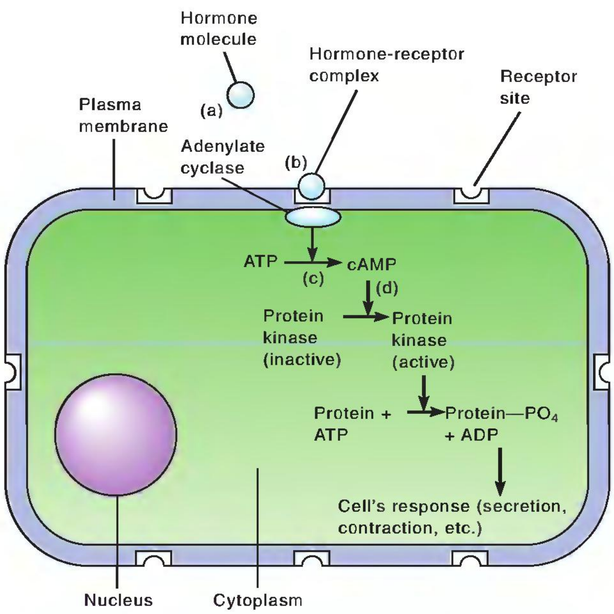

FIGURE 25.3

Steps of the Fixed-Membrane-Receptor Mechanism of Hormonal Action. *(a)* A protein hormone molecule (such as epinephrine) diffuses from the blood to a target cell. *(b)* The binding of the hormone to a specific plasma membrane receptor activates adenylate cyclase (a membrane-bound enzyme system). *(c)* This enzyme system catalyzes cyclic AMP formation (the second messenger) inside the cell. *(d)* Cyclic AMP (cAMP) diffuses throughout the cytoplasm and activates an enzyme called protein kinase, which then phosphorylates specific proteins in the cell, thereby triggering the biochemical reaction, leading ultimately to the cell's response.

and diffuse easily into the cytoplasm, where they initiate their response by binding to cytoplasmic receptors.

FIXED-MEMBRANE-RECEPTOR MECHANISM

With the fixed-membrane-receptor mechanism, an endocrine cell secretes a water-soluble hormone that circulates through the blood stream (figure 25.3*a*). At the cells of the target organ, the hormone acts as a "first or extracellular messenger," binding to a specific receptor site for that hormone on the plasma membrane (figure 25.3*b*). The hormone-receptor complex activates the enzyme adenylate cyclase in the membrane (figure 25.3*c*). The activated enzyme converts ATP into a nucleotide called cyclic AMP, which becomes the "second (or intracellular) messenger." Cyclic AMP diffuses throughout the cytoplasm and activates an enzyme called protein kinase, which causes the cell to respond with its distinctive physiological activity (figure 25.3*d*). After inducing the target cell to perform its specific function, the enzyme phosphodiesterase inactivates cyclic AMP. In the meantime, the receptor on the plasma membrane loses the first messenger and now becomes available for a new reaction.

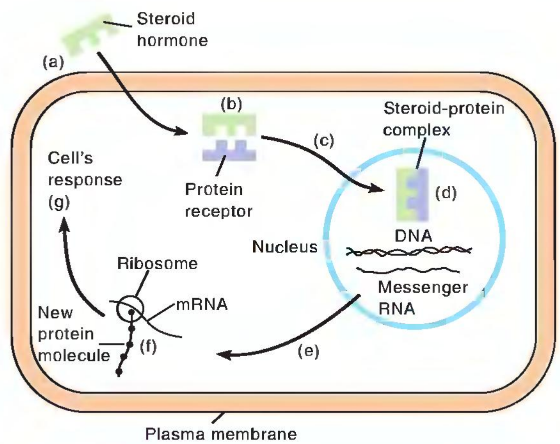

FIGURE 25.4

Steps of the Mobile-Receptor Mechanism. *(a)* A steroid hormone molecule (e.g., testosterone) diffuses from the blood to a target cell and then across the plasma membrane of the target cell. *(b)* Once in the cytoplasm, the hormone binds to a receptor that *(c)* carries it into the nucleus. *(d)* This steroid-protein complex triggers transcription of specific gene regions of DNA. *(e)* The messenger RNA transcript is then translated into a gene product via *(f)* protein synthesis in the cytoplasm. *(g)* The new protein then mediates the cell's response.

MOBILE-RECEPTOR MECHANISM

Because steroid hormones pass easily through the plasma membrane, their receptors are inside the target cells. The mobile-receptor mechanism involves the stimulation of protein synthesis. After being released from a carrier protein in the bloodstream, the steroid hormone enters the target cell by diffusion and binds to a specific protein receptor in the cytoplasm (figure 25.4*a,b*). This newly formed steroid-protein complex acquires an affinity for DNA that causes it to enter the nucleus of the cell, where it binds to DNA and regulates the transcription of specific genes to form messenger RNA (figure 25.4*c,d*). The newly transcribed mRNA leaves the nucleus and moves to the rough endoplasmic reticulum, where it initiates protein synthesis (figure 25.4*e,f*). Some of the newly synthesized proteins may be enzymes whose effects on cellular metabolism constitute the cellular response attributable to the specific steroid hormone (figure 25.4*g*).

SOME HORMONES OF INVERTEBRATES

The survival of any group of animals depends on growth, maturation, and reproduction coinciding with the most favorable seasons of the year so that climate and food supply are optimal. Thus, chemicals regulating growth, maturation, and reproduction probably were among the first hormones to appear during the course of animal evolution.

The first hormones were probably neurosecretions. As discussed next, most of the chemicals functioning as hormones in invertebrate animals are neurosecretions called neuropeptides.

Only a few of the more complex invertebrates (e.g., molluscs, arthropods, echinoderms) have hormones other than neurosecretions. What follows is a brief overview of some invertebrate neuropeptides and hormones.

PORIFERA

The porifera (sponges) do not have classical endocrine glands. Since sponges do not have neurons, they also do not have neurosecretory cells.

CNIDARIANS

The nerve cells of *Hydra* contain a growth-promoting hormone that stimulates budding, regeneration, and growth. For example, when the hormone is present in the medium in which fragments of *Hydra* are incubated, "head" regeneration is accelerated. This so-called "head activator" also stimulates mitosis in *Hydra.*

PLATYHELMINTHS

Zoologists identified neurosecretory cells in various flatworms over 30 years ago. These cells are in the cerebral ganglion and along major nerve cords. The neuropeptides that the cells produce function in regeneration, asexual reproduction, and gonad maturation. For example, neurosecretory cells in the scolex of some tapeworms control shedding of the proglottids or the initiation of strobilization.

NEMERTEANS

Nemerteans have more cephalization than platyhelminths and a larger brain, composed of a dorsal and ventral pair of ganglia connected by a nerve ring. The neuropeptide that these ganglia produce appears to control gonadal development and to regulate water balance.

NEMATODES

Although no classical endocrine glands have been identified in nematodes, they do have neurosecretory cells associated with the central nervous system. The neuropeptide that this nervous tissue produces apparently controls ecdysis of the old cuticle. The neuropeptide is released after a new cuticle is produced and stimulates the excretory gland to secrete an enzyme (leucine aminopeptidase) into the space between the old and new cuticle. The accumulation of fluid in this space causes the old cuticle to split and be shed.

MOLLUSCS

The ring of ganglia that constitutes the central nervous system of molluscs is richly endowed with neurosecretory cells. The neuropeptides that these cells produce help regulate heart rate, kidney function, and energy metabolism.

In certain gastropods, such as the common land snail *Helix*, a specific hormone stimulates spermatogenesis; another hormone, termed egg-laying hormone, stimulates egg development; and hormones from the ovary and testis stimulate accessory sex organs. In all snails, a growth hormone controls shell growth.

In cephalopods, such as the octopus, and squid, the optic gland in the eye stalk produces one or more hormones that stimulate egg development, proliferation of spermatogonia, and the development of secondary sexual characteristics.

ANNELIDS

Since annelids have a well-developed and cephalized nervous system, a well-developed circulatory system, and a large coelom, their correspondingly well-developed endocrine control of physiological functions is not surprising. The various endocrine systems of annelids are generally involved with morphogenesis, development, growth, regeneration, and gonadal maturation. For example, in polychaetes, juvenile hormone inhibits the gonads and stimulates growth and regeneration. Another hormone, gonadotropin, stimulates the development of eggs. In leeches, a neuropeptide stimulates gamete development and triggers color changes. Osmoregulatory hormones have been reported in oligochaetes, and a hyperglycemic hormone that maintains a high concentration of blood glucose has been reported for the oligochaete, *Lumbricus.*

ARTHROPODS

The endocrine systems of advanced invertebrates (crustaceans and insects) are excellent examples of how hormones regulate growth, maturation, and reproduction. Much is known about hormones and their functioning in these animals.

The endocrine system of a crustacean, such as a crayfish, controls functions such as ecdysis (molting), sex determination, and color changes. Only ecdysis is discussed here.

X-organs are neurosecretory tissues in the crayfish eye stalks (figure 25.5*a*). Associated with each X-organ is a sinus gland that accumulates and releases the secretions of the X-organ. Other glands, called Y-organs, are at the base of the maxillae. X-organs and Y-organs control ecdysis as follows. In the absence of an appropriate stimulus, the X-organ produces molt-inhibiting hormone (MIH), and the sinus gland releases it (figure 25.5*b*). The target of this hormone is the Y-organ. When MIH is present in high concentrations, the Y-organ is inactive. Under appropriate internal and external stimuli, MIH release is prevented, and the Y-organ releases the hormone ecdysone, which leads to molting (figure 25.5*c*).

The sequence of events in insects is similar to that of crustaceans, but it does not involve a molt-inhibiting hormone. The presence of an appropriate stimulus to the central nervous system activates certain neurosecretory cells (pars intercerebralis) in the optic lobes of the brain (figure 25.6*a*). These cells secrete the hormone ecdysiotropin, which axons transport to the corpora cardiaca (a mass of neurons associated with the brain). The corpora cardiaca

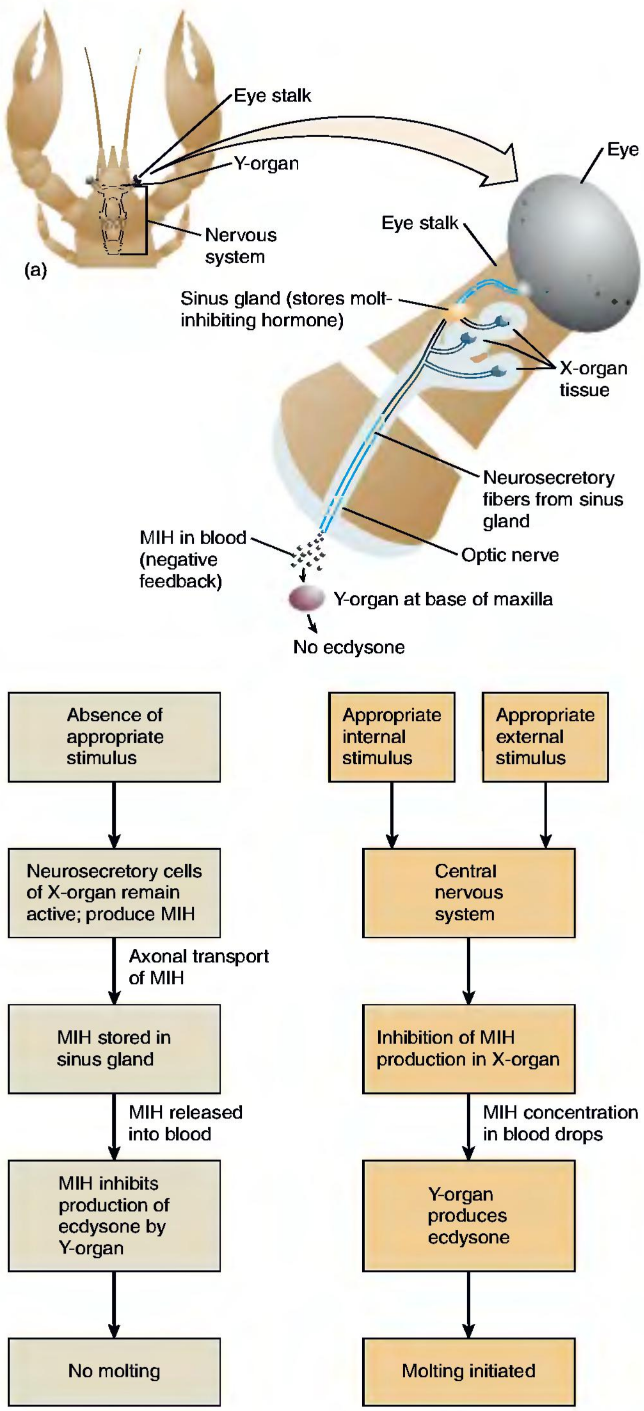

FIGURE 25.5

Hormonal Control of Ecdysis (Molting) in Crustaceans. *(a)* Neurosecretory apparatus in a crustacean eye stalk. *(b)* Flow diagram of the events inhibiting molting and *(c)* causing molting. (MIH = molt-inhibiting hormone.)

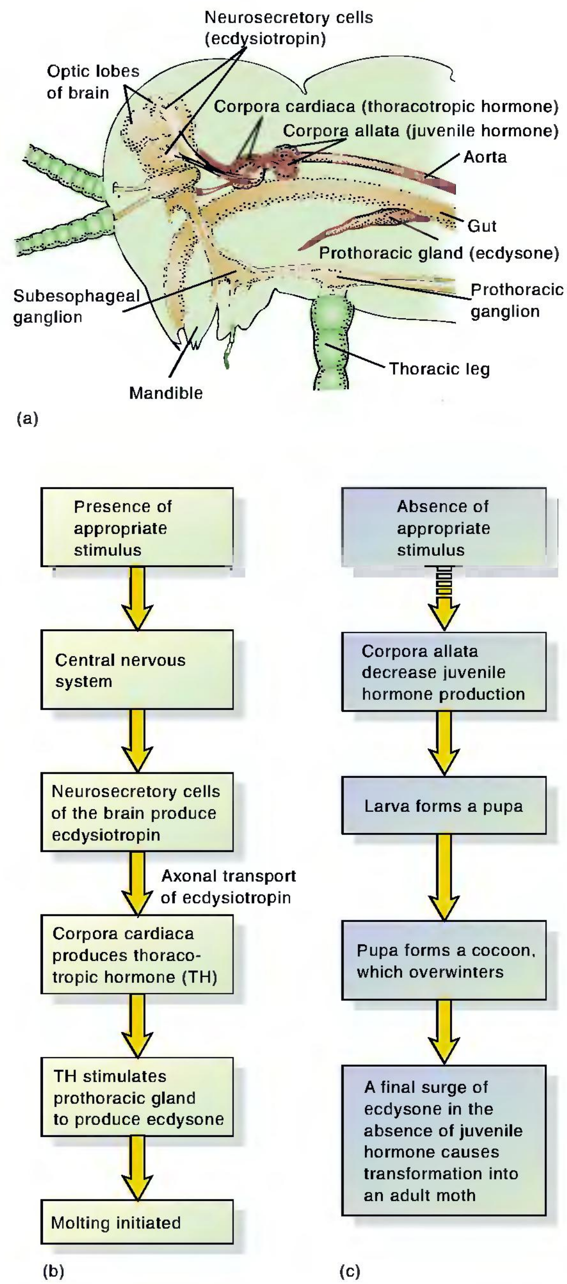

FIGURE 25.6

Control of Ecdysis (Molting) and Development (Metamorphosis) in an Insect. *(a)* Anterior end of an insect, showing the location of the brain hormone, juvenile hormone, and ecdysone secretory centers. *(b)* Flow diagram of the events initiating molting in an insect. *(c)* Flow diagram of the events of insect metamorphosis as regulated by a decrease in the production of juvenile hormone.

produces thoracotropic hormone, which is carried to the prothoracic glands, stimulating them to produce and release ecdysone, which induces molting (figure 25.6*b*)—in particular, the reabsorption of some of the old cuticle and the development of a new cuticle.

Other neurosecretory cells in the brain and nerve cords produce the hormone bursicon. Bursicon influences certain aspects of epidermal development, such as tanning (i.e., hardening and darkening of the chitinous outer cuticle layer). Tanning is completed several hours after each molt.

Another hormone, juvenile hormone (JH), is also involved in the morphological differentiation that occurs during the molting of insects. Just behind the insect brain are the paired corpora allata (figure 25.6*a*). These structures produce JH. High concentrations of JH in the blood of an insect inhibit differentiation. In the absence of an appropriate environmental stimulus, the corpora allata decrease JH production, which causes the insect larva to differentiate into a pupa (figure 25.6*c*). The pupa then forms a cocoon to overwinter. In the spring, a final surge of ecdysone, in the absence of JH, transforms the pupa into an adult moth.

ECHINODERMS

Since echinoderms are deuterostomes, they are more closely allied with chordates than are the protostome invertebrates. However, the endocrine systems of echinoderms provide few insights into the evolution of chordate endocrine systems, because echinoderm hormones and endocrine glands are very different from those of chordates. Zoologists do know, however, that the radial nerves of sea stars contain a neuropeptide called gonad-stimulating substance. When this neuropeptide is injected into a mature sea star, it induces immediate shedding of the gametes, spawning behavior, and meiosis in the oocytes. The neuropeptide also causes the release of a hormone called maturation-inducing substance, which has various effects on the reproductive system.

AN OVERVIEW OF THE VERTEBRATE ENDOCRINE SYSTEM

Since vertebrates have been studied more than invertebrates, vertebrates have the best understood system of hormonal control. *As the earliest vertebrates evolved, hormone-producing cells and tissues developed, and came to be controlled in several ways. Sets of nerve cells in the brain direct some endocrine tissues, such as the medullary areas of the adrenal glands. The hypothalamus of the brain and the pituitary gland (hypophysis) control others. Still others function independently of either nerves or the pituitary gland.*

Vertebrates possess two types of glands (figure 25.7). One type, **exocrine** (Gr. *exo*, outside + *krinein*, to separate) **glands,** secrete chemicals into ducts that, in turn, empty into body cavities or onto body surfaces (e.g., mammary, salivary, and sweat glands). The second type, **endocrine** (Gr. *endo*, within + *krinein*, to separate)

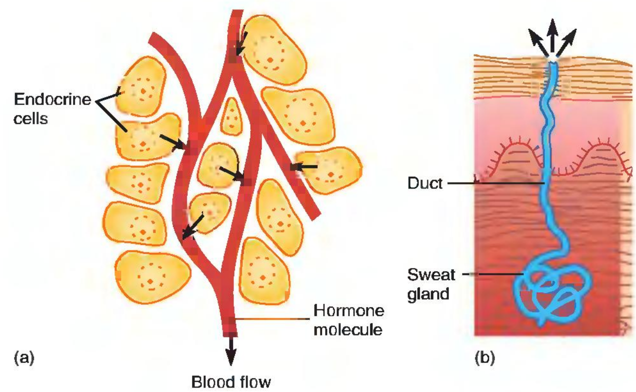

FIGURE 25.7

Vertebrate Glands with and without Ducts. *(a)* An endocrine gland, such as the thyroid, secretes hormones into the extracellular fluid. From there, the hormones pass into blood vessels and travel throughout the body. *(b)* An exocrine gland, such as a sudoriferous (sweat) gland, secretes material (sweat) into a duct that leads to a body surface.

glands, have no ducts, and instead secrete chemical messengers, called hormones, directly into the tissue space next to each endocrine cell. The hormones then diffuse into the bloodstream, which carries them throughout the body to their target cells.

ENDOCRINE SYSTEMS OF VERTEBRATES OTHER THAN BIRDS OR MAMMALS

Since this text uses a phylogenetic approach to describe form and function in animals, endocrine regulation in vertebrates other than birds or mammals is now discussed. Birds and mammals are the subject of the last part of this chapter.

Vertebrates other than birds or mammals have somewhat similar endocrine systems, but differences do exist. Recent research has revealed the following three aspects of endocrinology that relate to species differences among these vertebrates:

1. Hormones (or neuropeptides) with the same function in different species may not be chemically identical.
2. Certain hormones are species-specific with respect to their function; conversely, some hormones produced in one species may be completely functional in another species.
3. A hormone from one species may elicit a different response in the same target cell or tissue of a different species.

The examples that follow illustrate these three principles and also present a comparative survey of endocrine function in selected vertebrates.

When more ancient groups of vertebrates are compared with more recent ones, one general tendency surfaces: older groups seem to have simpler endocrine systems. For example, many of the hormones present in mammals are absent in fishes. In

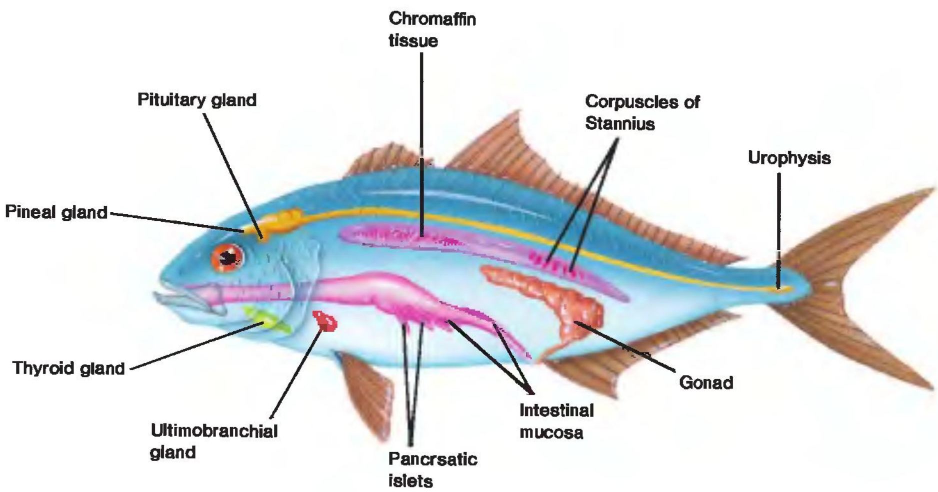

FIGURE 25.8

Approximate Locations of Endocrine Tissues (Glands) in a Bony Fish.

fishes, the brain and spinal cord are the most important producers of hormones, with other glands being rudimentary (figure 25.8). In jawed fishes, three major regions secrete neuropeptides. The two in the brain are the **pineal gland** of the epithalamus and the **preoptic nuclei** of the hypothalamus. The pineal gland produces neuropeptides that affect pigmentation and apparently inhibit reproductive development, both of which are stimulated by light. One specific hormone that the pineal gland produces, **melatonin,** has broad effects on body metabolism by synchronizing activity patterns with light intensity and day length. The preoptic nuclei produce various other neuropeptides that control different functions in fishes (e.g., growth, sleep, locomotion). The third major region of fishes that has neuropeptide function is the urophysis. The **urophysis** (Gr. *oura,* tail + *physis,* growth) is a discrete structure in the spinal cord of the tail. The urophysis produces neuropeptides that help control water and ion balance, blood pressure, and smooth muscle contractions. Other than these functions, little else is known of its functions or the significance of its absence in more complex vertebrates.

In many fishes, amphibians, and reptiles, hormones (e.g., melatonin) from the pineal gland control variations in skin color. When this hormone produced by one species is injected into another species, it can induce dramatic color changes (figure 25.9). This type of experiment indicates that some hormones have a close chemical similarity (point 2 at the beginning of this section), despite the distant evolutionary relationships among the animals producing them. Another example is the hormone prolactin (produced by the **pituitary gland**). Prolactin stimulates reproductive migrations in many animals (e.g., the movement of salamanders to water). Prolactin causes brooding behavior in some fishes. It also helps control water and salt balances, and is essential for certain saltwater fishes to enter freshwater during spawning runs.

FIGURE 25.9

Hormonal Control of Frog Skin Color. The light-colored frog on the left was immersed in water containing the hormone melatonin. The dark-colored frog on the right received an injection of melanocyte-stimulating hormone.

From an evolutionary perspective, evidence indicates that the thyroid gland in the earliest vertebrates evolved from a pouchlike structure (the endostyle) that carried food particles in the front end of the digestive tract. This explains why the thyroid gland is in the neck on the ventral side of the pharynx in all vertebrates. How did this feeding mechanism turn into an endocrine gland? One possible hypothesis is that as the developing pouch gradually lost all connection with the pharynx, it

TABLE 25.1
MAJOR VERTEBRATE ENDOCRINE TISSUES AND HORMONES

SOURCE	HORMONES	TARGET CELLS AND PRINCIPAL ACTIONS
Anterior lobe of pituitary (adenohypophysis)	Somatotropin (STH, or growth hormone [GH])	Stimulates growth of bone and muscle; promotes protein synthesis; affects lipid and carbohydrate metabolism; increases cell division
	Adrenocorticotropic hormone (ACTH)	Stimulates secretion of adrenocortical steroids; is involved in stress response
	Thyrotropin (TSH) of thyroid-stimulating hormone	Stimulates thyroid gland to synthesize and release thyroid hormones concerned with growth, development, metabolic rate
	Endorphins	Decrease pain
	Gonadotropins: Luteinizing or interstitial cell-stimulating hormone (LH or ICSH)	In ovary: Forms corpora lutea; secretes progesterone; probably acts in conjunction with FSH
		In testis: Stimulates the interstitial cells, thus promoting the secretion of testosterone
	Follicle-stimulating hormone (FSH)	In ovary: Stimulates growth of follicles; functions with LH to cause estrogen secretion and ovulation
		In testis: Acts on seminiferous tubules to promote spermatogenesis
	Prolactin (PRL)	Initiates milk production by mammary glands; acts on crop sacs of some birds; stimulates maternal behavior in birds
Intermediate or posterior lobe of pituitary	Melanocyte-stimulating hormone (MSH)	Expands amphibian melanophores; contracts iridophores and xanthophores; promotes melanin synthesis; darkens the skin; responds to external stimuli
Posterior lobe of pituitary (neurohypophysis) releases these hormones produced by the hypothalamus	Antidiuretic hormone (ADH or vasopressin)	Elevates blood pressure by acting on arterioles; promotes reabsorption of water by kidney tubules
	Oxytocin	Affects postpartum mammary gland, causing ejection of milk; promotes contraction of uterus; has possible action in parturition and in sperm transport in female reproductive tract

became independent of the digestive system both functionally and structurally. As a result, a functionally novel structure arose from an ancestral structure with an unrelated function. The shape of the thyroid varies among vertebrates. It may be a single structure (e.g., many fishes, reptiles, and some mammals), or it may have several to many lobes. The major hormones that this gland produces are thyroxine (T_4) and triiodothyronine (T_3), which control the rate of metabolism, growth, and tissue differentiation in vertebrates.

As noted in point 3 at the beginning of this section, the same hormone(s) in different vertebrates may regulate related but different processes. The hormones thyroxine and triiodothyronine are excellent examples of this point. For example, in most animals, thyroxine and triiodothyronine regulate overall metabolism. In amphibians, they play an additional role in metamorphosis (figure 25.10). Specifically timed changes in the concentrations of three hormones—prolactin, thyroxine, and triiodothyronine—control metamorphosis in the frog. Low thyroxine and triiodothyronine concentrations and high prolactin concentrations in young tadpoles stimulate larval growth and prevent metamorphosis. As the hypothalamus and pituitary glands develop in the growing tadpole, the hypothalamus releases thyroid-stimulating hormone and prolactin-inhibiting hormone. Their release causes the pituitary gland to release thyroid-stimulating hormone and to cease production of prolactin. As a result, the concentrations of thyroxine and triiodothyronine rise, triggering the onset of metamorphosis. Tail resorption and other metamorphic changes follow.

In jawed fishes and primitive tetrapods, several small **ultimobranchial glands** form ventral to the esophagus (*see figure 25.8*). These glands produce the hormone calcitonin that helps regulate the concentration of blood calcium.

Specialized endocrine cells **(chromaffin tissue)** or glands **(adrenal glands)** near the kidneys prepare some vertebrates for stressful emergency situations (figure 25.11). These tissues and glands produce two hormones (epinephrine or adrenaline, and norepinephrine or noradrenaline) that cause vasoconstriction increased blood pressure, changes in the heart rate, and increased

Hypothalamus	Thyroid-stimulating hormone (TSH)	Stimulates release of TSH by anterior pituitary
	Adrenocorticotropin-releasing hor-mone (CRH)	Stimulates release of ACTH by anterior pituitary
	Gonadotropin-releasing hormone(GnRH)	Stimulates gonadotropin release by anterior pituitary
	Prolactin-inhibiting factor (PIF)	Inhibits prolactin release by anterior pituitary
	Somatostatin	Inhibits release of STH by anterior pituitary
Thyroid gland	Thyroxine, triiodothyronine	Affect growth, amphibian metamorphosis, molting, metabolic rate in birds and mammals, development
	Calcitonin	Lowers blood calcium level by inhibiting calcium reabsorption from bone
Parathyroid glands	Parathormone	Regulates calcium concentration
Pancreas, islet cells	Insulin (from beta cells)	Promotes glycogen synthesis and glucose utilization and uptake from blood
	Glucagon (from alpha cells)	Raises blood glucose concentration
Adrenal cortex	Glucocorticoids (e.g., cortisol)	Promote synthesis of carbohydrates and breakdown of proteins; initiate antiinflammatory and antiallergic actions; mediate response to stress
	Mineralocorticoids (e.g., aldosterone)	Regulate sodium retention and potassium loss through kidneys, and water balance
Adrenal medulla	Epinephrine (adrenaline)	Mobilizes glucose; increases blood flow through skeletal muscle; increases oxygen consumption; increases heart rate
	Norepinephrine	Elevates blood pressure; constricts arterioles and venules
Testes	Androgens (e.g., testosterone)	Maintain male sexual characteristics; promote spermatogenesis
Ovaries	Estrogens (e.g., estradiol)	Maintain female sexual characteristics; promote oogenesis
Corpus luteum	Progesterone	Maintains pregnancy; stimulates development of mammary glands

blood glucose levels. These hormones are involved in the "fight-or-flight" reactions.

ENDOCRINE SYSTEMS OF BIRDS AND MAMMALS

With some minor exceptions, birds and mammals have a similar complement of endocrine glands (figure 25.12). Table 25.1 summarizes the major hormones these vertebrates produce.

BIRDS

The endocrine glands in birds include the ovary, testes, adrenals, pituitary, thyroid, pancreas, parathyroids, pineal, hypothalamus, thymus, ultimobranchial, and bursa of Fabricius (figure 25.12*a*). Since the hormones that most of these glands produce and their effects on target tissues are nearly the same as in mammals, they are discussed in the next section on mammals. A discussion of some unique hormones and their functions in birds follows.

In some birds (e.g., pigeons and doves), the pituitary gland secretes the hormone prolactin. Prolactin stimulates the production of "pigeon's milk" by desquamation (sloughing off cells) in the pigeon's crop. Prolactin also stimulates and regulates broodiness and certain other kinds of parental behavior, and along with estrogen, stimulates full development of the **brood (incubation) patch** (figure 25.13). The brood patch helps keep the eggs at a temperature between 33 and 37° C.

The bird's thyroid gland produces the hormone thyroxine. In addition to the major vertebrate functions listed in table 25.1, thyroxine regulates the normal development of feathers and the molt cycle, and plays a role in the onset of migratory behavior.

In male birds, the testes produce the hormone testosterone. Testosterone controls the secondary sexual characteristics of the male, such as bright plumage color, comb (when present), and spurs—all of which strongly influence sexual behavior.

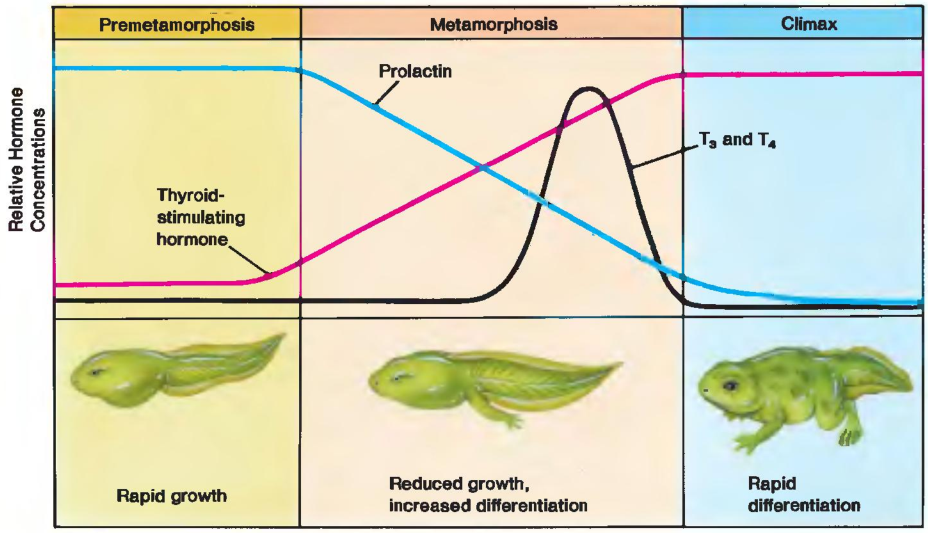

FIGURE 25.10

Frog Tadpole Metamorphosis. The thyroid hormones triiodothyronine (T_3) and thyroxine (T_4) regulate the metamorphosis of an aquatic frog tadpole into a semiterrestrial or terrestrial adult. The anterior pituitary secretes thyroid-stimulating hormone, which regulates thyroid gland activity. During the premetamorphosis (tadpole) stage, the pituitary and thyroid glands are relatively inactive. This keeps the concentration of thyroid-stimulating hormones, T_3 and T_4, at low concentrations. The high prolactin concentration in tadpoles stimulates larval growth and prevents metamorphosis. During metamorphosis, the concentrations of the thyroid hormones markedly increase, and prolactin decreases. These hormonal fluctuations induce rapid differentiation, climaxing in the adult frog.

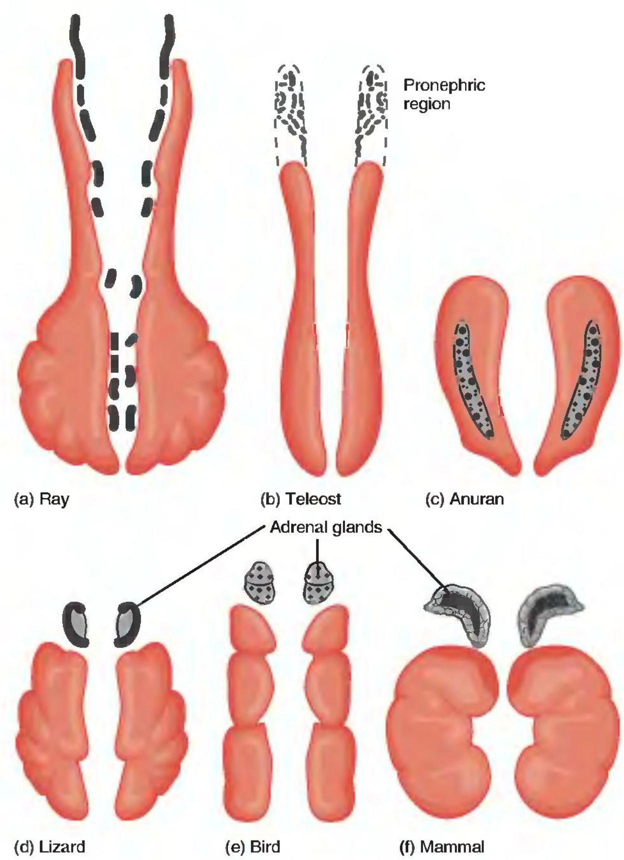

FIGURE 25.11

Chromaffin Tissue and Adrenal Glands in Selected Vertebrates. The chromaffin tissue (steroidogenic) produces steroid hormones and is shown in gray. The aminogenic tissue that produces norepinephrine and epinephrine is shown in black. The kidneys are shown in brown. Note the reversed location of the two components in lizards and mammals. *(a)* In jawless and cartilaginous fishes (elasmobranchs), aminogenic tissue develops as clusters near the kidneys. *(b)* In teleosts, the chromaffin tissue is generally at the anterior end of the kidney (pronephric region). *(c)* In anurans, the chromaffin tissue is interspersed in a diffuse gland on the ventral surface of each kidney. *(d)* In lizards, the chromaffin tissue forms a capsule around the steroidogenic-producing tissue. *(e)* In birds, the chromaffin tissue is interspersed within an adrenal capsule. *(f)* In most mammals, the chromaffin tissue forms an adrenal medulla, and the steroidogenic tissue forms the cortex.

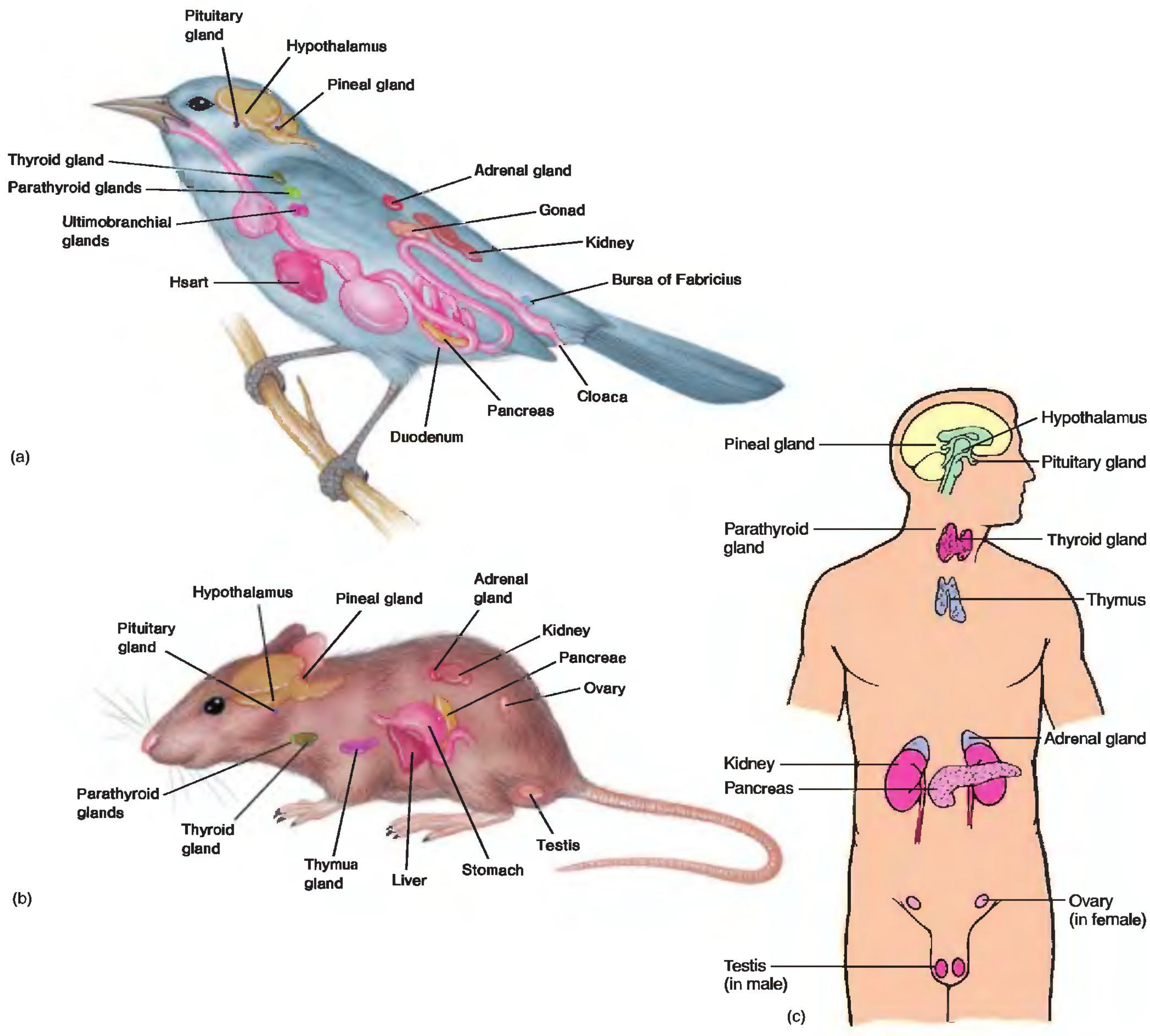

FIGURE 25.12

Endocrine Glands of Birds and Mammals. Locations of the major endocrine glands of *(a)* a bird, *(b)* a rat, and *(c)* a human.

The ultimobranchial glands are small, paired structures in the neck just below the parathyroid glands. They secrete the hormone **calcitonin,** which is involved in regulating blood calcium concentrations.

The **bursa of Fabricius** is a sac that lies just dorsal to the cloaca and empties into it. Although well developed during the bird's embryological development, it begins to shrink soon after hatching. Its tissues produce secretions that are responsible for the maturation of white blood cells (B lymphocytes), which play an important role in immunological reactions.

MAMMALS

Zoologists know more about the endocrine organs, hormones, and target tissues of mammals than of any other animal group. This is

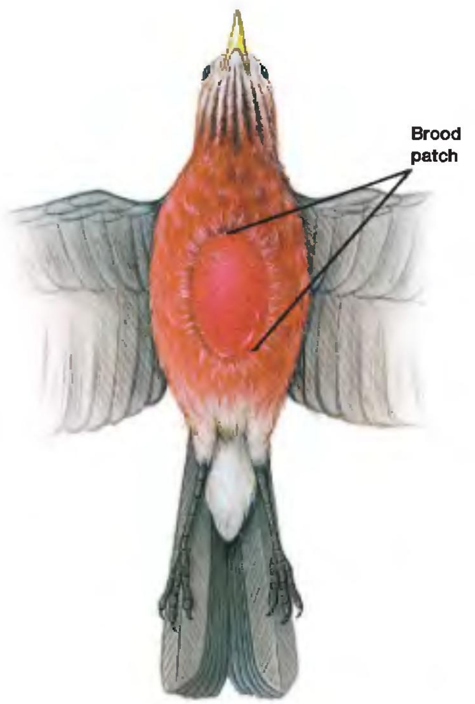

FIGURE 25.13

A Bird's Brood Patch. In this example, a robin's single brood patch appears (due to the effect of the hormone prolactin) a few days before eggs are laid. Prolactin causes the down feathers to drop from the abdomen of the incubating robin, and the bare patch becomes swollen and richly supplied with blood vessels. After laying the eggs, the robin settles on its nest and brings this warm patch in contact with its eggs, thereby transferring heat to the developing embryos.

especially true for the human body. A brief overview of mammalian endocrinology follows.

Pituitary Gland (Hypophysis)

The pituitary gland (also known as the hypophysis) is directly below the hypothalamus (*see figure 25.12c*). The pituitary has two distinct lobes: the anterior lobe (adenohypophysis) and the posterior lobe (neurohypophysis) (figure 25.14). The two lobes differ in several ways: (1) the adenohypophysis is larger than the neurohypophysis; (2) secretory cells called pituicytes are in the adenohypophysis, but not in the neurohypophysis; and (3) the neurohypophysis has a greater supply of nerve endings. Pituicytes produce and secrete hormones directly from the adenohypophysis, whereas the neurohypophysis obtains its hormones from the neurosecretory cells in the hypothalamus, storing and releasing them when they are needed. These modified hypothalamic nerve cells project their axons down a stalk of nerve cells and blood vessels, called the infundibulum, into the pituitary gland, directly linking the nervous and endocrine systems.

The pituitary of many vertebrates (but not in humans, birds, and cetaceans) also has a functional **intermediate lobe (pars intermedia)** of mostly glandular tissue. Its secretions (e.g., melanophore-stimulating hormone) in response to external stimuli induce changes in the coloration of the body surface of many animals.

Hormones of the Neurohypophysis The neurohypophysis does not manufacture any hormones. Instead, the neurosecretory cells of the hypothalamus synthesize and secrete two hormones, antidiuretic hormone and oxytocin, which move down nerve axons into the neurohypophysis, where they are stored in the axon terminals until released.

Diuretics stimulate urine excretion, whereas antidiuretics decrease urine secretion. When a mammal begins to lose water and becomes dehydrated, antidiuretic hormone (ADH, or vasopressin) is released and increases water absorption in the kidneys so that less urine is secreted. Because less urine is secreted, water is retained. This negative feedback system thus restores water and solute homeostasis.

Oxytocin plays a role in mammalian reproduction by its effect on smooth muscle. It stimulates contraction of the uterus or uteri to aid in the expulsion of the offspring and promotes the ejection of milk from the mammary glands to provide nourishment for the newborn.

Both ADH and oxytocin are thought to have evolved from a similar ancestral chemical messenger that helped control water loss and, indirectly, solute concentrations. For example, the neurohypophysis is notably larger in animals that live in arid parts of the world, where water conservation is crucial. Also, the structure of the two hormones is similar except for a difference in two of the amino acids.

Hormones of the Adenohypophysis The true endocrine portion of the pituitary is the adenohypophysis, which synthesizes six different hormones (figure 25.14). All of these hormones are polypeptides, and all but two are true tropic hormones, hormones whose primary target is another endocrine gland. The two nontropic hormones are growth hormone and prolactin.

Growth hormone (GH), or somatotropin (STH), does not influence a particular target tissue; rather, it affects all parts of the body that are concerned with growth. It directly induces the cell division necessary for growth and protein synthesis in most types of cells by stimulating the uptake of amino acids, RNA synthesis, and ribosome activity.

Prolactin (PRL) has the widest range of actions of the adenohypophyseal hormones. It plays an essential role in many aspects of reproduction. For example, it stimulates reproductive migrations in many mammals, such as elk and caribou. Prolactin also enhances mammary gland development and milk production in female mammals. (Oxytocin stimulates milk ejection from the mammary glands, but not its production.)

Thyrotropin, or thyroid-stimulating hormone (TSH), stimulates the thyroid gland's synthesis and secretion of thyroxine, the main thyroid hormone.

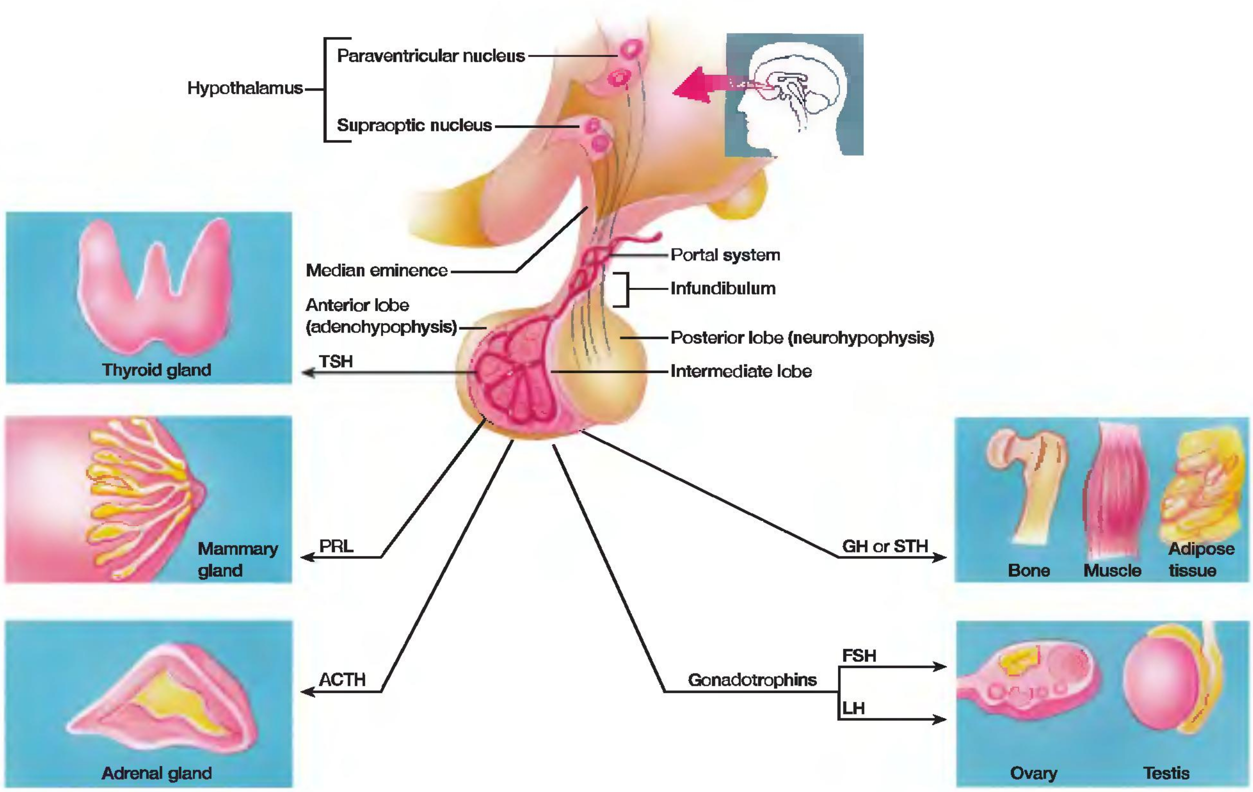

FIGURE 25.14

Functional Links between the Pituitary Gland and the Hypothalamus. Target areas for each hormone are shown in the corresponding box. The blood vessels that make up the hypothalamic-hypophyseal portal system provide the functional link between the hypothalamus and the adenohypophysis, and the axons of the hypothalamic neurosecretory cells provide the link between the hypothalamus and the neurohypophysis. (TSH = thyroid-stimulating hormone; PRL = prolactin; ACTH = adrenocorticotropic hormone; GH = growth hormone; STH = somatotropin; FSH = follicle-stimulating hormone; LH = luteinizing hormone.)

Adrenocorticotropic hormone (ACTH) stimulates the adrenal gland to produce and secrete steroid hormones called glucocorticoids (cortisol). Secretion of ACTH is regulated by the secretion of corticotropin-releasing factor from the hypothalamus, which, in turn, is regulated by a feedback system that involves such factors as stress, insulin, ADH, and other hormones.

The adenohypophysis produces two gonadotropins (hormones that stimulate the gonads): luteinizing hormone and follicle-stimulating hormone. Luteinizing hormone (LH) receives its name from the corpus luteum, a temporary endocrine tissue in the ovaries that secretes the female sex hormones estrogen and progesterone. In the female, an increase of LH in the blood stimulates ovulation, the release of a mature egg(s) from an ovary. In the male, the target cells of LH are cells in the testes that secrete the male hormone testosterone. In the female, follicle-stimulating hormone (FSH) stimulates the follicular cells in the ovaries to develop into mature eggs and to produce estrogen. In the male, FSH stimulates the cells of the testes to produce sperm.

The pineal gland (or pineal body) is so named because it is shaped like a pine cone. Its distinctive cells evolved from the photoreceptors of lower vertebrates; they synthesize melatonin, and are most active in the dark. Light inhibits the enzymes needed for melatonin synthesis. Because of its cyclical production, melatonin can affect many physiological processes and adjust them to diurnal and seasonal cycles. *The use of melatonin by mammals is an evolutionary adaptation to help ensure that periodic activities of mammals occur at a time of the year when environmental conditions are optimal for those activities.* In humans, decreased melatonin secretion may help trigger the onset of puberty, the age at which reproductive structures start to mature.

Thyroid Gland

The **thyroid gland** is in the neck, anterior to the trachea (*see figure 25.12*). Two of its secretions are thyroxine and triiodothyronine, both of which influence overall growth, development, and

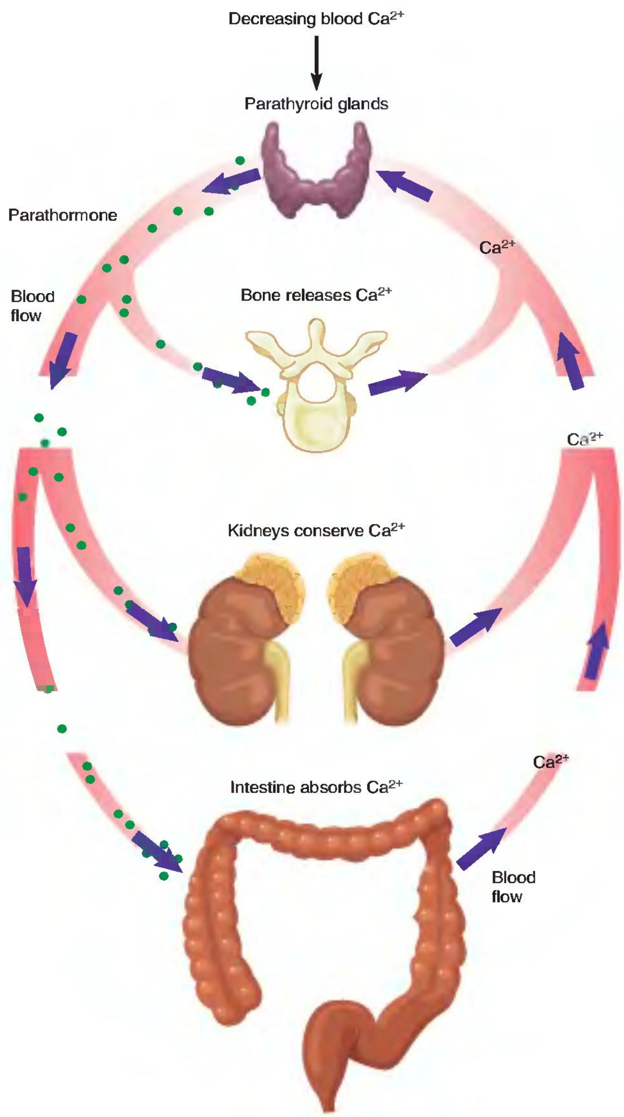

FIGURE 25.15

Hormonal Feedback. The negative feedback mechanism of the parathyroid glands (parathormone). Parathormone stimulates bones to release calcium and the kidneys to conserve calcium. It indirectly stimulates the intestine to absorb calcium. The result increases blood calcium, which then inhibits parathormone secretion.

metabolic rates. Another thyroid hormone, calcitonin, helps control extracellular levels of calcium ions (Ca^{2+}) by promoting the deposition of these ions into bone tissue when their concentrations rise. Once calcium returns to its homeostatic concentration, thyroid cells decrease their secretion of calcitonin.

Parathyroid Glands

The **parathyroid glands** are tiny, pea-sized glands embedded in the thyroid lobes, usually two glands in each lobe (*see figure 25.12*). The parathyroids secrete parathormone (PTH), which regulates the concentrations of calcium (Ca^{2+}) and phosphate (HPO_2^{-4}) ions in the blood.

When the calcium concentration in the blood bathing the parathyroid glands is low, PTH secretion increases and has the following effects: It stimulates bone cells to break down bone tissue and release calcium ions into the blood. It also enhances calcium absorption from the small intestine into the blood. Finally, PTH promotes calcium reabsorption by the kidney tubules to decrease the amount of calcium excreted in the urine. Figure 25.15 shows the negative feedback system for parathormone.

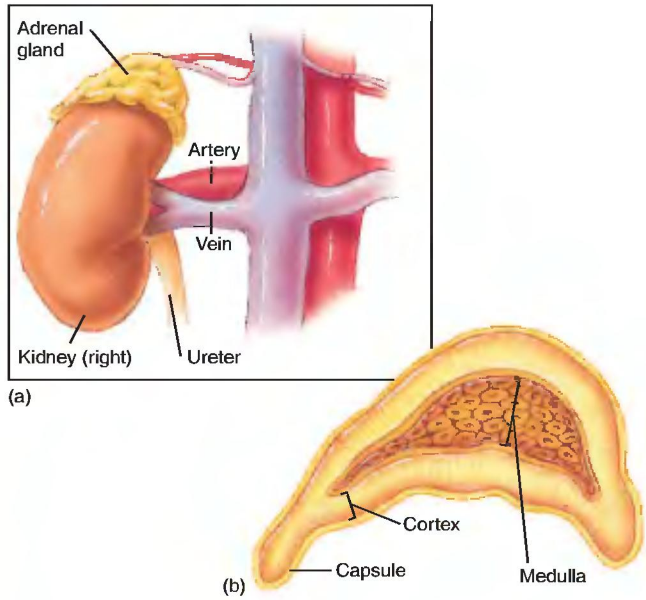

FIGURE 25.16

Adrenal Gland of a Mammal. *(a)* An adrenal gland sits on top of each kidney. *(b)* Each gland contains two structurally, functionally, and developmentally distinct regions. The outer cortex is endocrine and produces glucocorticoids (cortisol), mineralocorticoids (aldosterone), and androgens (sex hormones). The inner medulla is nervous tissue that produces epinephrine (adrenaline) and norepinephrine (noradrenaline).

Adrenal Glands

In mammals, two adrenal glands rest on top of the kidneys. Each gland consists of two separate glandular tissues. The inner portion is the medulla, and the outer portion, which surrounds the medulla, is the cortex (figure 25.16).

Adrenal Cortex The adrenal cortex secretes three classes of steroid hormones: glucocorticoids (cortisol), mineralocorticoids (aldosterone), and sex hormones (androgens, estrogens). The glucocorticoids, such as **cortisol,** help regulate overall metabolism and the concentration of blood sugar. They also function in defense responses to infection or tissue injury. Aldosterone helps maintain concentrations of solutes (such as sodium) in the extracellular fluid when either food intake or metabolic activity

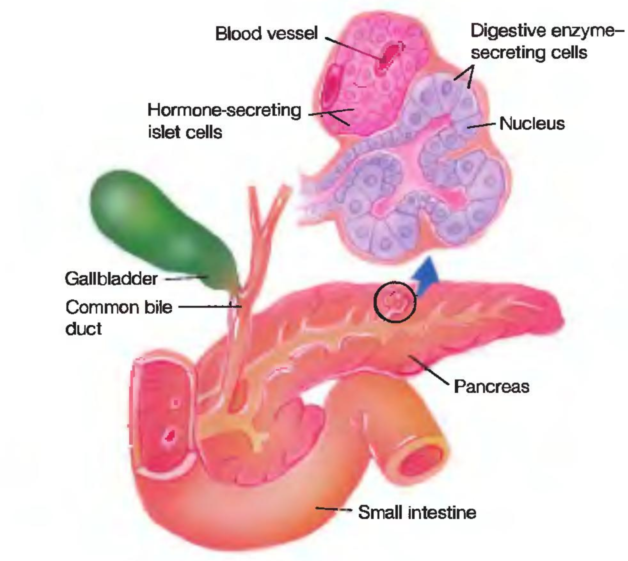

FIGURE 25.17

Pancreas. The hormone-secreting cells of the pancreas are arranged in clusters or islets closely associated with blood vessels. Other pancreatic cells secrete digestive enzymes into ducts.

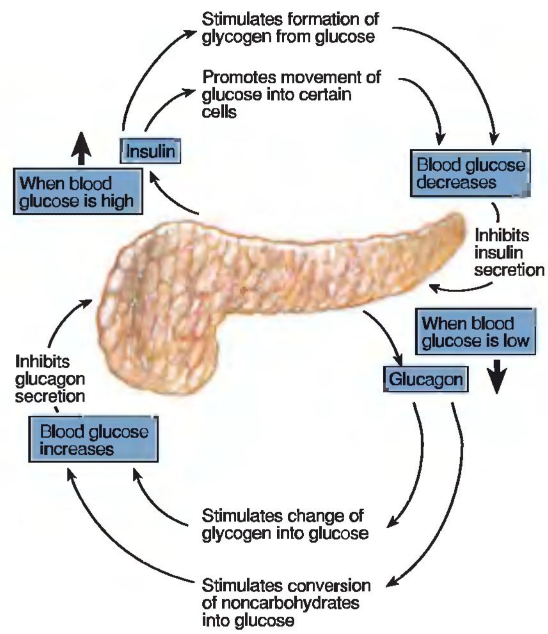

FIGURE 25.18

Two Pancreatic Hormones (Insulin and Glucagon) Regulate the Concentration of Blood Glucose. The negative feedback mechanism for regulating glucagon and insulin secretion helps maintain a relatively stable blood glucose concentration.

changes the amount of solutes entering the bloodstream. Aldosterone also promotes sodium reabsorption in the kidneys and, thus, water reabsorption; hence, it plays a major role in maintaining the homeostasis of extracellular fluid. Normally, the sex hormones that the adrenal cortex secretes have only a slight effect on male and female gonads. These sex hormones consist mainly of weak male hormones called androgens and lesser amounts of female hormones called estrogens.

Adrenal Medulla The adrenal medulla is under neural control. It contains neurosecretory cells that secrete epinephrine (adrenaline) and norepinephrine (noradrenaline), both of which help control heart rate and carbohydrate metabolism. Brain centers and the hypothalamus govern the secretions via sympathetic nerves.

During times of excitement, emergency, or stress, the adrenal medulla contributes to the overall mobilization of the body through the sympathetic nervous system. In response to epinephrine and norepinephrine, the heart rate increases, blood flow increases to many vital organs, the airways in the lungs dilate, and more oxygen is delivered to all cells of the body. This group of events is sometimes called the "fight-or-flight" response and permits the body to react strongly and quickly to emergencies.

Pancreas

The **pancreas** is an elongated, fleshy organ posterior to the stomach (figure 25.17). It functions both as an exocrine (with ducts) gland to secrete digestive enzymes and as an endocrine (ductless) gland. The endocrine portion of the pancreas makes up only about 1% of the gland. This portion synthesizes, stores, and secretes hormones from clusters of cells called pancreatic islets.

The pancreas contains 200,000 to 2,000,000 **pancreatic islets** scattered throughout the gland. Each islet contains four special groups of cells, called alpha (α), beta (β), delta (δ), and F cells. The alpha cells produce the hormone glucagon, and beta cells produce insulin. The delta cells secrete somatostatin, the hypothalamic growth-hormone inhibiting factor that also inhibits glucagon and insulin secretion. F cells secrete a pancreatic polypeptide that is released into the bloodstream after a meal and inhibits somatostatin secretion, gallbladder contraction, and the secretion of pancreatic digestive enzymes.

When glucose concentrations in the blood are high, such as after a meal, beta cells secrete insulin. Insulin promotes the uptake of glucose by the body's cells, including liver cells, where excess glucose can be converted to glycogen (a storage polysaccharide). Insulin and glucagon are crucial to the regulation blood glucose concentrations. When the blood glucose concentration is low, alpha cells secrete glucagon. Glucagon stimulates the breakdown of glycogen into glucose units, which are released into the bloodstream to raise the blood glucose concentration to the homeostatic level. Figure 25.18 illustrates the negative feedback system that regulates the secretion of glucogon and insulin and the maintenance of appropriate blood glucose concentrations.

TABLE 25.2
SOME OTHER MAJOR SOURCES OF VERTEBRATE HORMONES

GLAND/ORGAN	HORMONE	FUNCTION	TARGET AREA
Placenta	Estrogens, progesterone, human chorionic gonadotropin (hCG), human chorionic somatomammotropin (hCS)	Maintain pregnancy	Ovaries, mammary glands, uterus
Digestive tract	Secretin	Stimulates release of pancreatic juice to neutralize stomach acid	Cells of pancreas
	Gastrin	Stimulates digestive enzymes and HCl in stomach	Stomach mucosa
	Cholecystokinin (CCK)	Stimulates release of pancreatic enzymes and bile from gallbladder	Pancreas, gallbladder
Heart	Atriopeptin	Lowers blood pressure, maintains fluid balance	Blood vessels, kidneys
Kidneys	Erythropoietin	Stimulates red blood cell production	Bone marrow
	Urotensin	Stimulates constriction of arteries	Major arteries
	Calcitrol	Aids in the absorption of dietary calcium and phosphorus	Small intestine
Adipose tissue	Leptin	Suppresses appetite	Brain

Gonads

The **gonads** (ovaries and testes) secrete hormones that help regulate reproductive functions. In the male, the testes secrete testosterone, which acts with luteinizing and follicle-stimulating hormones that the adenohypophysis produces to stimulate spermatogenesis. Testosterone is also necessary for the growth and maintenance of the male sex organs, promotes the development and maintenance of sexual behavior, and in humans, stimulates the growth of facial and pubic hair, as well as enlargement of the larynx, which deepens the voice. The testes also produce inhibin, which inhibits the secretion of FSH.

Four major classes of ovarian hormones help to regulate female reproductive functions. Estrogens (estrin, estrone, and estradiol) help regulate the menstrual and estrus cycles and the development of the mammary glands and other female secondary sexual characteristics. The progestins (primarily progesterone) also regulate the menstrual and estrus cycles, and the development of the mammary glands, and aid in placenta formation during pregnancy. Relaxin, which is produced in small quantities, softens the opening of the uterus (cervix) at the time of delivery. The ovaries also produce inhibin, which inhibits the secretion of FSH.

Thymus

The **thymus gland** is near the heart *(see figure 25.12)*. It is large and conspicuous in young birds and mammals, but diminishes in size throughout adulthood. The major hormonal product of the thymus is a family of peptide hormones, including thymopoietin (TP) and alpha_1 and beta_4 thymosin, that appear to be essential for the normal development of the immune system.

Other Sources of Hormones

In addition to the major endocrine glands, other glands and organs carry on hormonal activity. Table 25.2 summarizes some of these.

SUMMARY

1. For metabolic activity to proceed smoothly in an animal, the chemical environment of each cell must be maintained within fairly narrow limits (homeostasis). This is accomplished using negative feedback systems that involve integrating, communicating, and coordinating molecules called messengers.
2. Specialized cells secrete chemical messenger molecules. These chemical messengers can be categorized as local chemical messengers (lumones), neurotransmitters (e.g., acetylcholine), neuropeptides, hormones, and pheromones (e.g., sex attractants).
3. A hormone is a specialized chemical messenger that an endocrine gland or tissue produces and secretes. Hormones are usually