CHAPTER 26

Chemical Regulation

Objectives

Introduction Explain how testosterone affects humans and the behavior of cichlid fish.

The Nature of Chemical Regulation

26.1 Define a hormone and compare the mechanisms and functions of the endocrine and nervous systems.

26.2 Compare the two general mechanisms by which hormones trigger changes in target cells.

The Vertebrate Endocrine System

26.3 Describe the different types and functions of vertebrate endocrine organs.

26.4, 26.5 Describe the functions of and interrelationships between the hypothalamus and the anterior and posterior pituitary glands.

Hormones and Homeostasis

26.6 Describe the functions of the thyroid gland. Describe the symptoms of hypothyroidism, hyperthyroidism, and a goiter.

26.7 Explain how the thyroid and parathyroid maintain calcium homeostasis.

26.8, 26.9 Explain how insulin and glucagon work to manage blood glucose levels. Explain what occurs in the different types of diabetes.

26.10 Compare the functions of the hormones released by the adrenal medulla and the adrenal cortex.

26.11 Describe the benefits and risks of using glucocorticoid drugs.

26.12 Describe the three major categories of sex hormones and note their functions.

Key Terms

hormone
endocrine gland
target cell
neurosecretory cells
endocrine system
neurotransmitter
local regulator
prostaglandin
steroid hormone
pineal gland
thymus gland
hypothalamus
posterior pituitary
anterior pituitary
releasing hormone
inhibiting hormone
TRH (TSH-releasing hormone)
TSH (thyroid-stimulating hormone)
thyroxine
oxytocin
antidiuretic hormone (ADH)
adrenocorticotropic hormone (ACTH)
follicle-stimulating hormone (FSH)
luteinizing hormone (LH)
growth hormone (GH)
prolactin (PRL)
endorphin
thyroid gland
T_4 (thyroxine)

T_3 (triiodothyrodine)	islet cell	norepinephrine
goiter	glucagon	corticosteroid
parathyroid gland	diabetes mellitus	mineralocorticoid
calcitonin	hypoglycemia	glucocorticoid
parathyroid hormone (PTH)	adrenal gland	gonad
antagonistic hormone	adrenal medulla	estrogen
pancreas	adrenal cortex	progestin
insulin	epinephrine	androgen

Word Roots

andro- = male; **-gen** = produce (*androgens:* the principal male steroid hormones, such as testosterone, which stimulate the development and maintenance of the male reproductive system and secondary sex characteristics)

endo- = inside (*endorphin:* a hormone produced in the brain and anterior pituitary that inhibits pain perception)

epi- = above, over (*epinephrine:* a hormone produced as a response to stress; also called adrenaline)

lut- = yellow (*luteinizing hormone:* a gonadotropin secreted by the anterior pituitary)

para- = beside, near (*parathyroid glands:* four endocrine glands, embedded in the surface of the thyroid gland, that secrete parathyroid hormone and raise blood calcium levels)

pro- = before; **-lact** = milk (*prolactin:* a hormone produced by the anterior pituitary gland; it stimulates milk synthesis in mammals)

tri- = three; **-iodo** = violet (*triiodothyrodine:* one of two very similar hormones produced by the thyroid gland and derived from the amino acid tyrosine)

Lecture Outline

Introduction *Testosterone and Male Aggression*

A. The male sex hormone testosterone has been associated with male aggression in a variety of species. The difficulty for researchers in the field of endocrinology is to definitively prove the association between aggression and testosterone levels.

B. The cichlid fish *(Oreochromis mossambicus)* has been extensively studied. Its testosterone levels rise when in battle over territory. Even spectator cichlid fish demonstrate elevated levels of testosterone when viewing other male cichlid fish in battle over territory.

C. Testosterone in males develops and maintains the reproductive organs and secondary sex characteristics. But how does one define aggression in humans? Is it a desire to fight, or can it be determined through psychological testing? At best, researchers agree that testosterone has little if any direct measurable effect on humans and aggressive behavior.

D. Testosterone is classified with a group of chemical signals (hormones) that coordinate body functions at the basic level, including such activities as metabolism, energy usage, and growth. This chapter will cover the subject of hormones and other chemical signals with an emphasis on homeostasis.

I. The Nature of Chemical Regulation

Module 26.1 Chemical signals coordinate body functions.

A. **Hormones** are chemicals produced by **endocrine glands** or **neurosecretory cells** (Figure 26.1A). They have a controlling effect on another part of the body (at specific **target cells**).

B. Collectively, all hormone-secreting tissues constitute the **endocrine system.** This system is particularly important in controlling whole-body activities such as metabolic rate, growth, maturation, and reproduction.

C. Neurosecretory cells secrete **neurotransmitters** that play a role in nerve impulse conduction (Modules 28.6–28.8) and are also transported in the blood to target cells (for example, a muscle cell or an endocrine cell) (Figure 26.1B, C).

D. **Local regulators** are secreted into the interstitial fluid and cause changes in cells near the point of secretion. Interleukins (Module 24.13) and **prostaglandins** (for example, Module 27.18) are types of local regulators with a wide range of functions.
NOTE: Prostaglandins play a role in the inflammatory response, and it is the inhibition of prostaglandins that is a cause of ulcers (Modules 21.8–9).

E. *Preview:* The nervous system is the subject of Chapters 28 and 29.

F. The two systems, endocrine and nervous, coordinate most of their activities. The nervous system provides split-second control, and the endocrine system provides control over longer duration, from minutes to days.

Module 26.2 Hormones affect target cells by two main signaling mechanisms.

A. Nonsteroid hormones are made from amino acids. Nonsteroid hormones (the first messenger) never enter their target cell, but exert their effects via a signal-transduction pathway (Module 11.13). They interact with a surface protein of that cell, inducing a cascade that produces the desired effects (Figure 26.2A).

B. There are three main classes of nonsteroid hormones:
   1. Amine hormones are modified versions of single amino acids.
   2. Peptide hormones are short chains of amino acids (three amino acids or more).
   3. Protein hormones are long chains of amino acids.

   NOTE: Amine hormones are derived from tyrosine.

C. **Steroid hormones** are lipids made from cholesterol and can diffuse through the phospholipid membrane. Most interact with the DNA in the nuclei of their target cells by turning a gene on or off, stimulating the synthesis of new proteins by those cells (Figure 26.2B).

D. The same hormone can affect different cells differently.

II. The Vertebrate Endocrine System

Module 26.3 Overview: The vertebrate endocrine system.

A. Endocrine glands secrete into the blood.
Review: Contrast this with the nonendocrine (exocrine) glands of the GI tract (Chapter 21), which secrete into body cavities.

B. The endocrine system is composed of glands, spread throughout the body (Figure 26.3). Some (e.g., pituitary, thyroid) are endocrine specialists. Others (e.g., the pancreas) have both endocrine and nonendocrine (exocrine) functions.
NOTE: Structures with endocrine functions that are not indicated in Figure 26.3 include the heart (atrial natriuretic factor) and the kidneys (erythropoietin).

C. General features shared by the endocrine systems of all vertebrates are listed in Table 26.3.

D. Only the sex organs and the adrenal cortex produce steroid hormones that enter the target cells directly. Most hormone action is by means of signal transduction.

E. Some hormones (e.g., sex hormones) affect body tissues generally. Some have specific targets in or out of the endocrine system.

F. The endocrine and nervous systems are closely associated (see the "Regulated by" column in Table 26.3).

G. The **pineal gland** (not discussed in this chapter) secretes melatonin, which links environmental light conditions with activities that show daily or seasonal rhythms. A major role is to cue reproductive activity. Rising levels cue reproduction in sheep and deer that breed in the fall. Lowering levels cue reproduction in mammals that breed in the spring.
Preview: Biological clocks in animals are discussed in Module 37.9.

H. The **thymus gland** (not discussed in this chapter) is important in the immune system, stimulating the development and differentiation of T cells in early childhood. This gland virtually disappears but still remains functional in adults.
Review: The role of the thymus and T cells (Module 24.5).

Module 26.4 The hypothalamus, closely tied to the pituitary, connects the nervous and endocrine systems.

A. The **hypothalamus** is the endocrine system's master control center (Figure 26.4A). It receives information from nerves about the internal condition of the body and about the external environment. It signals the pituitary gland, which in turn secretes hormones that influence many body functions, including those of other endocrine glands.

B. The posterior lobe of the pituitary gland consists of an extension of the hypothalamus. Composed of nervous tissue, it stores and secretes hormones made in the hypothalamus. *NOTE:* The release of the hormones stored in the **posterior pituitary** is under the control of nerve impulses from the hypothalamus.

C. The anterior lobe of the pituitary gland is composed mostly of glandular tissue. The **anterior pituitary** synthesizes its own hormones, several of which control other endocrine glands.

D. The hypothalamus controls the pituitary by secreting **releasing hormones** and **inhibiting hormones.**

E. For example, secretion by the hypothalamus of TRH (thyroid-releasing hormone) induces the anterior pituitary to secrete TSH (thyroid-stimulating hormone). TSH causes the thyroid to release thyroxine into the blood. Thyroxine increases the metabolic rates of most cells. Increased thyroxine levels have negative-feedback (Module 20.13) control on the release of TSH and TRH (Figure 26.4B).

Module 26.5 The hypothalamus and pituitary have multiple endocrine functions.

A. Neurosecretory cells extend from the hypothalamus into the posterior pituitary and synthesize the hormones **oxytocin** and **antidiuretic hormone** (ADH: Module 25.11). Oxytocin induces contraction of the uterine muscles during childbirth (Module 27.18) and causes the mammary glands to release milk during nursing. ADH helps the kidneys retain water (Figure 26.5A).
Review: The role of water retention by the kidneys is discussed in Module 25.9.

B. A second set of neurosecretory cells of the hypothalamus secretes releasing and inhibiting hormones that are carried by small vessels to the anterior pituitary (Figure 26.5B).

Under the control of releasing hormones, the anterior pituitary can release **thyroid-stimulating hormone (TSH), adrenocorticotropic hormone (ACTH), follicle-stimulating hormone (FSH),** or **luteinizing hormone (LH),** all of which activate other endocrine glands. These glands' hormonal secretions all exhibit negative-feedback control on the anterior pituitary.

C. Other hormones produced by the anterior pituitary include **growth hormone (GH,** which promotes the development and enlargement of all body parts in young mammals), **prolactin (PRL,** which stimulates mammals to produce milk, regulates larval development of amphibians, and regulates salt and water balance in fishes), and **endorphins** (the body's natural painkillers).

III. Hormones and Homeostasis

Module 26.6 The thyroid regulates development and metabolism.

A. Thyroid hormones affect virtually all vertebrate tissues. Two very similar iodine-containing amine hormones are produced by the **thyroid gland: Thyroxine (T_4)** and **triiodothyronine (T_3)** have four and three iodine atoms per molecule, respectively.

B. In amphibians, thyroid hormones trigger tissue reorganization during metamorphosis.

C. In mammals, thyroid hormones control the early development of bone and nerve cells.

D. In adult mammals, thyroid hormones maintain normal blood pressure, heart rate, muscle tone, and digestive and reproductive functions.

E. Hyperthyroidism causes overheating, profuse sweating, irritability, high blood pressure, and weight loss.

F. Hypothyroidism causes lethargy, intolerance to cold, and weight gain. It is often accompanied by the enlargement of the thyroid, a condition called a **goiter,** which occurs when too little iodine is consumed in the diet (Figure 26.6A). This condition results from an interruption of normal negative-feedback control on TSH release by the pituitary (Figure 26.6B). Hypothyroidism in children can cause cretinism.
NOTE: Severe hypothyroidism in adults results in myxedema.

Module 26.7 Hormones from the thyroid and parathyroids maintain calcium homeostasis.

A. Appropriate levels of blood calcium are essential for nerve and muscle cell functions, blood clotting, and active transport across cell membranes.

B. Together, secretions from these two types of glands keep Ca^{2+} ions at a concentration of 9–11 mg per 100 mL of blood.

C. **Calcitonin** from the thyroid and **parathyroid hormone (PTH)** from the **parathyroid glands** are **antagonistic hormones;** that is, they have opposite effects (Figure 26.7).
NOTE: In adults, calcitonin plays a relatively minor (if any) role in the regulation of Ca^{2+} levels.

D. Calcitonin lowers the Ca^{2+} level whenever that level rises above about 10 mg/100 mL. It causes Ca^{2+} to be deposited in bone and absorbed less by the intestine, and it causes the kidneys to reabsorb less Ca^{2+} as they form urine.

E. PTH raises the Ca^{2+} level whenever that level falls below about 10 mg/100 mL. It causes Ca^{2+} to be released from bone, absorbed more by the intestine, and reabsorbed more by the kidneys.
NOTE: In the kidneys, PTH promotes the conversion of vitamin D to its active form. In turn, vitamin D promotes the absorption of calcium and phosphate from the alimentary canal (Module 21.4), the retention of these minerals by the kidneys, and their release from bone into blood.

F. Low levels of PTH result in low levels of calcium in the blood. This can lead to convulsive contractions of skeletal muscle.
NOTE: These contractions of skeletal muscle are called tetany.
NOTE: The effects of hyperparathyroidism include demineralization of bone.

Module 26.8 Pancreatic hormones manage cellular fuel.

A. **Insulin** and **glucagon** are antagonistic hormones produced by **islet cells** in the **pancreas** (Figure 26.8).

B. Insulin is a protein hormone produced by beta islet cells. Glucagon is a peptide hormone produced by alpha islet cells.

C. The set point that controls hormone balance is about 90 mg glucose/100 mL.

D. Rising blood glucose level (after a meal) stimulates the beta islet cells to secrete insulin. The blood glucose level falls because insulin stimulates all body cells to take more glucose from the blood. The liver converts most glucose into stored glycogen. Other cells metabolize glucose into energy, stored fats, or proteins.

E. Falling blood glucose level (during a fast) stimulates the alpha islet cells to secrete glucagon. The blood glucose level rises because glucagon makes liver cells convert glycogen to glucose, as well as convert fatty acids and amino acids to glucose.

Module 26.9 Connection: Diabetes is a common endocrine disorder.

A. Much of the function of insulin has been discovered in people with **diabetes mellitus,** which occurs in about five out of 100 people.

B. This disease occurs when there is not enough insulin produced to maintain proper absorption of glucose from the blood or when body cells do not respond to normal levels of insulin. The glucose concentration of blood becomes so high (hyperglycemia) that glucose is excreted by the kidneys.

C. Type I diabetes develops before age 15 and involves the destruction of beta islet cells, by disease or by hereditary immune system dysfunction (Module 24.16). Type I diabetes is controlled by the injection of recombinant human insulin.
NOTE: However, not everyone with a genetic predisposition to Type I diabetes gets Type I diabetes.

D. Type II diabetes is usually associated with older people (40+ and obese) and occurs when body cells do not respond correctly to insulin. Type II diabetes is usually controlled by diet, antidiabetic drugs, and exercise.
NOTE: Risk for Type II diabetes has a major genetic component.

E. Early signs of diabetes include lethargy, a craving for sweets, frequent urination, and thirst. A glucose-tolerance test is used to detect diabetes (Figure 26.9). A less traumatic procedure is a two-hour postprandial glucose determination in conjunction with a fasting glucose level.
NOTE: These early signs are frequently referred to as polyphagia (excessive hunger), polyuria (excessive urination), and polydipsia (frequent thirst).

F. **Hypoglycemia** occurs in some people who secrete too much insulin. Symptoms appear 2–4 hours after a meal and include hunger, weakness, sweating, and nervousness. In severe cases, convulsions can lead to death in people whose brains do not receive enough glucose.

Module 26.10 The adrenal glands mobilize responses to stress.

A. The **adrenal glands** are associated with the kidneys and are composed of two functionally different parts: the **adrenal medulla** in the center produces the "fight-or-flight" hormones; the **adrenal cortex** at the outside produces hormones that provide slower, longer term responses to stress.

B. Stress produces a cascade effect. Stressful stimuli (negative or positive) activate certain hypothalamus cells. These cells send signals along nerve cells through the spinal cord to stimulate the adrenal medulla (Figure 26.10).

C. The adrenal medulla ensures a rapid, short-term response to stress. When stimulated, the adrenal medulla releases **epinephrine** (adrenaline) and **norepinephrine** (noradrenaline) into the bloodstream. Both hormones stimulate liver and muscle cells to release glucose, making more energy available for cellular fuel. They increase blood pressure, breathing rate, and metabolic rate and change blood-flow patterns. Epinephrine dilates blood vessels in the brain and skeletal muscles but constricts vessels elsewhere, directing blood to critical areas.
NOTE: The secretion is mostly of epinephrine.

D. The adrenal cortex causes slower responses. It responds to endocrine signals (ACTH) from the pituitary. When stimulated, the adrenal cortex secretes a family of steroid hormones, the **corticosteroids.** These hormones help the body function normally, whether stressed or not. **Mineralocorticoids** affect salt and water balance. **Glucocorticoids** promote the synthesis of glucose from noncarbohydrate sources. In addition, high levels of the glucocorticoids can suppress the body's defense system and can control excessive inflammation.
NOTE: Hypersecretion of the adrenal cortex can cause Cushing's disease. Symptoms of Cushing's disease include a pendulous (fatty) abdomen and a fatty hump on the back of the neck. Hyposecretion of the adrenal cortex can cause Addison's disease. Symptoms of Addison's disease includes dehydration and weight loss.
NOTE: The adrenal cortex also secretes both androgens and estrogens.

Module 26.11 Connection: Glucocorticoids offer relief from pain, but not without serious risks.

A. Physicians often prescribe glucocorticoids to relieve the pain of athletic injuries (Figure 26.11).

B. Unfortunately they depress the activity of the adrenal glands and may have dangerous side effects, such as psychological changes.

Module 26.12 The gonads secrete sex hormones.

A. Sex hormones are steroid hormones produced by the **gonads** that affect growth and development and regulate reproductive cycles and sexual behavior.

B. The three categories of sex hormones—**androgens, estrogens,** and **progestins**—are all found in both females and males, but in different proportions.

C. Females have a high ratio of estrogens to androgens. Estrogens stimulate the development and maintenance of the female reproductive system and secondary sex characteristics, such as smaller body size, higher voice, breasts, and wider hips. Progestins (progesterone) are most active in human females, where they prepare the uterus to support the developing embryo.
Preview: The role of these hormones in the menstrual and ovarian cycles is discussed in Module 27.5.

D. Males have a high ratio of androgens (e.g., testosterone) to estrogens. Androgens stimulate the development and maintenance of the male reproductive system and secondary sex characteristics, such as deeper voice, more body hair, and larger skeletal muscles.
Review: Anabolic steroids, artificial analogs of testosterone (Module 3.10).
Preview: The role of these hormones in regulating sperm production is discussed in Module 27.3.

E. The hypothalamus and anterior pituitary control the release of sex hormones. The anterior pituitary synthesizes FSH and LH, which stimulate the ovaries and testes to synthesize and secrete sex hormones.
Preview: Module 27.3.

Class Activities

1. Engage the students in thought experiments concerning the potential effects of hypersecretion or hyposecretion of the hormones discussed in this chapter.
2. Ask your students if they can think of situations under which a genetic predisposition to Type II diabetes might be an advantage. (Ask your students if, historically, food has been as plentiful and easily obtainable as it is in the U.S. today.)

Transparency Acetates

Figure 26.1A	Hormone from an endocrine cell
Figure 26.1B	Hormone from a neurosecretory cell
Figure 26.1C	Neurotransmitter
Figure 26.2A	A hormone that binds a plasma-membrane receptor
Figure 26.2B	A hormone that binds an intracellular receptor
Figure 26.3	The major endocrine glands in humans
Table 26.3	Major vertebrate endocrine glands and some of their hormones
Figure 26.4A	Location of the hypothalamus and pituitary
Figure 26.4B	Control of thyroxine secretion
Figure 26.5A	Hormones of the posterior pituitary
Figure 26.5B	Hormones of the anterior pituitary
Figure 26.6B	Why a goiter forms
Figure 26.7	Calcium homeostasis
Figure 26.8	Glucose homeostasis
Figure 26.9	Results of glucose-tolerance tests
Figure 26.10	How the adrenal glands control our responses to stress (Layer 1)
Figure 26.10	How the adrenal glands control our responses to stress (Layer 2)

Media

See the beginning of this book for a complete description of all media available for instructors and students. Animations and videos are available in the Campbell Image Presentation Library. Media Activities and Thinking as a Scientist investigations are available on the student CD-ROM and web site.

Animations and Videos	File Name
Nonsteroid Hormone Animation	26-02A-NonsterHormoneAnim.mov
Steroid Hormone Animation	26-02B-SteroidHormoneAnim.mov

Activities and Thinking as a Scientist	Module Number
Web/CD Activity 26A: *Overview of Cell Signaling*	26.2
Web/CD Activity 26B: *Nonsteroid Hormone Action*	26.2
Web/CD Activity 26C: *Steroid Hormone Action*	26.2
Web/CD Thinking as a Scientist: *How Do Thyroxine and TSH Affect Metabolism?*	26.6
Web/CD Activity 26D: *Human Endocrine Glands and Hormones*	26.12