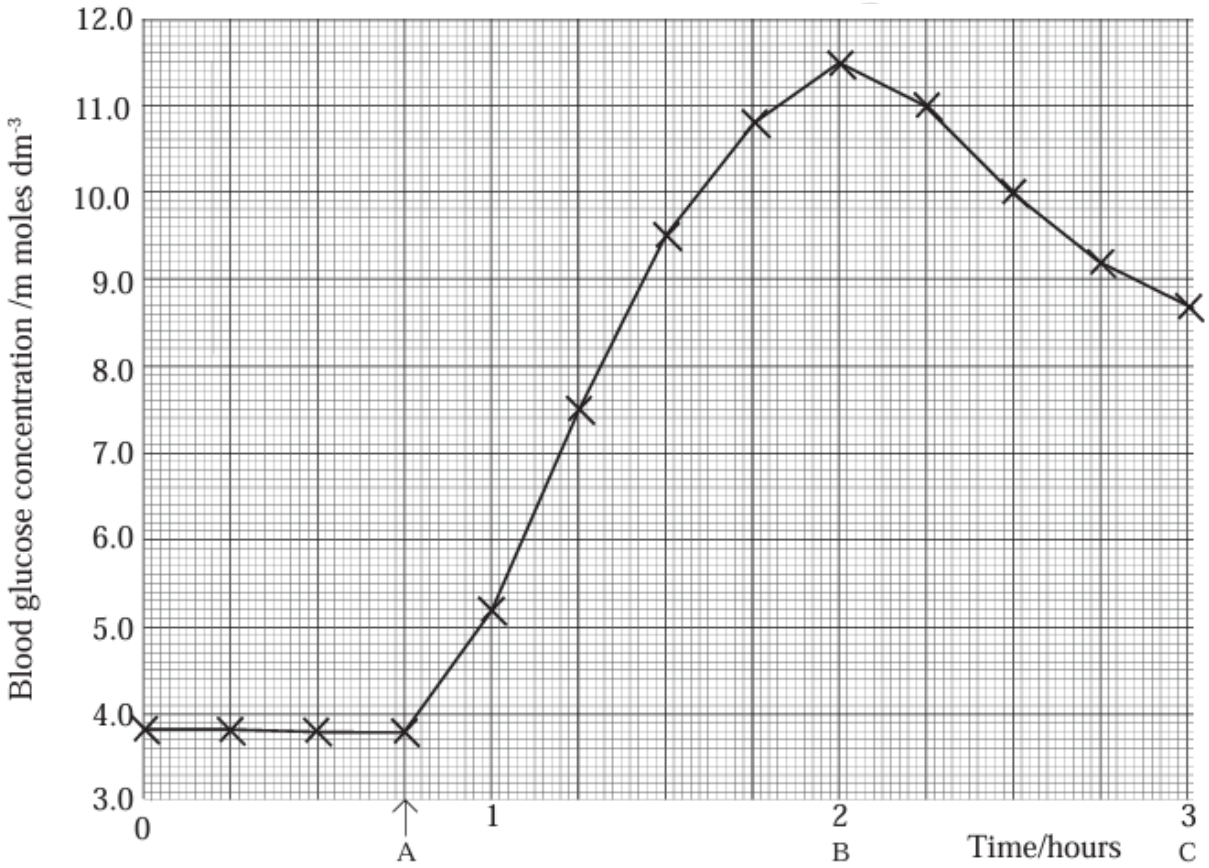
(iii)Give one example of negative feedback control and one example of positive feedback control in mammals.

(b)State one example of homeostatic control in each of the following organisms

Amoeba: .....
.....

Marram grass:.....
.....
Human:.....

2. The graph below shows the changes in blood glucose concentration of a human subject over several hours. Prior to point A the subject had not eaten or drunk for a period of 8 hours. At point A the subject drank 200 cm3 of a suspension containing 100 mg of glucose.



(a)(i) Comment on the blood glucose concentration prior to point A.

(ii) By reference to the graph determine the increase in blood glucose concentration between 1 hour and 1 hour 30 minutes

(b)With reference to the hormones involved, and to the biochemical changes occuring, explain thechanges that occur in blood glucose concentration between A and B and B and C.

3.

Read through the following passage which refers to ADH and then fill in the spaces with the most appropriate word or words.

The presence or absence of ADH in the blood is controlled by ..... . Receptors in the ..... sense an increase in the ..... of the blood plasma and transmit nerve impulses to the ..... which releases ADH into the blood by ..... . ADH attaches onto target receptors on the ..... cell membranes. It has the effect of making these membranes .....which thus allows water to be..... .

4.

The table below lists a number of homeostatic actions which are stimulated by certain hormones. Write the name of one hormone for each action in the appropriate box. Some hormones may be named more than once.

Action	Hormone
Breakdown of glycogen in the liver	
Non-shivering thermogenesis	
Lowering of blood glucose concentration	
Acceleration of heart beat	
Reduction of water loss in urine	
Increase in flow of gastric juice	
Increase in antibody release by plasma cells	

5.

The table below shows a typical daily water balance of a human body.

Water gain		Water loss	
Food	850cm^3	Faeces	130cm^3
Drink	1450cm^3	Exhaled air	430cm^3
Respiration (all cells)	380cm^3	Sweat	600cm^3
		Urine	1520cm^3
Total	2680cm^3	Total	2680cm^3

(a)(i) Why must water gain be balanced by water loss?

(ii) Select two of the above quantities which would increase during a period of vigorous exercise. In both cases explain why the values increase

(iii) Suggest why only small volumes of concentrated urine are produced during very hot weather.

(b)Explain how the human controls water loss

6.

The table below shows the frequency at which the contractile vacuole of an Amoeba empties in various concentrations of sea water.

Percentage concentration of sea water	Number of times contractile vacuole empties per hour
0 (pure water)	95
10	76
20	69
30	41
40	21
50	9
60	2
70	0
80	0

(a)What is the function of the contractile vacuole in Amoeba?

(b) Explain how the contractile vacuole carries out its function.

(c) Explain the change in the rate of emptying of the contractile vacuole shown in the table.

7. (a) In the box below is a list of drugs which affect the nervous system, (i) to (v), and a jumbled list of drug actions, A to E. Select the correct drug activity for each drug by placing the appropriate letter in the relevant box.

Drug		Letter
Atropine	(i)	
Curare	(ii)	
Caffeine	(iii)	
Crack/cocaine	(iv)	
Nicotine	(v)	

A. Reduces threshold of stimulation of neurones allowing facilitation (easier excitation).

B. Blocks action of acetylcholine at parasympathetic postganglionic nerve endings.

C. Blocks acetylcholine action at neuromuscular junctions.

D. Mimics action of acetylcholine on postsynaptic membranes. E. Interferes with normal functioning of brain transmitters serotonin and dopamine.

(b)The frequency of the heart beat is regulated by the autonomic nervous system and thus can be increased or decreased by the action of certain chemicals and drugs.

(i) What effect does stimulation by the sympathetic nervous system and parasympathetic nervous system have on the frequency of the heart beat?

ii) The following table shows the effect of certain substances on the rate of the heart beat. Complete the table by writing ‘increased’ or ‘decreased’ in the appropriate boxes.

Chemical	Effect on rate of heart beat
adrenaline	
acetylcholine	
atropine	
nicotine	
thyroxine	

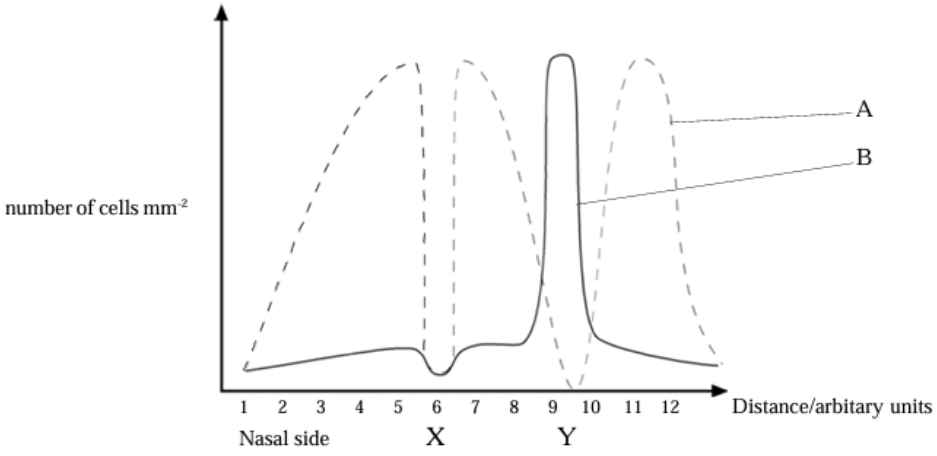
8.

(a) The table below relates to certain types of receptor found in the body. Complete the empty boxes by writing in one main function for each type of receptor and one main site in the body where each receptor can be found.

Receptor	Function	Site
Proprioceptor		
Thermoreceptor		
Baroreceptor		
Osmoreceptor		

[8]

(b) The graph below shows the number of receptor cells in the human retina along a one millimetre wide belt from the nasal side of the retina to the other side. Distances are in arbitary units.

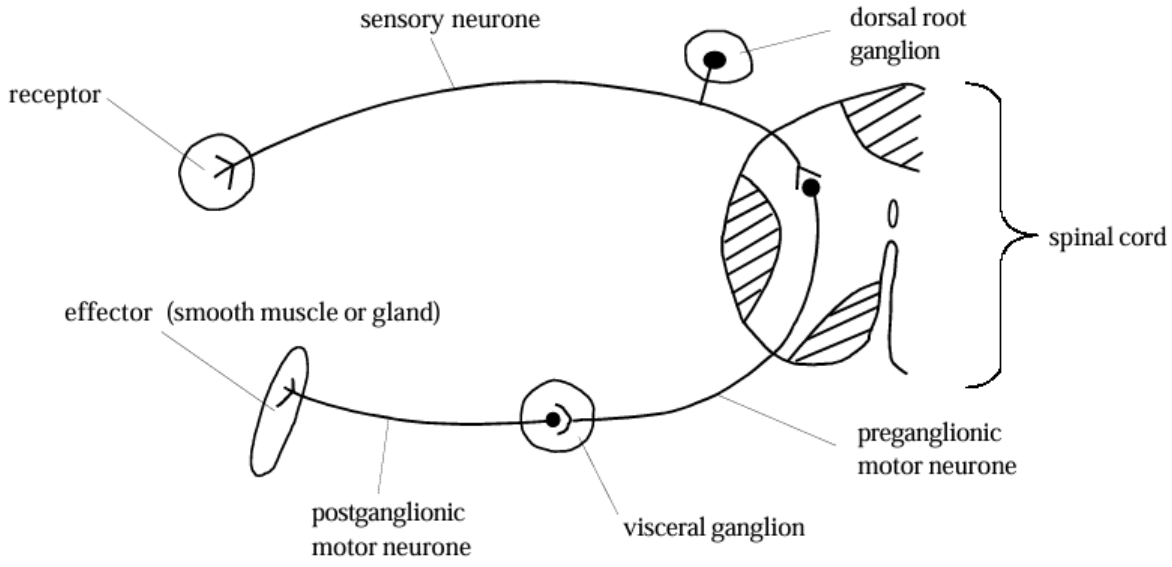


(i) Name the two types of receptor A and B and state their main function

ii) Suggest an explanation for the numbers of receptors found at X and Y.

9.

The diagram shows the spinal cord and neurones involved in a simple autonomic reflex arc.



(a) State three ways in which this reflex arc differs from an arc in the voluntary nervous system (such as the knee jerk reaction).

(b) The table below indicates some effects of sympathetic and parasympathetic stimulation. If an effect is correct put a tick (✓) in the appropriate box and if it is incorrect place a cross (✗) in the appropriate box.

Effect	Sympathetic stimulation	Parasympathetic stimulation
Increases cardiac output		
Constricts pupils		
Increases peristalsis in gut		
Increases sweat secretion		
Stimulates bronchoconstriction		
Stimulates salivation		
Causes vasoconstriction of skin arterioles		

(a)What is a 'conditioned reflex' and how may it become established?

(b)How do industries sometimes use conditioning when advertising their products?

(c)Distinguish 'short term memory' from 'long term memory'