CHAPTER

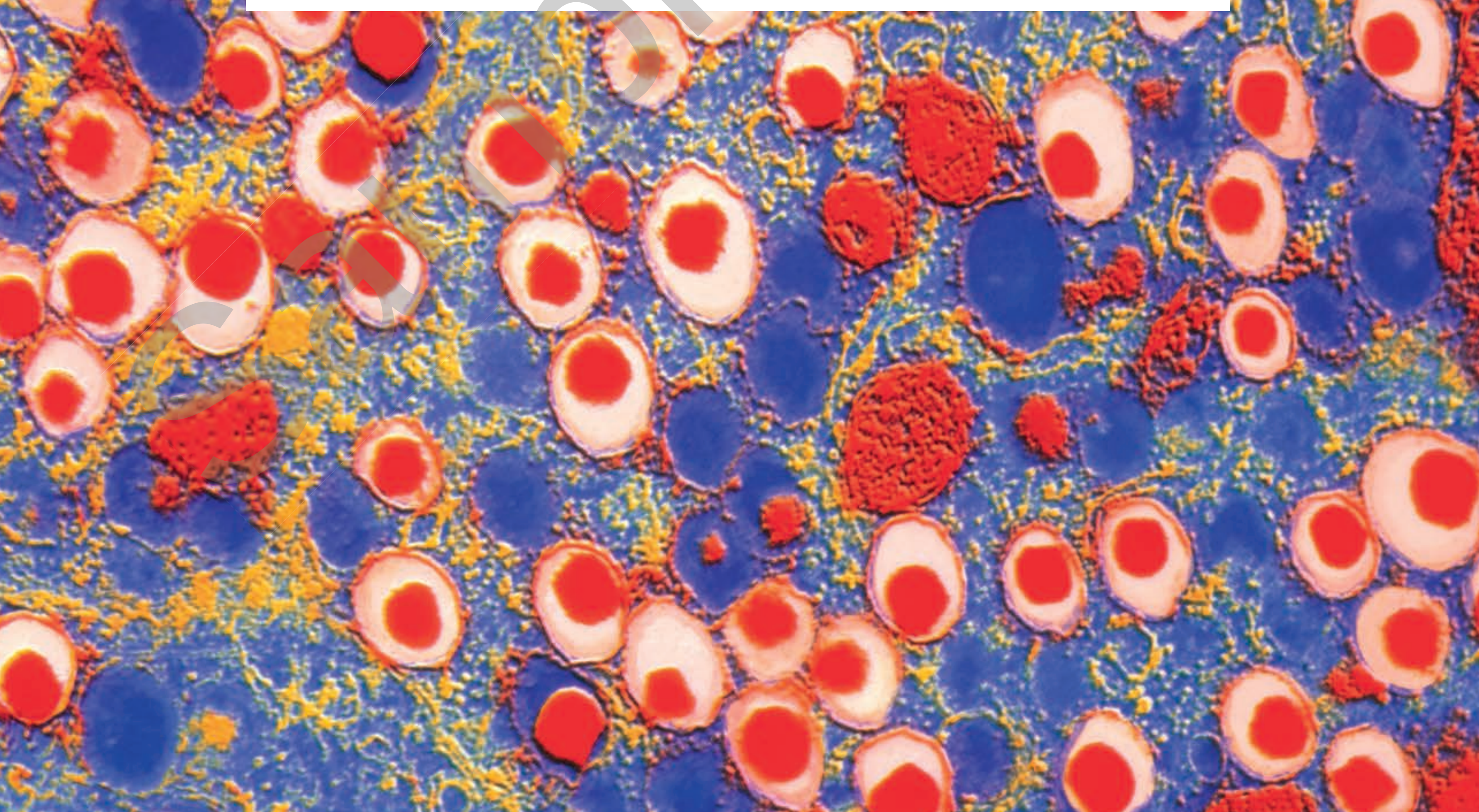
05 Regulation of systems

Organisms are constantly experiencing changes in their external environment. To function effectively, an organism must be able to regulate and maintain a stable internal environment. For vascular plants regulation of water balance is essential, and for animals regulation of body temperature, blood glucose and water balance is critical to healthy functioning.

In this chapter you will examine some of the ways in which organisms regulate and maintain functionality of their internal environment and the consequences of malfunctions in homeostatic mechanisms.

Key knowledge

- regulation of water balance in vascular plants **5.1**
- regulation of body temperature, blood glucose and water balance in animals by homeostatic mechanisms, including stimulus–response models, feedback loops and associated organ structures **5.2**
- malfunctions in homeostatic mechanisms: type 1 diabetes, hypoglycaemia, hyperthyroidism. **5.3**



5.1 Regulatory mechanisms in plants

Plants carry out two energy-transforming processes. Cellular respiration occurs throughout all of the cells in vascular plants, requiring oxygen and producing carbon dioxide. However, photosynthesis occurs primarily in cells in the leaves, where chloroplasts in the cells convert water and carbon dioxide, in the presence of sunlight, into glucose, water and oxygen. To undergo both of those processes there are specialised tissues and structures in place to exchange gases and move substances. You learnt about the specialised cells and tissues for water transport in vascular plants in Chapter 4. In this section, you will learn about how plants use these specialised structures to regulate water balance.

GAS EXCHANGE IN VASCULAR PLANTS

Most plants do not have specialised organs for gas exchange. Simple plants, such as mosses, have leaves that are small and extremely thin—only one cell thick—so each cell is in direct contact with the surrounding environment. Gases such as oxygen and carbon dioxide can easily diffuse directly between the air and the contents of each cell. In **vascular plants** (plants with conducting tissue), the exchange of oxygen and carbon dioxide in the leaves, stems and roots occurs by diffusion through special openings in the epidermis called **stomata** (singular stoma).

> Stomata in the leaves regulate the exchange of gases between a plant and its external environment.

Recall from Chapter 4 that the rate of movement of gases between plants and the atmosphere is regulated by the stomata, the main route through which gas exchange occurs. When the stomata are closed, the exchange of oxygen, carbon dioxide and water vapour between the plant and its environment virtually stops. Only small quantities of gases are able to pass directly through the epidermis and the overlying cuticle (the outer waxy layer).

Plant cells are loosely packed, allowing rapid diffusion of gases through intercellular spaces, which are filled with air (Figure 5.1.1). During gas exchange, oxygen and carbon dioxide diffuse from these air spaces through the water film covering the cells and into the cells along concentration gradients. Diffusion also occurs against the concentration gradient.

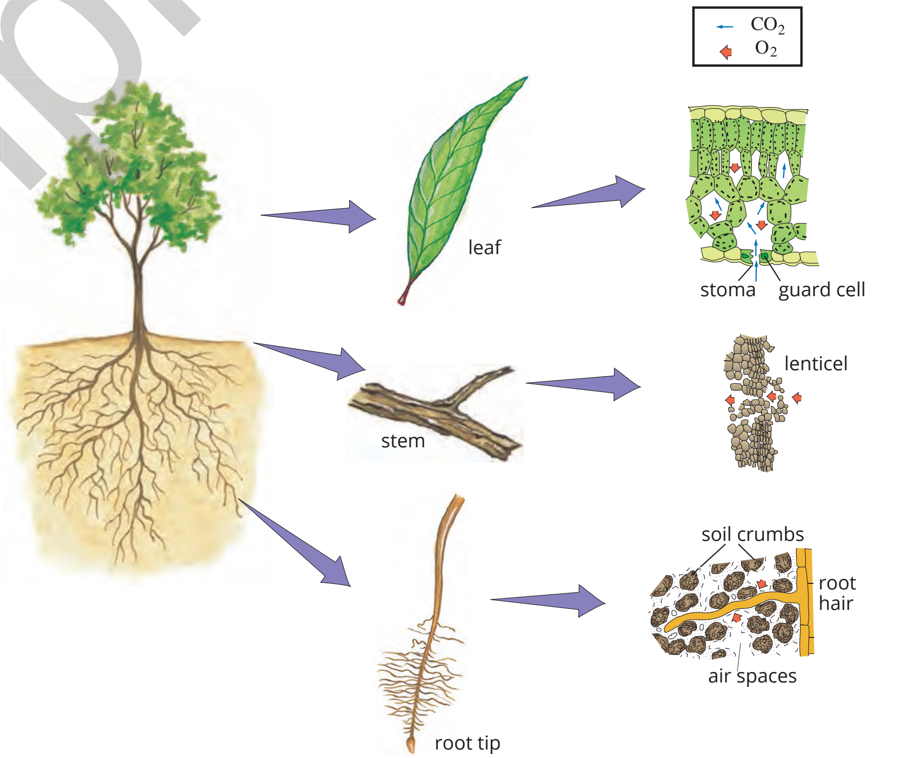


FIGURE 5.1.1 Routes of gas exchange with cells of leaves, stems and roots

Stomata

Stomata are tiny pores in the epidermis, bordered by two highly specialised epidermal cells called **guard cells** (Figure 5.1.2). Unlike other epidermal cells, guard cells contain chloroplasts. Stomata can occur on any part of a plant except the roots, but in most species they are most abundant on the lower epidermal surface of the leaves.

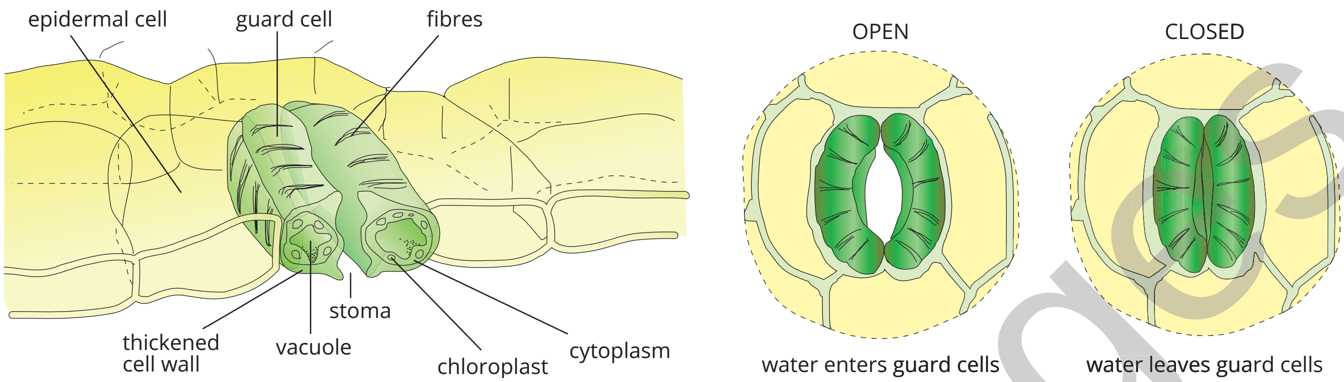


FIGURE 5.1.2 Gas exchange in leaves occurs through stomata. When water enters guard cells, they expand, opening the stoma. Guard cells expand lengthwise because they have a thickened inner cell wall with cellulose fibres that prevent the cells expanding in width.

The number and size of stomata on a leaf vary according to the plant species and the environmental conditions under which it has grown. In a typical plant, most stomata are on the underside of the leaves (Figure 5.1.3), away from the drying effect of the Sun's rays. In contrast, stomata in floating aquatic plants, such as water lilies, are confined to the upper epidermis. In plants such as eucalypts, which are adapted to dry conditions, stomata are often in sunken pits in the surface of the leaves. This reduces the direct flow of air across the leaves and so reduces water loss.

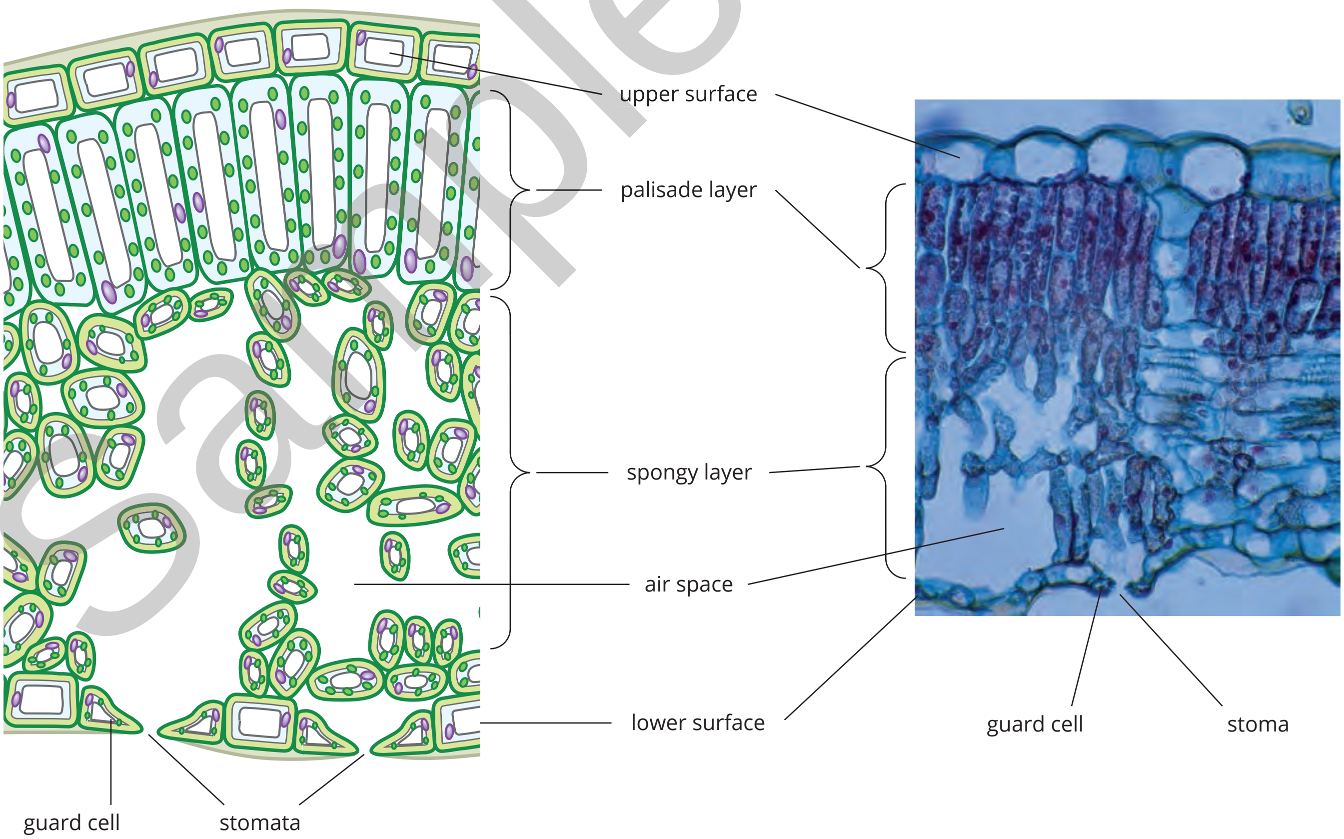


FIGURE 5.1.3 Cross-section of a leaf. Most stomata are on the underside of the leaves, away from the drying effect of the Sun's rays.

Controlling guard cells

Guard cells have the following structural features relating to their function.

- They are joined at their ends in pairs.
- Their cell walls are thicker on the side adjacent to the stoma.
- Bands of inelastic fibres run around each cell wall.

When water passes into the guard cells, their internal fluid pressure, or **turgor**, increases. This causes them to expand in the only direction possible: lengthways. The guard cells buckle and open the stoma.

Terrestrial plants, like terrestrial animals, must reduce loss of water by evaporation. The moist surfaces that they use for gas exchange are major sites of water loss. Therefore, the stomata act to balance the plant's need to obtain carbon dioxide for photosynthesis against the dangers of drying out due to the loss of water from the leaves.

Stomata close when it is hot and dry to prevent excess water loss from the plant.

During daylight, when plants undergo photosynthesis, large volumes of carbon dioxide and oxygen are exchanged with the environment through open stomata. At night, when photosynthesis is not occurring, stomata are usually closed. Stomata also close during the day if it is very hot and dry. This prevents excessive water loss, but also drastically reduces the rate of photosynthesis.

WS 16

Thus, conditions that usually favour the opening of stomata are abundant water, bright light and low internal carbon dioxide concentrations.

Stems and roots

In the epidermis of green stems, as in the leaf epidermis, there are stomata through which gas exchange takes place. In woody stems and mature roots, the epidermis is replaced by a layer of cork cells that are waterproof and airproof. Air passes freely through groups of these loosely packed cells to the cells beneath. Each group of loosely packed cells is called a **lenticel**.

Roots exchange gases with the air in spaces in the soil. Oxygen readily diffuses into the film of moisture surrounding **root hairs**, and then into the roots themselves. When soil is waterlogged due to excessive rain or poor drainage, the spaces in the soil are filled with water instead of air. Because the amount of oxygen dissolved in water is so much less than the amount of oxygen in air, the roots may not be able to get enough oxygen for their needs. The root cells may die, killing the plant. Many indoor plants are killed by over-watering.

MOVEMENT OF WATER AND SOLUTES

Vascular plants use **vascular tissue** to transport water and mineral ions absorbed from the soil and sugars produced in the leaves to cells throughout the plant. Vascular tissue forms continuous, closed tubular pathways through roots, stems and leaves and is visible as veins in leaves and the stringy parts of celery. There are two types of vascular tissue: xylem and phloem. You learnt about the structure of xylem and phloem in Chapter 4 and you will learn more about the function of these vascular tissues in this section.

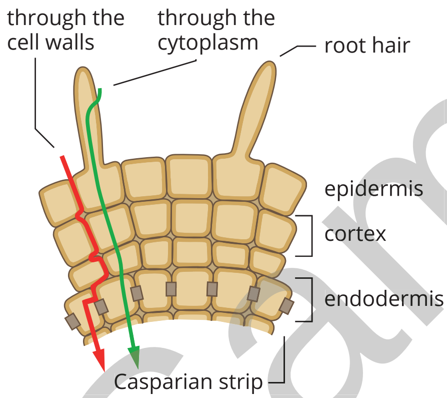


FIGURE 5.1.4 Water and mineral ions move through the roots via the extracellular pathway (red arrow) and the cytoplasmic pathway (green arrow). From the Casparian strip, water can no longer travel along the extracellular pathway and is forced into the cytoplasm before moving into the xylem.

Root absorption

There are two possible pathways for movement of water and mineral ions absorbed from the soil through the roots. These are the extracellular pathway and the cytoplasmic pathway. In the **extracellular pathway**, most water and some mineral ions pass through or between cell walls (Figure 5.1.4). In the **cytoplasmic pathway**, most mineral ions and some water pass through the cytoplasm of living root cells (Figure 5.1.4).

The cytoplasmic pathway involves substances entering a root hair cell by crossing the cell's plasma membrane, and then passing from cell to cell through microscopic channels called **plasmodesmata** (singular plasmodesma). The three types of transport that move substances across plasma membranes along the cytoplasmic pathway are as follows:

- **Active transport**—Most dissolved mineral ions are selectively taken into roots by active transport. Proteins in the plasma membrane of root cells, specific for each ion, are used for this purpose. As a result, the concentration of ions in the vascular tissue of roots can be more than 100 times their concentration in the water of the surrounding soil.
- **Osmosis**—The high concentration of ions in the vascular tissues of terrestrial plants creates a very large osmotic gradient. The **osmotic gradient** is the difference between the concentration of solutions on either side of a semi-permeable membrane. Large amounts of water move into root cells along the osmotic gradient.
- **Diffusion**—Some mineral ions such as potassium and phosphate enter the roots by diffusion. The uptake of these nutrients therefore depends on the rate of water uptake.

You learnt about active transport, osmosis and diffusion in Chapter 2.

Water and mineral ions are absorbed from the soil through the roots via the extracellular pathway or the cytoplasmic pathway.

Entering the xylem

From either of the two pathways through the roots, water and mineral ions must then reach the xylem tissue. You learnt in Chapter 4 that the **xylem** consists of hollow chains of dead cells that transport water and mineral ions upwards from the roots. Between the roots and the xylem is a waterproof layer of cells that form a barrier known as the **Casparian strip** (Figure 5.1.4). At this barrier, water travelling through the extracellular pathway is forced into the cytoplasm. In this way, the Casparian strip ensures the regulation of the substances entering the xylem.

Root pressure

In some plants the osmotic gradient draws in so much water from the roots that it can travel up to 10 metres up the stem. This is known as **root pressure** (Figure 5.1.5). Root pressure causes the rising of sap (water and mineral ions) in spring in deciduous plants such as birch trees, but does not occur in all plants.

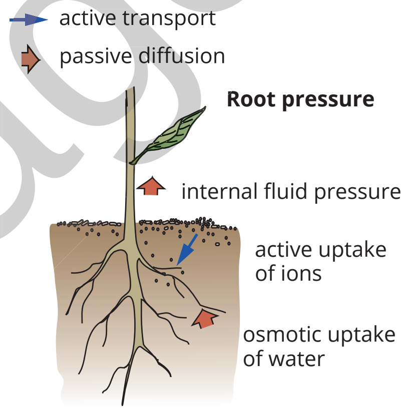


FIGURE 5.1.5 Internal fluid pressure (root pressure) in the roots of some plants causes fluid to rise through the xylem vessels.

Transpiration

Transpiration is the passive movement of water through a plant from the roots, including its evaporation through the stomatal pores in leaves. The plant uses a small amount of water for metabolic processes, but 99% of the water absorbed by the roots is lost via transpiration.

Transpiration is a passive process: it does not require energy expenditure by the plant. It is driven by the heat energy in sunlight, which breaks the **cohesive bonds** between water molecules, allowing evaporation through the stomata.

Water molecules are very cohesive; that is, they have a strong tendency to stick together. When water evaporates from the cell walls of the leaf, cohesion between the water molecules remaining in the leaf draws water from nearby xylem vessels to replace the lost water.

In this way thousands of leaf cells, each drawing water from xylem, create a differential pressure that pulls water up xylem vessels from the roots. This continuous one-way flow of water from roots to leaves is called the **transpiration stream**. The pull of transpiration can be strong enough to draw water to the top of the tallest tree, more than 100 metres high.

Although transpiration is the cause of 99% of a plant's water loss, it is vital because it enables plants to:

- absorb the water necessary for the process of photosynthesis
- transport mineral ions to leaf cells and fruits
- cool down and not become overheated.

Transpiration is the movement of water through a plant—from absorption by the roots to its evaporation from the leaves.

Factors that affect transpiration rates

Water vapour is lost from leaves mainly by transpiration through open stomata. The total surface area across which transpiration takes place is related to the degree of opening of all stomata. This is by far the most important factor affecting the rate of transpiration. The greater the number of stomata and more open they are, the more surface area there is from which water can be lost.

Other factors that affect the rate of transpiration (Figure 5.1.6) include:

- humidity—transpiration rates decrease when there is a lot of water vapour in the air (i.e. a high level of humidity), because this reduces the water concentration gradient between leaf spaces and air, so fewer water molecules evaporate into the air.
- temperature—transpiration rates increase as temperature increases because heat energy increases the rate of evaporation of water.
- wind—air currents increase the rate of transpiration by moving water vapour away from the leaf and therefore increasing the rate of evaporation of water.

Environmental factors such as sunlight and humidity affect the rate of transpiration and therefore the rate of water uptake by the roots of the plant. The rate of transpiration is low at night because it is cooler and more humid, and because stomata are usually closed. The leaves of some plants that live in exposed conditions have developed structural features that reduce the rate of transpiration. For example, some plants have hairs on the leaf surface, which create a layer of relatively undisturbed, humid air.

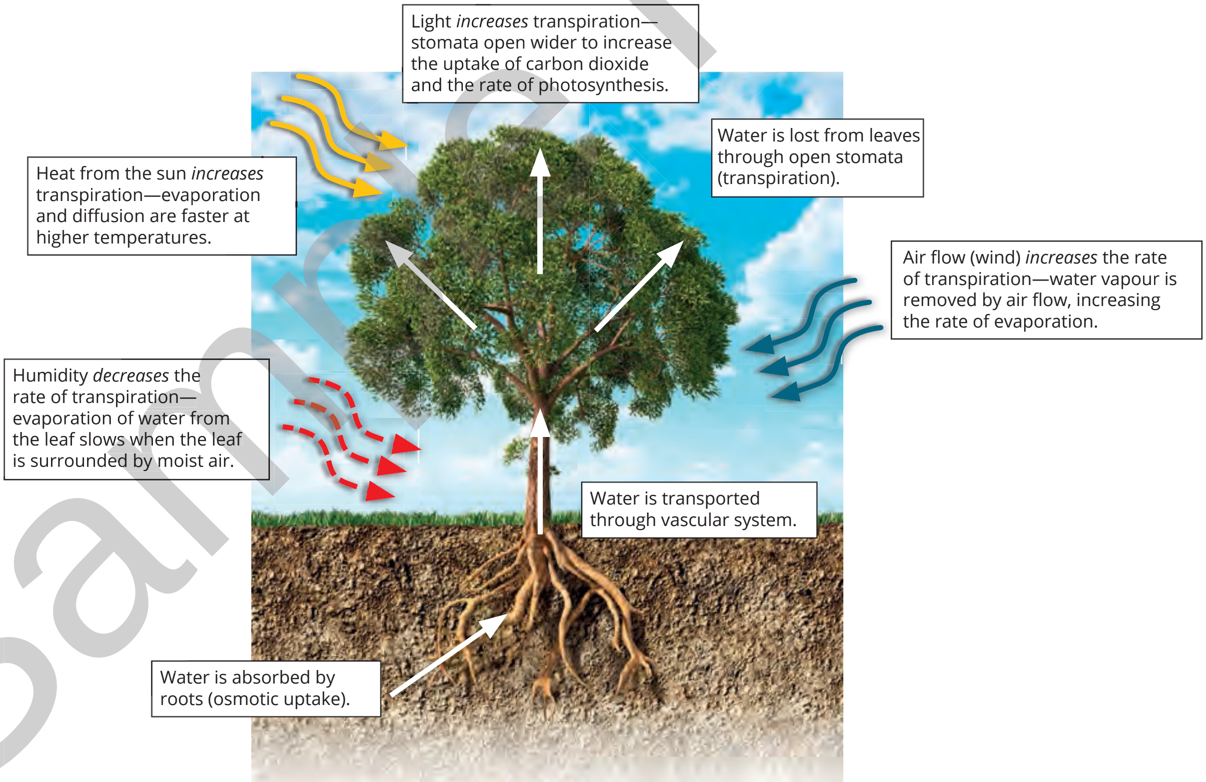


FIGURE 5.1.6 Transpiration is the movement of water through the xylem vessels of vascular plants and into the atmosphere through leaf stomata, in the form of water vapour.

CASE STUDY ANALYSIS

Water transport adaptations in desert plants

Plants that live in deserts need specialised strategies to survive the hot, dry conditions (Figure 5.1.7). In an environment where water is scarce, plants have developed special structures that enable extremely efficient uptake and storage of this precious resource. Cactus plants are specialised to hold large volumes of water in their fleshy leaves, stems and roots. When water does come along, they need to be able to absorb as much as possible, as fast as possible. Their roots are shallow and cover a large area, enabling them to efficiently absorb water from the soil.

Because cacti need to hold onto water once they have it, most cacti are spiny, bitter tasting or toxic, which deters thirsty animals. A thick, waxy cuticle also protects the leaves from damage and reduces water evaporation. While most plants open their stomata during the day, in a hot, dry environment this would lead to substantial water loss through transpiration (Figure 5.1.8). To overcome this problem, cacti open their stomata at night and use a type of photosynthesis called crassulacean acid metabolism (CAM). At night when stomata are open, carbon dioxide is taken in and converted to malic acid, which is stored in the vacuoles of mesophyll cells. In daylight, when the stomata stay closed to reduce water loss, the stored malic acid is broken down, releasing carbon dioxide which diffuses into chloroplasts for conversion into glucose and carbohydrates, completing the photosynthetic process. CAM photosynthesis is excellent for conserving water, but the rate of photosynthesis is slow. This is why many cacti grow very slowly.

Analysis

1 Plants live in a wide variety of environments, including the dry deserts where cacti live, warm and wet tropical rainforests, and slightly drier and cooler temperate savannas with grasses and scattered trees. Determine which plant in Figure 5.1.8 is the:
   - **a** tropical plant
   - **b** desert plant
   - **c** temperate plant.

2 At what time are the stomata of the desert plant most likely to be open? Explain why this would be the case.

3 At what time are the stomata of the temperate plant most likely to be open? Explain why this would be the case.

4 Describe the trend in transpiration rate for the tropical plant in comparison to the other plants, and explain why this trend exists.

FIGURE 5.1.7 Cacti have many special adaptations that enable them to absorb and store water in harsh, dry environments.

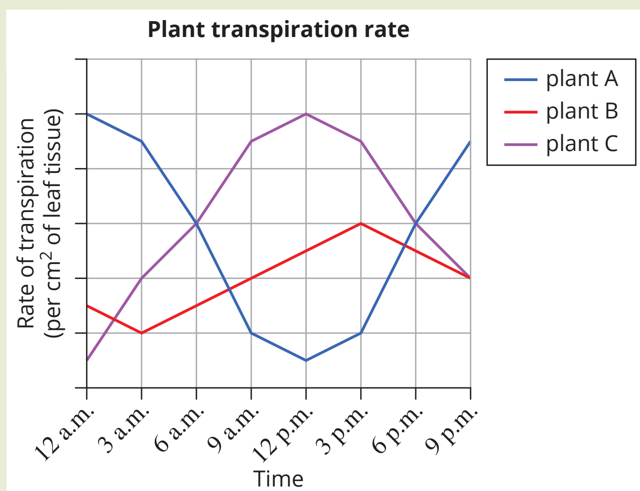


FIGURE 5.1.8 Rate of transpiration in three plants in different environments over 24 hours

Translocation: sources and sinks

Translocation is the transport of organic solutes (e.g. sugars) from the leaves (sources) to other plant tissues (sinks).

The transport of organic solutes from the leaves to other tissues in the plant is known as **translocation**. Leaves produce carbohydrates in the form of sugars during photosynthesis. The non-photosynthetic tissues of the plant also need these carbohydrates and other organic compounds, such as amino acids, hormones and proteins, so these nutrients are transported from the **sources** (the leaves) to the **sinks** (regions where the nutrients are needed, such as roots, stems, flowers and fruits).

The vascular tissue through which these organic solutes move is the **phloem**, and the material that flows through it is known as phloem sap. This sap is composed of around 90% sucrose. Sucrose is a disaccharide that dissolves easily in water, making it a good transport material. It is produced in the chloroplasts of the chlorenchyma (parenchyma cells with chloroplasts) and pumped into the companion cells. From the companion cells the sucrose flows into the sieve tube cells (Figure 5.1.9). Transport in individual sieve tube cells is in one direction only, but bundles of sieve tube cells can transport sap in both directions: upwards to leaves and fruit, or downwards to the roots.

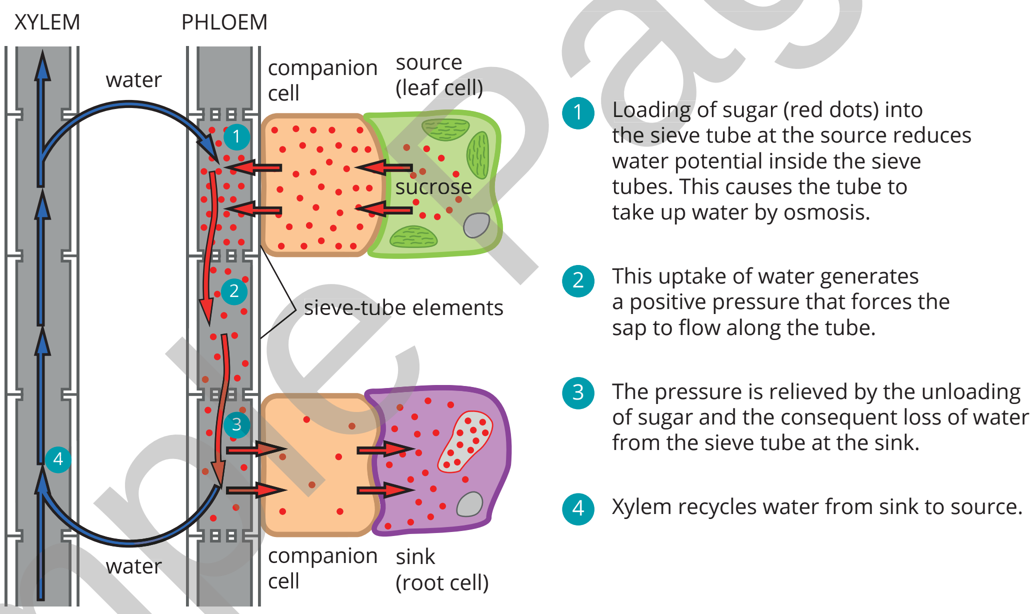


FIGURE 5.1.9 The movement of fluid through the phloem is the result of active pumping of sugars, with water flowing along an osmotic gradient. Sugars and water enter the phloem sieve tubes in leaves in this way and are translocated throughout the plant. Sugars are actively unloaded from sieve tubes where they are required.

Translocation is an active process. It involves the flow of cytoplasm in sieve tubes driven by a pressure gradient, and requires the expenditure of energy by the plant. This pressure gradient begins in the leaves, where sucrose is actively pumped into phloem sieve tube cells. This creates an osmotic gradient that draws water passively into the sieve cells. As water enters, it increases the fluid pressure (turgor) in sieve cells, which pushes fluid from these cells into adjacent sieve cells.

While this is happening in the leaves, sucrose is being actively removed from sieve cells in roots, growing shoots and developing fruit. This causes an osmotic gradient that draws water out of sieve cells and lowers their turgor pressure.

Fluid pressure is therefore high in sieve tube cells in leaves and low in sieve tube cells in roots and growing shoots. A bulk flow of the contents of sieve tubes occurs along this fluid pressure gradient, from sources to sinks. Translocation stops if the cells in the stem die.

5.1 Review

SUMMARY

- Stomata are found in the epidermis of leaves and some stems. They are the main route through which gas exchange occurs in plants.
- Conditions favouring the opening of stomata are abundant water, bright light and low internal carbon dioxide concentrations.
- Roots exchange gases with air in well-aerated soil spaces.
- Most terrestrial plants, including ferns, conifers and flowering plants, have vascular tissues (xylem and phloem) that are specialised for transporting fluid.
- The vascular tissues that support the regulation of water in vascular plants are:
  - xylem, which carries water and mineral ions from roots to leaves
  - phloem, which carries sugars and other organic molecules from leaves to roots.
- Water and inorganic nutrients (mineral ions) are absorbed by the root hairs from the soil by one of two pathways:
  - extracellular pathway
  - cytoplasmic pathway.
- Water and mineral ions are transported through xylem vessels as sap. This transportation occurs in one direction only: from roots to leaves.
- Transpiration is the evaporation of water from stomata in leaves. It is a passive process (driven by energy from sunlight) that also draws water up from the roots, through the xylem, following what is known as the transpiration stream.
- The rate of transpiration is affected by:
  - the number of stomata and their degree of opening
  - temperature
  - humidity
  - wind.
- Translocation is the transport of organic materials from the leaves to the roots, stems, flowers and fruits of the plant, through the sieve tube cells and companion cells of the phloem tissue.
- Translocation is an active process and requires an expenditure of energy by the plant.
- Translocation is driven by a pressure gradient that begins in leaves (sources), where sucrose is actively pumped into phloem sieve cells while being actively removed from sieve cells in roots, growing shoots and developing fruit (sinks).

KEY QUESTIONS

Knowledge and understanding

1. Explain how the structural features of guard cells relate to their function in opening and closing the stomata.
2. Xylem and phloem have different transport functions in vascular plants. Outline the functions of these vascular tissues.
3. Root cells have no chlorophyll, and being underground they are not exposed to sunlight, yet they continue to grow. How do roots obtain their nutrients?
4. Explain why transpiration is vital to plants.
5. Determine whether each of the following environmental factors increases or decreases transpiration rates in plants.
   a high temperature
   b high humidity
   c darkness
   d strong wind

Analysis

6. Predict what will happen to gas exchange in a pot plant if you add excessive amounts of water to it.
7. A student set up an experiment at home to measure and compare the amount of water two different plants release through transpiration and evaporation. The student used the leaves of roses from their garden and the leaves of sunflowers that were in a vase away from the sun. The student securely taped a clear bag around the leaf of the sunflowers but was not able to completely seal the bag around the leaves of the roses due to the thorns. The bags were left on both of the plants overnight. As water transpired and evaporated from the leaves, the vapour condensed and was collected in the bag in the form of liquid water. The sunflower leaves released 35 mL of water whereas the rose leaves released 10 mL. The student concluded that the leaves of the sunflower have a higher transpiration rate than the leaves of roses. Evaluate the design of the experiment and the student's conclusions.

5.2 Homeostatic mechanisms in animals

FIGURE 5.2.1 Sweating results in evaporative cooling and is one of the human body's homeostatic mechanisms to regulate body temperature.

Organisms and cells are constantly experiencing changes in their environment. These changes to the internal and external conditions can adversely affect the survival, growth and function of the organism. The internal environment of an organism must always remain within tolerable limits, even when conditions in the external environment fluctuate widely. When a change occurs in the external environment, an adjustment must be made to the internal environment.

Living organisms rely on their external environments to provide adequate levels of nutrients, water and oxygen and suitable physical conditions, such as light and temperature. Organisms have a range of mechanisms that allow them to adapt to changing conditions while maintaining a stable internal environment (Figure 5.2.1). If an organism is not able to adapt to its external environment, it will suffer cellular damage and possibly death when conditions change.

In this section you will look at how animals regulate their internal environment to maintain stability at the organ, tissue, cellular and intracellular level to sustain life.

Body temperature, blood glucose and water balance are some of the most important factors that are regulated by homeostatic mechanisms. These mechanisms will be explored in detail in this section.

MAINTAINING EQUILIBRIUM

An animal is able to bring about balance or equilibrium in its internal environment by coordinating a number of systems, such as circulatory, respiratory, immune, digestive and excretory, and by changing their behaviour.

Homeostasis

Homeostasis is the maintenance of a stable internal environment within an organism. When an organism is healthy and functioning well, its systems are in homeostasis. Homeostasis is achieved by a variety of mechanisms that respond to keep internal environments within certain limits. This maintains conditions at an optimum level when the internal or external environment changes.

> A response is a physiological or behavioural change in an organism as a result of receiving a stimulus.

Animals coordinate the activities of their cells, tissues, organs and systems so that **responses** occur in an integrated and controlled manner. Detecting and responding to a stimulus requires an effective internal communication system. Communication in animals is achieved by hormonal and nervous system mechanisms, which transmit information between different parts of the organism and translate environmental disturbances into signals that can be interpreted and responded to. For example, the iris of the human eye detects light and responds by dilating or constricting to regulate the amount of light that enters the eye (Figure 5.2.2).

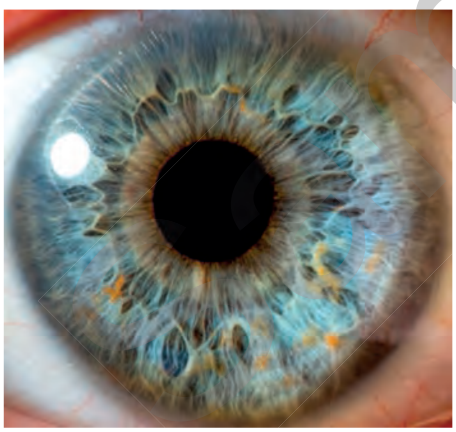


FIGURE 5.2.2 The iris is a pigmented muscle that responds to a light stimulus by dilating and constricting to regulate the amount of light entering the eye.

The two most important systems in maintaining homeostasis in animals are the **endocrine system** (which produces hormones) and the **nervous system**. Physiological and behavioural responses to environmental change that are carried out by both the endocrine and nervous systems include:

- short-term and long-term regulation of growth
- maturation and reproduction
- homeostatic regulation of the internal environment.

The nervous system also provides rapid responses to:

- produce efficient coordinated movement to detect and avoid predators
- find and capture prey.

These regulatory systems are the most developed in mammals, which are able to maintain a relatively stable internal environment in the face of changing conditions.

Although in many ways hormonal systems and nervous systems appear distinctly different, they share one common feature: they both involve chemical communication. Chemical communication involves signals being passed from one cell to the next by the release of specific **signalling molecules**, known as **hormones** and **neurotransmitters**. Hormones are released from glands or other tissues, and neurotransmitters are released from nerve endings. These molecules exert their effects by highly specific interactions with a receptor on, or within, the responding or target cell. **Receptors** are specialised structures that can detect a specific stimulus and initiate a response.

Homeostasis comes from Greek *homoios* and *stasis*, meaning 'staying in the same place'.

Feedback loops

Feedback loops may involve the endocrine and nervous systems working together to regulate the internal environment.

A stimulus is an environmental factor that an organism can detect and respond to.

Negative feedback loops promote stability in the internal environment and maintain homeostasis by responding to changes in the body and adjusting the variables to their original or optimal state. They are **stimulus–response mechanisms** in which the response produced reduces the effect of the original stimulus by reversing its direction. For example, if the concentration of a substance in the blood is too high, a negative feedback loop will lower the concentration. If the concentration is too low, a negative feedback loop will increase the concentration. Most feedback loops in biological systems are negative.

Negative feedback loops are called negative because the information produced by the feedback causes a reversal of the size or effect of the stimulus. Negative feedback loops maintain stability through the action of the nervous or hormonal systems, or both acting together.

An example of a negative feedback loop is the regulation of blood glucose levels by the hormone **insulin**. When blood glucose levels are high, receptors detect the change and the pancreas secretes insulin. This lowers the blood glucose levels until homeostasis is reached, at which point the pancreas stops releasing insulin.

The hypothalamus is known as the control centre of the brain—it receives information from all parts of the body and regulates the internal environment through the secretion of hormones.

A negative feedback loop acts as follows (see Figure 5.2.3):

1 The system is in a stable state. A change (**stimulus**) occurs.
2 The change is detected by an appropriate receptor.
3 The receptor sends a signal to a **control centre** (**hypothalamus** or transmission molecules).
4 The control centre sends a signal to an appropriate **effector** or a specific effector cell, tissue or organ.
5 The effector responds to the signal, and the original state is restored.

An effector is a cell or tissue that responds to a stimulus.

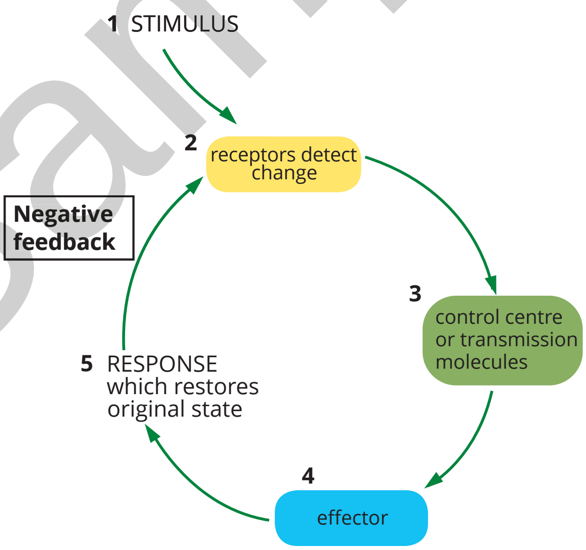


FIGURE 5.2.3 When the response reduces the initial stimulus or disturbance, it is operating as a negative feedback mechanism.

In the control centre information from sensory receptors is received and compared with a set-point (the optimal value for the functioning of that organism). This information is processed with other information about the state of the organism, and an appropriate response is initiated.

Regulation therefore involves fluctuations around the set-point. The size of the fluctuations depends on:

- the sensitivity of the receptor
- the tolerance of the control centre to variation from the set-point
- the efficiency of the effector.

Some features of the internal environment, such as blood glucose levels, can vary considerably; others, such as body temperature in mammals, are tightly controlled.

In contrast to negative feedback loops, **positive feedback loops** force an organism out of homeostasis by maintaining the direction of the stimulus, and sometimes increasing the stimulus. An example of a positive feedback loop is uterine contractions during childbirth. The hormone oxytocin stimulates the uterus to contract, causing pain. Rather than the nervous system signalling the endocrine system to lower the oxytocin and reduce the pain, more oxytocin is produced to stimulate stronger contractions. The contractions work to push the baby into the birth canal and continue until the baby is born.

Table 5.2.1 summarises the differences between negative and positive feedback loops.

TABLE 5.2.1 Comparison between negative and positive feedback loops

	Negative feedback loop	Positive feedback loop
Result	The response is opposite to the stimulus. Hence if a decrease was detected, the response would be to increase the signal, and vice versa.	The response is the same as the stimulus. Hence if an increase was detected, the response would be to further increase the signal.
Homeostasis maintenance	supports homeostasis by bringing back a balance internally	breaks down homeostasis by causing an imbalance internally
Frequency	occurs often	is less common
Examples	• regulation of body temperature; for example, if there was a decrease in body temperature (stimulus), the response would be to increase the body temperature, and vice versa. • regulation of blood pressure and blood glucose levels in humans	• release of oxytocin during childbirth to stimulate uterine contractions • release of prolactin during breastfeeding to promote breastmilk production

WS 17

Receptors—detecting external and internal stimuli

Animals have sensory receptors to detect aspects of their environment that may affect their ability to survive and reproduce. The types of sensory receptors present and their sensitivity differ substantially between animals, and are related to the way animals have adapted to their environments. For example: a wombat has less visual acuity for distinguishing small objects than an eagle; dogs use chemical scents much more than humans; some moths have chemoreceptors that can detect a single molecule of pheromone; and platypuses can detect weak electric currents. Some animals respond to different parts of the electromagnetic spectrum—for example, snakes can detect infrared radiation and bees see ultraviolet light.

In humans, the five senses (vision, hearing, taste, smell and touch) are perceived through sense organs (eyes, ears, tongue, nose and skin) that collect and process sensory information. Receptors that detect external stimuli are known as **exteroreceptors**. These are usually located close to the surface of the body and detect stimuli such as pain and pressure. Some receptors detect internal states, such as blood pressure and blood chemistry (e.g. oxygen and carbon dioxide levels), and are known as **interoreceptors** or visceral receptors. From a functional point of view, the types of sensory receptors involved in these senses can be classified as **photoreceptors** (vision), **chemoreceptors** (taste, smell, communication), **mechanoreceptors** (hearing, balance, pressure, touch) and **thermoreceptors** (temperature) (Table 5.2.2).

TABLE 5.2.2 Types of receptors and examples found in complex animals, and the stimuli each of the receptors responds to

Receptor type	Examples	Received stimuli
mechanoreceptor	pressure (touch) receptors blood vessels: • baroreceptors	stretching of blood vessel wall
	skin: • Meissner corpuscle • Pacinian corpuscle	• light touch • heavy touch
	proprioreceptors: • muscle spindles • Golgi cells • joint receptors	• movement, position of body • gravity • movement with ligaments
	labyrinth in the vertebrate ear: • sacculus and utriculus • semicircular canals • ciliated cells in the cochlear duct	• gravity and linear acceleration • angular acceleration • sound waves
chemoreceptor	taste buds, olfactory epithelium	specific chemical compounds
thermoreceptor	• thermoreceptors in blood-sucking insects and ticks • pit organs in pit vipers • nerve endings and receptors in the skin and tongue of many animals	heat
electroreceptor	organs in the skin of some fish	electric currents in water
photoreceptor	• eyespots • ommatidia in arthropods • rods and cones in the retina of the vertebrate eye	light energy

CASE STUDY ANALYSIS

Dietary calcium deficiency

Many people in Victoria become vitamin D deficient through the winter months because of the lack of sun exposure. Vitamin D is necessary at all times as it is required to help your body reabsorb an important mineral, calcium. Therefore vitamin D deficiency may lead to a decrease in levels of blood calcium.

Calcium is stored in the bones, and is essential for keeping them healthy and strong. Many of the cells in the body need calcium for proper cell functioning. Any imbalance could have serious effects on the human body. Hence, for homeostasis to be maintained specific responses are put into place (Figure 5.2.4).

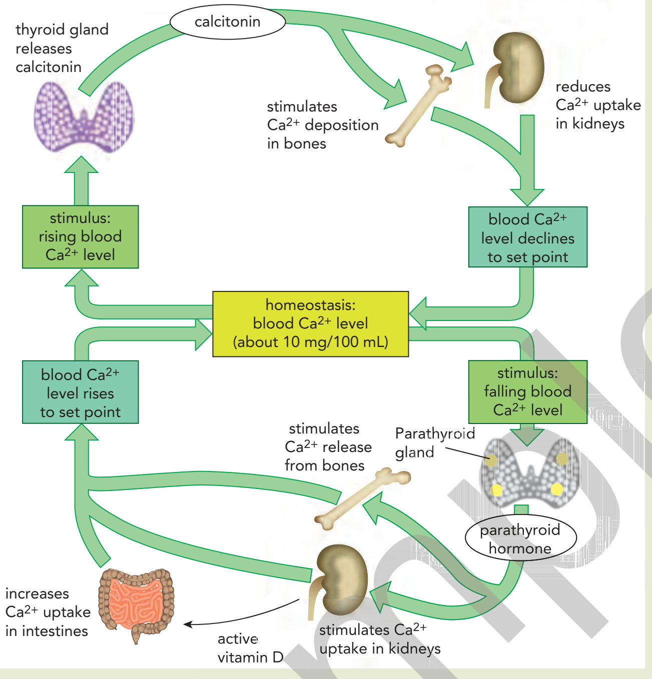


FIGURE 5.2.4 Feedback loop showing the response to the changes in blood calcium levels in humans

Analysis

1. What type of feedback loop is observed in Figure 5.2.4? Explain your answer.
2. A chemoreceptor receives a signal that there has been an increase in the levels of calcium in the blood. A message is sent to the hypothalamus (the control centre) which then activates the appropriate signalling mechanisms. Identify the effector and response using the diagram, and define each term.
3. 'Low blood calcium levels may cause the bones to weaken.' Do you agree with this statement or not? Use Figure 5.2.4 to explain your reasoning.
4. The parathyroid gland releases parathyroid hormone into the blood after it receives a signal from the hypothalamus (the control centre). How does this reinforce the fact that, to reach equilibrium, the endocrine and nervous systems need to work together?

REGULATION OF BODY TEMPERATURE

The maintenance of core body temperature within a specific range is called **thermoregulation**. Regulation of body temperature in humans involves a complex negative feedback pathway with several sensory inputs and many effector responses that act together to maintain a stable body temperature. The control centre for measuring the body temperature set-point (37°C) is in the hypothalamus. A change in the temperature of the hypothalamus initiates regulatory responses that can reduce heat loss or initiate heat production or heat exchange (Figure 5.2.5).

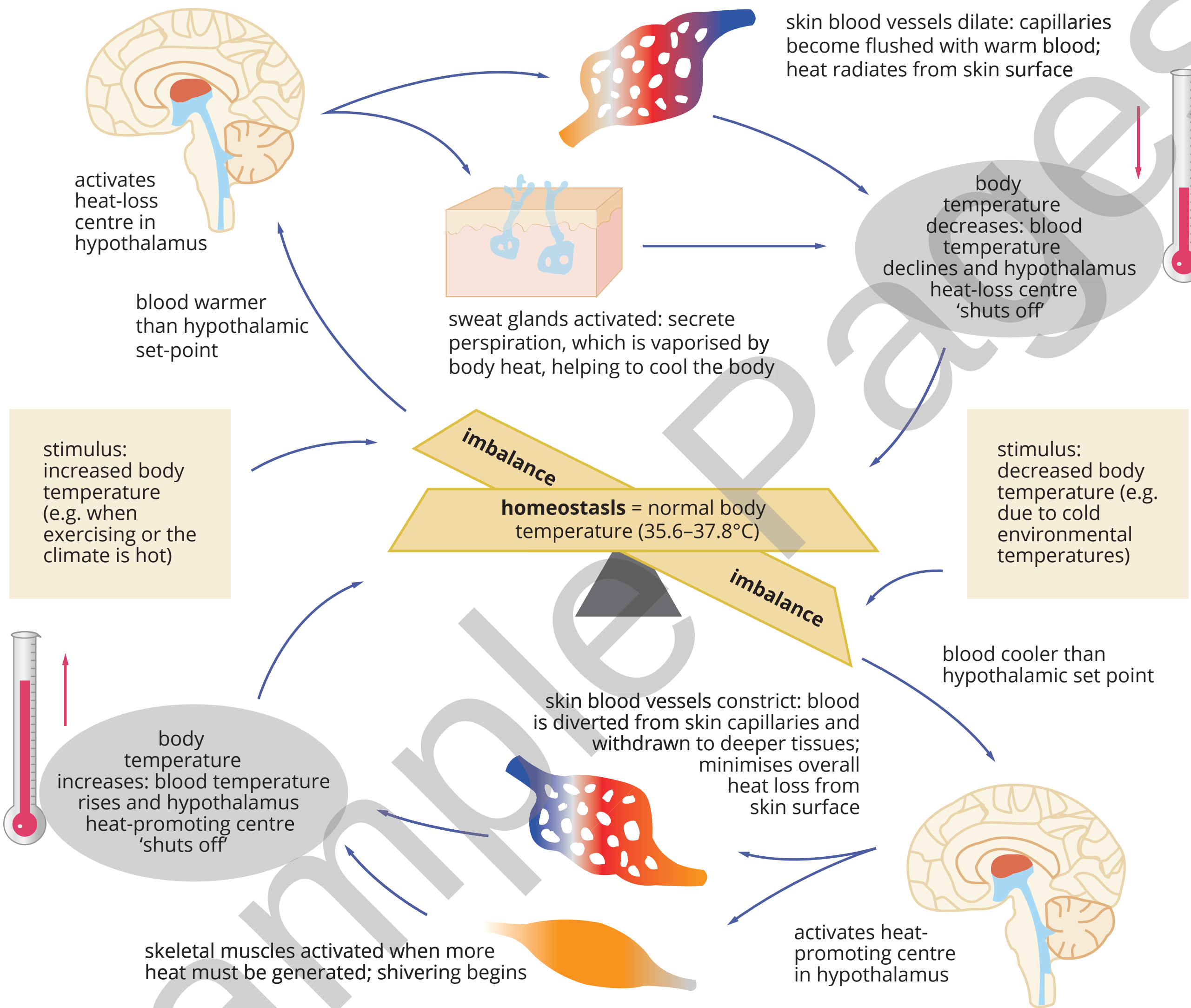


FIGURE 5.2.5 Thermoregulation in humans involves a range of regulatory mechanisms that function to maintain thermal homeostasis (normal body temperature) for optimal functioning of the organism.

Detecting temperature change

Regulation of temperature in humans is an example of the way different sensory receptors work together to produce an integrated response. Arterial blood has the most constant temperature. The relatively constant temperature of many other parts of the body indicates that they are well-supplied with arterial blood.

In **endotherms** (e.g. mammals and birds), a group of temperature-sensitive cells in the hypothalamus act as misalignment detectors, triggering homeostatic responses if blood temperature deviates from the optimal temperature range, or set-point. Lowering or raising the temperature of the hypothalamus initiates regulatory changes in heat production or heat exchange.

Temperature receptors are also found in the skin. A decrease in environmental temperature detected by these receptors will initiate regulatory responses such as decreased blood flow to the skin to reduce heat loss, and behavioural changes such as moving into a warmer or more sheltered environment. These responses take place long before there has been any change in the internal temperature of the body. Skin temperature receptors act as disturbance detectors, detecting changes in the external environment and triggering responses before there is a change in core body temperature.

As the environmental temperature falls, disturbance detectors stimulate responses that reduce heat loss and increase heat production. The reverse occurs as environmental temperature increases. If the arterial temperature falls despite the regulatory responses that have been initiated, or if it rises because the responses made have been too effective, these changes will be detected by the misalignment receptors in the brain, which will fine-tune the temperature-regulating mechanisms.

The value of the disturbance detectors in the skin is to reduce fluctuations in arterial blood temperature, providing a more precise control around the set-point level than there would be if misalignment detectors (the brain's temperature receptors) alone were involved.

Heat loss

Organisms are constantly exchanging heat with their environment. This heat exchange occurs through four mechanisms (Figure 5.2.6):

- **conduction**—Occurs when the temperature of the organism and the environment are different. Heat exchange is a result of direct contact (e.g. a lizard basking on a warm rock).
- **convection**—Transmission of heat from a warmer region to a colder region, resulting from the movement of liquid or gas (e.g. heat moves from the inside of living organisms to the body surface by convection).
- **radiation**—Occurs all the time, without direct contact, regardless of temperature differences between the organism and their environment (e.g. heat radiating from dark coloured surfaces).
- **evaporation**—Heat loss by water evaporation. This occurs most rapidly when the air is hot and dry (e.g. sweating).

BIOFILE

Sweating: an efficient cooling mechanism

Humans are one of the few animals that produce sweat to cool down. Adults can sweat up to 4 litres per hour during vigorous exercise. Even when not exercising, sweating plays an important role in thermoregulation through evaporative cooling. When warm sweat (which is about 99% water, with sodium chloride and some other substances) comes into contact with cooler air, it evaporates, carrying heat away and lowering your body temperature. It does this through a process of energy (and therefore heat) transfer.

Sweating is an important physiological adaptation in humans. It uses evaporative cooling to regulate the body's temperature and prevent overheating.

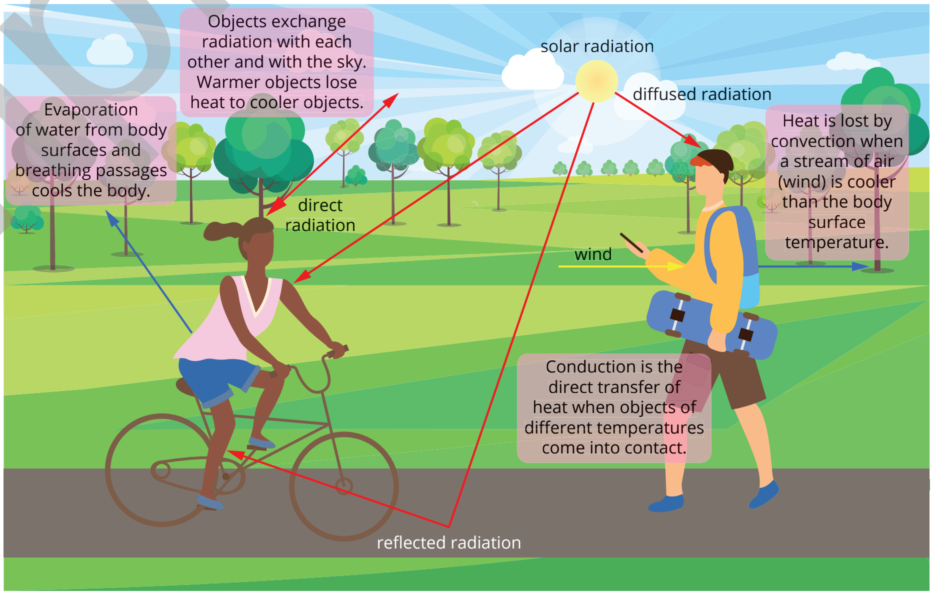


FIGURE 5.2.6 Methods of heat exchange between a human and the environment

CASE STUDY

Fever

A fever is an increase in your body temperature above the normal range or set-point and is a common symptom of an infection (Figure 5.2.7). Fever is one of your body's defences against infection, working to raise your body's internal temperature above the tolerable limits of the invading pathogens.

Pathogenic viruses and bacteria contain substances called pyrogens. An example of a pyrogen is the lipopolysaccharides found in some bacterial cell walls. Pyrogens induce fever by triggering your body's immune response, signalling the hypothalamus to increase your body's temperature.

The body responds to these signals from the hypothalamus by initiating a variety of warming activities in order to generate and retain heat. Peripheral blood vessels are constricted to reduce blood flow and heat loss through the skin. The reduction in blood flow to your skin makes you look pale and feel cold, even though your body is working to retain heat. If your body temperature is still too low, you might start shivering to generate more heat. Your body temperature will continue to increase until it reaches the new higher set-point of the hypothalamus. The fever is maintained until the invading organisms are eliminated and their effect on the hypothalamus ceases. The fever then makes you feel hot and flushed, and the mechanisms that were used to warm your body are reversed; blood vessels dilate, shivering stops and sweating works to cool your body back to the normal temperature range.

A body temperature above 41.5°C is considered extremely high and requires immediate medical attention. Extreme fevers are known as hyperpyrexia and are most commonly caused by a haemorrhage inside the skull. Some infections and sepsis (blood infection) may also lead to hyperpyrexia.

FIGURE 5.2.7 (a) Thermal scanning cameras are used to monitor the skin temperature of passengers arriving at airports in an effort to prevent the global spread of infectious diseases. (b) Teams in airports around the world were equipped with thermal guns to measure the temperatures of travellers from Liberia, Sierra Leone and Guinea in an effort to prevent an Ebola pandemic in 2014.

FIGURE 5.2.8 A close-up of a human forearm with goose bumps. The contraction of blood vessels and small muscles (arrectores pilorum) that are attached to the base of each hair follicle pull the hair into an upright position. In this position the skin resembles plucked goose skin.

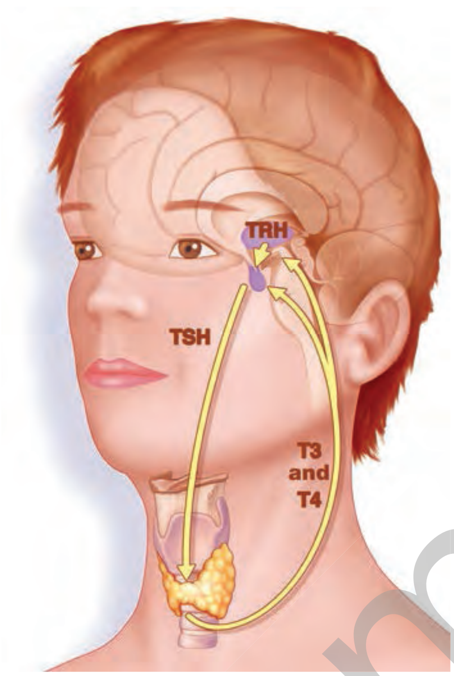


FIGURE 5.2.9 The thyroid is a gland that produces hormones that stimulate cellular respiration. The hypothalamus releases TRH, which stimulates the secretion of TSH by the pituitary gland, which in turn stimulates production of T3 and T4 hormones by the thyroid. The increase in cellular respiration creates thermal energy.

Responding to cold

A number of nervous and endocrine responses occur rapidly to reduce heat loss from the body and increase heat production when the body becomes too cold.

The following involuntary responses reduce heat loss from the body:

- **vasoconstriction** (constriction of the blood vessels in the skin)—This reduces heat loss from the skin, as the amount of blood moving close to the exposed surface is reduced.
- **piloerection**—The constriction of the piloerector muscles around hair follicles ('goose bumps'), which increases the insulating effect of the hairs (Figure 5.2.8). This response has a minimal effect in humans but in animals with thick fur, the layer of trapped air increases significantly and reduces heat loss from the body.
- **shivering thermogenesis**—The production of metabolic heat is increased through shivering. This involuntary movement of the muscles generates large amounts of heat. Shivering thermogenesis is stimulated by adrenaline.
- **non-shivering thermogenesis** in brown fat (brown adipose tissue or BAT)—Increased cellular activity in BAT, a tissue specialised for heat production, causes the tissues to warm up. The heat produced is carried to other parts of the body in the blood. Brown fat contains many mitochondria (which give it its brown colour), fat-metabolising enzymes and an extensive vascular network. Brown fat is capable of high rates of aerobic metabolism using a pathway, which breaks down fats to produce large amounts of heat, but little ATP (energy). This mechanism is crucial in many baby animals and hibernators.
- increasing **metabolism** (the rate of cellular respiration)—Metabolic processes in the internal organs are the main source of heat when the organism is at rest (Table 5.2.3). In humans, around 60% of the energy released during cellular respiration is transformed into thermal energy. In humans, the overall metabolic rate, and therefore the rate of heat production, is controlled by hormones.
- **thyrotropin releasing hormone (TRH)** secretion by the hypothalamus—TRH acts on the anterior pituitary to secrete **thyroid stimulating hormone (TSH)**. As the name suggests, TSH acts on the thyroid gland to release thyroid hormones, tri-iodothyronine (T3) and thyroxine (T4) (Figure 5.2.9). T3 and T4 hormones regulate metabolic processes, increasing heat production and body temperature. The amount of T3 and T4 in the bloodstream is regulated by the pituitary gland via a negative feedback loop; if there is too much or too little T3 or T4, the pituitary gland reduces or increases the amount of TSH it secretes. This mechanism allows a very delicate regulation of the level of thyroid hormones in the blood.

TABLE 5.2.3 Major sources of heat production in humans. Metabolic processes in the internal organs are the main source of heat when a person is at rest. During physical activity, the heat generated in the muscles increases.

Organs	Participation in heat production at rest (%)	Participation in heat production during physical effort (%)
brain	16	2
internal organs	56	22
skeletal muscles	15	73
other organs	13	3

Animals, including humans, may also change their behaviour to reduce heat loss and increase heat production in the body. Some examples include changing body shape or decreasing surface area (e.g. curling up to make yourself small or huddling together), seeki†ng shelter to reduce exposure to cold temperatures and increasing physical activity. You will learn more about behavioural adaptations of animals in Chapter 9.

Responding to heat

As well as responding to cooler temperatures, animals can adjust their internal environment in response to high external temperatures. Many of the responses to heat work in the opposite way to the responses to cold temperatures. Some of the internal processes that take place in animals when it is hot include:

- **evaporative cooling**—This is a very effective way of losing heat energy from the body as water (sweat) changes to water vapour. Sweat glands are distributed over much of the human body and release sweat onto the skin surface via pores when your body temperature rises. Most animals do not sweat in the same way as humans, but many use panting, where their breathing is fast but shallow, to increase evaporative cooling. Spraying water on your skin (Figure 5.2.10) produces the same evaporative cooling effect as sweating.
- **vasodilation** (dilation of the blood vessels in the skin)—This means more blood is sent to the extremities. Heat is lost to the environment by radiation and convection, especially if it is windy. Furry animals often have areas of bare skin that are rich in blood vessels in order to allow vasodilation to take place.

Animals may also change their behaviour to release excess heat or to avoid increasing their body temperature. Some examples include changing body shape or increasing surface area (e.g. standing with your arms outstretched), swimming or bathing in cool water, seeking shade during the hottest parts of the day and decreasing physical activity.

FIGURE 5.2.10 Long-distance runners spray water on their skin to take advantage of evaporative cooling. This enables their bodies to work at maximum efficiency, and helps to prevent them from becoming dangerously hot.

BIOFILE

Rosy cheeks

Children often have rosy cheeks in cold weather. This is a result of increased blood flow to the cold tissues following vasodilation (opening of the blood vessels). Cold-induced vasodilation functions to warm parts of the body that have been exposed to the cold. By increasing the blood to the exposed area, the risk of injury from extreme cold is reduced. As vasodilation allows heat to escape the body, it can be maintained only for short periods in cold conditions. If the body does not warm up after a while, vasoconstriction occurs to minimise heat loss.

Rosy cheeks from exposure to cold are caused by the dilation of blood vessels (vasodilation). Vasodilation increases blood flow to exposed skin to counteract the cold.

BIOFILE

Apocrine glands

The apocrine glands are associated with hair follicles and are mainly in the armpits and groin. These glands extend deep into the dermis and secrete proteins and fats into canals of the hair follicles. The sweat secreted by apocrine glands is usually thicker than that secreted by the eccrine glands, and is the source of 'body odour'.

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REGULATION OF BLOOD GLUCOSE

FIGURE 5.2.11 Blood glucose levels can be tested by pricking the finger and placing a small drop of blood on a piece of absorbent material, which is tested by an electronic device. The person pictured here has a BGL of 6.4 mmol/L.

Blood glucose level (BGL), sometimes called blood glucose level, is the concentration of glucose in the blood of mammals, including humans. This level is constantly changing in your body and is tightly regulated by homeostatic mechanisms. **Glucose** is the main source of energy for your body's cells. Eating carbohydrates and doing physical activity will change blood glucose levels throughout the day. The more carbohydrates you eat, the more insulin you will produce. Glucose is stored in the body in the form of a polymer called **glycogen**. When the body needs glucose, the glycogen is broken back down into usable glucose for cellular respiration, which is the energy-producing reaction in cells. If BGL is not maintained within its optimal range, **hyperglycaemia** (BGL too high) or **hypoglycaemia** (BGL too low) can develop, leading to a range of long-term health problems, such as diabetes (Figure 5.2.11).

Detecting blood glucose level change

Cells in the pancreas detect changes in BGL. Blood glucose concentration is regulated so it remains within a range of about 3.5–8 mmol/L. A deviation from these levels in either direction will result in a response by clusters of specialised cells in the pancreas, called the islets of Langerhans (Figure 5.2.12). These cells detect blood glucose levels and release insulin and glucagon to maintain blood glucose levels within the normal range. **Glucagon** is a hormone that stimulates the conversion of glycogen to glucose, which raises BGL.

There are also glucose-sensing neurons in the hypothalamus in the brain. Scientists believe that these glucose-sensing neurons play a key role in food intake, thus helping to regulate blood glucose concentrations.

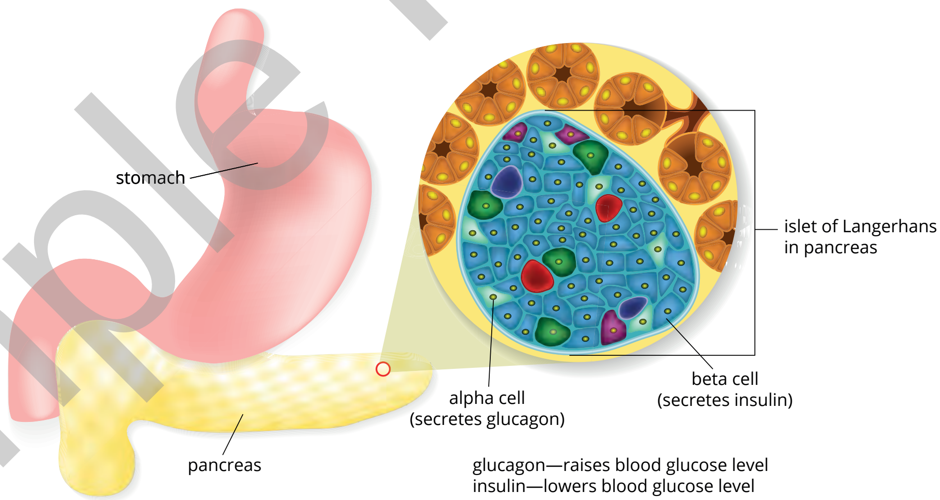


FIGURE 5.2.12 Groups of specialised cells in the pancreas, called the islets of Langerhans, detect blood glucose levels and secrete either insulin (from beta cells) or glucagon (from alpha cells) to maintain blood glucose levels within the normal range.

BIOFILE

Carbohydrates and blood glucose levels

Simple carbohydrates consist of only one or two sugar molecules (monosaccharides and disaccharides). Because of this they can be rapidly digested and absorbed, raising blood glucose levels quickly. Some sources of simple carbohydrates are table sugar, soft drinks and lollies. These foods provide a short burst of energy but contain very little nutrition.

Complex carbohydrates (polysaccharides) are starches made up of longer chains of sugars, and take longer to break down and absorb. Foods such as white bread and cakes contain refined starches, while unrefined starches are found in whole grain foods, such as brown rice and wholemeal bread, and starchy vegetables. Foods that contain unrefined complex carbohydrates provide a steady energy supply, minimising spikes in blood glucose levels, and also provide beneficial nutrients and fibre.

Responding to high blood glucose levels

When glucose levels rise above about 5 mmol/L, the islets of Langerhans in the pancreas release insulin. Insulin increases the conversion of glucose to glycogen, fats or fatty acids for storage in the liver and skeletal muscles. The overall effect of insulin is to lower BGL (Figure 5.2.13, Table 5.2.4).

Responding to low blood glucose levels

When glucose levels fall below about 5 mmol/L, the islets of Langerhans in the pancreas release glucagon (Figure 5.2.13, Table 5.2.4). Adrenaline also raises BGL by its actions on fat cells and the liver.

BIOFILE

Glycogen storage

It is often said that glycogen is synthesised and stored in the liver, but this is only partly true. Most glycogen is actually synthesised and stored in skeletal muscle cells. The human liver can store about 100 g of glycogen, whereas skeletal muscle can store about 500 g. When the glycogen-storing capacity of the body is full, excess glucose is stored mainly as triglycerides (fats).

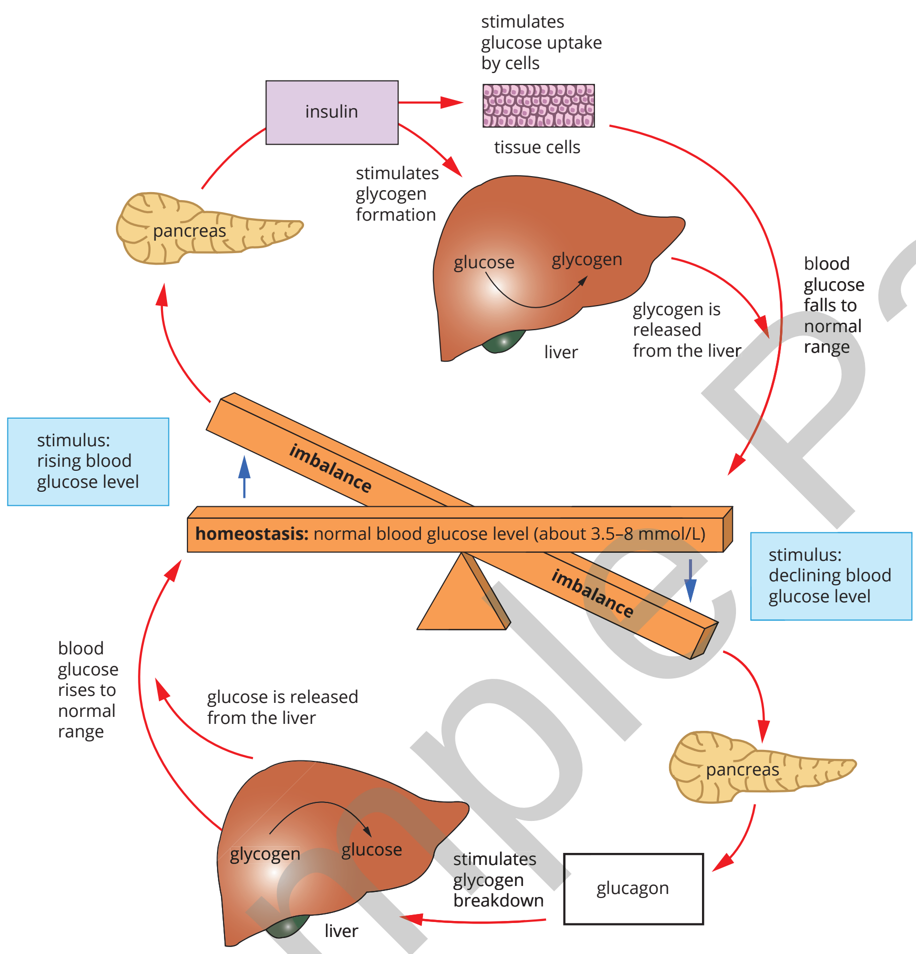


FIGURE 5.2.13 The regulation of blood glucose level (BGL) by insulin and glucagon. When BGL is too high, insulin is secreted by the beta cells in the pancreas. This stimulates glucose uptake and storage as glycogen in the liver, reducing BGL. When BGL is too low, glucagon is secreted by the alpha cells in the pancreas. This stimulates glycogen breakdown and the release of glucose from the liver, increasing BGL to within the normal range.

TABLE 5.2.4 Changes observed in blood glucose levels—hormones secreted and effects on the body

Blood glucose level	Hormone secreted	Effect on blood glucose concentration in the body
higher than normal	Insulin is produced and secreted by the beta cells of the islets of Langerhans.	Insulin stimulates glucose uptake into muscle and liver cells. Glucose is then converted into glycogen, and blood glucose levels fall.
lower than normal	Glucagon is produced and secreted by the alpha cells of the islets of Langerhans.	Glucagon stimulates the breakdown of glycogen into glucose in the liver. This releases glucose into the blood leading to raised blood glucose levels.

BIOFILE

Effects of dehydration

The effects of dehydration can range from mildly uncomfortable to life-threatening. The following table shows the typical symptoms of dehydration in humans. The progressively worsening symptoms are typical of those experienced by someone without sufficient water in a hot, dry environment, such as a person lost in a desert.

Progressive symptoms caused by dehydration

Water volume lost (%)	Symptoms
0	no symptoms
1	thirsty but not uncomfortable
2	uncomfortably strong thirst
3	dry mouth, fatigue, stumbling, headache, irritability
4	strong fatigue, nausea, lack of concentration
5	decision-making and coordination strongly impaired, sleepiness
6	reduced ability to sweat, rapid, pounding heartbeat, tingling and numbness in fingers and toes
7	fever, confusion, dry skin, inability to stand
8	dizziness, laboured breathing, extreme fatigue
9	muscle spasms, delirium
10	blood circulation impaired, kidney failure
> 10	unconsciousness, likely general organ failure and death

REGULATION OF WATER BALANCE

Some animals maintain water balance simply by living in environments where fresh water is freely available. Others can regulate the composition of their internal environment, allowing them to live in drier or saltier environments. The maintenance of an internal balance between water and solute concentrations is called **osmoregulation**.

Animals that control their cells' solute concentrations and maintain a stable internal environment are known as **osmoregulators**. Most animals are osmoregulators, including land animals, freshwater animals and some marine (saltwater) animals. Animals that conform to changes in their external environment, matching the solute concentrations in their cells to their surroundings, are known as **osmoconformers**. Osmoconformers are mostly marine invertebrates, such as sea jellies and crabs.

Maintaining water balance is necessary to control salt concentrations. Salts form ions in solution, and cells require the concentrations of ions to be held within narrow limits for biochemical processes to occur efficiently (Figure 5.2.14). Some ions (such as the hydrogen carbonate ion) are also important for regulating the pH of body fluids, which must be at a suitable pH for enzymes and other molecules to function efficiently. Maintaining the correct concentrations of ions is achieved by regulating both water and salt balance.

Water balance involves regulating the intake and loss of both water and salts. In organisms, net movement of water occurs as a result of osmosis, which is regulated by solute concentrations. Water moves across a semi-permeable membrane from regions of lower solute concentration (higher concentration of free water molecules) to regions of higher solute concentration (lower concentration of free water molecules).

The amount of water lost or gained throughout the day differs between individuals and depends on the amount of exercise, temperature, humidity, and food and fluid intake. Urination rather than water intake is a better indicator of whether an individual has good water balance. A healthy person with adequate hydration would usually urinate four to eight times per day, and the urine would be pale yellow.

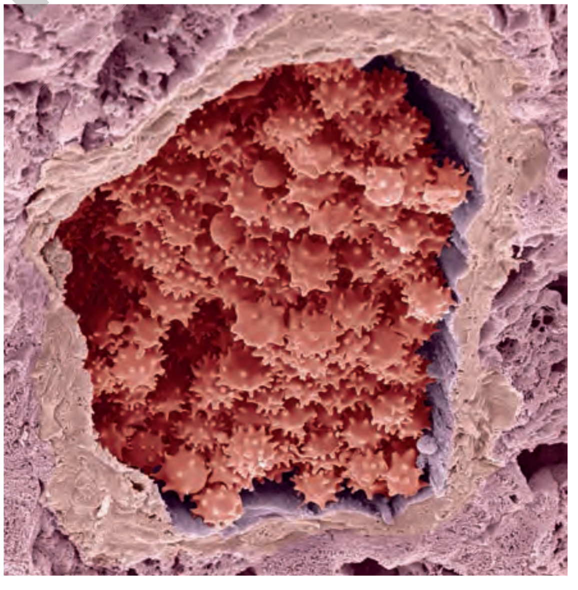


FIGURE 5.2.14 The maintenance of constant osmotic pressure in the blood is important because it prevents red cells from dehydrating or bursting. This scanning electron micrograph (SEM) of a section through an arteriole shows crenated (wrinkled) red blood cells caused by dehydration.

Water gain and loss

The total volume of fluid taken into the body depends on diet and activity levels, and typically varies from about 2 to 16 L. The minimum water requirement for fluid replacement in a 70 kg person in a cool climate is about 3000 mL per day. Of this, about 400–600 mL is obtained by eating, and about 400 mL is produced by cellular respiration. (This is called metabolic water because it is produced in cellular respiration.) The remainder of about 2000–2200 mL must be obtained by drinking.

For this person, water will be lost mainly in urine (500–1500 mL per day), evaporation from the respiratory system (400–800 mL per day), sweat (100–800 mL per day), and faeces (100–200 mL per day).

Salt gain and loss

Salt intake varies greatly depending on diet. The three major salt groups in the human diet are sodium salts, potassium salts and calcium salts.

Daily sodium salt intake (mostly as sodium chloride) ranges from about 1 to 10 g per day, mainly in bread, meat and processed cereal products. Highly processed foods usually contain more sodium salts than unprocessed foods. The recommended daily intake for Australians is 1.6 g.

Daily potassium salt intake (mainly potassium chloride and potassium citrate) ranges from about 2.0 to 4.0 g per day. The recommended daily intake for Australians is 4.7 g. Highly processed foods usually have a much lower potassium salt content that unprocessed foods.

Daily calcium salt intake (mainly in dairy foods and green vegetables) is up to about 2.4 g per day. The recommended daily intake for Australians is 1.0–1.3 g, depending on age.

Salts are lost mainly in urine but also in sweat and faeces. The kidney filters excess salts from the blood and excretes them into the urinary system. However, most salts are reabsorbed into the blood plasma for recirculation to tissues.

Hormonal control of water balance

Water and solute concentration are monitored by **osmoreceptors** in the hypothalamus and **baroreceptors** in the atria of the heart. Osmoreceptors are sensitive to blood solute concentrations, while baroreceptors detect changes in blood pressure, which is an indication of the volume of blood. Collectively, these receptors detect the solute concentration in blood and extracellular fluid. The unit of measurement used for these blood solute concentrations is **osmolality**, because they contribute to osmotic effects on cells.

> Osmolality is a measure of the concentration of particles (such as sodium and chloride ions) that affect osmosis.

Because plasma membranes are permeable to water, the osmolality in the extracellular fluid is about the same as it is in the intracellular fluid (cytosol). Changes in the osmolality of the extracellular fluid will therefore affect cytosol concentrations, which can cause problems with cellular metabolic reactions. Compared to extracellular fluid, the cytosol of cells is high in potassium and magnesium and low in sodium and chloride ions.

Antidiuretic hormone (ADH), also called vasopressin, regulates water reabsorption. It is synthesised in the hypothalamus and transported to the posterior pituitary gland, where it is stored. When osmoreceptors in the hypothalamus detect an increase in the osmolality of the blood, a signal is sent to the posterior pituitary gland, and ADH is released.

ADH acts on the kidneys to increase the permeability to water of the distal tubules and collecting ducts. The collecting ducts run through the medulla of the kidney, which has high salt levels (and therefore a higher osmotic potential). This causes the absorption of water from the tubules back into the blood by osmosis, decreasing urine output; the urine becomes more concentrated and has a darker yellow colour. As the blood returns to a normal concentration, negative feedback stops the production of ADH.

Conversely, if the osmoreceptors detect a decrease in osmolality (e.g. if too much water has been taken into the body), ADH release will be stopped. This reduces the reabsorption of water and consequently increases urine volume; the urine becomes more dilute and has a paler yellow colour (Figure 5.2.15).

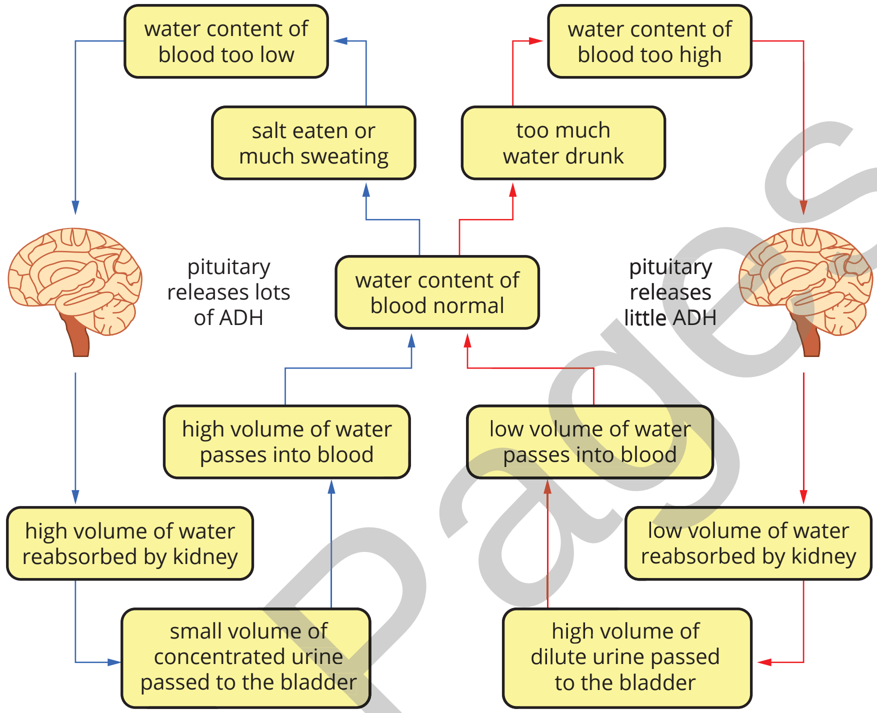


FIGURE 5.2.15 Hormonal control of water balance by antidiuretic hormone (ADH)

A number of substances such as nicotine, alcohol and narcotics can interrupt the feedback control of water balance in the body. This can also occur because of pain, stress or hypothermia (lowered body temperature).

Changes in blood osmolality or blood pressure also stimulate counteracting response. Initially an enzyme called **renin** is secreted from the kidneys in response to these changes (Figure 5.2.16). Renin then triggers a series of reactions involving other hormones that results in the release of **aldosterone** from the adrenal glands situated above the kidney. Aldosterone simultaneously regulates sodium and potassium levels by increasing potassium excretion into the urine and causing sodium reabsorption into the blood. This causes more water to be drawn into the blood by osmosis, thus increasing blood volume and pressure.

A lack of aldosterone can result in low sodium levels, high potassium levels and high acid levels in the blood. These are potentially dangerous conditions. People with an aldosterone deficiency suffer from Addison's disease and must take a synthesised hormone called fludrocortisone acetate.

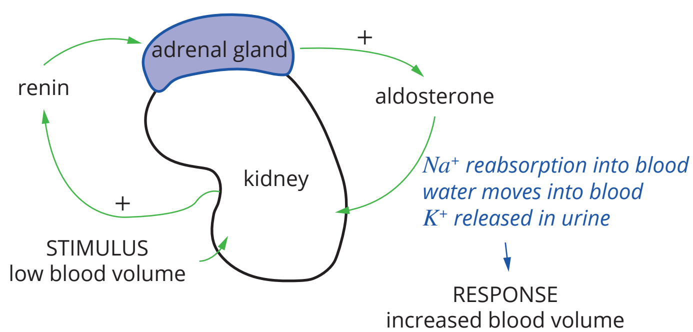


FIGURE 5.2.16 Hormonal control of sodium and potassium levels by renin and aldosterone

CASE STUDY

Salmon: osmoregulation in fresh and salt water

Some animals, like salmon, are able to survive in a relatively wide range of salt concentrations, making them different to other animals, like humans, who can only function efficiently in a narrow range of salt concentrations. The gills of salmon are adapted to transport salt ions through specialised transport mechanisms. This unique adaptation allows salmon to spend part of their lives in fresh water and part in salt water (Figure 5.2.17).

Salmon in salt water

When salmon are in salt water there will be more water molecules inside the body cells than outside the cells, so water will move out of the cells via osmosis. This leads to a high concentration of salt in the blood, which is recognised by receptors in the hypothalamus. Those receptors stimulate the pituitary gland to release a hormone into the blood, which initiates the transport of salt ions (Na^+ and Cl^-) out of the body via the gills. Salmon also rely on their kidneys to remove excess salts. Since living in salt water leads to dehydration, salmon have to drink many litres of water a day. In addition, another hormone released by the pituitary gland, antidiuretic hormone (ADH), signals to the kidneys to reabsorb more water before excretion. This leads the kidneys to remove excess salts through the production of very concentrated urine.

Salmon in fresh water

When the salmon are living in fresh water there will be more water molecules outside the body cells than inside the cells, so water molecules will move into the body cells via osmosis. This increased movement of water into the body cells leads to salt loss and high water levels. The hypothalamus detects the high water level and stimulates the pituitary gland to release a hormone into the bloodstream, which stimulates the gills to actively absorb salts from the water. Due to their high water levels while living in fresh water, salmon do not actively drink water and they excrete large volumes of dilute urine from their kidneys.

FIGURE 5.2.17 Red salmon (*Oncorhynchus nerka*) migrate from a freshwater river to a saltwater ocean as juveniles and return to the same river as adults to spawn (reproduce).

WS 15 WS 18 PA 9

5.2 Review

SUMMARY

Homeostasis

- Homeostasis is the maintenance of a stable internal environment within an organism.
- Regulation in animals involves internal communication by the endocrine (hormone) and nervous systems to integrate and coordinate the activities of cells, tissues, organs and systems.
- In both endocrine and nervous systems, signals are passed from one cell to the next by chemical communication—the release of signalling molecules (hormones and neurotransmitters) and their detection by matching receptors on the target cells.
- The nervous system provides rapid responses to produce efficient coordinated movement.
- Hormones are specific, effective in low concentrations and generally slower and more indirect than nervous responses.

Feedback systems

- Negative feedback loops are stimulus–response mechanisms that respond to changes in the body by adjusting variables back to their original or optimal state, reversing the direction of the stimulus.
- Positive feedback loops are the opposite of negative feedback loops. They promote a process rather than reversing the effect of the stimulus.

Regulation of body temperature

- A change in the temperature of the hypothalamus initiates regulatory responses that can involve heat production or heat exchange.
- Temperature receptors are found in the skin and the hypothalamus.
- Heat is lost from the body by conduction, convection, radiation and evaporation.
- Responses to cold environmental temperatures include:
  - vasoconstriction
  - piloerection
  - shivering thermogenesis
  - non-shivering thermogenesis
  - increasing metabolism
  - TRH secretion by the hypothalamus.
- Responses to hot environmental temperatures include evaporative cooling and vasodilation.

Regulation of blood glucose

- Blood glucose levels are detected by receptor cells in the pancreas and neurons in the hypothalamus.
- When glucose levels rise, insulin is released from the beta cells in the islets of Langerhans in the pancreas. Insulin causes a decrease in BGL by acting on a number of tissues to:
  - increase conversion of glucose to fat in fat cells
  - increase uptake of glucose in muscle and fat cells
  - increase conversion of glucose to the storage compound glycogen for storage in the liver.
- When glucose levels decrease, glucagon is released from alpha cells in the islets of Langerhans which stimulates the conversion of glycogen to glucose.
- Adrenaline acts on
  - skeletal muscle and the liver to increase breakdown of glycogen to glucose
  - fat cells to increase fat breakdown for energy.

Regulation of water balance

- Water enters body cells throughout the day from drinking, eating and cellular respiration.
- Water is mainly lost from the body in urine, faeces, sweat and from the lungs.
- Osmoreceptors in the hypothalamus and baroreceptors in the atria of the heart detect the osmolality of the blood.
- An increase in blood osmolality causes:
  - release of ADH from the pituitary; ADH acts on the kidney to increase water absorption back into the blood
  - increase in urine concentration and decrease in urine output.
- A decrease in blood osmolality causes:
  - decrease in ADH levels
  - increase in urine volume.
- Low blood volume stimulates the secretion of aldosterone:
  - renin is secreted from the kidneys
  - renin causes release of aldosterone
  - aldosterone causes absorption of sodium into the blood
  - aldosterone causes potassium excretion into the urine
  - blood volume and blood pressure increase.

KEY QUESTIONS

Knowledge and understanding

1 What is homeostasis and why is it important?

2 List the five parts of the negative feedback loop.

3 **a** What are three mechanisms animals use to produce heat?
b What are three mechanisms animals use to lose heat?

4 **a** What does osmolality measure?
b Which two receptors detect changes in osmolality in the blood?

5 What is ADH and what is its role?

6 How do negative feedback loops function? Explain using an example.

7 Compare and contrast the role of insulin and glucagon in the human body.

Analysis

8 The urine of a healthy person with adequate hydration is a pale yellow colour, whereas the urine of a less-hydrated person is darker yellow. Explain this colour difference.

5.3 Malfunctions in homeostatic mechanisms

> A disease is any condition that impairs, or has the potential to impair, the normal functioning of the body.

The regulation of the internal environment, and thus the functionality and health of your body, is maintained by homeostatic mechanisms. These mechanisms are extremely sensitive to changes in internal conditions. However, homeostatic mechanisms can malfunction because of factors such as genetic disorders, ageing, poor nutrition, insufficient physical activity or exposure to harmful substances.

A malfunction in a homeostatic mechanism causes an imbalance and a subsequent oversupply or undersupply of substances to cells. Many diseases are associated with malfunctions in homeostatic mechanisms.

Hormonal balance plays a key role in regulating the internal environment. The endocrine system makes, stores and releases hormones that act as chemical messengers that trigger and direct functions in the body. The endocrine system controls vital functions in growth and development, metabolism, reproduction and tissue repair, among many others. Malfunctions in the endocrine system often lead to a disruption in a homeostatic mechanism, which can have an adverse effect on the body (Figure 5.3.1).

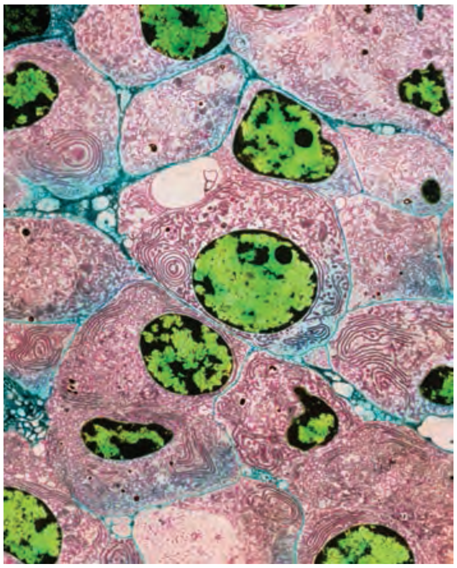


FIGURE 5.3.1 Coloured transmission electron micrograph (TEM) of thyroid cancer cells

Diseases of the endocrine system fall into three groups:

- **hypersecretion** (oversupply) of hormones
- **hyposecretion** (undersupply) of hormones
- cancers of endocrine glands.

Examples of conditions and diseases involving the endocrine glands include hypoglycaemia, diabetes, Graves' disease, Cushing's disease, acromegaly, congenital hypothyroidism, Addison's disease and hyperthyroidism. In this section you will explore type 1 diabetes, hypoglycaemia and hyperthyroidism in detail.

TYPE 1 DIABETES

Type 1 diabetes is caused by a malfunction of the pancreas, which leads to a deficiency in insulin secretion. It is an **autoimmune disease** in which the body's immune system destroys the insulin-producing beta cells in the islets of Langerhans in the pancreas (Figures 5.3.2). Insulin allows the muscle, liver and fat cells to absorb glucose from the blood and store it until the body needs energy, for example in between meals. Treatment of type 1 diabetes involves artificially increasing the insulin supply by injections or an insulin pump.

> An autoimmune disease occurs when a person's immune system mistakenly targets the body's own cells. Examples of autoimmune diseases are type 1 diabetes, Graves' disease and multiple sclerosis.

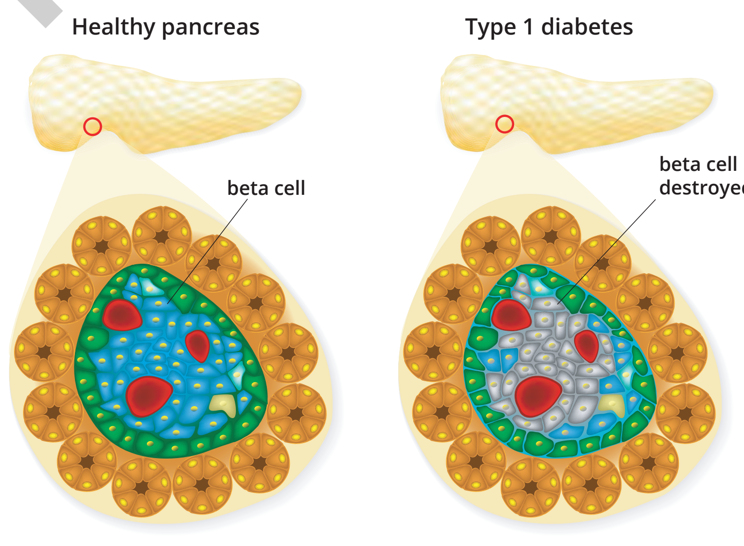


FIGURE 5.3.2 In type 1 diabetes, beta cells in the islets of Langerhans are destroyed. This means that the pancreas cannot secrete enough insulin to convert glucose to glycogen, and blood glucose levels can increase to dangerous levels.

The onset of type 1 diabetes symptoms often occurs in childhood to early adulthood, and there is currently no cure or way of preventing the disease. People with type 1 diabetes must monitor their blood glucose levels (BGL) and inject or pump insulin into their bodies every day. Type 2 diabetes is also a disturbance of glucose homeostasis. In this disorder the pancreas still makes insulin, but the body's cells do not respond. This form of diabetes often appears later in life, but is increasingly common in younger people, and is more common in those who are overweight or obese and have a sedentary lifestyle. It can often be managed by diet, exercise and medication.

Causes of type 1 diabetes

Scientists are unsure what causes the beta cells in the islets of Langerhans in the pancreas to be destroyed in type 1 diabetes. There is some evidence for a link between the Coxsackie A and B4 viruses (which are common in children) and the onset of the autoimmune disease. Other childhood viruses, including enterovirus, mumps, polio and rubella, have also been suggested as triggers for type 1 diabetes. Without functioning beta cells, the body cannot secrete the insulin required to convert glucose to glycogen in the liver and to stimulate glucose uptake into muscle and fat. This causes blood glucose levels to increase to dangerously high levels (Figure 5.3.3).

Symptoms of type 1 diabetes

Insulin deficiency results in hyperglycaemia (high blood glucose levels) and accelerates the breakdown of fat for the body to use as energy. Symptoms of the disease include:

- glucose in the urine
- increased urine production
- excessive thirst
- excessive hunger
- ketosis
- weight loss
- fatigue
- blurred vision
- irritability
- muscle cramps
- skin infections
- delayed wound healing
- tingling or numbness in the feet.

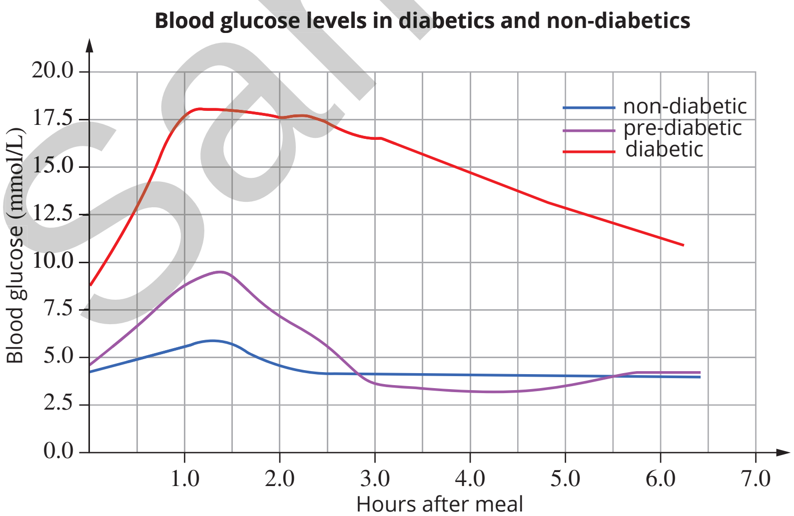


FIGURE 5.3.3 Graph indicating blood glucose levels after a meal in pre-diabetic and diabetic patients compared with a non-diabetic control group

BIOFILE

Diabetic complications

People with type 1 diabetes are at risk of several serious and even fatal conditions. In the short term, ketoacidosis (the release of ketones into the blood for energy production when insulin is not available) can lead to severe dehydration, vomiting, blurred vision and fainting. In extreme cases the person may become comatose.

Long-term risks include heart failure, vision impairment and possibly blindness, obesity, slow wound healing, skin infections, nerve damage causing a loss of sensation in the limbs, and insufficient blood supply to the hands and feet.

Injecting too much insulin, or over-exercising after injecting insulin, can result in dangerously low blood glucose levels (hypoglycaemia). This can result in a rapid loss of consciousness if not treated promptly. The usual first aid treatment is drinking fruit juice or sucking on a lolly such as barley sugar to boost blood glucose levels quickly (see figure below). This can be followed by more complex carbohydrates once the patient is more alert.

First aid for hypoglycaemia usually involves drinking fruit juice or sucking on a lolly to boost blood glucose levels quickly.

FIGURE 5.3.4 A dipstick test for glucose in urine. The pad is dipped in the urine, and the colour of the pad is checked against the chart. This gives an estimate of the glucose level in the urine. A high level is usually an indication of diabetes, although other conditions or the use of certain medications can cause high glucose levels.

FIGURE 5.3.5 (a) A diabetic woman injecting insulin with an insulin pen, which delivers the correct dose of insulin. (b) This person is wearing a continuous glucose monitoring device and insulin pump. The monitor measures blood glucose levels and sends the levels to the pump to help the pump's internal calculator recommend an insulin dose.

PA 7

Longer-term consequences are kidney and eye disease. All of these symptoms occur because of the elevated levels of glucose in the blood. Glucose is excreted in the urine because the raised blood glucose levels exceed the filtration capacity of the kidneys (normally the kidneys prevent glucose from entering the urine). Glucose escaping into the nephron tubules draws in more water, by osmosis, increasing the volume of urine produced. As a result, more frequent urination leaves the body dehydrated and feeling thirsty. The presence of glucose in urine is a simple test for diabetes (Figure 5.3.4).

Dehydration can lead to blurred vision as the lens loses moisture and the blood vessels are damaged. This can result in blindness if left untreated. The raised glucose levels in blood cause chemical reactions with molecules on the surface of neurons and cells lining the small blood vessels. The resulting damage to the body's nerves can result in loss of sensation in limbs, while damage to capillaries contributes to kidney malfunction and eye disease (diabetic retinopathy).

Management of type 1 diabetes

Artificial insulin

As well as managing their diet, people with type 1 diabetes must receive insulin artificially. This is usually by injection (Figure 5.3.5a). Blood glucose levels are monitored by pricking a finger and testing a small drop of blood with a blood glucose meter or a chemical strip.

Alternatively, an electrode placed under the skin and connected to a continuous glucose monitoring device warns a person when their glucose level is reaching a high (or low) level (Figure 5.3.5b). The monitor can be coupled to an electronic pump that delivers insulin when blood glucose levels reach a predetermined level. An improved system called an 'artificial pancreas' is currently being tested in several countries, including Australia. This system uses a monitoring and feedback system to deliver insulin as the body requires it, in the same way that the pancreas produces insulin.

Transplants

Pancreas transplants from deceased donors are usually given to patients with serious complications from diabetes. Human pancreas cells can also be transplanted into a patient's liver, where they begin to produce insulin. This process is called pancreatic islet transplantation. Although it is still in the experimental stage, it may become widely available in the next few years. Recipients of pancreas or pancreatic islet transplants must take **immuno-suppressant drugs** for the rest of their lives to prevent their bodies from rejecting the transplanted organ. These drugs can have side effects such as high blood pressure, fatigue, and increased risk of bacterial and viral infections.

Gene therapy

Gene therapy, in which the gene that codes for insulin is inserted into the patient's cells, is a potential future treatment for diabetes. Trials in the USA have been successful in diabetic rats, targeting the liver because of the organ's regenerating ability. A major benefit of gene therapy is that patients would not require immunosuppressant drugs.

HYPOGLYCAEMIA

As discussed in Section 5.2, hypoglycaemia is a lower than normal blood glucose level (BGL), i.e. less than 4 mmol/L. A lot of people mistakenly think that hypoglycaemia only happens to people with diabetes, but it may develop in non-diabetic people. Hypoglycaemia may be caused by an overproduction of insulin or an underlying reason such as anorexia, excessive alcohol consumption or even pregnancy.

Causes of hypoglycaemia

Hypoglycaemia is divided into two main categories: reactive hypoglycaemia and fasting (non-reactive) hypoglycaemia.

Reactive hypoglyceamia is the most common form, and occurs 3–5 hours after a meal. The cause of reactive hypoglyceamia is an overproduction of insulin (Figure 5.3.6). Insulin released from the pancreas stimulates glucose uptake by tissue cells and glycogen formation in the liver, which in turn leads a decrease in blood glucose levels.

Fasting hypoglycaemia is rare and does not occur after a meal like reactive hypoglycaemia. Fasting hypoglycaemia appears in people suffering from severe diseases such as pancreatic tumours, extensive liver damage (e.g. from severe alcoholism), prolonged starvation (e.g. anorexia) and various cancers. It can also occur during pregnancy.

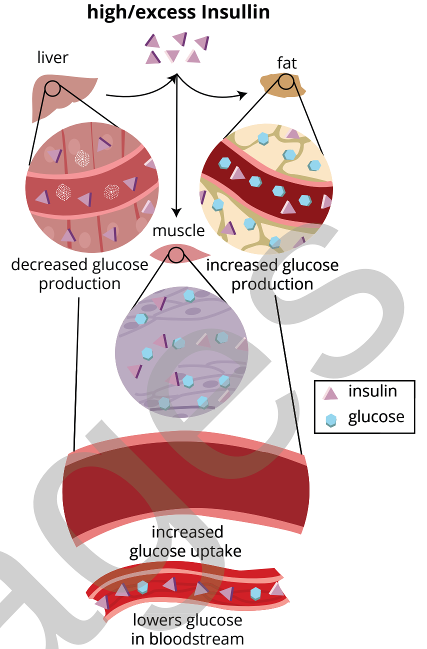


FIGURE 5.3.6 Excessive insulin production causes low blood glucose levels due to an increased uptake of glucose in muscle and fat cells and a reduction in the production of glucose.

Symptoms of hypoglycaemia

Glucose is the primary fuel for the brain, so when glucose levels are low the first effects observed are brain related. Symptoms of hypoglycaemia may differ depending on the cause, but common symptoms include:

- shaking
- confusion
- headaches
- dizziness
- moodiness
- drowsiness
- seizures or convulsions
- sweating
- feeling anxious and nervous
- nausea
- hunger
- feeling sleepy
- faster heartbeat
- pale skin.

Management of hypoglycaemia

To be able to manage and treat hypoglycaemia it is important to identify the cause. In some cases simply eating sugary foods may help raise the blood glucose levels fast. Other more severe cases of hypoglycaemia may be managed by an injection of glucagon. Glucagon is a hormone that stimulates the conversion of glycogen to glucose, which raises blood glucose levels.

BIOFILE

Insulin from microbes

Insulin for human use was once extracted from animals, mostly pigs, but it is now produced mainly by genetically engineered microbes. The gene that codes for insulin is inserted into yeast or bacteria (e.g. *Escherichia coli*), which are cloned to produce large quantities of insulin (see figure below). These organisms are grown in culture and produce insulin on a large scale.

Bacteria with the insulin gene are cultured to produce large quantities of insulin.

CASE STUDY

Brown fat and diabetes management

A study led by endocrinologist Dr Paul Lee at the Garvan Institute of Medical Research in Sydney is investigating the link between brown fat and diabetes. Brown fat is rich in mitochondria and plays an important role in generating heat in hibernating animals and babies. Cool environments promote the growth of brown fat, while warm environments suppress it. Dr Lee wanted to investigate how brown fat is regulated in humans, its role in metabolism, and how this influences blood glucose levels and diabetes.

In this research, study participants slept in temperature-controlled rooms for four months: 24°C for the first month (the body does not have to work to produce or lose heat at this temperature), 19°C for the second month, 24°C for the third month and then 27°C for the last month. Participants completed a 'thermal metabolic evaluation' at the end of each month.

As expected, brown fat increased during the cooler month (19°C) and decreased during the warmer month (27°C). The researchers also found that increased brown fat led to heightened insulin sensitivity. This means that people with more brown fat need less insulin to bring their blood glucose levels down. With increased efficiency in household heating over the last few decades, the average home temperature in the UK and USA has risen from 19°C to 22°C. This temperature change is enough to reduce brown fat production.

The researchers speculate that this shift in household temperature, along with unhealthy diets and lack of exercise, may have contributed to the rise in obesity in these populations. The findings from this research indicate that people with diabetes may be able to regulate their brown fat deposits, making themselves more sensitive to insulin and therefore less reliant on large doses of insulin. This research could also open new avenues for diabetes management.

HYPERTHYROIDISM

Hormones secreted by the thyroid gland interact with cells throughout the body. They are responsible for regulating growth, development and metabolic rate, along with many other vital functions. Malfunction of the thyroid can therefore have widespread and serious effects on a range of organs and bodily functions (Table 5.3.1).

Hyperthyroidism is a condition in which excess amounts of the hormones triiodothyronine (T3) and thyroxine (T4) are secreted by the thyroid gland. T3 and T4 are made from an amino acid (tyrosine) and contain iodine. Blood tests for these hormones and thyroid stimulating hormone (TSH) are used to diagnose the condition. When T3 and T4 are oversupplied by the thyroid, a negative feedback message is sent to the hypothalamus to decrease the release of thyrotropin releasing hormone (TRH). This in turn decreases the synthesis of TSH from the pituitary gland. Increased metabolic activity is only one of the effects of hyperthyroidism listed in Table 5.3.1, which causes the body to work harder and faster.

> '*Hyper*' is a prefix that indicates an excess of a certain kind, whereas '*hypo*' is a prefix that indicates a deficiency.

A positive blood test for hyperthyroidism shows elevated levels of T3 and T4 and decreased TSH levels. Thyroid malfunctions affect about 6–7% of the population. Hyperthyroidism occurs in about 2% of the Australian population. The disease most commonly affects people over the age of 60 and women are 5 to 8 times more likely to develop hyperthyroidism.

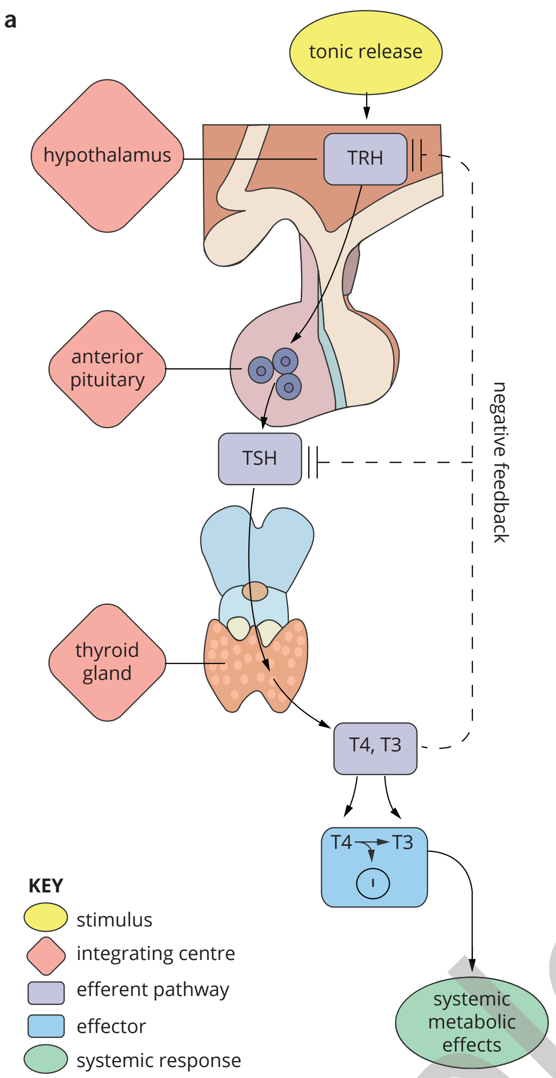
In **hypothyroidism** the thyroid produces less T3 and T4 than the body needs. Hypothyroidism also can have serious effects on health, including decreased glucose metabolism, low heart rate and blood pressure, sluggish muscle action and depressed ovarian function.

TABLE 5.3.1 The major effects of thyroid hormones T3 and T4 in the human body. Hyperthyroidism results from an excess of T3 and T4 secreted from an overactive thyroid gland (hypersecretion).

Process or system affected	Normal physiological effects (T3 and T4 hormones within normal range)	Effects of hyperthyroidism (excess T3 and T4 hormones)
basal metabolic rate (BMR)/ temperature regulation	promotes normal oxygen use and BMR; heat production via the digestion of food and thyroid hormones; enhances effects of sympathetic nervous system	BMR above normal; increased body temperature, heat intolerance; increased appetite; weight loss
carbohydrate/lipid/ protein metabolism	promotes glucose metabolism; mobilises fats; essential for protein synthesis; enhances liver's synthesis of cholesterol	enhanced breakdown of glucose, proteins, and fats; weight loss; loss of muscle mass
nervous system	promotes normal development of nervous system in fetus and infant; promotes normal adult nervous system function	irritability, restlessness, insomnia, personality changes, bulging eyes (in Graves' disease)
cardiovascular system	promotes normal functioning of the heart	increased sensitivity to adrenal gland hormones (e.g. adrenaline and dopamine) leads to rapid heart rate and possible palpitations; high blood pressure; if prolonged, heart failure
muscular system	promotes normal muscular development and function	muscle atrophy and weaknes
skeletal system	promotes normal growth and maturation of the skeleton	in children, excessive skeletal growth initially, followed by early epiphyseal closure and short stature; in adults, demineralisation of skeleton
gastrointestinal (GI) system	promotes normal GI motility and tone; increases secretion of digestive juices	excessive GI motility; diarrhoea; loss of appetite
reproductive system	promotes female reproductive ability and lactation	in females, depressed ovarian function; in males, impotence
integumentary system	promotes normal hydration and secretory activity of skin	skin flushed, thin, and moist; hair fine and soft; nails soft and thin

Causes of hyperthyroidism

There are many causes of hyperthyroidism. The most common cause is an autoimmune disease called Graves' disease. In patients with Graves' disease, the immune system makes an antibody called thyroid stimulating immunoglobulin (TSI), which mimics TSH, stimulating the thyroid to make more T3 and T4 hormones than the body needs (Figures 5.3.7 and 5.3.8 on page xx). The trigger for the production of the antibody is unknown, but a combination of environmental and genetic factors are thought to contribute. Infection caused by some viruses and bacteria, stress, childbirth, excess iodine (through food or contrast dyes used for imaging) and some medications have been linked to the onset of Graves' disease. People with other autoimmune diseases such as type 1 diabetes, as well as smokers and those with tumours of the testes or ovaries, have a higher risk of developing the disease.



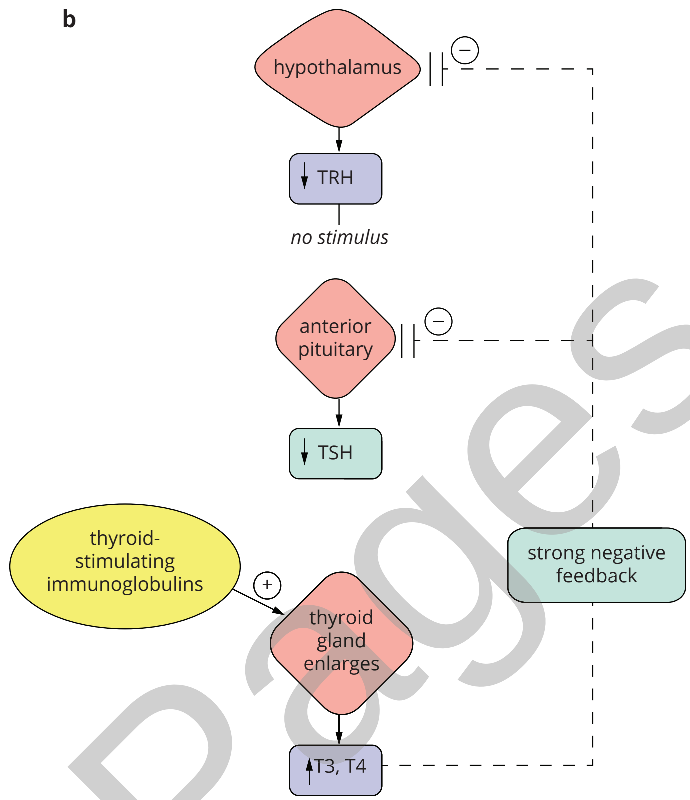


FIGURE 5.3.7 (a) The normal negative feedback loop between the thyroid gland, the pituitary gland and the hypothalamus. (b) The malfunctioning negative feedback loop that leads to hyperthyroidism in someone with Graves' disease.

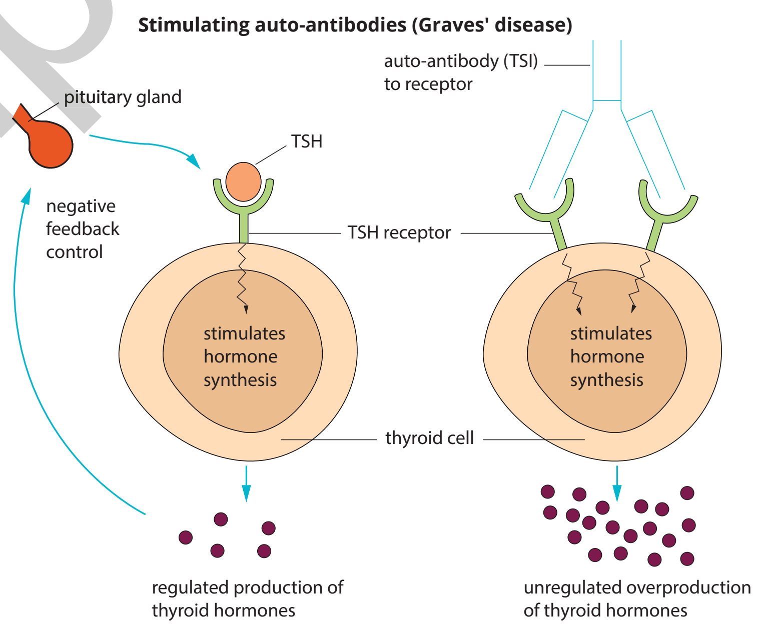


FIGURE 5.3.8 Thyroid stimulating immunoglobulin (TSI) acts on cells in the same way as thyroid stimulating hormone (TSH) to trigger the synthesis and release of T3 and T4. This results in an excess of these thyroid hormones and hyperthyroidism in people with Graves' disease.

Symptoms of hyperthyroidism

The symptoms of hyperthyroidism can include some or all of the following:

- goitre (a visibly enlarged thyroid) or thyroid nodules (Figure 5.3.9a)
- weight loss
- rapid heartbeat (tachycardia)
- irregular heartbeat (arrhythmia)
- pounding heart (palpitations)
- increased appetite
- nervousness, anxiety and irritability
- changes in bowel patterns (more frequent)
- fatigue, muscle weakness
- tremor—usually a fine trembling in your hands and fingers
- breast development in men
- bulging eyes (exophthalmos) (Figure 5.3.9b)
- nausea and diarrhoea
- sweating and heat intolerance
- changes in menstrual patterns
- increased sensitivity to heat
- light or absent menstrual periods
- trouble sleeping
- skin thinning, blushing, flushing or being itchy or clammy
- fine, brittle hair or hair loss

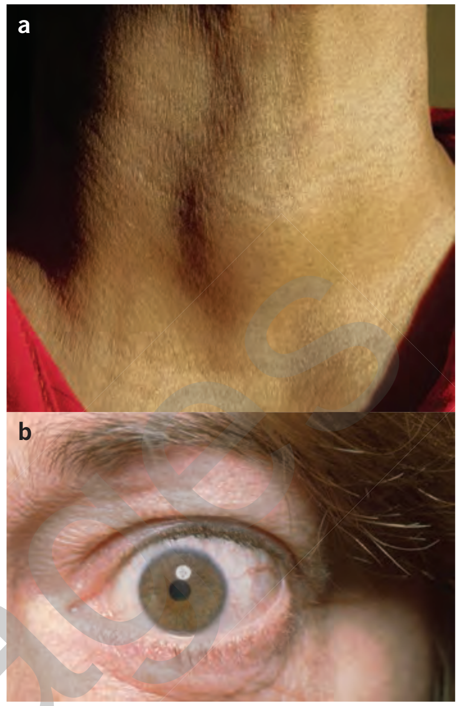


FIGURE 5.3.9 Two common symptoms of hyperthyroidism. (a) An enlarged thyroid gland, called a goitre. (b) In Graves' disease, bulging eyes result when thyroid stimulating immunoglobulin (TSI) produces inflammation and swelling of the soft tissues in the eye.

Management of hyperthyroidism

The symptoms of hyperthyroidism can be treated with drugs called beta-blockers, which act on the circulatory and nervous systems to slow down the increased heartbeats and tremors associated with the disease. However, these drugs do not have an effect on the thyroid itself.

Sometimes anti-thyroid drugs are prescribed to interfere with the thyroid's ability to make hormones. These drugs act on the thyroid gland to slow the production of hormones to normal levels and reduce or eliminate the symptoms. Only 20–30% of patients have long-term success in treating hyperthyroidism with anti-thyroid drugs.

Radioactive iodine treatment is the most widely used permanent treatment for hyperthyroidism. (Iodine is needed to make T3 and T4 hormones.) Thyroid cells are the only cells in the body that absorb iodine. Taken orally, the radioactive iodine (I-131) is absorbed by the thyroid cells. I-131 emits beta radiation, which kills thyroid cells.

Surgery is another permanent cure and involves the removal of all or part of the thyroid. Removal or destruction of the thyroid means the patient will suffer from hypothyroidism, and must take thyroid pills such as levothyroxine for the rest of their life.

BIOFILE

Hypothyroidism

In contrast, to hyperthyroidism, underactivity of the thyroid gland can cause hypothyroidism as a result of insufficient production of the thyroid hormones. Symptoms of this disease in adults are weight gain, lethargy, slow heart rate, hair loss and sensitivity to cold. In children, hypothyroidism can cause delays in growth and mental development. Babies are screened for this disorder a few days after birth. Raised levels of TSH in the blood indicate possible hypothyroidism. The main cause of hypothyroidism is lack of iodine in the diet, which is essential for the production of thyroid hormones. This deficiency can be resolved by adding potassium iodide to table salt. In countries where iodine deficiency is not a widespread problem, the most common cause of hypothyroidism is an autoimmune disease called Hashimoto's thyroiditis.

5.3 Review

SUMMARY

- Malfunctions in homeostatic mechanisms lead to imbalances and a subsequent oversupply or undersupply of substances needed by cells.
- Many diseases are associated with malfunctions in homeostatic mechanisms.
- The endocrine system is particularly important for maintaining homeostasis, and malfunctions in this system can affect the whole body.

Diabetes

- There are two types of diabetes: type 1 (genetic and may be caused by a virus) and type 2 (often late onset and related to lifestyle).
- The cause of type 1 diabetes is the autoimmune destruction of the insulin-producing beta cells in the islets of Langerhans. People with type 1 diabetes do not produce enough insulin. Without treatment, blood glucose concentration can rise to dangerous levels.
- Symptoms of type 1 diabetes include glucose in the urine, increased urine production, excessive thirst, weight loss, fatigue, blurred vision, irritability, muscle cramps, skin infections and delayed wound healing.
- Treatment and management of type 1 diabetes includes daily insulin supplements by injection or insulin pump, and a strictly controlled diet. Pancreas transplants may be required for people with serious complications caused by type 1 diabetes. Potential treatments include pancreatic islets transplants, an artificial pancreas and gene therapy.

Hypoglycaemia

- Hypoglycaemia is the condition where a person experiences low blood glucose levels (BGL), less than 4 mmol/L.
- Hypoglycaemia can be caused by an overproduction of insulin or other underlying conditions, such as excess alcohol consumption.
- Symptoms of hypoglycaemia include shaking, dizziness, anxiety, hunger, nausea and fatigue.
- Treatment for hypoglycaemia includes eating sugary foods or an injection of glucagon to stimulate the conversion of glycogen to glucose to raise BGL.

Hyperthyroidism

- Hyperthyroidism is the over-secretion of the thyroid hormones triiodithyronine (T3) and thyroxine (T4).
- Symptoms of hyperthyroidism include goitre, weight loss, heartbeat irregularities, increased appetite, nervousness, changes in bowel movements, fatigue, tremor, bulging eyes, nausea, heat intolerance, changes in menstrual patterns, and hair loss.
- Treatment for hyperthyroidism involves the use of beta-blockers, anti-thyroid drugs or radioactive iodine I-131, or surgery.

KEY QUESTIONS

Knowledge and understanding

1 Type 1 diabetes is an autoimmune disease. What effect does type 1 diabetes have on the pancreas and blood glucose levels?

2 What is the difference between reactive hypoglycaemia and fasting hypoglycaemia?

3 Define hyperthyroidism.

4 **a** How is thyroid disease diagnosed?
b How would blood test results differ between someone with hyperthyroidism and hypothyroidism?

5 Discuss how malfunctions in homeostatic mechanisms can lead to disease, using an example.

Analysis

6 Use Figure 5.3.3 on page XXX to answer the following questions.
a What is the blood glucose concentration of each of the three patients an hour after the meal?
b Describe two trends that can be seen in the graph of the diabetic patient.
c Explain why there is such a big difference between the blood glucose levels of the diabetic patient and the non-diabetic patient an hour after the meal.

7 Why do people with diabetes sometimes need to have sweet drinks or food?

8 Infer how brown fat might be important in diabetes management.

Chapter review

05

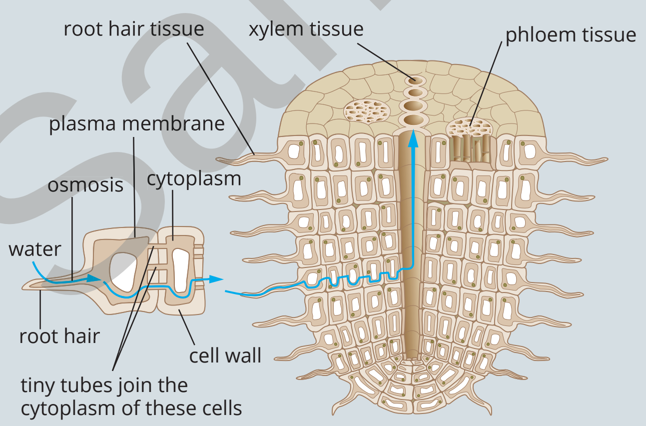
KEY TERMS

active transport
aldosterone
antidiuretic hormone (ADH)
autoimmune disease
baroreceptor
blood glucose level (BGL)
Casparian strip
chemoreceptor
cohesive bond
conduction
control centre
convection
cytoplasmic pathway
diffusion
effector
endocrine system
endotherm
evaporation
evaporative cooling
exteroreceptor
extracellular pathway
glucagon
glucose
glycogen
guard cell
homeostasis
hormone
hyperglycaemia
hypersecretion
hyperthyroidism
hypoglycaemia
hyposecretion
hypothalamus
hypothyroidism
immuno-suppressant drug
insulin
interoreceptor
lenticel
mechanoreceptor
metabolism
negative feedback loop
nervous system
neurotransmitter
non-shivering thermogenesis
osmoconformer
osmolality
osmoreceptor
osmoregulation
osmoregulator
osmosis
osmotic gradient
phloem
photoreceptor
piloerection
plasmodesmata (singluar plasmodesma)
positive feedback loop
radiation
receptor
renin
response
root hair
root pressure
shivering thermogenesis
signalling molecule
sink
source
stimulus
stimulus–response mechanism
stomata (sing. stoma)
thermoreceptor
thermoregulation
thyroid stimulating hormone (TSH)
thyrotropin releasing hormone (TRH)
translocation
transpiration
transpiration stream
turgor
type 1 diabetes
vascular plant
vascular tissue
vasoconstriction
vasodilation
xylem

REVIEW QUESTIONS

Knowledge and understanding

1. What is meant by the terms 'sources' and 'sinks'?
2. Create a summary table comparing xylem and phloem transport. Outline what each tissue transports and the direction of transport.
3. List the key factors that influence the rate of transpiration in plants.
4. Describe the pathway of water absorption in the diagram of plant root tissue below.



5. Why is it important for an organism to be able to regulate its internal environment?
6. Arrange the following terms from first to last in the order of their involvement in a physiological response: control centre, effector, receptor, response, stimulus.
7. What is the similarity between neurotransmitters and hormones?
8. How do organisms exchange heat with their environment? Explain each of the four methods of heat exchange using examples.
9. Summarise the thermoregulatory mechanisms that occur during and immediately after a fever.
10. **a** Explain the principle of negative feedback in homeostasis.
    b Using a diagram, explain how a low body temperature can be increased. In your diagram, draw and label an arrow to show where negative feedback occurs.
11. Draw a table to list ways a healthy person may gain or lose water in a day.
12. What change in the blood acts as a stimulus for ADH release?

13 Describe how negative feedback is involved in ADH action and water balance.

14 Diseases of the endocrine system fall into three groups. What are they? Provide an example of each.

15 List three ways of managing type 1 diabetes.

Application and analysis

16 Celery curls are an attractive way of serving celery. They are made by taking sections of celery stalk, making several lengthwise cuts in one end and submerging them in cold water. The cut parts of the celery start to curl. If the cuts are made too close together, long strings of celery will peel away. Explain what causes the celery ends to curl.

17 **a** What is the association of gas exchange with transpiration in plants?

b How does wind affect transpiration rates?

c Why is the rate of transpiration lower at night?

18 The rates of transpiration in plants were measured in three different environments over a period of 6 hours. The results are shown below.

Environment 1—23°C, night, with wind speeds of 15 km/h and an average humidity of 88%

Environment 2—24°C, day, with wind speeds of 15 km/h and an average humidity of 84%

Environment 3—33°C, day, with wind speeds of 20 km/h and an average humidity of 80%

a Order the environments from highest to lowest expected rates of transpiration and give reasons to support your answer.

b Identify the variables that would need to be kept constant when measuring rates of transpiration for your conclusion to be valid.

19 Occasionally a person is born without sweat glands, so they cannot lose heat through sweating. A person without sweat glands and a person with normal sweat glands were placed in cool, dry conditions and their skin and mouth temperatures were recorded. The two people were then placed in a moist, hot environment, and further recordings were made. The results of the experiment are recorded in the table. Deduce which person (A or B) was born without sweat glands. Explain your reasoning.

Response	Person A		Person B	
	Cool, dry	Hot, moist	Cool, dry	Hot, moist
skin temperature (°C)	33.8	40.5	32.7	37.4
oral temperature (°C)	36.9	38.6	36.8	37.2
water loss from skin and lungs (mL)	not recorded	20.0	not recorded	282.0
urine volume (mL)	not recorded	280.5	not recorded	12.6

20 **a** Copy and complete the following table to summarise the two hormones that play a vital role in blood glucose regulation.

Hormone	Site of production	Target organs	Main functions
insulin			
glucagon			

b Name the hormone that is produced in insufficient amounts in type 1 diabetes.

c Blood glucose levels in a non-diabetic and diabetic person after eating similar meals are shown in the following graph. Which line on the graph represents the diabetic individual? Explain your reasoning using the data presented in the graph.