The Anatomy and Physiology of the Endocrine System

CHAPTER 1

INTRODUCTION

The endocrine system is a highly specialised and essential component of human physiology, comprising a network of glands and organs that secrete chemical messengers known as hormones. These hormones regulate a wide range of biological processes, including growth, metabolism, reproduction and the body's responses to stress and environmental changes. Unlike localised signalling within the nervous system, endocrine signalling is systemic, as hormones are released into the bloodstream and delivered to target organs throughout the body.

The primary purpose of the endocrine system is to ensure that the internal environment remains in a stable, dynamic state that is referred to as homeostasis. This system plays a particularly critical role during key life stages such as puberty, pregnancy and ageing, where hormonal modulation is essential to physiological adaptation. By maintaining chemical balance, the endocrine system supports overall health and ensures that cellular and organ functions align with the body's needs at any given moment.

Although the endocrine and nervous systems both contribute to maintaining homeostasis, they differ considerably in their methods and characteristics of control. The nervous system uses rapid electrical impulses to provide immediate responses, whereas the endocrine system operates more slowly, but its hormonal signals tend to have longer-lasting effects. These distinctions are summarised in Table 1.1.

Together, the nervous and endocrine systems comprise the neuroendocrine system, which integrates short-term and long-term regulation to maintain physiological equilibrium.

A foundational concept underpinning endocrine function is homeostasis, the maintenance of a stable internal environment despite fluctuations in the external environment. Through the controlled secretion of hormones, the endocrine system maintains essential parameters such as blood glucose levels, electrolyte concentrations, body temperature and blood pressure. Disruptions to hormonal regulation can lead to significant pathophysiological conditions, including diabetes mellitus, thyroid dysfunction and adrenal insufficiency.

Regulation within the endocrine system is achieved primarily through feedback mechanisms. The most common is negative feedback, which serves to stabilise physiological variables. In this mechanism, a deviation from a set point triggers hormonal responses that correct the imbalance, and once the desired state is restored, hormone secretion is reduced. A classic example is the regulation of blood glucose: elevated glucose levels stimulate insulin release from the pancreas; as glucose levels return to normal, insulin secretion diminishes.

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Table 1.1 The nervous and the endocrine systems

Feature	Nervous system	Endocrine system
Messenger type	Electrical impulses and neurotransmitters	Hormones (chemical messengers)
Speed of response	Very rapid (milliseconds)	Slower (seconds to days)
Duration of effect	Short-lived	Prolonged
Transmission method	Via neurones and synapses	Through the bloodstream
Target specificity	Precise, localised	Broad, affecting multiple organs or tissues
Area of effect	Localised; restricted to specific synaptic connections	Widespread; hormone receptors may be located in various parts of the body
Control mechanism	Often voluntary or reflexive; involves rapid feedback loops	Primarily involuntary; regulated by negative or positive feedback mechanisms
Primary function	Coordination of immediate responses to stimuli, including movement and sensation	Regulation of long-term processes such as growth, metabolism, reproduction and mood
Communication pathway	Direct synaptic transmission	Endocrine glands release hormones into circulation

In contrast, positive feedback amplifies a physiological change rather than reversing it. This mechanism is less common but plays vital roles in specific scenarios such as childbirth. During labour, the hormone oxytocin increases uterine contractions, which in turn further stimulates oxytocin release, creating a self-reinforcing loop until delivery occurs.

In Table 1.2, hormonal control is likened to a thermostat. Just as a thermostat raises the heat when the room gets too cold, the pancreas releases insulin when blood glucose levels rise. As glucose levels return to normal, insulin release is reduced, just as the heat shuts off once the desired temperature is reached. This negative feedback prevents overheating or, in biological terms, overcorrection.

This positive feedback is rare but purposeful; for example lactation, where the infant's suckling stimulates oxytocin release, causing milk ejection, which in turn encourages more suckling and further oxytocin secretion.

Understanding these concepts, particularly the comparative features of endocrine and nervous systems, the principles of homeostasis and the roles of feedback mechanisms, prepares the practitioner with a critical foundation for interpreting hormonal function in the clinical setting.

The endocrine system comprises a network of small but vital organs that are distributed throughout the body, each of them responsible for secreting hormones directly into the bloodstream ('endo' meaning within and 'crine' meaning to secrete). These hormones regulate a wide range of physiological processes that are essential to homeostasis. The organs that produce hormones can be broadly classified into three main categories (Tortora and Derrickson 2023):

1. Endocrine glands: These are specialised organs whose sole function is the synthesis and release of hormones. Key examples include the following:
   - The pituitary gland
   - The thyroid gland

Table 1.2 Comparing thermostat mechanisms with endocrine system regulation

Thermostat system component	Endocrine equivalent	Function
Thermostat	Hypothalamus	Serves as the body's control centre, continuously monitoring internal conditions and initiating hormonal responses to maintain balance
Temperature sensor	Receptors in the hypothalamus or organs (sensory receptors such as thermoreceptors, chemoreceptors)	Detects deviations from set point and changes in internal variables (such as temperature or glucose levels) and relay this information to regulatory centres such as the hypothalamus
Heating/ cooling system	Endocrine glands (e.g. thyroid, pancreas, adrenal glands)	Responds to signals by releasing hormones. Receive signals from the hypothalamus or pituitary gland and secrete hormones to restore the internal environment to its optimal range
House temperature	Physiological variable (e.g. blood glucose)	Represents the condition being regulated; the body works to keep this within a narrow, healthy range
Feedback loop	Hormone level feedback (primarily negative feedback)	Modulates hormone production by increasing or decreasing secretion depending on whether the desired internal balance has been achieved

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- The parathyroid glands
- The adrenal glands

2. Organs with endocrine and non-endocrine functions: These organs have primary roles unrelated to hormone production, but they also contain substantial areas of hormone-secreting tissue. Examples include:
   - The hypothalamus, which integrates nervous and endocrine responses
   - The pancreas, which has both digestive and endocrine roles
3. Other hormone-producing tissues: There are various other tissues and organs that contain scattered hormone-secreting cells. These include:
   - The stomach
   - The small intestine, among others

The influence of the endocrine system extends to virtually all cell types, tissues and organs in the human body. While many hormones and their effects have been identified, it is likely that others remain undiscovered, highlighting the complexity and evolving nature of endocrine science.

THE ENDOCRINE ORGANS

The location of the major endocrine organs within the human body is shown in Figure 1.1. These organs typically have an extensive blood supply, delivered by a network of blood vessels. Within each gland, hormone-producing cells are organised in branching networks that

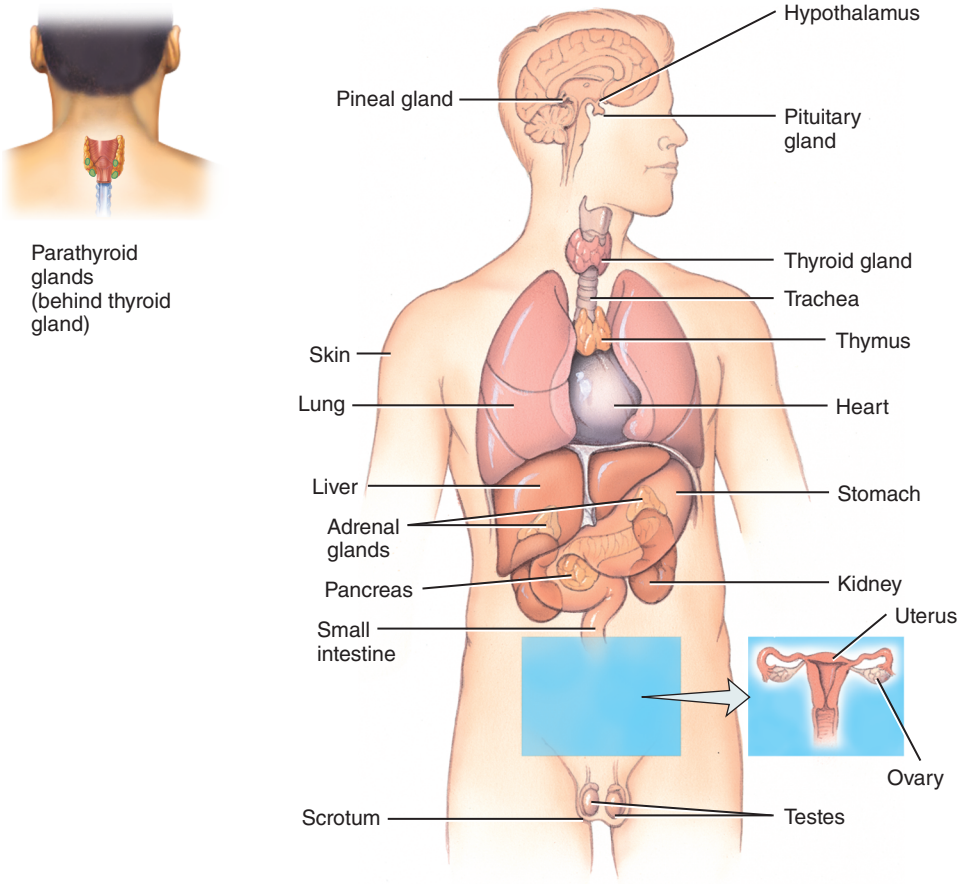

FIGURE 1.1 The location of endocrine glands. *Source*: Reproduced with permission from Tortora and Derrickson (2009). With permission of John Wiley & Sons.

surround the vascular supply. This close association between endocrine cells and blood vessels enables the efficient and rapid release of hormones into the bloodstream. Once released, hormones are transported throughout the body to reach specific target cells and tissues, where they exert their regulatory effects.

ENDOCRINE SIGNALLING

In anatomy and physiology, there are many terms that share similar suffixes or endings, often relating to the same processes or regions of the body. It is crucial to recognise and understand these similarities, as they can easily lead to confusion if not carefully distinguished. Endocrine, paracrine, autocrine and exocrine signalling describe different ways that cells communicate or send signals, especially through hormones or chemical messengers (see Table 1.3).

HORMONES AS CHEMICAL MESSENGERS

Hormones are chemical messengers secreted by cells into the bloodstream or extracellular fluid, where they influence the activity of other cells. Unlike the nervous system, which transmits signals rapidly along dedicated pathways (neurones, akin to telegraph wires), the

Table 1.3 Comparison of endocrine, paracrine, autocrine and exocrine signalling

Type of signalling	Definition	Target of action	Example
Endocrine	Hormones are secreted into the bloodstream and travel to distant target cells	Distant cells or organs	Insulin released by the pancreas acts on muscle and liver cells
Paracrine	Hormones or signalling molecules act locally on neighbouring cells	Nearby cells within the same tissue	Histamine released in tissue acts on local immune cells
Autocrine	The hormone or molecule acts on the same cell that produced it	The cell that secreted the hormone	Certain cytokines in immune cells stimulating the cell that released them
Exocrine	Substances are secreted into ducts leading to external surfaces or cavities	External body surfaces or organ lumens	Sweat glands releasing sweat to the skin; pancreas releasing digestive enzymes into the duodenum

endocrine system works more like a radio broadcast. The hormone is the signal sent out broadly, but only cells equipped with the right 'receiver', hormone receptors, can detect and respond to it (Clare 2025). Box 1.1 considers a more contemporary communication analogy.

BOX 1.1 COMPARING NEURAL AND HORMONAL COMMUNICATION

From fibre-optics to Wi-Fi

Nervous system, likened to a fibre-optic broadband

- Think of the nervous system as superfast fibre-optic internet.
- Signals travel rapidly along neural pathways, much like data along cables to precise destinations.
- It is high-speed, point-to-point communication – perfect for split-second reflexes, movement and focused tasks.
- The effect is immediate but short-lived – like refreshing a web page or sending an instant message.

Endocrine system, likened to a Wi-Fi broadcast

- In contrast, the endocrine system resembles a Wi-Fi signal.
- Hormones are released into the bloodstream, akin to signals sent into the air.
- Any device (cell) with the proper receiver (hormone receptor) can pick up the message.
- This communication is broad-reaching, affecting many systems, with longer-lasting effects, such as syncing data to multiple devices over time.

This analogy makes the distinction in speed, specificity and longevity.

As hormones travel through the blood, they come into contact with almost every cell in the body. However, they only affect those cells that have specific receptors for that hormone, known as target cells. This interaction works much like a lock and key: the hormone (key) fits precisely into its receptor (lock), enabling the cell to respond appropriately (see Figure 1.2).

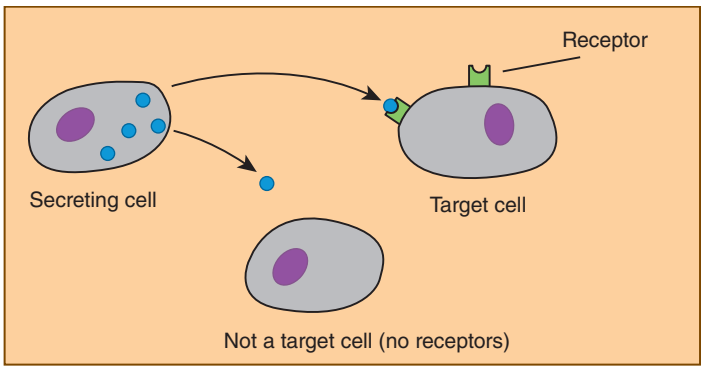

FIGURE 1.2 Target and non-target cells

Hormone receptors can be located either on the surface of the target cell or inside it, depending on the type of hormone.

Most hormones are derived from amino acids, while others are steroid hormones made from cholesterol. Because amino acid-based hormones cannot pass through the cell membrane, their receptors are found on the cell's surface. These hormones influence the cell by activating enzymes or other molecules inside the cell, often triggering a cascade of reactions. A well-known example of this is the cyclic adenosine monophosphate signalling pathway.

Steroid hormones, however, are small and lipid-soluble; this allows them to cross the cell membrane easily. Their receptors are located inside the cell. Once inside, they find a special receptor and turn on certain genes, which leads the cell to make new proteins.

An exception to these categories is thyroid hormone, which, although not a steroid, is small and lipid-soluble and can diffuse directly into the cell.

FACTORS INFLUENCING HORMONE ACTION

The response of a target cell depends on several factors: the hormone's concentration in the blood, the number of receptors on the cell and the affinity (strength of binding) between the hormone and its receptor. These factors can change quickly in response to varying conditions. The concentration of a hormone at its target site is determined by the following:

- Rate of hormone production: This is the primary and most tightly regulated factor.
- Rate of hormone delivery: Influenced by blood flow to the target cells or organs.
- Rate of hormone removal: Hormones are broken down and eliminated, with their half-life affecting how long they remain active. Hormones with a short half-life disappear quickly when the production stops, while those with a longer half-life persist longer.

Hormone levels can be adjusted rapidly by changing production rates. Longer-term regulation involves altering the number of receptors on target cells. This process is called upregulation or downregulation.

- Upregulation occurs when receptor numbers increase in response to low hormone levels, making the cell more sensitive.
- Downregulation happens when receptor numbers decrease due to prolonged high hormone levels, causing the cell to become less responsive or desensitised.

THE TRANSPORTATION OF HORMONES

The majority of hormones are secreted directly into the systemic bloodstream (Knight 2021). However, a subset is released into specialised localised networks called portal circulations. There are two primary portal systems: one between the hypothalamus and the anterior pituitary gland, and the hepatic portal system, which channels blood through the portal vein into the liver.

Steroid hormones are predominantly transported in the bloodstream bound to carrier proteins, with less than 10% circulating as the biologically active 'free fraction' (Tortora and Derrickson 2023). This distinction has clinical relevance.

Blood tests are often used to assess both the bound and free fractions of hormones. A typical example is thyroid function testing, which measures concentrations of both bound thyroxine (T4) and free T4.

Unlike steroid hormones, which need to attach to carrier proteins to travel through the bloodstream, water-soluble hormones do not require any such assistance. They dissolve directly in blood plasma and move around independently. This difference in transport also affects how quickly the body can use these hormones and how long they stay active in the system.

EFFECTS OF HORMONES

Hormones are chemical messengers that travel through the bloodstream to reach specific target cells, where they bind to receptors and trigger a series of cellular responses. These responses can vary depending on the type of hormone, the target tissue and the specific receptors that are involved. Understanding how hormones influence cellular activity is essential for recognising their role in maintaining homeostasis, supporting growth and development and coordinating responses to internal and external stimuli.

Once a hormone binds to its receptor on or within a target cell, it can produce one or more of the following effects:

- Modification of membrane permeability or electrical state: Alters the permeability of the cell membrane or its membrane potential by opening or closing ion channels. This can influence the movement of ions such as sodium, potassium or calcium across the membrane, affecting processes such as nerve impulse transmission and muscle contraction.
- Stimulation of protein or enzyme synthesis: Some hormones activate genes within the cell's nucleus, leading to the synthesis of new proteins or regulatory molecules, such as enzymes, which can influence metabolic processes and cellular function.
- Activation or inhibition of enzymes: Hormones may cause the activation or deactivation of pre-existing enzymes, altering the rate of specific biochemical reactions within the cell.
- Cause secretory activity: Certain hormones stimulate cells to release other substances, such as digestive enzymes, hormones or mucus, supporting processes, for example, digestion, metabolism or immune responses.
- Promotion of cell division (mitosis): Hormones can trigger the replication and division of cells, contributing to tissue growth, repair and regeneration.

These actions demonstrate the powerful and diverse influence hormones exert across different organ systems, highlighting their crucial role in regulating physiological balance.

CONTROL OF HORMONE RELEASE

The production and secretion of most hormones are triggered by a specific stimulus, which may originate either internally or externally – for example, an increase in blood glucose levels or exposure to a cold environment. Following this initial trigger, hormone levels are typically regulated by a negative feedback mechanism.

As illustrated in Figure 1.5, a stimulus (such as elevated blood glucose) prompts the release of a hormone (e.g. insulin). Once the hormone reaches its target tissue and initiates the required physiological response, the resulting change, such as the reduction in blood glucose, feeds back to the endocrine organ. This feedback further inhibits hormone release, thereby preventing overproduction and maintaining homeostasis.

Hormones are usually released in response to one of the three main types of stimuli, although some organs may respond to more than one (Marieb and Hoehn 2022):

- Humoral stimulus: This happens when hormone release is triggered by changes in the levels of certain substances in the blood, such as ions or nutrients. For example, when calcium levels in the blood drop, the parathyroid glands release parathyroid hormone (PTH) to increase calcium levels.
- Neural stimulus: In some cases, the nervous system directly causes hormone release. This is less common. One example is when the sympathetic nervous system becomes active during stress and directly stimulates the adrenal medulla to release adrenaline and noradrenaline.
- Hormonal stimulus: Some hormones are released in response to signals from other hormones. These are often released in patterns or rhythms. For example, the anterior pituitary gland releases thyroid-stimulating hormone (TSH), which then prompts the thyroid gland to produce and release thyroxine (T4).

PHYSIOLOGY OF THE ENDOCRINE ORGANS

The endocrine organs regulate vital body functions by producing and secreting hormones into the bloodstream (Knight 2021). Each gland has a specific role, yet they often work together to maintain internal balance. This section outlines how these organs function at a physiological level, focusing on how hormones are synthesised, released and how they act on target tissues. A clear understanding of this physiology is essential for making appropriate and safe responses to people who may have health issues associated with their endocrine system.

THE HYPOTHALAMUS AND THE PITUITARY GLAND

The Hypothalamus

The hypothalamus is a small, cone-shaped structure in the brain, weighing approximately 4 g, and is located just above the pituitary gland, to which it is connected by a thin stalk called the infundibulum (or pituitary stalk). It plays a crucial role in coordinating several vital functions. One of its most important roles is serving as a key link between the nervous and endocrine systems through its connection with the pituitary gland. Nearly all hormone secretion from the pituitary is regulated by either hormonal signals or nerve impulses originating from the hypothalamus (see Figure 1.3).

The hypothalamus receives input from almost all areas of the nervous system and plays a central role in hormonal regulation. It is also subject to negative feedback control from the very hormones it helps to regulate via the pituitary gland. When levels of a particular hormone in the bloodstream fall, this change is detected by the hypothalamus. In response, it releases

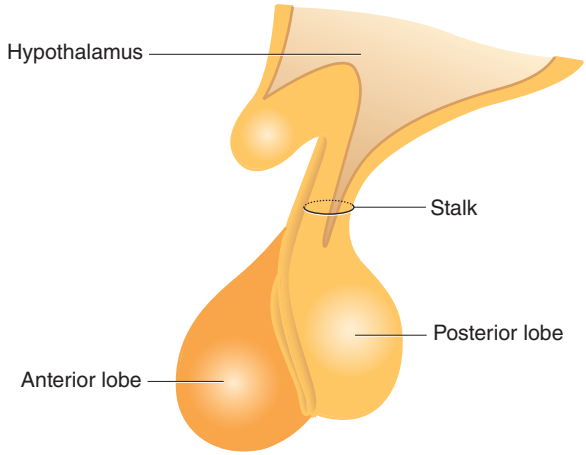

FIGURE 1.3 The hypothalamus and pituitary gland

a specific releasing hormone or releasing factor, which travels to the pituitary gland and stimulates the release of the relevant hormone. That hormone then acts on the target gland or tissue, which produces the final hormone needed by the body. As blood levels of this target hormone rise, receptors in the hypothalamus detect the change and reduce the release of the initial releasing hormone, helping to restore balance.

The Pituitary Gland

The pituitary gland is a small, pea-sized endocrine organ located at the base of the brain and connected to the hypothalamus by a thin stalk known as the infundibulum. Despite its small size, the pituitary secretes at least nine major hormones and is often referred to as the 'master gland' due to its broad regulatory influence. It has two main parts, each with a distinct structure and function:

Posterior Pituitary (Neurohypophysis): The posterior lobe is composed mainly of nerve fibres that originate in the hypothalamus and terminate on capillaries in the posterior pituitary. It does not produce hormones itself but instead stores and releases two hormones made in the hypothalamus: oxytocin and antidiuretic hormone. Because of this, it is best considered a hormone storage site rather than a true endocrine gland. The hypothalamus and posterior pituitary are connected via a bundle of nerve fibres called the hypothalamic–hypophyseal tract.

Oxytocin plays a key role in childbirth by stimulating uterine contractions and is also involved in the milk ejection ('let-down') reflex during breastfeeding. In men and non-pregnant women, it may be involved in sexual arousal and orgasm (Jenkins and Tortora 2013).

Antidiuretic hormone helps conserve body water by increasing the kidneys' reabsorption of water. It acts on the collecting ducts in the kidneys, making them more permeable to water. Antidiuretic hormone is stored in the posterior pituitary and released in response to nerve impulses. Its release is stimulated by:

- Increased plasma osmolality (e.g. higher sodium levels)
- Reduced extracellular fluid volume
- Pain or stress
- Certain drugs

Anterior Pituitary (Adenohypophysis): The anterior lobe is larger than the posterior lobe and wraps partially around it and the infundibulum. It consists of glandular tissue and is responsible for producing and releasing several key hormones. Unlike the posterior pituitary, it has no direct nerve connection with the hypothalamus. Instead, it is connected via a special blood vessel network known as the hypothalamic–hypophyseal portal system. Through this system, blood carries releasing and inhibiting hormones from the hypothalamus directly to the anterior pituitary, where they influence hormone production.

Hormones released by the anterior pituitary gland are shown in Table 1.4.

The anterior lobe of the pituitary gland contains five distinct types of hormone-secreting cells:

1. Somatotrophs – which produce growth hormone
2. Lactotrophs – responsible for secreting prolactin
3. Thyrotrophs – which release TSH
4. Gonadotrophs – which produce both LH and FSH
5. Corticotrophs – which secrete ACTH

Table 1.5 provides further detail concerning the hormones secreted.

THE THYROID GLAND

The thyroid gland is a butterfly-shaped organ located at the front of the neck, sitting on the trachea just below the larynx (see Figure 1.4). It consists of two lobes connected by a narrowband of tissue called the isthmus. The top parts of the lobes are referred to as the upper poles, and the bottom parts are known as the lower poles. Each lobe is composed of spherical, hollow follicles surrounded by a network of capillaries; as a result, the gland has a rich blood supply.

Table 1.4 Hormones released by the anterior pituitary gland

Hypothalamus	Anterior pituitary gland	Target organ or tissues	Action
Growth hormone-releasing factor	Growth hormone	Many (especially bones)	Stimulates growth of body cells
Growth hormone release-inhibiting factor	Growth hormone (inhibits release)	Many	
Thyrotropin-releasing hormone (TRH)	TSH	Thyroid gland	Stimulates thyroid hormone release
Corticotropin-releasing hormone (CRH)	Adrenocorticotropic hormone (ACTH)	Adrenal cortex	Stimulates corticosteroid release
Prolactin-releasing hormone	Prolactin	Breasts	Stimulates milk production
Prolactin-inhibiting hormone	Prolactin (inhibits release)	Breasts	
Gonadotropin-releasing hormone (GnRH)	Follicle-stimulating hormone (FSH) and luteinising hormone (LH)	Gonads	Various reproductive functions

Table 1.5 Hormones associated with the anterior lobe of the pituitary gland: effects and regulation

Hormone	Effects	Regulation
GH	Promotes the growth of bone, cartilage and soft tissue by stimulating the production and release of insulin-like growth factor (IGF-1).	Regulated by growth hormone-releasing hormone (GHRH) and growth-hormone-release-inhibiting hormone (somatostatin) from the hypothalamus. GH and IGF-1 exert negative feedback on the hypothalamus.
Prolactin	Stimulates milk secretion in the breast.	Inhibited by dopamine from the hypothalamus. Intermittently increased by prolactin-releasing hormone in response to infant suckling.
FSH	In males, stimulates sperm production. In females, promotes early maturation of ovarian follicles and oestrogen secretion.	Regulated by GnRH. Testosterone and oestrogen exert negative feedback on the hypothalamus.
LH	In females, responsible for final maturation of ovarian follicles and oestrogen secretion. In males, stimulates testosterone secretion.	Also regulated by GnRH. Sex hormones provide negative feedback on GnRH release.
TSH	Stimulates thyroid gland activity, increasing production and secretion of thyroxine (T4) and triiodothyronine (T3).	Triggered by TRH from the hypothalamus. Inhibited by somatostatin. Free T3 and T4 provide negative feedback to both the hypothalamus and anterior pituitary.
ACTH	Stimulates production of cortisol and androgens from the adrenal cortex. Also promotes aldosterone production in response to electrolyte changes.	Regulated by CRH from the hypothalamus, particularly in response to stress. Cortisol provides negative feedback to the hypothalamus and anterior pituitary.

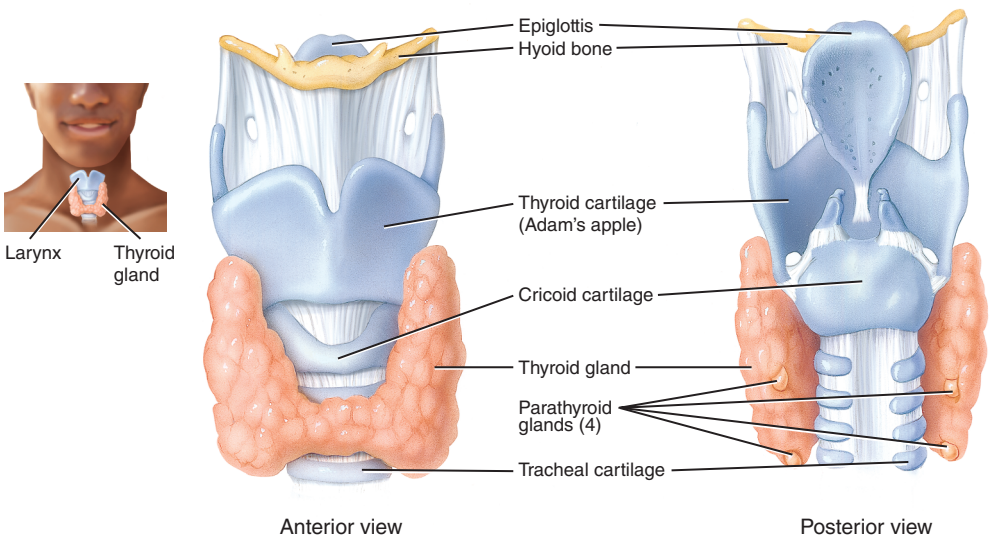

FIGURE 1.4 Position of the thyroid gland and parathyroid glands. *Source*: Reproduced with permission from Tortora and Derrickson (2009). With permission of John Wiley & Sons.

The follicles of the thyroid gland are made up of a single layer of epithelial cells that surround a central cavity filled with thyroglobulin, a protein that has iodine molecules attached to it. Thyroid hormones are produced from this combination. One of the thyroid gland's unique features is its ability to produce and store large amounts of hormone, enough to last up to 100 days (Hall and Hall 2020).

The thyroid produces two types of hormones: thyroxine (T4) and triiodothyronine (T3), both of which require iodine. Iodide from the diet is absorbed and concentrated by the thyroid, where it is converted into iodine in the follicle cells. This iodine is then attached to the amino acid tyrosine, and these iodinated tyrosine molecules are combined to form T3 and T4. This process is entirely stimulated by TSH. T4 is the main hormone released by the thyroid, but it is converted into the more active T3 form within target tissues. Most circulating thyroid hormone is bound to transport proteins in the blood, with only a small amount in the free, active form. T3 binds less strongly to these proteins than T4. Thyroid hormone affects nearly every cell in the body, with the exception of the following:

- The adult brain
- The spleen
- The testes
- The uterus
- The thyroid gland itself

Both T3 and T4 can easily cross cell membranes and bind to receptors inside the cell. In target cells, thyroid hormone activates enzymes involved in glucose metabolism, a process known as the calorigenic effect. The result is:

- An increase in basal metabolic rate
- Greater oxygen use by cells
- More heat production by the body

Basal metabolic rate refers to the energy the body uses at rest in a neutral environment. As it rises, oxygen consumption also increases since oxygen is needed to generate energy.

In addition, thyroid hormone helps maintain blood pressure by increasing the number of receptors in blood vessel walls.

The release of thyroid hormone is controlled by a negative feedback loop involving the hypothalamus and pituitary gland (see Figure 1.5).

Plasma levels of thyroid hormones are monitored by the hypothalamus and anterior pituitary. When T4 levels rise, they inhibit the release of TRH from the hypothalamus and reduce TSH secretion from the pituitary. This negative feedback limits further thyroid hormone release. Conversely, low T4 levels reduce this inhibition, prompting increased TRH and TSH production, which in turn stimulates the thyroid.

TSH promotes the release of T3 and T4, so reduced TSH leads to decreased hormone output. Certain conditions, such as pregnancy or prolonged cold exposure, increase metabolic demand and can stimulate TRH release, temporarily overriding the negative feedback system (Tortora and Derrickson 2023).

T4 has a half-life of around seven days and T3 around one day. These hormones are mainly broken down in the liver and muscles. While iodine is largely recycled, some is lost through urine and faeces, making daily dietary intake of iodide essential.

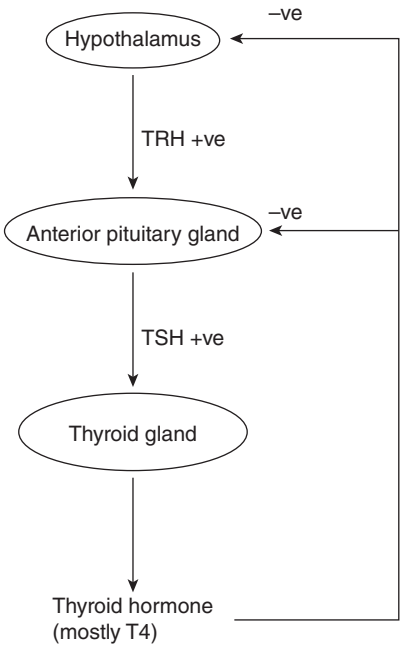

FIGURE 1.5 Negative feedback control of thyroid hormone production

Alongside the thyroid epithelial cells, C cells (located between the follicles) produce the hormone calcitonin. Calcitonin plays a role in regulating calcium and phosphorus metabolism by lowering blood calcium levels. It does this by reducing the activity of osteoclasts, cells that break down bone and release calcium and phosphorus into the bloodstream. Because of this effect, calcitonin is used to treat osteoporosis and may have potential in managing osteoarthritis (Srinivasan et al. 2020). Additionally, it reduces calcium reabsorption in the kidneys, promoting its excretion in urine.

THE PARATHYROID GLANDS

The parathyroid glands are small structures located on the posterior surface of the thyroid gland (Figure 1.4). Typically, there are two pairs, though this can vary, with some individuals having up to four pairs (Marieb and Hoehn 2022). The hormone-secreting cells, known as parathyroid chief cells, are arranged in clusters around a dense capillary network and are responsible for producing PTH, the primary regulator of calcium balance in the body. PTH acts mainly on bones and kidneys to:

- Increase calcium absorption in the intestines
- Enhance calcium reabsorption in the kidneys
- Stimulate osteoclasts, promoting the release of calcium from bones

Calcium is essential for nerve impulse transmission, muscle contraction and blood clotting. Blood calcium levels are continuously monitored by the parathyroid glands. When levels fall, PTH production increases.

Calcitriol, a hormone released by the kidneys in response to low blood calcium, also plays a regulatory role. It promotes calcium absorption from the gut and reabsorption in the

kidneys. PTH stimulates calcitriol release, but when calcitriol levels become high, it inhibits further PTH secretion, helping to prevent excessive calcium levels. Calcitriol also suppresses calcitonin release, reinforcing its role in calcium homeostasis.

THE ADRENAL GLANDS

The adrenal glands are complex; they are multifunctional organs whose secretions are essential for maintaining homeostasis. The adrenal glands are found on top of each kidney (Figure 1.6). The right gland is roughly triangular in shape; the left, which is commonly the larger of the two, is crescent-shaped. The glands are encased in a connective tissue capsule and embedded in an area of fat. Adrenal glands have a rich blood supply from many blood vessels.

Each adrenal gland is actually made up of two distinct parts that work like separate glands. These two major regions have different structures and perform different functions within the body (Figure 1.7):

- Adrenal medulla
- Adrenal cortex

THE ADRENAL MEDULLA

The adrenal medulla is the inner section of the adrenal gland, accounting for about 30% of its total mass. Its primary role is to secrete catecholamines, which include the following:

- Adrenaline
- Noradrenaline
- Dopamine

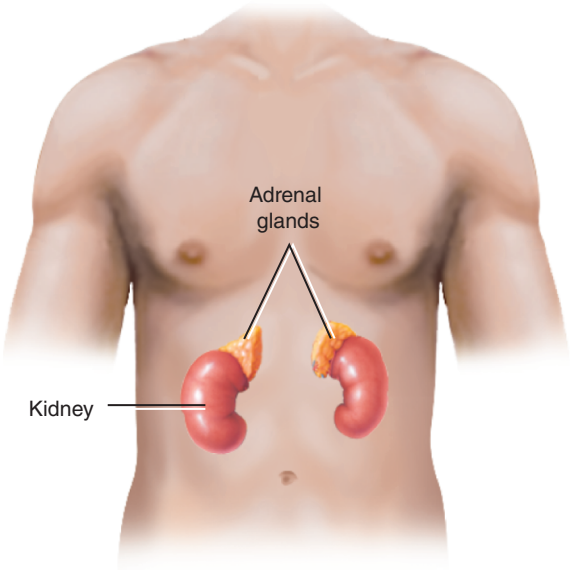

FIGURE 1.6 Position of the adrenal glands. *Source*: Reproduced with permission from Tortora and Derrickson (2009). With permission of John Wiley & Sons.

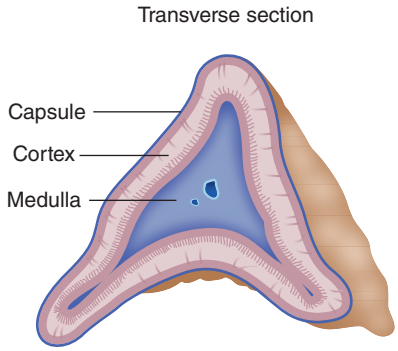

FIGURE 1.7 Cross-section of the adrenal gland. *Source:* Reproduced with permission from Peate (2017). With permission of John Wiley & Sons.

The adrenal medulla functions as a modified, densely innervated sympathetic ganglion composed of cells containing granules. Approximately 90% of these cells release adrenaline, while the remaining 10% secrete noradrenaline. The specific cells responsible for dopamine secretion are not yet clearly identified.

Catecholamines have diverse effects, such as the following:

- Stimulating the nervous system
- Promoting metabolic processes such as glycogen breakdown in the liver and muscles
- Increasing metabolic rate and heart rate
- Enhancing alertness, although adrenaline often triggers anxiety and fear
- Causing widespread vasoconstriction (noradrenaline)
- Inducing vasoconstriction in the skin and internal organs but vasodilation in skeletal muscles (adrenaline)

While adrenaline and noradrenaline are important for normal bodily function, the hormones produced by the adrenal medulla mainly serve to amplify sympathetic nervous system activity rather than being essential themselves.

Catecholamine release is triggered by sympathetic nervous system signals from the hypothalamus in response to stimuli such as:

- Pain
- Anxiety
- Excitement
- Low blood volume (hypovolaemia)
- Low blood glucose (hypoglycaemia)

The adrenal medulla receives blood from the adrenal cortex, which is rich in corticosteroids. These corticosteroids regulate the enzymes that convert noradrenaline into adrenaline, so increased corticosteroid levels boost this conversion. When the hypothalamus activates during an emergency, the adrenal medulla responds broadly to prepare the body for a fight-or-flight reaction. Catecholamines have a very short half-life in the bloodstream – less than two minutes – because they are quickly broken down by enzymes in the blood.

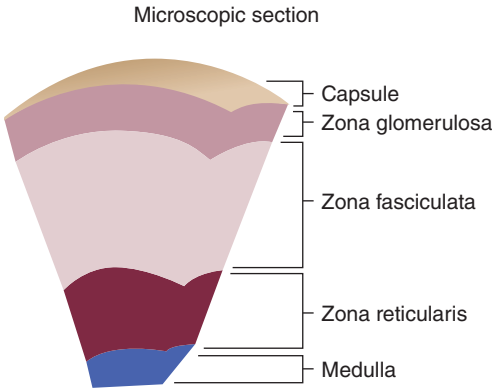

FIGURE 1.8 Cross-section of the adrenal cortex. *Source:* Reproduced with permission from Peate (2017). With permission of John Wiley & Sons.

ADRENAL CORTEX

The outer part of each adrenal gland is made up of three distinct functional layers (Figure 1.8). Each layer is involved in the production of steroid-based hormones (known collectively as the corticosteroids):

1. Zona glomerulosa: Produces the mineralocorticoids.
2. Zona fasciculata: Produces the glucocorticoids.
3. Zona reticularis: This zone is also involved in the production of glucocorticoids but also produces small amounts of adrenal sex hormones (the gonadocorticoids).

Mineralocorticoids

Mineralocorticoids are the group of hormones whose main function is the regulation of the concentration of the electrolytes in the blood. There are several known mineralocorticoids, but the most common is aldosterone, which accounts for 95% of all the mineralocorticoids synthesised and is also the most potent.

There are several mechanisms that regulate the release of aldosterone. The primary control mechanism is the production of angiotensin II by the renin–angiotensin system in response to reduced blood pressure in the kidneys or reduced sodium delivery to the distal tubules of the kidneys. Raised levels of potassium and reduced levels of sodium in the blood are also known to have a direct effect on the adrenal cortex and stimulate the release of mineralocorticoids. However, in response to a severe, non-specific stressor, hypothalamic release of CRH stimulates the increased release of ACTH. This increase in ACTH stimulates a slight increase in the release of aldosterone, leading to a slight increase in blood volume and pressure, which will help to maintain the delivery of oxygen and nutrients to the tissues (see Figure 1.9).

Glucocorticoids

There appears to be no cell within the body that does not have receptors for the glucocorticoid hormones. The glucocorticoid hormones have several effects:

- They influence the metabolism of most body cells.
- They promote glycogen storage in the liver.
- They stimulate the generation of glucose during fasting.

- They increase blood glucose levels.
- They are involved in providing resistance to stressors.
- They potentiate the vasoconstrictor effect of catecholamines.
- They decrease the permeability of vascular endothelium.
- They promote the repair of damaged tissues by promoting the breakdown of stored protein to create amino acids.
- They suppress the immune system.
- They suppress inflammatory processes.

The glucocorticoid hormones include the following:

- Cortisol (hydrocortisone)
- Cortisone
- Corticosterone

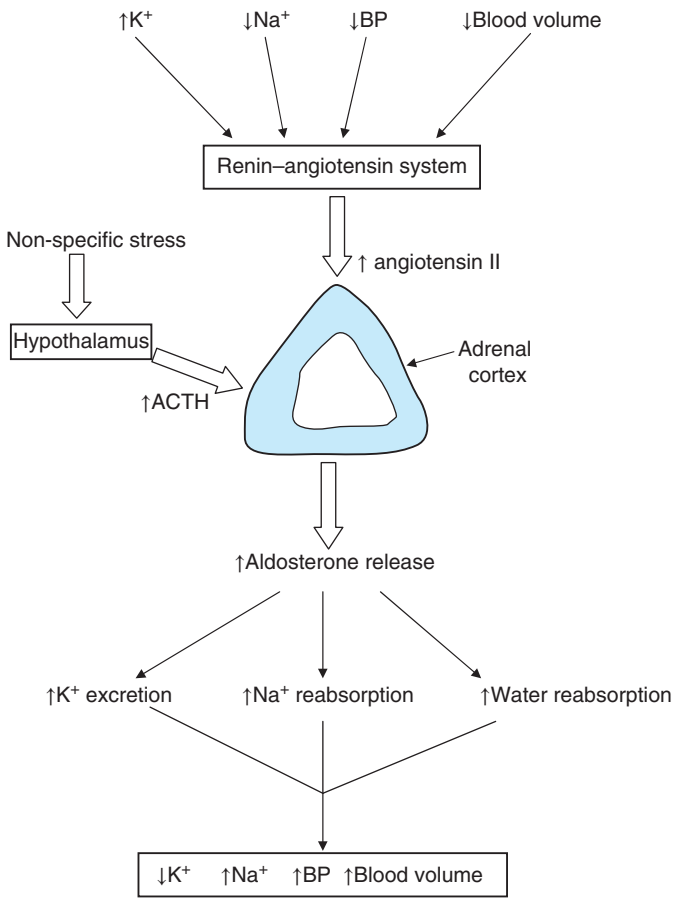

FIGURE 1.9 Control of aldosterone secretion. *Source:* Reproduced with permission from Peate (2017). With permission of John Wiley & Sons.

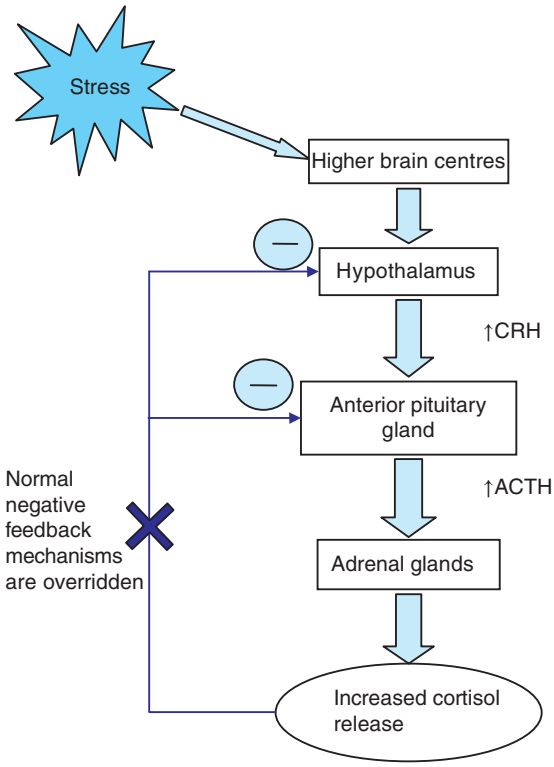

FIGURE 1.10 Response of the endocrine system to stress. *Source:* Reproduced with permission from Peate (2017). With permission of John Wiley & Sons.

Only cortisol is secreted in any significant amounts. Cortisol is normally released in a rhythmical pattern, with most being released shortly after a person wakes from sleep and the lowest amount being released just before and shortly after sleep commences.

Cortisol release is stimulated by ACTH from the anterior pituitary gland. ACTH releases cholesterol from the cytoplasm in the cells, which is then converted and modified to create the steroid hormones. ACTH secretion is regulated by the release of CRH from the hypothalamus. Increasing levels of cortisol have a negative feedback effect on both the hypothalamus and the pituitary gland, inhibiting further release of both CRH and ACTH. However, this negative feedback system can be overridden by acute physiological stress (for instance, trauma, infection or haemorrhage) and mental stress. The increase in sympathetic nervous system activity in response to an acute stress triggers greater CRH release and thus there is a significant increase in subsequent cortisol production (Figure 1.10).

THE PANCREAS

The pancreas is an elongated, retroperitoneal (located behind the peritoneum) organ situated adjacent to the duodenum, the initial segment of the small intestine (see Figure 1.11). It comprises two functionally and structurally distinct components: exocrine and endocrine tissue.

The exocrine pancreas constitutes much of the organ and consists of acinar cells and an extensive ductal network. Acinar cells synthesise and secrete a bicarbonate-rich fluid containing digestive enzymes, which is delivered into the duodenum via the pancreatic duct, facilitating the enzymatic breakdown of macronutrients.

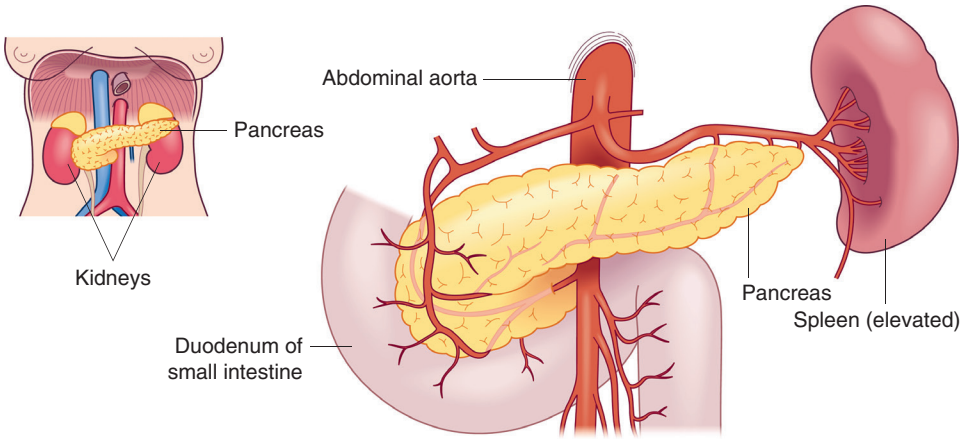

FIGURE 1.11 The pancreas

Scattered within the exocrine tissue are clusters of endocrine cells known as the islets of Langerhans. These islets serve as the principal site of endocrine function within the pancreas. Each islet is composed of three predominant hormone-secreting cell types:

1. Alpha cells, responsible for glucagon secretion
2. Beta cells, the most prevalent cell type, responsible for insulin secretion
3. Delta cells, which produce somatostatin

Table 1.6 summarises the main cell types found within the islets and their respective characteristics.

The islet architecture is spatially organised, with beta cells typically occupying a central position, encircled by alpha- and delta cells (see Figure 1.12). This cytoarchitectural arrangement facilitates paracrine signalling among the cell types and supports efficient hormonal regulation.

Islets are highly vascularised, receiving approximately 10–15% of the pancreatic arterial blood flow despite comprising only 1–2% of the organ's total mass (Clare 2025). This rich vascular supply ensures rapid hormone diffusion into the systemic circulation.

The pancreas is innervated by both the sympathetic and parasympathetic divisions of the autonomic nervous system. Neural input modulates endocrine activity, particularly the regulated secretion of insulin and glucagon, via complex neurohormonal pathways. The high vascularity and innervation allow for rapid hormonal signalling and integration with neuronal input.

INSULIN

Insulin is a key hormone primarily recognised for its role in lowering blood glucose concentrations (Clare 2025). It exerts its glucose-lowering effects through several mechanisms:

- Facilitation of glucose uptake: Insulin promotes the transport of glucose into insulin-sensitive tissues, notably skeletal muscle and adipose tissue. It is important to note that glucose uptake in the brain and liver is largely insulin-independent (the liver and the brain do not need insulin to take in glucose).
- Promotion of glycogen synthesis: In the liver, insulin stimulates the enzymatic pathways responsible for converting glucose into glycogen for storage.

Table 1.6 Main cell types found within the islets

Cell type	Percentage of islet cells	Hormone secreted	Primary function	Location within islet
Beta cells	Approximately 60–80%	Insulin	Lowers blood glucose by promoting glucose uptake in cells and glycogen synthesis in the liver	Central core
Alpha cells	Approximately 15–20%	Glucagon	Raises blood glucose by stimulating glycogenolysis and gluconeogenesis in the liver	Peripheral region
Delta cells	Approximately 5–10%	Somatostatin	Inhibits the release of insulin, glucagon and GH; regulates islet hormone secretion	Scattered, often peripheral
PP cells	Less than 5%	Pancreatic polypeptide	Regulates both endocrine and exocrine pancreatic secretion; may influence hepatic glycogen levels and gastrointestinal secretions	Primarily in the posterior pancreatic head (not uniformly distributed)
Epsilon cells	Less than 1%	Ghrelin	Stimulates appetite and GH secretion; role in islet function not fully defined	Scattered, more abundant in fetal pancreas

Source: Adapted from Tortora and Derrickson (2023) and Da Silva Xavier (2018).

Beyond its effects on carbohydrate metabolism, insulin also plays significant roles in how the body uses protein, lipids (fats) and minerals:

- Protein: Insulin helps the body build proteins and prevents the breakdown of muscle.
- Lipid (fats): When the liver has stored enough glycogen, insulin moves excess glucose into making fatty acids (lipogenesis). It stops the breakdown of fat and encourages fat storage in adipose (fat) tissue. This creates a fat-sparing effect, meaning the body uses glucose for energy instead of breaking down fat.
- Minerals: Insulin helps move minerals such as potassium, phosphate and magnesium into cells, which is important for maintaining normal levels in the blood and preventing complications such as high potassium (hyperkalaemia).

Insulin secretion is primarily triggered by elevated blood glucose levels. However, increased plasma concentrations of amino acids and fatty acids can also stimulate insulin release. Additionally, cephalic phase responses, such as the sight, smell or anticipation of food, activate parasympathetic neural pathways that augment insulin secretion. The pancreas receives

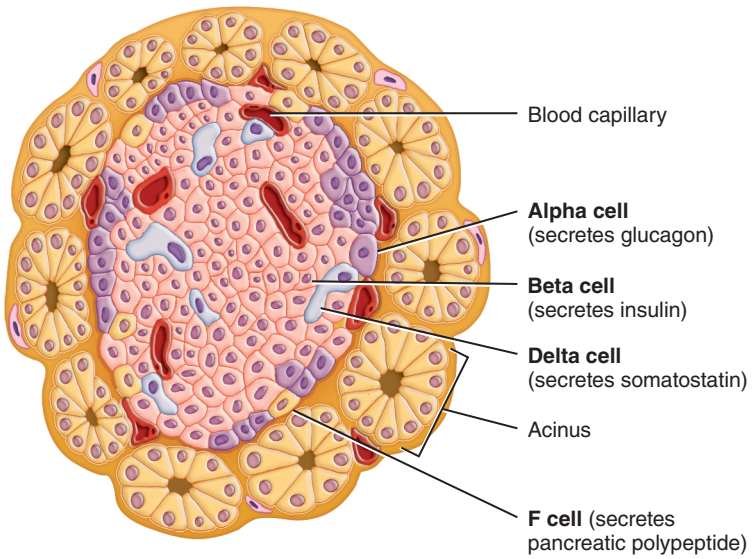

FIGURE 1.12 Pancreatic islet surrounding acini

both sympathetic and parasympathetic innervation, and autonomic nervous input plays a critical role in modulating the secretion of insulin (as well as glucagon).

As plasma glucose levels decline, insulin secretion is downregulated. Reduced insulin availability leads to diminished glycogen synthesis and the activation of glycogenolytic enzymes within the liver. Insulin has a short biological half-life of approximately five minutes and is predominantly degraded in the liver.

GLUCAGON

Glucagon is a hormone that helps keep blood glucose levels stable, especially during fasting or between meals. This is vital because the brain and nerve cells rely on glucose as their main energy source. While insulin lowers blood glucose, glucagon has the opposite effect (see Figure 1.13 and Table 1.7). It helps increase blood glucose by:

- Breaking down glycogen stored in the liver into glucose (glycogenolysis)
- Promoting gluconeogenesis, where the liver makes new glucose from sources such as amino acids
- Supporting the breakdown of fat (triglycerides) in fat tissue, releasing fatty acids for energy in other cells and saving glucose for the brain

The synthesis and release of glucagon are triggered by decreases in blood glucose concentration and elevated circulating amino acid levels, such as those occurring after a protein-rich meal. Additionally, blood glucagon levels increase during physical exercise; however, it remains unclear whether this rise is directly due to the exercise stimulus or secondary to the exercise-induced reduction in blood glucose.

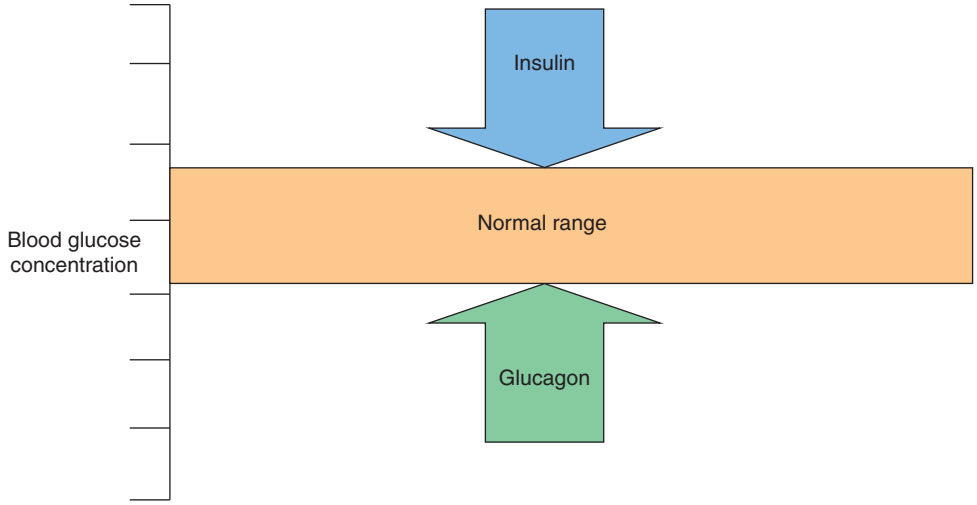

FIGURE 1.13 Effects of insulin and glucagon on blood glucose concentrations

Table 1.7 Comparison of insulin and glucagon

Feature	Insulin	Glucagon
Produced by	Beta cells (islets of Langerhans, pancreas)	Alpha cells (islets of Langerhans, pancreas)
Main role	Lowers blood glucose	Raises blood glucose
Glucose effect	Helps cells absorb glucose from the blood	Stimulates liver to release glucose into the blood
Action on glycogen	Promotes glycogen formation (storage) in liver	Stimulates glycogen breakdown in liver
Gluconeogenesis	Inhibits it	Activates it (makes glucose from amino acids)
Effect on fat	Increases fat storage, reduces fat breakdown	Slightly increases fat breakdown to provide energy
Effect on protein	Promotes protein synthesis	May break down protein for gluconeogenesis
Stimulated by	High blood glucose, amino acids, parasympathetic input	Low blood glucose, stress, sympathetic stimulation
Overall function	Stores energy and promotes tissue building	Releases energy, especially during fasting or stress

Conversely, glucagon secretion is suppressed when blood glucose levels are elevated. It is not yet fully established whether this inhibition is a direct consequence of high glucose or mediated indirectly via increased insulin levels, given that insulin is known to suppress glucagon release.

SOMATOSTATIN

This hormone is released by a broad range of tissues. The physiological effect of somatostatin in the pancreas is to slow the release of insulin and glucagon; it does this in a paracrine way; the hormone is released and has its effect locally. The exact mechanism of control of this hormone is unknown.

THE GONADS

The gonads are the principal reproductive organs: testes in males and ovaries in females. These structures are responsible for the production of gametes (spermatozoa in males and ova in females) and also function as endocrine glands through the secretion of sex hormones.

THE OVARIES

The ovaries synthesise two primary categories of steroid hormones: oestrogens and progesterone. These hormones play a central role in the development, maintenance and functional regulation of the female reproductive system, as well as the development of secondary sexual characteristics. At puberty, oestrogens stimulate the development of breast tissue, the redistribution of adipose tissue and the maturation of reproductive structures, including the uterus and vagina.

Progesterone primarily prepares the endometrial lining of the uterus for potential implantation of a fertilised ovum. Together, oestrogens and progesterone coordinate the cyclical changes of the female menstrual cycle.

THE TESTES

Male sex hormones, collectively referred to as androgens, are predominantly represented by testosterone, which is produced by the Leydig (interstitial) cells of the testes. The adrenal cortex also contributes a minor amount. Testosterone secretion begins during fetal development, is briefly reactivated postnatally, remains minimal throughout childhood and significantly increases during puberty. This hormone is essential for the development of male reproductive organs, the acceleration of skeletal and muscular growth, enlargement of the larynx (resulting in voice deepening), the distribution of body and facial hair and the enhancement of male libido.

Testosterone synthesis is regulated by a negative feedback loop involving hypothalamic GnRH and gonadotropins (LH and FSH) secreted by the anterior pituitary.

Table 1.8 summarises the endocrine functions of the gonads, including hormone production and physiological functions.

Table 1.8 Endocrine function of the gonads

Aspect	Ovaries	Testes
Primary function	Produce ova and secrete sex hormones (oestrogens and progesterone)	Produce spermatozoa and secrete sex hormones (mainly testosterone)
Main hormones	Oestrogens and progesterone	Testosterone (and minor amounts from adrenal cortex)
Key functions	Oestrogens promote breast development, fat distribution and maturation of the uterus and vagina at puberty. Progesterone thickens the uterine lining for potential pregnancy. Both hormones regulate the menstrual cycle	Testosterone promotes the development of reproductive organs, skeletal and muscular growth, larynx enlargement, body hair growth and increased libido

(*Continued*)

Table 1.8 (*Continued*)

Aspect	Ovaries	Testes
Hormonal regulation	Controlled by gonadotropins (FSH and LH) from the anterior pituitary, regulated via hypothalamic input	Regulated by a negative feedback loop involving the hypothalamus (GnRH) and anterior pituitary (LH and FSH)
Hormonal secretion timeline	Begins at puberty and continues throughout reproductive life	Initiated during fetal development, briefly reactivated postnatally, minimal during childhood, increases at puberty

Table 1.9 Hormonal functions of other organs

Organ	Endocrine function
Thymus gland	Produces thymosin, a hormone essential for the development and maturation of the immune system, particularly T-lymphocytes.
Stomach	The gastric mucosa secretes gastrin in response to food presence, which stimulates the production of hydrochloric acid and pepsin for digestion.
Small intestine	Releases secretin and cholecystokinin. Secretin stimulates the pancreas to release an alkaline fluid to neutralise stomach acid, while cholecystokinin promotes gallbladder contraction (releasing bile) and stimulates pancreatic enzyme secretion.
Heart	Specialised cells in the atrial wall produce atrial natriuretic hormone, also known as atriopeptin, which helps regulate blood pressure and fluid balance.
Placenta	Acts as a temporary endocrine gland during pregnancy. It secretes human chorionic gonadotropin, which maintains the uterine lining by stimulating the ovaries to produce necessary hormones.

OTHER ENDOCRINE GLANDS

In addition to the primary endocrine glands discussed in this chapter, several other organs exhibit endocrine functions as part of their broader physiological roles. These include the thymus, stomach, small intestine, heart and placenta, all of which produce and secrete hormones that contribute to homeostasis and systemic regulation (see Table 1.9).

CONCLUSION

An understanding of the anatomy and physiology of the endocrine system provides an essential foundation for recognising and managing disorders that arise from hormonal imbalances or glandular dysfunction. The endocrine system is a complex and highly integrated network of glands that secrete hormones to regulate a wide range of physiological processes essential for health and survival. These include growth and development, metabolism, reproduction and the body's response to internal and external stressors. Unlike the rapid responses of the nervous system, the endocrine system typically exerts longer-lasting effects through the circulation of hormones in the bloodstream.

Understanding the anatomy and physiology of the major endocrine glands, such as the pituitary, thyroid, adrenal glands, pancreas and gonads, along with the roles of lesser-known hormone-producing organs, provides a crucial foundation for recognising how homeostasis is maintained. It also offers insight into how disruptions in hormonal signalling can lead to dysfunction and disease.

GLOSSARY OF TERMS

Adrenal glands: A pair of glands located above the kidneys that produce hormones such as cortisol, aldosterone and adrenaline.

Aldosterone: A steroid hormone produced by the adrenal cortex that helps regulate sodium and potassium levels and maintain blood pressure.

Anterior pituitary: The front portion of the pituitary gland that secretes several hormones, including growth hormone, ACTH, TSH, LH and FSH.

Endocrine glands: Ductless glands that release hormones directly into the bloodstream to regulate body functions.

Endocrine system: A system of glands and hormone-producing cells that control and coordinate bodily functions through chemical signalling.

Follicle-stimulating hormone (FSH): A hormone secreted by the anterior pituitary that stimulates the growth of ovarian follicles in females and sperm production in males.

Glucagon: A hormone secreted by the alpha cells of the pancreas that raises blood glucose levels by promoting glycogen breakdown and gluconeogenesis.

Gonads: The primary reproductive organs (testes in males and ovaries in females) that produce sex hormones and gametes.

Growth hormone (GH): A hormone secreted by the anterior pituitary that stimulates growth, cell reproduction and repair.

Homeostasis: The maintenance of a stable internal environment within the body.

Hormone: A chemical messenger secreted by endocrine glands that travels through the bloodstream to target organs.

Hypothalamus: A region of the brain that links the nervous system to the endocrine system via the pituitary gland and regulates many autonomic processes.

Insulin: A hormone produced by beta cells in the pancreas that lowers blood glucose levels by facilitating cellular uptake and storage of glucose.

Islets of Langerhans: Clusters of endocrine cells in the pancreas that produce hormones such as insulin, glucagon and somatostatin.

Luteinising hormone (LH): A hormone secreted by the anterior pituitary that triggers ovulation in females and testosterone production in males.

Negative feedback: A regulatory mechanism in which a stimulus causes an opposite output in order to maintain homeostasis.

Pancreas: A gland with both endocrine and exocrine functions; it produces insulin, glucagon and digestive enzymes.

Parathyroid glands: Small glands located on the posterior surface of the thyroid that secrete parathyroid hormone (PTH) to regulate calcium levels.

Pituitary gland: A small gland at the base of the brain often referred to as the ‘master gland’ because it controls other endocrine glands.

Posterior pituitary: The back portion of the pituitary gland that stores and releases hormones produced by the hypothalamus, including ADH and oxytocin.

Steroid hormones: Hormones derived from cholesterol, such as cortisol, oestrogen and testosterone, which pass through cell membranes to act on intracellular receptors.

Target organ: The specific organ or tissue that a hormone affects.

Testosterone: The primary male sex hormone responsible for the development of male secondary sexual characteristics and reproductive function.

Thyroid gland: A butterfly-shaped gland in the neck that produces hormones (T3 and T4) involved in regulating metabolism.

Thyroid-stimulating hormone (TSH): A hormone released by the anterior pituitary that stimulates the thyroid gland to produce thyroid hormones.

MULTIPLE CHOICE QUESTIONS

1. Which of the following glands is often referred to as the 'master gland'?
   a) Thyroid gland
   b) Pineal gland
   c) Pituitary gland
   d) Adrenal gland

2. What hormone is secreted by the beta cells of the pancreas?
   a) Glucagon
   b) Insulin
   c) Somatostatin
   d) Adrenaline

3. Which gland secretes melatonin?
   a) Pituitary gland
   b) Pineal gland
   c) Adrenal gland
   d) Hypothalamus

4. Which of the following hormones is produced by the adrenal medulla?
   a) Aldosterone
   b) Cortisol
   c) Adrenaline
   d) Testosterone

5. What is the main function of parathyroid hormone?
   a) Lower blood calcium levels
   b) Promote insulin secretion
   c) Stimulate thyroid hormone release
   d) Increase blood calcium levels

6. Which hormone regulates the body's metabolic rate?
   a) TSH
   b) Thyroxine (T4)
   c) ACTH
   d) Insulin

7. What is the function of aldosterone?
   a) Increase heart rate
   b) Regulate sodium and potassium balance
   c) Increase glucose uptake
   d) Stimulate milk production

8. The islets of Langerhans are located in which gland?
   a) Adrenal
   b) Thyroid
   c) Pancreas
   d) Pituitary

9. The hypothalamus regulates the endocrine system by controlling the:
   a) Adrenal glands
   b) Pineal gland
   c) Pituitary gland
   d) Parathyroid glands

10. What structure connects the hypothalamus to the pituitary gland?
    a) Corpus callosum
    b) Optic chiasm
    c) Infundibulum
    d) Pineal body

REFERENCES

Clare, C. (2025). The endocrine system (Chapter 17). In: *Fundamentals of Anatomy and Physiology*, 4e (ed. I. Peate and Evans, S). Wiley: Oxford.

Da Silva Xavier, G. (2018). The cells of the islet of Langerhans. *Journal of Clinical Medicine* 12 (7): 54. https://doi.org/10.3390/jcm7030054.

Hall, J.E. and Hall, M.E. (2020). *Guyton and Hall Textbook of Medical Physiology*, 14e. St Louis: Elsevier.

Jenkins, G. and Tortora, G.J. (2013). *Anatomy and Physiology: From Science to Life*, 3e. Singapore: John Wiley & Sons.

Knight, J. (2021). Endocrine system 1: Overview of the endocrine system and hormones. *Nursing Times* 117 (5): 38–42.

Marieb, E.N. and Hoehn, K.N. (2022). *Human Anatomy & Physiology, Global Edition*, 2e. San Francisco: Pearson.

Peate, I. (2017). *Fundamentals of Applied Pathophysiology: An Essential Guide for Nursing Students*, 3e. Oxford: John Wiley & Sons, Ltd.

Srinivasan, A., Wong, F.X., and Karponis, D. (2020). Calcitonin: A useful old friend. *Journal of Musculoskeletal and Neuronal Interactions* 20 (4): 600–609.

Tortora, G.J. and Derrickson, B.H. (2009). *Principles of Anatomy and Physiology*, 12e. Hoboken, NJ: John Wiley & Sons, Inc.

Tortora, G.J. and Derrickson, B.H. (2023). *Principles of Anatomy and Physiology, International Adaptation*, 16e. New Jersey: Wiley.