5
HOMEOSTASIS CONTROLS BLOOD GLUCOSE AND BODY TEMPERATURE

UNIT 3 CONTENT

SCIENCE INQUIRY SKILLS

- identify, research and construct questions for investigation; propose hypotheses; and predict possible outcomes
- design investigations, including the procedure(s) to be followed, the materials required, and the type and amount of primary and/or secondary data to be collected; conduct risk assessments; and consider research ethics, including animal ethics
- conduct investigations, including the collection of data related to homeostasis and the use of models of disease transmission, safely, competently and methodically for the collection of valid and reliable data
- represent data in meaningful and useful ways, including the use of mean, median, range and probability; organise and analyse data to identify trends, patterns and relationships; discuss the ways in which measurement error, instrumental accuracy, the nature of the procedure and the sample size may influence uncertainty and limitations in data; and select, synthesise and use evidence to make and justify conclusions
- select, use and/or construct appropriate representations, including diagrams, models and flow charts, to communicate conceptual understanding, solve problems and make predictions.
- communicate to specific audiences, and for specific purposes, using appropriate language, nomenclature, genres and modes, including scientific reports

SCIENCE UNDERSTANDING

Homeostasis

- homeostatic processes involve nerves and hormones in maintaining the body's internal environment within tolerance limits through the control of metabolism and physiological and behavioural activities
- thermoregulation occurs by the control of heat exchange and metabolic activity through physiological and behavioural mechanisms
- blood sugar levels are maintained by controlling of sugar uptake, its storage and release by cells and use in metabolism; these processes involve the hormones of the pancreas and adrenal glands

Source: School Curriculum and Standards Authority, Government of Western Australia

5.1 HOMEOSTASIS

Think of the last time you ran to catch a bus or a train, or ran up several flights of stairs. After such vigorous activity you may have been sweating, your face may have been red, you would have been breathing heavily, and you would have been able to feel your heart beating forcefully and rapidly. All these responses would have occurred automatically, without any conscious thought on your part. Such responses are a part of homeostasis. **Homeostasis** is the process of keeping the environment inside the body fairly constant.

Our body cells work best at a particular temperature, when surrounded by fluid with a particular pH, when given a constant supply of oxygen and glucose, and when wastes are constantly removed. Maintaining these, and other optimum conditions for cell functioning, is all part of homeostasis.

Homeostatic mechanisms help us to be independent of our external environment. For example, if you suddenly plunge into a cold swimming pool, the cells of your brain, liver, stomach, heart and other internal organs will continue to function normally despite the sudden change in external temperature.

iStock.com/tomch

FIGURE 5.1 Homeostasis makes us relatively independent of the external environment

The body's cells are surrounded by fluid, the composition and temperature of which must be maintained within very narrow limits. The important aspects of the internal environment that the body needs to regulate include:

- core body temperature
- pH and concentrations of dissolved substances in the body fluids
- concentration of glucose in the blood
- concentration of oxygen and carbon dioxide in the blood and other body fluids
- blood pressure
- concentration of metabolic wastes.

The maintenance of this **steady state** does not mean that nothing changes. Instead, there is a dynamic equilibrium in which the input and output of materials and energy are balanced. All the systems of the body contribute to homeostasis, not only to supply the cells' needs, but also to maintain a constant cellular environment.

To maintain homeostasis, the body must be able to both sense changes in the internal and external environment and compensate for those changes. The nervous and endocrine systems are the main sensory and controlling body systems; in the case of homeostasis, they operate through feedback systems, many of which involve negative feedback.

Feedback systems

A **feedback system** is a circular situation in which the body responds to a change, or **stimulus**, with the response altering the original stimulus and thus providing feedback. Feedback systems can be negative or positive, depending on whether the response decreases or increases the original stimulus. For example, when we exercise our muscles use glucose to release the energy required for muscle contraction. The muscles absorb glucose from the blood and, consequently, the blood glucose level tends to fall. This is the stimulus. The liver responds by releasing more glucose into the blood. Thus, the response has caused the blood glucose level to go up, which is the *opposite* of the fall in glucose that initiated the response. In this way, the blood glucose level is maintained within a range that is acceptable for efficient cellular functioning.

Feedback systems have a number of common features.

- The *stimulus* is the change in the environment that causes the system to operate.
- The *receptor* detects the change.
- The ***modulator*** is a control centre responsible for processing information received from the receptor and for sending information to the effector.
- The *effector* carries out a response counteracting or enhancing the effect of the stimulus.
- *Feedback* is achieved because the original stimulus has been changed by the response.

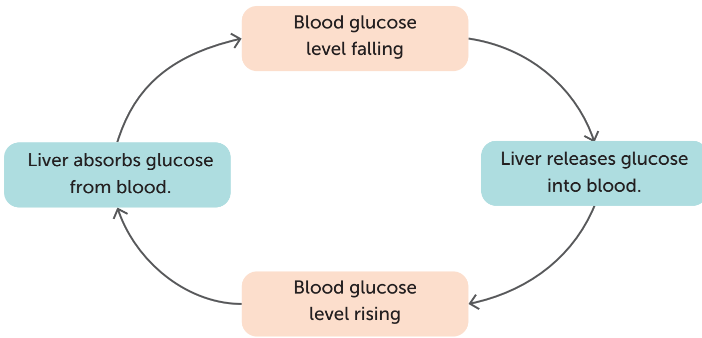


FIGURE 5.2 Example of a feedback system: the feedback loop controlling the body's blood glucose level

In science, a **model** is a simplified representation of something that is fairly complex. The stimulus–response–feedback model is a simple way of explaining how homeostatic mechanisms work.

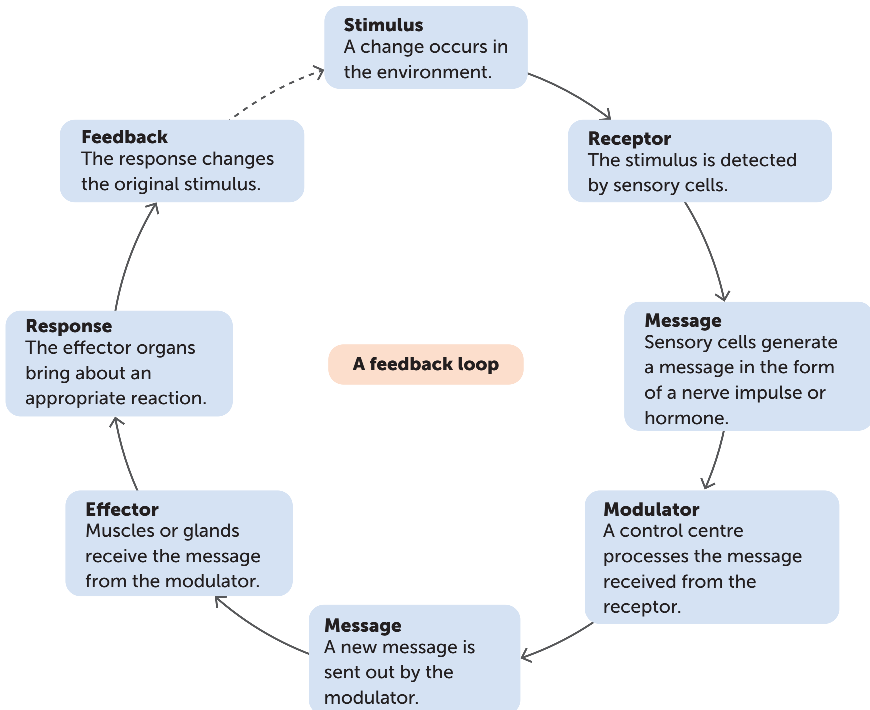


FIGURE 5.3 The stimulus–response–feedback model

Key concept

A feedback loop involves a stimulus, receptor, modulator, effector, response and feedback.

Homeostasis and feedback loops
This website has more information about homeostasis and feedback loops.

Homeostatic mechanisms are controlled by both the nervous system and the endocrine system. Both systems detect when the body is beginning to deviate from its normal balanced state: the nervous system sends electrical messages to the appropriate organs so that the change is counteracted; the glands of the endocrine system secrete chemical messengers, or hormones, into the blood. Hormones, however, generally work more slowly than nerve impulses in coordinating homeostasis.

Negative feedback

In homeostatic mechanisms the response has the effect of reducing or eliminating the stimulus that caused it. This is called **negative feedback**. For example, if you feel cold your response to the stimulus might be to put on a jumper. This response reduces or eliminates the original stimulus of feeling cold. Negative feedback systems are also called **steady state control systems**, as they return the body to a steady state.

An analogy that is often used to explain a negative feedback loop is that of an air-conditioning system in a room or building. Suppose that the thermostat is set to a comfortable 22°C. On a warm day, when the temperature rises above 22°C, the thermostat automatically switches the air conditioner on so that cool air is brought into the room. The air in the room becomes cooler and the thermostat then switches the air conditioner off when it reaches its target temperature. This process repeats itself so that the air temperature remains relatively constant.

Figure 5.4 shows how the components of the air-conditioning system correspond to the components of a negative feedback loop. Note that the temperature fluctuates above and below the temperature set on the thermostat. It is the same with the human body. Things such as the concentration of blood glucose and body temperature fluctuate around a normal level. This fluctuation is called a **dynamic equilibrium**. The point around which conditions fluctuate is called the **set point**. For the air conditioner in our scenario, the set point is 22°C; for human body temperature, the set point is 37°C. **Tolerance limits** are the upper and lower limits between which the levels fluctuate. Within these limits the body functions normally; however, a rise above, or a fall below, them means that the individual's tolerance limits have been exceeded and dysfunctions will occur.

Negative feedback
This website has a simple quiz on negative feedback. Test yourself!

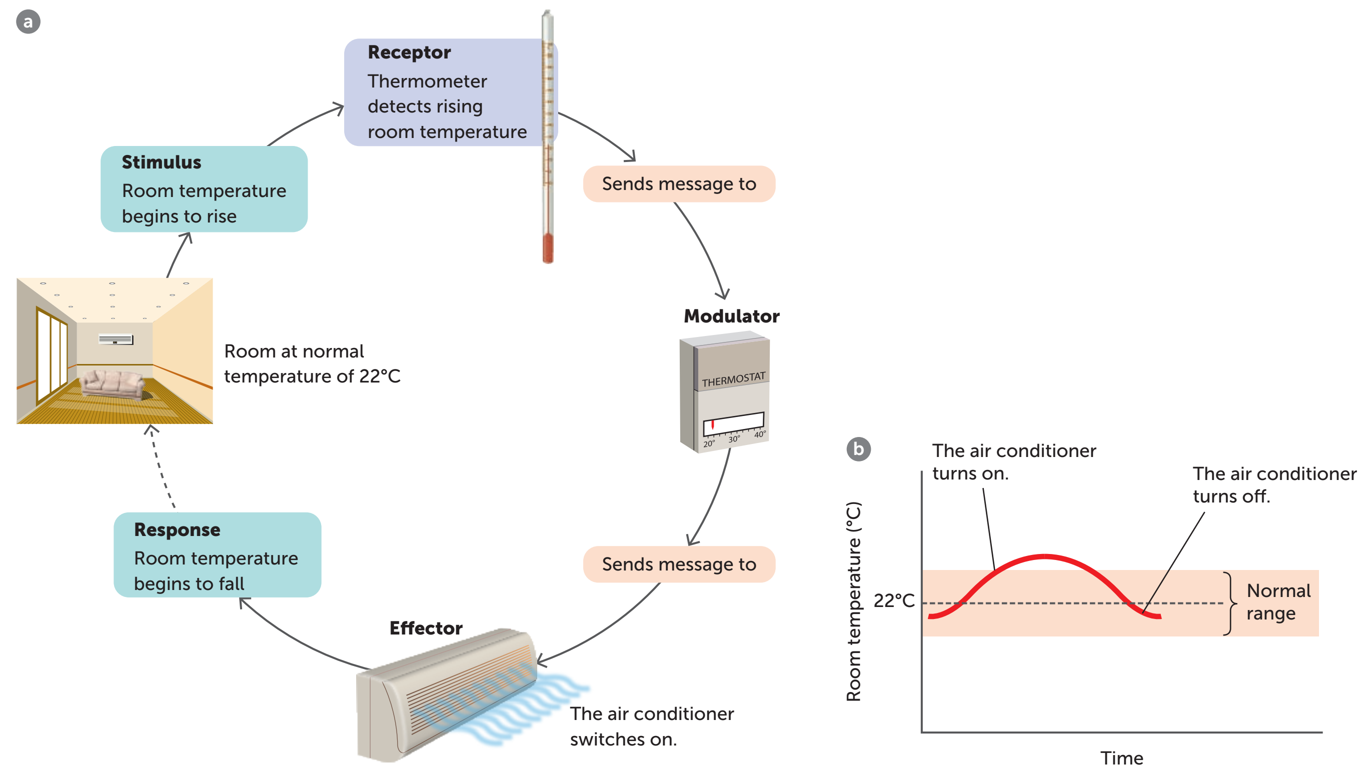


FIGURE 5.4 a An air-conditioning system uses negative feedback to keep the room temperature fairly constant.
b Room temperature fluctuates around the temperature determined by the thermostat

Key concept

Negative feedback systems maintain homeostasis by producing a response that is the opposite of the original change.

Positive feedback

Positive feedback has no role in homeostasis, but it is included here so that you can understand the difference between positive and negative feedback. When **positive feedback** occurs, the response to a stimulus reinforces and intensifies the stimulus. The intensified stimulus results in an even greater response, and so on. Obviously, this could not result in homeostasis, but there are a few situations in which it does occur in the human body where it is important in controlling processes that must be completed quickly.

An example of positive feedback occurs during childbirth, a process that must be completed as rapidly as possible to avoid stress and injury to mother and baby. Labour is initiated by the secretion of the hormone oxytocin from the posterior lobe of the pituitary gland. Oxytocin causes contractions of the uterus. The contractions push the baby's head against the mother's cervix. Stimulation of the cervix causes it to send nerve impulses to the brain, which responds by instructing the pituitary to secrete more oxytocin. The increased oxytocin makes the uterus contract more strongly. These contractions push the baby's head more forcibly against the cervix, which sends even more impulses to the brain, and so the uterine contractions are increasingly intensified. Once the baby is delivered, the cervix is no longer stretched; it ceases sending nerve impulses to the brain and the positive feedback cycle stops.

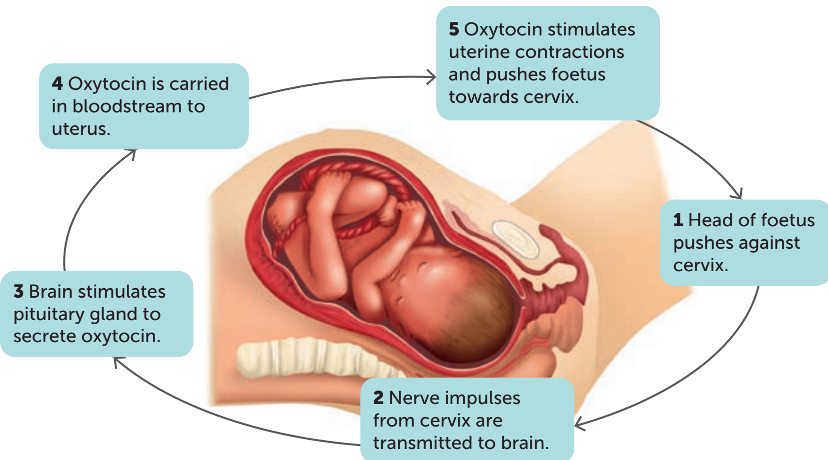


FIGURE 5.5 Childbirth is regulated by a positive feedback system

Another example of positive feedback is blood clotting. This process must be completed quickly to minimise blood loss.

However, positive feedback can sometimes be harmful. An example is a high fever. A small rise in body temperature can be beneficial in fighting infection; however, if body temperature rises above 42°C, a dangerous positive feedback loop can occur. The raised body temperature causes a higher metabolic rate that produces more heat, which raises the temperature still further. This increases the metabolic rate and so the temperature spirals upwards. Unless medical treatment is given, death will result when body temperature reaches about 45°C.

WS
5.1 Homeostasis

Questions 5.1

RECALL KNOWLEDGE

1. Define 'homeostasis'.
2. Fill in the blanks for the negative feedback loop.
   Stimulus → ______________ → ______________ → ______________ → ______________ → feedback
3. List four characteristics that are maintained by homeostasis.
4. Describe two positive feedback systems.
5. Use a flow chart to model the feedback loop when drinking water maintains fluid levels in the body on a very hot day.

APPLY KNOWLEDGE

6. Explain the difference between the set point and tolerance limit.
7. Explain why a positive feedback system would not achieve homeostasis.

5.2 REGULATION OF BLOOD SUGAR

Sugar in the blood is in the form of glucose. When we talk about 'blood sugar', we are really talking about the amount of glucose in the blood. All cells need a constant supply of glucose because it is the source of energy for all the cells' activities, such as movement, reproduction, synthesising molecules, active transport and many others. Energy is released from glucose molecules by cellular respiration.

Glucose + oxygen → carbon dioxide + water + energy

The body's source of glucose is the food we eat. Carbohydrates in our food are broken down into glucose during digestion and then absorbed into the blood through the walls of the small intestine. After a meal, blood glucose concentration can rise sharply. Homeostatic mechanisms then begin to operate to reduce the blood glucose concentration and maintain it at the normal level. Any excess glucose in the blood must be removed and stored ready for use in cellular activities between meals.

Science Photo Library/John Birdsall Social Issues Photo Library

FIGURE 5.6 A glucometer (blood glucose meter) being used to measure the level of glucose in the blood. A small sample of blood is taken from a prick in the patient's finger, and placed on the white strip of the glucometer. This patient's reading of 10.4 millimoles/litre (mmol/L) is equivalent to 187mg of glucose per decilitre of blood (mg/dl)

Glucose and glycogen

Glucose is stored as **glycogen**, a molecule made of long chains of glucose molecules. The body is able to store about 500g of glycogen: about 100g is stored in the liver and the remainder in skeletal muscle cells. Excess glucose in the is converted to glycogen for storage. Alternatively, when there is not enough glucose in the blood, some of the glycogen can be converted to glucose.

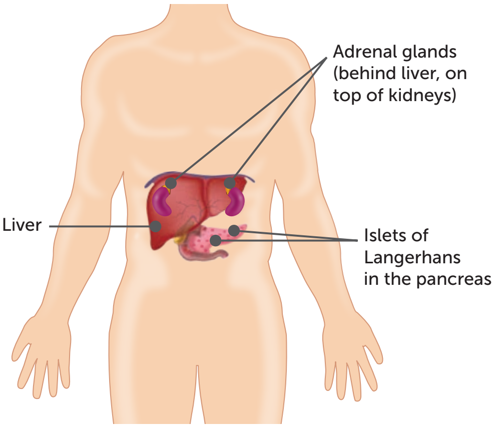
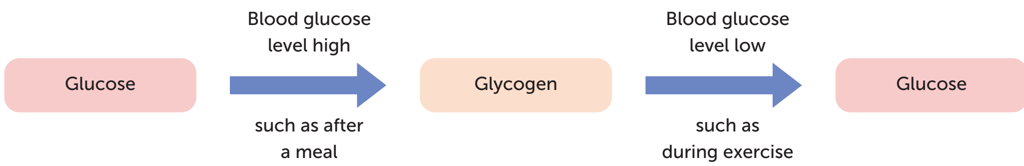


FIGURE 5.7 The main organs involved in the regulation of blood glucose. The pancreas and adrenal glands secrete hormones that affect the level of glucose in the blood, while the liver stores excess glucose as glycogen

FIGURE 5.8 A summary of glucose–glycogen conversions



Role of the liver

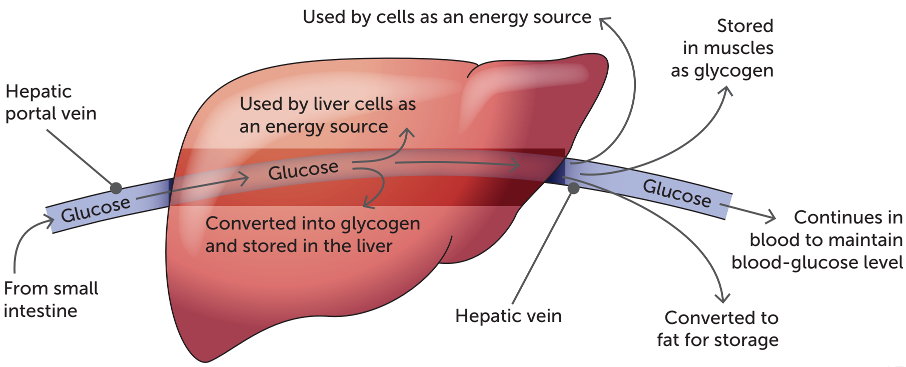
The liver is in the upper part of the abdominal cavity just below the diaphragm. It is the largest gland in the body and has a very important role in the control of blood sugar concentration. The liver is able to convert glucose into glycogen for storage, or glycogen to glucose for release into the blood.

Most of the liver's blood supply comes through the hepatic portal vein, which brings blood directly from the stomach, spleen, pancreas, and small and large intestines. Thus, the liver has the first chance to absorb the nutrients from digested food.

After a typical meal containing a high proportion of carbohydrates is consumed, the breakdown products, mainly glucose, are absorbed into the blood capillaries of the villi of the small intestine. The hepatic portal vein carries the glucose to the liver, where a number of things may occur. Glucose may:

- be removed from the blood by the liver to provide energy for liver functioning
- be removed by the liver and/or muscles and converted into glycogen for storage
- continue to circulate in the blood, available for body cells to absorb and use as a source of energy
- be converted into fat for long-term storage if it is in excess of that required to maintain both normal blood sugar and tissue glycogen levels.

FIGURE 5.9 The fate of glucose absorbed in the small intestine



Glucose molecules are chemically joined in long chains to form glycogen molecules. This process, known as **glycogenesis**, is stimulated by the pancreatic hormone **insulin**. Glycogen itself cannot be used by cells; it must be converted back into glucose or to other simple sugars. Glycogen stored in the liver is available for conversion into glucose to maintain blood sugar levels and supply energy for liver activity. Glycogen in muscle cells provides the glucose required for muscle activity.

If the level of glucose in the blood drops below normal, the glycogen stored in the liver and muscle cells can be broken down into glucose. This process of converting glycogen back into glucose is called **glycogenolysis**. Most frequently, it occurs between meals and is stimulated by another pancreatic hormone, **glucagon**.

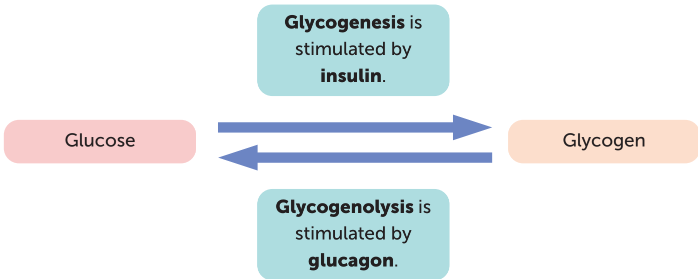


FIGURE 5.10 Glucose–glycogen conversions stimulated by pancreatic hormones

Glycogen stored in the liver is a short-term energy supply. It can provide glucose for body cell use for only about six hours if no other supply is available. If more energy is required, the body uses the energy reserves in stored fat.

TABLE 5.1 Terms relating to glucose metabolism

TERM	MEANING
Glycogenesis	Formation of glycogen from other carbohydrates, especially glucose (in Greek, *genesis* means 'origin' or 'creation')
Glycogenolysis	Breakdown of glycogen to glucose (in Greek, *lysis* means 'to separate or break down')
Gluconeogenesis	Conversion of fats or proteins into glucose (in Greek, *neo* means 'new')

Role of the pancreas

The pancreas is a pale grey gland, 12–15 cm long, lying partly in the curve of the duodenum. Within the pancreas are clusters of hormone-secreting cells called the **islets of Langerhans**. The cells in the islets are of two types:

- **alpha cells** that secrete glucagon
- **beta cells** that secrete insulin.

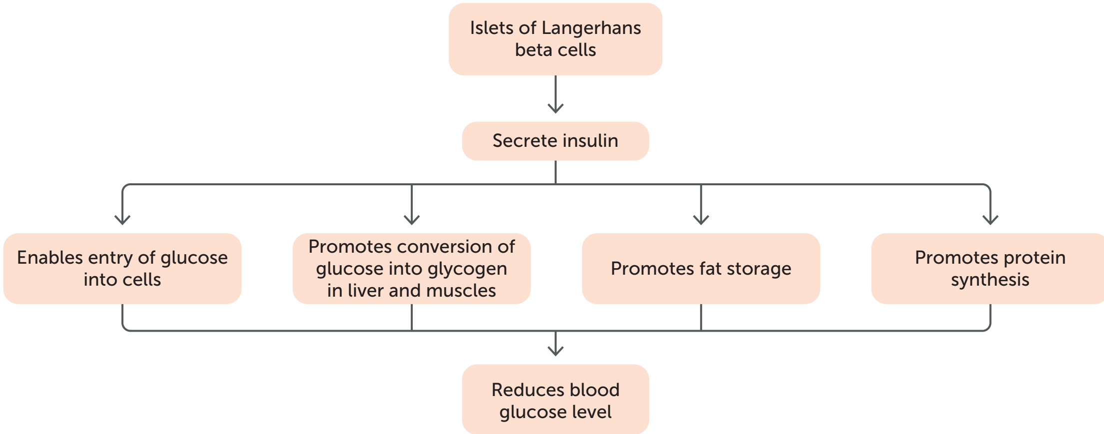
Insulin from the beta cells causes a *decrease* in blood glucose levels. It does so by:

- accelerating the transport of glucose from the blood into body cells, especially those of the skeletal muscles
- accelerating the conversion of glucose into glycogen in the liver and skeletal muscle (glycogenesis)
- stimulating the conversion of glucose into protein (protein synthesis)
- stimulating the conversion of glucose into fat (lipids) in adipose tissue, or fat storage tissue, a process called **lipogenesis**.

All these activities decrease blood glucose levels.

The level of blood glucose regulates the secretion of insulin via a negative feedback system. When blood glucose levels rise above normal, chemoreceptors in the beta cells of the islets of Langerhans stimulate those cells to secrete insulin. As the level of blood glucose decreases, the cells are no longer stimulated and production is reduced.

FIGURE 5.11 Effects of insulin on blood glucose levels



Glucagon from the alpha cells causes an *increase* in blood glucose levels. It does this by:

- stimulating glycogenolysis, the conversion of glycogen into glucose, in the liver
- stimulating **gluconeogenesis**, the production of new sugar molecules from fats (lipids) and amino acids, in the liver. This involves the breakdown of lipids in a process called **lipolysis**
- having a mild stimulating effect on protein breakdown.

The glucose formed is released into the blood, and the blood glucose level rises.

The regulation of the secretion of glucagon, like that of insulin secretion, is directly determined by the level of glucose in the blood and is controlled by a negative feedback system. When the blood glucose falls below normal, chemoreceptors in the alpha cells of the islets of Langerhans stimulate those cells to secrete glucagon. As the blood glucose level increases, the cells are no longer stimulated and production is reduced.

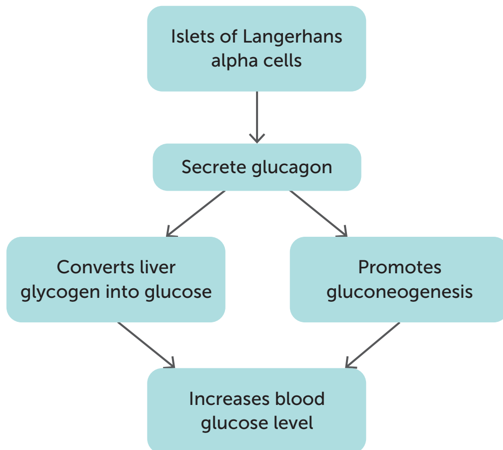
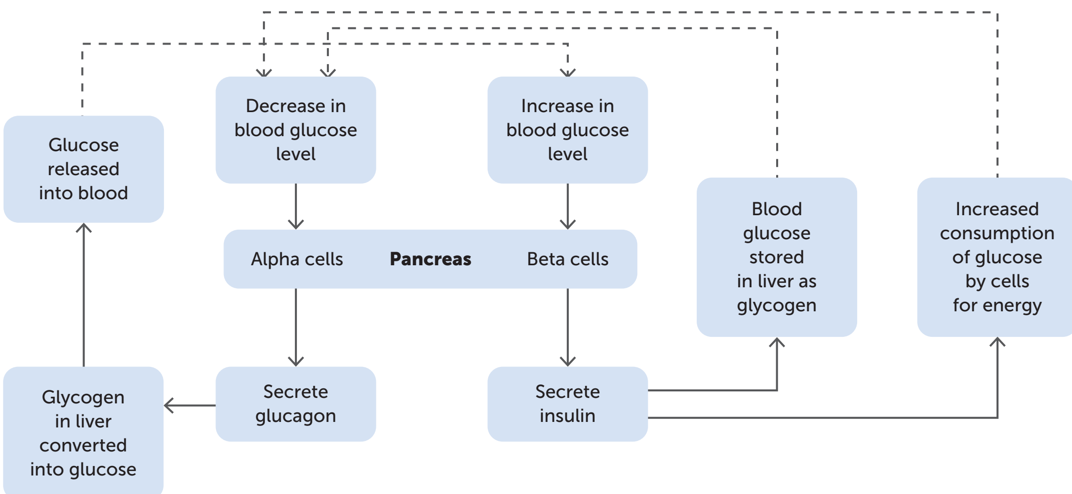


FIGURE 5.12 Effects of glucagon on blood glucose levels

FIGURE 5.13 Regulation of blood glucose by insulin and glucagon



Insulin and diabetes
This website provides more information on the role of insulin and glucagon in blood sugar regulation.

Blood sugar regulation
This website provides more information on the regulation of blood sugar.

Role of the adrenal glands

The adrenal glands are situated just above the kidneys, one gland above each. Each gland is composed of two distinct parts: the outer part is called the **cortex** and the inner part is the **medulla**. The adrenal glands produce a number of hormones, but in discussing the control of blood glucose, we are interested only in the secretion of glucocorticoids by the adrenal cortex, and the secretion of adrenaline (epinephrine) and noradrenaline (norepinephrine) by the adrenal medulla.

The adrenal cortex is stimulated to secrete its hormones by adrenocorticotropic hormone (ACTH) from the anterior lobe of the pituitary gland. The hormones secreted are glucocorticoids, the best known of which is **cortisol**. They regulate carbohydrate metabolism by ensuring that enough energy is provided to the cells. In doing so, they stimulate the conversion of glycogen into glucose during glycogenolysis. They also increase the rate at which amino acids are removed from cells, mainly muscle cells, and transported to the liver. Some of these amino acids may be converted into glucose by the liver during gluconeogenesis if glycogen and fat levels are low.

Glucocorticoids also promote the mobilisation of fatty acids from adipose tissue, allowing muscle cells to shift from using glucose to fatty acids for much of their metabolic energy.

The adrenal medulla synthesises adrenaline and noradrenaline, hormones that produce the same effects as those brought about by sympathetic nerves of the autonomic nervous system. One such effect is the increase of blood glucose levels. In particular, adrenaline elevates blood glucose levels through glycogenolysis and in doing so counteracts the effects of insulin. It stimulates the production of lactic acid from glycogen in muscle cells, which can then be used by the liver to manufacture glucose.

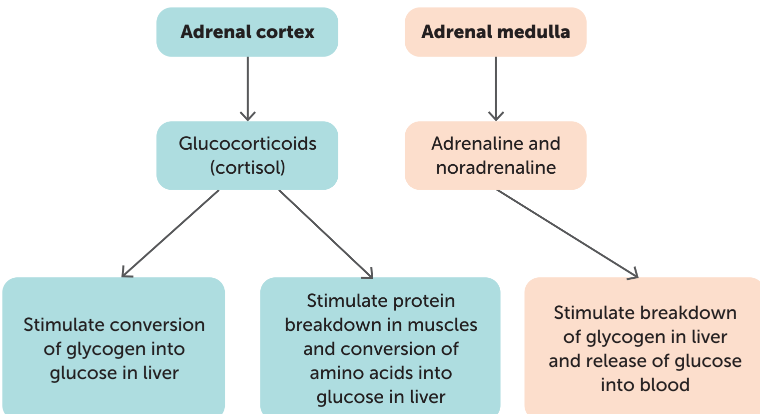


FIGURE 5.14 Effect of adrenal hormones on blood glucose levels

Blood glucose homeostasis

The normal level of glucose in the blood is between 4 and 6 millimoles per litre (5 mmol/L is equivalent to 90 mg/100 mL). Many activities take place to maintain the level within these narrow limits. Our discussion has covered the involvement of the liver, pancreas and adrenal glands. Homeostasis relies on the contribution of all three, working in an integrated manner. Figure 5.15 summarises the main influences on these processes.

5.2 Homeostasis of blood sugar

9780170449168

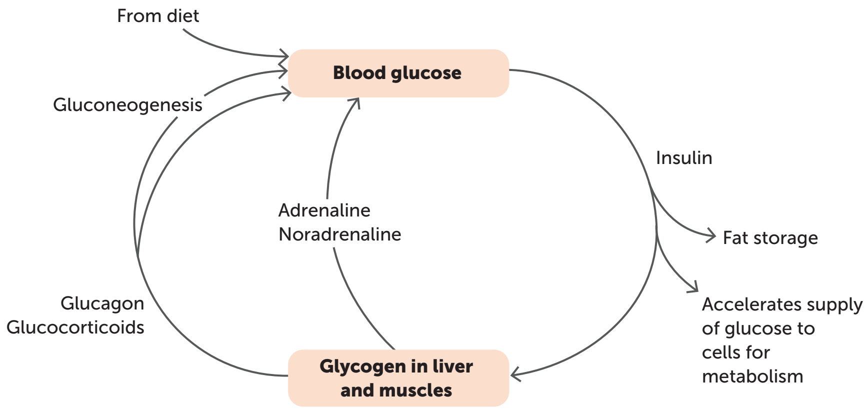


FIGURE 5.15 A summary of blood glucose homeostasis

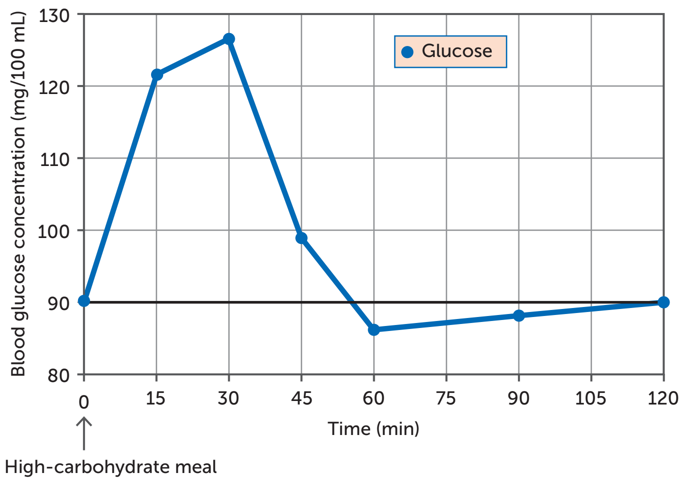


FIGURE 5.16 Change in blood glucose concentration over time following a high-carbohydrate meal

Questions 5.2

RECALL KNOWLEDGE

1 List the organs that play key roles in glucose homeostasis.

2 Define 'glycogenesis', 'glycogenolysis' and 'gluconeogenesis'.

3 Describe what happens to glucose from ingestion to it passing through the liver.

4 Blood glucose levels increase after eating carbohydrates.
 - a What is the key hormone that will initially be released?
 - b What organ produces this hormone?
 - c What cells within the organ produce this hormone?
 - d What responses does the hormone lead to?

5 Describe the role of the adrenal glands in controlling the level of glucose in the blood.

APPLY KNOWLEDGE

6 Write a word equation for cellular respiration and explain its significance in relation to glucose homeostasis.

7 Use the stimulus–response–feedback model to summarise how the pancreas responds after strenuous activity.

5.3 THERMOREGULATION

On a hot day you would probably get out of the sun, remove some of your outer clothing, and turn on a fan or air conditioner. These are behavioural responses to the high temperature, but at the same time changes would be occurring inside your body that you are not consciously aware of. All these responses, conscious and unconscious, work together to keep the body's core temperature within its tolerance limits. This regulation of body temperature – **thermoregulation** – makes us relatively independent of the environmental temperature.

Heat gain and heat loss

The body temperature of humans remains remarkably constant at about 36.8°C. This is an important aspect of homeostasis because the chemical reactions occurring in cells are very heat sensitive. A temperature of around 37°C is optimum for cellular reactions, and so cells maintained at this temperature function in a stable manner. To achieve this temperature, the heat gained by the body must exactly equal the heat lost from the body. Maintaining this balance is thermoregulation.

Under most conditions, the internal body temperature is higher than the surrounding environmental temperature. The heat produced from metabolic activity helps to maintain this higher level. However, during exercise and other strenuous activity, the increase in metabolic rate generates more heat than the body needs to keep its temperature constant. The excess heat needs to be removed or the body temperature will rise. Increased body temperature can cause nerve malfunction, change in the structure of proteins, and death. Therefore, it is extremely important for the body to be able to regulate its internal temperature and maintain it within fairly precise limits.

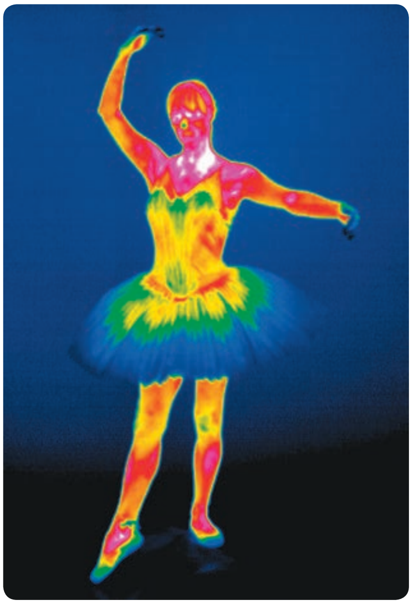

Science Photo Library/Tony McConnell

FIGURE 5.17 Thermogram of a ballerina showing relative temperatures at the surface of the body. The warmest areas are white, followed by red, yellow, green and blue, with purple being the coldest

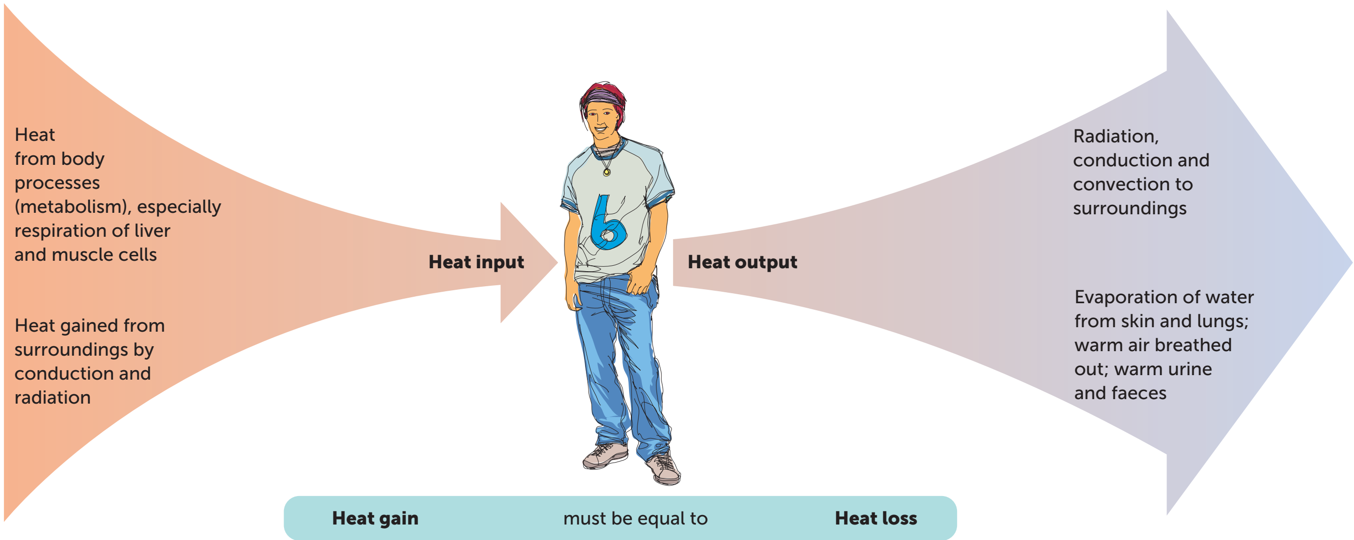


FIGURE 5.18 A constant human body temperature is achieved by a balance between heat gain and heat loss

Although body temperature remains fairly constant, variation does occur as a matter of course. This variation may result from activity or changes in external temperature. In addition, there is a characteristic daily body temperature cycle, with the lowest temperature generally occurring in the morning and the highest in the evening. Also, women have higher temperatures during the second half of the menstrual cycle as a result of the effects of the hormone progesterone.

Heat production

The carbohydrates, proteins and lipids that we eat contain energy in chemical bonds that hold the various parts of the molecule together. This energy is released when the food is oxidised during cellular respiration.

Some of the energy is used for muscle contraction, for active transport of substances across the cell membrane, for building up new complex molecules, and so on. Most of the energy, however, is released in the form of heat.

The rate at which energy is released by the breakdown of food is called the **metabolic rate**. Many factors, such as exercise, stress and body temperature, affect the metabolic rate of an individual. The factor with the greatest effect is exercise. During exercise, muscular activity can increase metabolic rate by up to 40 times, so very large quantities of heat are released.

Metabolic rate also increases in times of stress because of the activities of the autonomic division of the nervous system. Stimulation of sympathetic nerves releases noradrenaline from the nerve endings; noradrenaline increases the metabolic activity of cells. Strong sympathetic stimulation may cause dramatic increases in the metabolic rate, but usually for only a few minutes.

Rising body temperature is another factor that increases metabolic activity. For each 1°C rise in temperature, the rate of biochemical reactions increases by about 10%. Therefore, when an individual is suffering from a high fever, the metabolic rate may be up to double the normal rate.

Regulating body temperature

Temperature receptors

The body has temperature receptors, or **thermoreceptors**. Those in the skin and in some mucous membranes are called **peripheral thermoreceptors.** They detect temperature changes in the external environment and send this information to the hypothalamus. Others are located in the hypothalamus and are called **central thermoreceptors**. These receptors detect the temperature of the internal environment. There are additional thermoreceptors at various internal locations such as the spinal cord and the abdominal organs that provide the hypothalamus with information about the temperature of the internal environment.

There are two types of thermoreceptors: **cold receptors** are stimulated by temperatures lower than normal; and **heat receptors** detect temperatures higher than normal. When cold receptors are stimulated, the hypothalamus receives the information and initiates heat conservation and heat production mechanisms. If heat receptors are stimulated, mechanisms operate to reduce heat production and increase heat loss.

The skin and temperature regulation

Conduction, convection and radiation
This website explains conduction, convection and radiation in more detail.

The large surface area and location of the skin between the internal and external environment means that it is a very important organ in regulating body temperature. Heat can be lost from the skin by conduction, convection, radiation and evaporation. Therefore, changes in the skin can speed up or slow down the rate at which heat is lost from the body.

- **Conduction** is the transfer of heat by direct contact between particles.
- **Convection** is the transfer of heat by the movement of a liquid or a gas.
- **Radiation** is the transfer of heat by infrared radiation being emitted by objects.
- **Evaporation** is the process of a liquid forming a gas, which absorbs heat energy.

Key concept

Heat is lost by conduction, convection, radiation and evaporation.

9780170449168

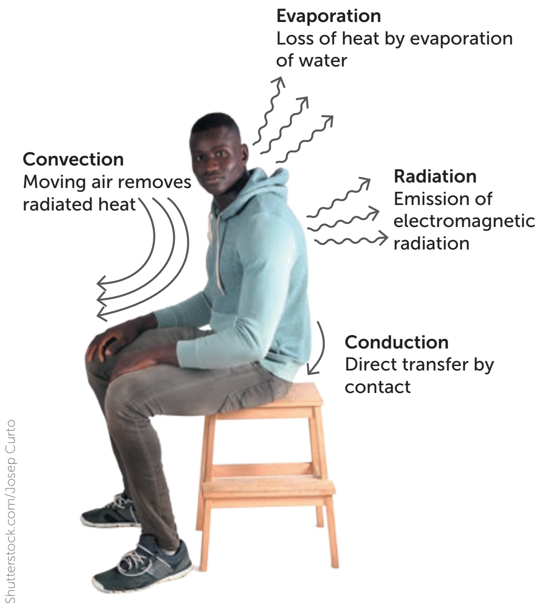


FIGURE 5.19 Methods of heat loss from the body

Blood vessels and heat loss

Blood vessels located in the dermis of the skin carry heat to the skin from the core of the body. The diameter of these arterioles is controlled by autonomic nerves. If the diameter is increased by **vasodilation**, more blood is transported to the capillaries in the skin and the rate of heat loss increases. Alternatively, if the diameter is reduced by **vasoconstriction**, less blood is transported to the capillaries in the skin and the rate of heat loss decreases.

Sweating and heat loss

When large amounts of body heat must be lost and skin blood vessels are already at maximum dilation, sweating must occur. **Sweating** is the active secretion of fluid by the **sweat glands** and the periodic contraction of cells surrounding the ducts to pump the **sweat** to the skin surface. The production and transport of sweat to the skin surface is stimulated by sympathetic nerves.

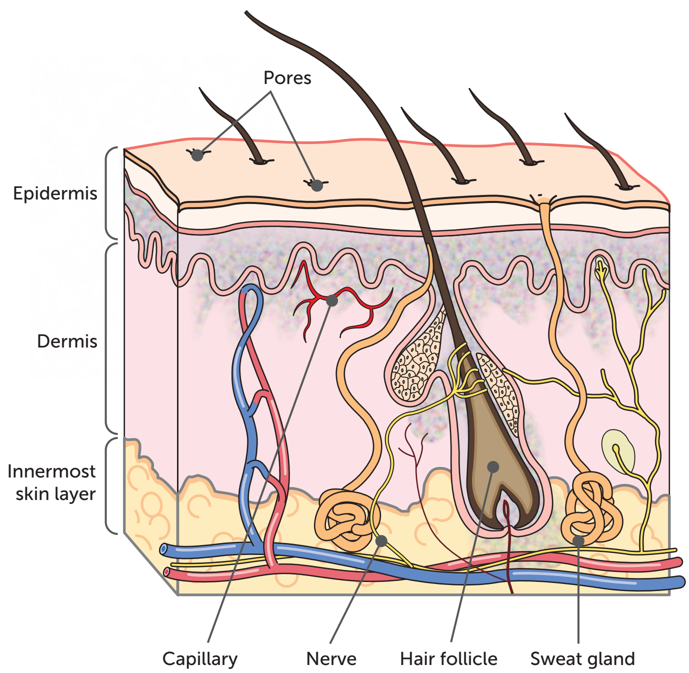


FIGURE 5.20 Section of skin showing sweat glands

Heat transfer
This website provides more information about the different methods of heat transfer: conduction, convection and radiation.

More on heat transfer
This website provides an animation of the various methods of heat transfer.

Sweat is water containing dissolved substances, primarily sodium chloride along with small amounts of urea, lactic acid and potassium ions. Evaporation of sweat from the skin has a cooling effect: heat is removed from the skin when liquid sweat changes into vapour. Cooling of the skin results in cooling of the blood flowing through the skin.

Even in the absence of sweating there is continual loss of water by evaporation from external body surfaces. This evaporation, along with water that is evaporated from the lungs and respiratory passages, accounts for a considerable proportion of the daily heat loss from the body.

Shivering and heat gain

Shivering is due to an increase in skeletal muscle tone, producing rhythmic muscle tremors that occur at a rate of around 10 to 20 per second. As no work is being done, the heat produced by the muscles is released as heat.

Preventing body temperature from falling

If the environmental temperature falls, or if a person goes from a warm room into a cold environment outside, the cold receptors in the skin send messages to the hypothalamus. The hypothalamus then sends out impulses aimed at reducing heat loss and increasing heat production so that body temperature is maintained. The body can respond by making physiological changes (changes in body functioning) and behavioural changes.

- Impulses from the hypothalamus stimulate sympathetic nerves that cause arterioles in the skin to constrict. This vasoconstriction decreases the flow of warm blood to the skin from the internal organs, thus decreasing the transfer of heat from the internal body organs to the skin. The skin becomes cooler because there is less warm blood flowing through it. Less heat will then be lost from the body surface. In this way, vasoconstriction of skin arterioles helps maintain body temperature in cold conditions.

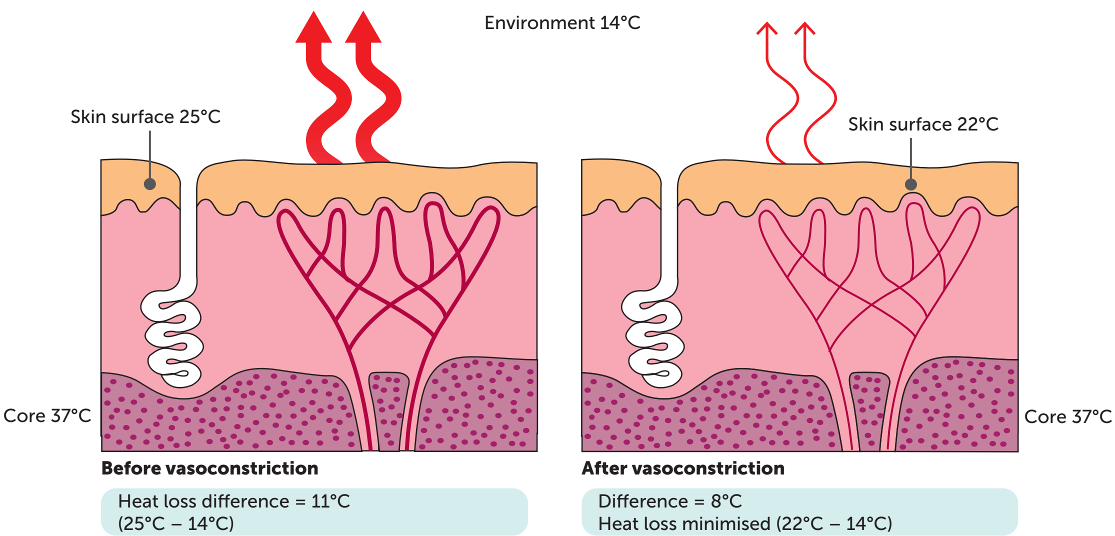


FIGURE 5.21 The effect of vasoconstriction in the skin

- A second response initiated by the hypothalamus is the stimulation of the adrenal medulla by sympathetic nerves. This stimulation results in the medulla secreting adrenaline and noradrenaline into the blood. These hormones bring about an increase in cellular metabolism that leads to an increase in heat production. This helps to maintain internal body temperature in conditions where there is rapid heat loss.

- A fall in body temperature causes the hypothalamus to send stimuli to the parts of the brain that cause shivering, which can increase body heat production several-fold within minutes. Shivering is under the primary control of the hypothalamus, but conscious input from the cerebral cortex can suppress the urge to shiver.
- The fourth response to a fall in body temperature is an increase in the production of thyroxine. The hypothalamus is able to cause the anterior lobe of the pituitary to secrete thyroid-stimulating hormone (TSH), which causes the thyroid gland to release thyroxine into the blood. The increased levels of thyroxine increase the metabolic rate, resulting in an increase in body temperature. This response is slower to have an effect, but it is longer lasting than other responses. The small change in metabolic rate that occurs between the warm summer months and cool winter ones is a result of this response.
- A behavioural response may occur if we become consciously aware of cold conditions. If we feel cold, we can behave in a way that reduces heat loss, such as by putting on an extra jumper or sheltering from a cold wind. Another behavioural response that helps to reduce heat loss is reducing the surface area of the body from which heat can be lost. You may have noticed that when you are cold in bed you tend to curl up into a ball.

Preventing body temperature from rising

When the weather is warm, or when we exercise, the heat produced by metabolism is greater than that needed to maintain a constant body temperature. This excess heat needs to be lost from the body, otherwise the core temperature will rise. Most heat loss occurs through the skin, although smaller amounts of heat are lost with the gases breathed out from the lungs, and with the faeces and urine.

The following responses ensure that body temperature does not rise.

- Vasodilation of skin arterioles increases blood flow through the skin. The skin becomes reddish in colour, surface temperature rises, and there is greater heat loss through radiation and convection.
- When environmental temperatures are above about 28°C, sweating is needed to increase heat loss from the body, as shown in Figure 5.22. The cooling effect of sweating is effective only in environments that are fairly dry. If the air is very humid, sweat cannot evaporate and, therefore, does not absorb heat from the body. If both humidity (the water vapour concentration of the air) and temperature are high, individuals often suffer considerable discomfort as the sweat remains

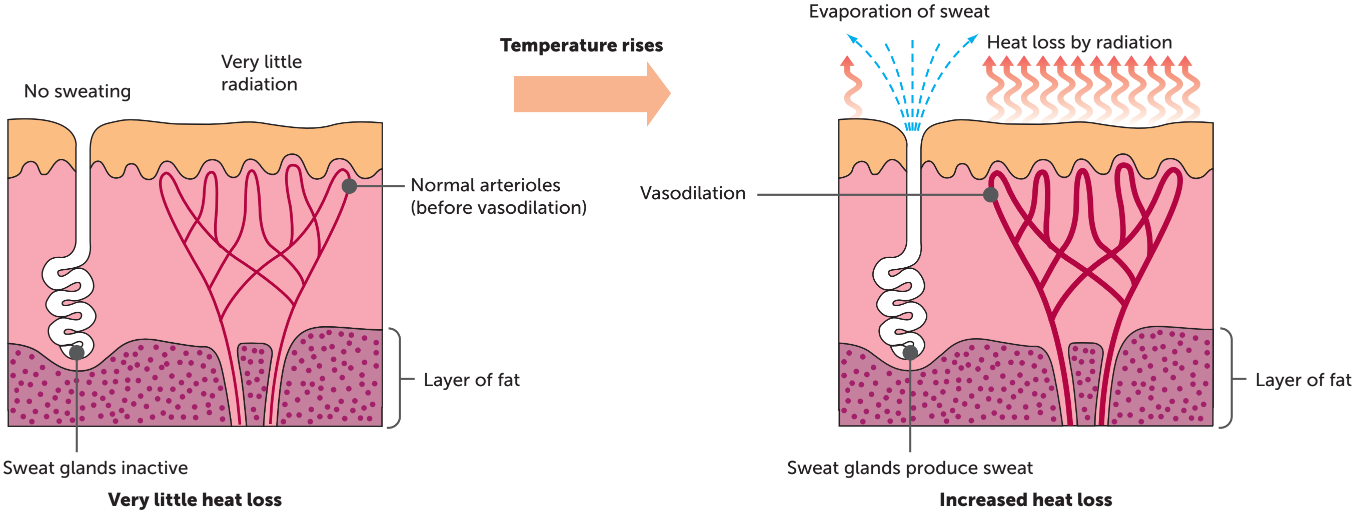


FIGURE 5.22 Heat loss from the skin can be increased by vasodilation of skin blood vessels and by sweating

on the skin or simply drips off. It is only in a low-humidity environment that sweating is a really effective means of preventing body temperature from rising. If environmental temperatures are greater than 37°C, heat is gained from the environment and the evaporation of sweat is then the only avenue for heat loss.

- In the long term there can be a decrease in metabolic rate, which means less heat is produced in the body. Such a decrease is brought about by reduction in the secretion of thyroxine, a response that occurs in summer when there is much less heat loss than in winter.
- Behavioural responses can also help to prevent the body temperature rising. Actions such as turning on a fan or air conditioner, removing external clothing, and reducing physical activity can all help to keep temperature constant.

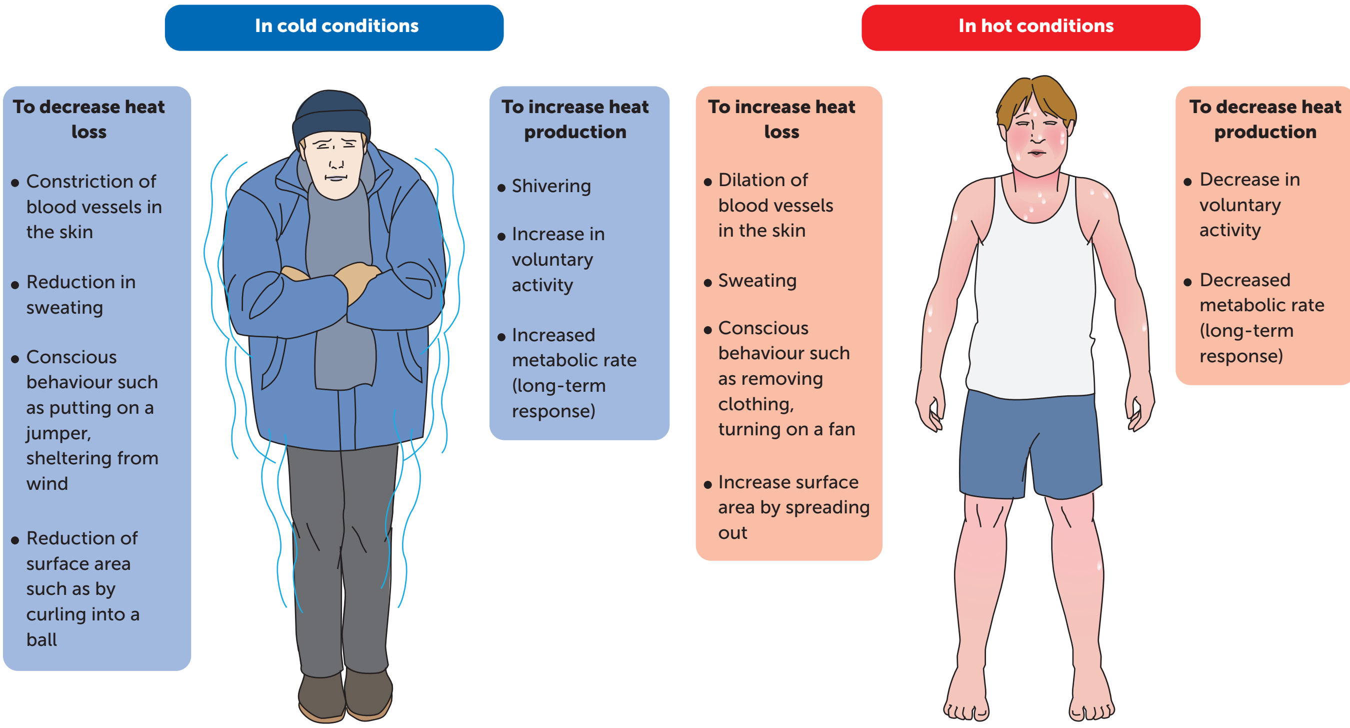


FIGURE 5.23 Mechanisms for regulating temperature

Control of thermoregulation

Activity 5.1
Investigating thermoregulation

As we have seen, it is the hypothalamus that exercises control over the various mechanisms involved in maintaining body temperature. The hypothalamus monitors the temperature of the blood and receives impulses from the peripheral thermoreceptors. Through negative feedback loops involving the autonomic division of the nervous system, it controls the diameter of skin arterioles, sweating, shivering and other mechanisms for maintaining temperature. Figure 5.24 summarises the role of the hypothalamus in thermoregulation.

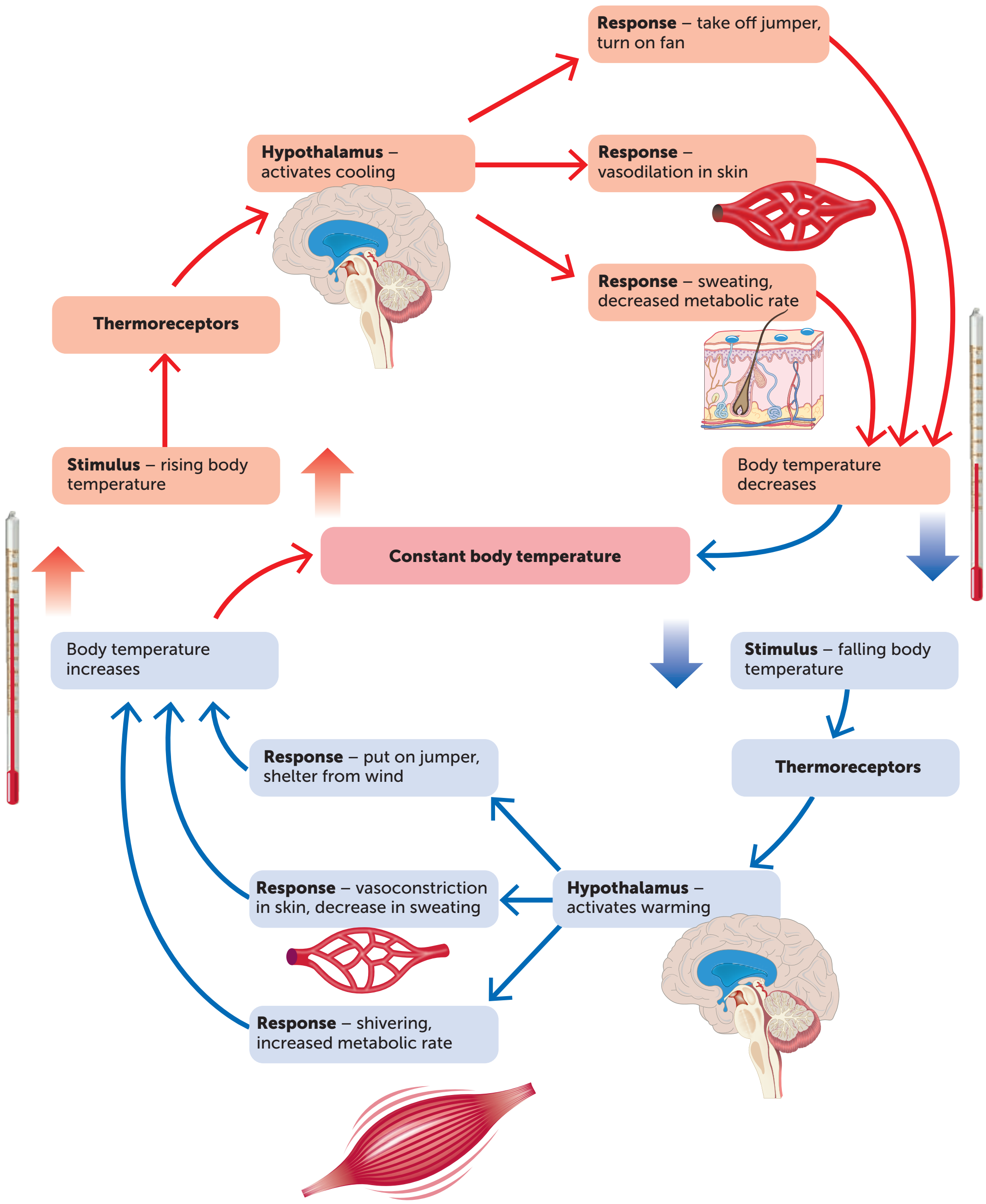


FIGURE 5.24 The role of the hypothalamus and mechanisms involved in maintaining a constant body temperature

Key concept

The hypothalamus receives information from thermoreceptors and initiates responses to maintain a core temperature of 36.8°C.

Temperature tolerance

A core body temperature over 42°C is dangerous and death usually occurs if it rises above about 45°C. High body temperature can result from a fever, but it can also occur in certain environmental conditions. When the temperature and relative humidity are high, it is difficult for the body to lose heat by radiation or evaporation. In this case, body temperature rises and the regulatory mechanisms cease. This is called **heat stroke** and it can be very serious, or even fatal, if brain cells are affected. Treatment consists of cooling the body as quickly as possible by immersing the patient in cold water.

Activity 5.2
Investigating experiments conducted in a heated room

Heat stroke
This website provides more information about heat stroke.

Heat exhaustion
This website provides more information about heat exhaustion.

Hypothermia
This website provides more information about hypothermia.

5.3 Homeostasis of body temperature

A condition that occurs more frequently than heat stroke is **heat exhaustion**. This condition occurs as a result of extreme sweating and vasodilation to lose heat. The loss of water in sweating reduces the volume of blood plasma and the vasodilation reduces resistance to blood flow. Blood pressure is thus reduced and output of blood from the heart decreases. The person may, therefore, collapse. Unlike in heat stroke, the body temperature is almost normal.

Extreme cold can also cause death. If a person's core temperature falls below 33°C, the metabolic rate is so low that heat production is unable to replace the heat lost and body temperature continues to fall. This condition is called **hypothermia**. Death can occur at core temperatures below 32°C, but people have been known to survive even lower temperatures.

Questions 5.3

RECALL KNOWLEDGE

1. Define 'thermoregulation' and state the set point for body temperature.
2. List the methods of heat loss.
3. Define 'metabolic rate' and list the reasons that the metabolic rate would:
   a. increase
   b. decrease.
4. State the location of thermoreceptors.
5. Why is the skin such an important organ in regulating body temperature?
6. Other than sweating, what other modes of evaporation occur in the body?
7. List five responses that the hypothalamus would trigger on a hot day. For each, classify them as responses from the nervous system or endocrine system.
8. Which is more dangerous – heat stroke or heat exhaustion? Explain why.

APPLY KNOWLEDGE

9. Heat will flow from areas of high temperature to low temperature until the temperatures are equal. Considering this process, explain how the body is able to maintain a temperature above that of the surrounding environment.
10. Use a Venn diagram to compare and contrast vasodilation and vasoconstriction.
11. Explain why sweating is more effective at cooling the body when the humidity is low.
12. Imagine that you forgot to take your sleeping bag on a camping trip in winter. Draw a flow chart to show the process that would occur as the temperature dropped overnight.
13. People who live in cold climates don't seem to 'feel' the cold as much as visitors to the area. Explain why this happens.

CHAPTER 5 ACTIVITIES

ACTIVITY 5.1 Investigating thermoregulation

Working with a partner or in a small group, design an investigation to answer a question, or questions, about thermoregulation.

Some ideas include:

- making the subject as hot as possible by seating them in front of a heater, covering them with blankets and soaking their feet in buckets of warm water
- making the subject as cold as possible by removing any jumpers, wrapping their body in a wet towel and turning on a fan, soaking their feet in iced water and sitting them in the coolroom of the school canteen.

You should consider:

1. What characteristics can you measure to determine the effect of changing the temperature?
2. What changes occur in core body temperature when the skin temperature is changed?
3. What changes are evident at the surface of the body when the environment is very hot or very cold?
4. Do changes in environmental temperature affect breathing rate, heart rate or blood pressure?
5. What factors were you able to control?
6. What conclusion can you make from your investigation?

ACTIVITY 5.2 Investigating experiments conducted in a heated room

Sir Charles Blagden (1748–1820) was an English doctor and scientist. In a report to the Royal Society in 1775, he was the first person to describe the link between sweating and regulation of body temperature. He carried out many experiments on thermoregulation and in 1775 published his results in a paper titled 'Experiments and Observations in an Heated Room'. In one of his experiments he spent 45 minutes in a chamber that was heated to more than 120°C. With him in the chamber were some research assistants, a dog and a piece of beef. They all emerged from the chamber unharmed, but the beef was cooked.

1. Beef is mostly muscle tissue from a cow or a bull. Explain how the men's muscles were unharmed after 45 minutes in the hot chamber, while the muscle from the cow was cooked.
2. Would you expect to see any changes in the appearance of the men after they had been in the hot chamber? Explain your answer.
3. The men were in the hot chamber for 45 minutes. Do you think they would be able to survive for a much longer period? Explain.
4. Do you think the men (and the dog) would have had anything to drink while in the chamber? Explain.
5. A sauna is a small room where people can experience heating in dry or humid conditions. The temperature in the room can vary from 60°C to 120°C. High humidity is used at lower temperatures, but at higher temperatures only dry heat is used. Explain why a high-humidity sauna should not be set to a high temperature.
6. Suggest some precautions that should be taken when using a sauna.

Experiments and observations in a heated room

9780170449168

CHAPTER 5 SUMMARY

- Homeostasis is maintenance of a constant internal environment, e.g. for temperature, blood glucose, pH and gas concentration. It is achieved by the endocrine system and the nervous system.
- A feedback system is a response that alters the original stimulus, providing feedback. In a negative feedback system, the response is the opposite of the original stimulus. In a positive feedback system, the response intensifies the original stimulus.
- Negative feedback systems (steady state control systems) maintain constant levels around the set point. The levels fluctuate between the tolerance levels and so the situation is called a dynamic equilibrium.
- A negative feedback system involves a stimulus, receptor, modulator, effector and feedback.
- Childbirth and blood clotting are examples of a positive feedback system.
- Glucose levels in the blood need to be between 4 and 6 mmol/L to supply the cells with glucose for cellular respiration.
- Insulin causes glucose to convert to glycogen by glycogenesis, which is stored in the liver and skeletal muscles.
- Under the influence of glucagon, glycogen can be broken down to produce glucose in the process of glycogenolysis.
- Glucose can also be produced from lipids and proteins in gluconeogenesis.
- The islets of Langerhans are hormone-producing cells in the pancreas. They contain alpha cells that secrete glucagon and beta cells that secrete insulin.
- Insulin is secreted when blood glucose levels rise. It lowers blood glucose levels by increasing the uptake of glucose by the cells, glycogenesis, and converting glucose to lipids and proteins.
- Glucagon is secreted in response to a decreased blood glucose level. It increases blood glucose levels by stimulating glycogenolysis, gluconeogenesis and protein breakdown.
- The adrenal cortex secretes glucocorticoids such as cortisol, which stimulates glycogenolysis and the breakdown of proteins and amino acids to increase blood glucose levels.
- The adrenal medulla secretes adrenaline and noradrenaline, which stimulate the conversion of glycogen to lactic acid and then glucose.
- Thermoregulation is the maintenance of body temperature at approximately 36.8°C by balancing heat loss and gain.
- Heat is produced during metabolism and absorbed from the surroundings. The rate of metabolism increases during exercise, with stress, and if body temperature increases.
- Heat is lost from the body by conduction, convection, radiation and evaporation.
- Thermoreceptors (either heat or cold receptors) detect changes in the temperature. Peripheral thermoreceptors detect the external temperature, while central thermoreceptors detect the internal temperature.
- The body loses heat via the skin. Blood in vessels in the dermis conduct heat to the outside of the body and sweat absorbs heat as it evaporates.
- To conserve heat, the hypothalamus triggers vasoconstriction; increased metabolism due to adrenaline, noradrenaline and thyroxine secretion; shivering and behavioural responses.
- To lose heat, the hypothalamus triggers vasodilation, sweating, decreased metabolism due to less thyroxine being secreted, and behavioural responses.
- Heat stroke occurs when the core body temperature is higher than 42°C.
- Heat exhaustion occurs when there is extreme vasodilation and sweating. The body temperature is almost normal, but low blood pressure may cause collapse.
- Hypothermia occurs when the body temperature falls below 33°C and the metabolic rate decreases.

CHAPTER 5 GLOSSARY

Alpha cell A type of cell in the islets of Langerhans in the pancreas that secretes the hormone glucagon

Beta cell A type of cell in the islets Langerhans in of the pancreas that secretes the hormone insulin

Central thermoreceptor A thermoreceptor located in the hypothalamus

Cold receptor A receptor that is stimulated by low temperature

Conduction The transfer of heat by direct contact between particles

Convection The transfer of heat by the movement of liquids or gases

Cortex The outer part of an organ – for example, the adrenal gland

Cortisol A hormone that, along with related hormones, promotes normal metabolism

Dynamic equilibrium A state reached when the rates of forward and reverse changes are equal; a stable, balanced or unchanging system results

Evaporation The process of a liquid forming a gas, which absorbs heat energy

Feedback system A situation where the response to a stimulus changes the original stimulus

Glucagon A hormone secreted by the pancreas that increases blood sugar level

Gluconeogenesis The process of producing glucose molecules from lipids and amino acids

Glycogen A polysaccharide made up of thousands of glucose molecules bonded together in branching chains; functions as a store of glucose molecules in muscle and liver cells

Glycogenesis The process whereby glucose molecules are chemically combined in long chains to form glycogen molecules

Glycogenolysis The process of converting glycogen back to glucose

Heat exhaustion The collapse of a person after exposure to heat, during which their body's heat-regulating mechanisms continue to function normally

Heat receptor A receptor that is stimulated by high temperature

Heat stroke The failure of a person's temperature-regulating mechanisms when exposed to excessive heat

Homeostasis The maintenance of a relatively constant internal environment despite fluctuations in the external environment

Hypothermia Abnormally low body temperature; the temperature drops below the level required to maintain normal body functions

Insulin A hormone, secreted by the pancreas, that decreases blood sugar level

Islets of Langerhans Clusters of endocrine cells in the pancreas; secrete the hormones insulin and glucagon

Lipogenesis The production of lipids (fats)

Lipolysis The breakdown of lipids (fats) in the body

Medulla The inner part of an organ – for example, the adrenal gland

Metabolic rate The rate at which energy is released to the body by the breakdown of food

Model A simplified representation of an idea or a process; may be a diagram, flow chart, a simplified description of a complex situation or a physical model such as a model of a cell; examples are the stimulus–response–feedback model and the lock and key model for enzyme action

Modulator A control centre responsible for processing information received from a receptor and for sending information to the effector

Negative feedback Feedback that reduces the effect of, or eliminates, the original stimulus

Peripheral thermoreceptor A temperature receptor in the skin and in some mucous membranes

Positive feedback Feedback that reinforces the original stimulus

Radiation The transfer of energy in the form of waves

Set point In a feedback system, the level at which a variable is to be maintained

Shivering Oscillating, rhythmic muscle tremors that increase body heat production

Steady state *see* homeostasis

Steady state control system A negative feedback system that maintains homeostasis

Stimulus Any change, internal or external, that causes a response

Sweat Fluid secreted by the sweat glands to help the body lose heat through evaporative cooling

Sweat gland A gland in the skin that produces sweat

Sweating The active secretion of fluid by the sweat glands

Thermoreceptor A temperature receptor; located in the skin or the hypothalamus

Thermoregulation The regulation of body temperature; the balance of heat gain and heat loss in order to maintain a constant internal body temperature independent of the environmental temperature

Tolerance limit The limit of factors such as temperature and fluid balance beyond which the body malfunctions

Vasoconstriction A decrease in the diameter of arterioles, restricting the flow of blood through them

Vasodilation An increase in the diameter of arterioles, increasing the flow of blood through them

CHAPTER 5 REVIEW QUESTIONS

Recall

1 a What is homeostasis?
  b What aspects of the internal environment need to be regulated?
2 Define 'tolerance limits'.
3 Describe the role of the liver in regulating blood sugar concentration.
4 Distinguish between glycogenesis, glycogenolysis and gluconeogenesis.
5 Which gland is involved in the secretion of insulin and glucagon? Identify the location of the gland.
6 Describe the influence of the hormones of the adrenal glands on blood sugar concentration.
7 Describe the ways in which the body can gain heat.
8 What are the two types of thermoreceptors, and in what parts of the body are they located?
9 a What responses are likely to occur if core body temperature begins to fall?
  b What responses are likely to occur if core body temperature begins to rise?

Explain

10 Explain what the following terms mean and their relevance to homeostasis:
  a dynamic equilibrium
  b set point.
11 Why is the stimulus–response–feedback mechanism referred to as a model?
12 a Using examples, explain the difference between positive and negative feedback.
  b Why would a negative feedback loop be able to achieve homeostasis?
13 After a meal, the blood glucose level often rises well beyond the normal level. Explain why this occurs.
14 Explain how insulin and glucagon regulate the concentration of glucose in the blood.
15 Explain why heat loss must equal heat gain.
16 The skin plays an important role in thermoregulation. Explain how it is able to achieve this function.

Apply

17 Apply the stimulus–response–feedback model to the response of the pancreas after a chocolate bar is eaten.
18 Compile a table that summarises the role of each of the following systems in regulating blood glucose level: nervous system, digestive system, endocrine system, circulatory system, muscular system, excretory system.
19 Draw a stimulus–response model to show the processes involved with shivering.
20 In very cold weather, it is our fingers and toes that often feel coldest.
  a Why are fingers and toes affected by cold more than other parts of the body?
  b The fingers and toes may appear white when very cold. Explain why.
21 Alcohol increases blood flow through the skin. If a person suggested 'a stiff drink' would warm them up, what would you advise them, and why?
22 As a first aider at a sports carnival, it is important that you know the difference between heat stroke and heat exhaustion. Explain how you will distinguish between the two conditions.
23 A thermogram shows the temperature at the surface of an object or body. Examine the thermogram shown in Figure 5.17.
  a What parts of the ballerina's skin are the hottest? The coolest?
  b Explain the reasons for the differences in skin temperature that you have described in your answer to part a of this question.

Extend

24 People with type 1 diabetes are unable to produce insulin.

- **a** Explain why patients have an increased blood glucose level.
- **b** One symptom of type 1 diabetes is tiredness. Explain why this occurs.

25 Vasoconstriction in the skin occurs when a person's body temperature is low, or when a person is very scared or very angry. (We say that someone is 'white with fear' or 'white with anger'.)

- **a** Apply the feedback model to each of these responses. Do they both fit the model? Explain your answer.
- **b** What is the advantage to a person of vasoconstriction in the skin:
  - **i** when their body temperature is tending to fall?
  - **ii** when they are scared or angry?

26 In the arms and legs there is exchange of heat between the arteries carrying blood to the limbs and the veins taking blood away from the limbs. This is called a countercurrent heat exchange. Find out how countercurrent heat exchange operates and describe its significance in maintaining core body temperature.

9780170449168