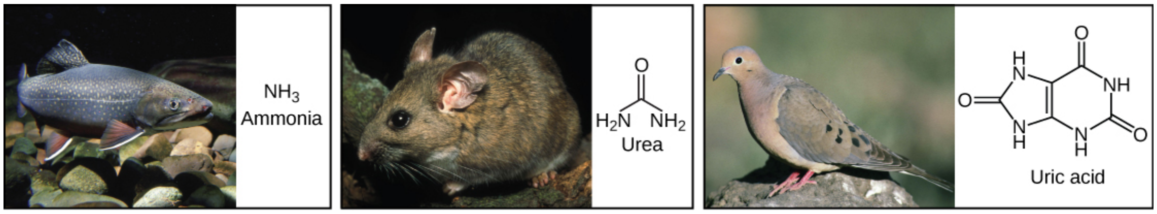
Nitrogenous Waste in Birds and Reptiles: Uric Acid

Birds, reptiles, and most terrestrial arthropods convert toxic ammonia to **uric acid** or the closely related compound guanine (guano) instead of urea. Mammals also form some uric acid during breakdown of nucleic acids. Uric acid is a compound similar to purines found in nucleic acids. It is water insoluble and tends to form a white paste or powder; it is excreted by birds, insects, and reptiles. Conversion of ammonia to uric acid requires more energy and is much more complex than conversion of ammonia to urea Figure 41.13.



(a) Many invertebrates and aquatic species excrete ammonia.

(b) Mammals, many adult amphibians, and some marine species excrete urea.

(c) Insects, land snails, birds, and many reptiles excrete uric acid.

Figure 41.13 Nitrogenous waste is excreted in different forms by different species. These include (a) ammonia, (b) urea, and (c) uric acid. (credit a: modification of work by Eric Engbretson, USFWS; credit b: modification of work by B. "Moose" Peterson, USFWS; credit c: modification of work by Dave Menke, USFWS)

Everyday Connection

Gout

Mammals use uric acid crystals as an **antioxidant** in their cells. However, too much uric acid tends to form kidney stones and may also cause a painful condition called gout, where uric acid crystals accumulate in the joints, as illustrated in Figure 41.14. Food choices that reduce the amount of nitrogenous bases in the diet help reduce the risk of gout. For example, tea, coffee, and chocolate have purine-like compounds, called xanthines, and should be avoided by people with gout and kidney stones.

Figure 41.14 Gout causes the inflammation visible in this person's left big toe joint. (credit: "Gonzosft"/Wikimedia Commons)

41.5 Hormonal Control of Osmoregulatory Functions

By the end of this section, you will be able to do the following:

- Explain how hormonal cues help the kidneys synchronize the osmotic needs of the body
- Describe how hormones like epinephrine, norepinephrine, renin-angiotensin, aldosterone, anti-diuretic hormone, and atrial natriuretic peptide help regulate waste elimination, maintain correct osmolarity, and perform other osmoregulatory functions

While the kidneys operate to maintain osmotic balance and blood pressure in the body, they also act in concert with hormones.

Hormones are small molecules that act as messengers within the body. Hormones are typically secreted from one cell and travel in the bloodstream to affect a target cell in another portion of the body. Different regions of the nephron bear specialized cells that have receptors to respond to chemical messengers and hormones. Table 41.1 summarizes the hormones that control the osmoregulatory functions.

Hormones That Affect Osmoregulation

Hormone	Where produced	Function
Epinephrine and Norepinephrine	Adrenal medulla	Can decrease kidney function temporarily by vasoconstriction
Renin	Kidney nephrons	Increases blood pressure by acting on angiotensinogen
Angiotensin	Liver	Angiotensin II affects multiple processes and increases blood pressure
Aldosterone	Adrenal cortex	Prevents loss of sodium and water
Anti-diuretic hormone (vasopressin)	Hypothalamus (stored in the posterior pituitary)	Prevents water loss
Atrial natriuretic peptide	Heart atrium	Decreases blood pressure by acting as a vasodilator and increasing glomerular filtration rate; decreases sodium reabsorption in kidneys

Table 41.1

Epinephrine and Norepinephrine

Epinephrine and norepinephrine are released by the adrenal medulla and nervous system respectively. They are the flight/fight hormones that are released when the body is under extreme stress. During stress, much of the body's energy is used to combat imminent danger. Kidney function is halted temporarily by epinephrine and norepinephrine. These hormones function by acting directly on the smooth muscles of blood vessels to constrict them. Once the afferent arterioles are constricted, blood flow into the nephrons stops. These hormones go one step further and trigger the **renin-angiotensin-aldosterone** system.

Renin-Angiotensin-Aldosterone

The renin-angiotensin-aldosterone system, illustrated in Figure 41.15 proceeds through several steps to produce **angiotensin II**, which acts to stabilize blood pressure and volume. Renin (secreted by a part of the juxtaglomerular complex) is produced by the granular cells of the afferent and efferent arterioles. Thus, the kidneys control blood pressure and volume directly. Renin acts on angiotensinogen, which is made in the liver and converts it to **angiotensin I**. **Angiotensin converting enzyme (ACE)** converts angiotensin I to angiotensin II. Angiotensin II raises blood pressure by constricting blood vessels. It also triggers the release of the mineralocorticoid aldosterone from the adrenal cortex, which in turn stimulates the renal tubules to reabsorb more sodium. Angiotensin II also triggers the release of **anti-diuretic hormone (ADH)** from the hypothalamus, leading to water retention in the kidneys. It acts directly on the nephrons and decreases glomerular filtration rate. Medically, blood pressure can be controlled by drugs that inhibit ACE (called ACE inhibitors).

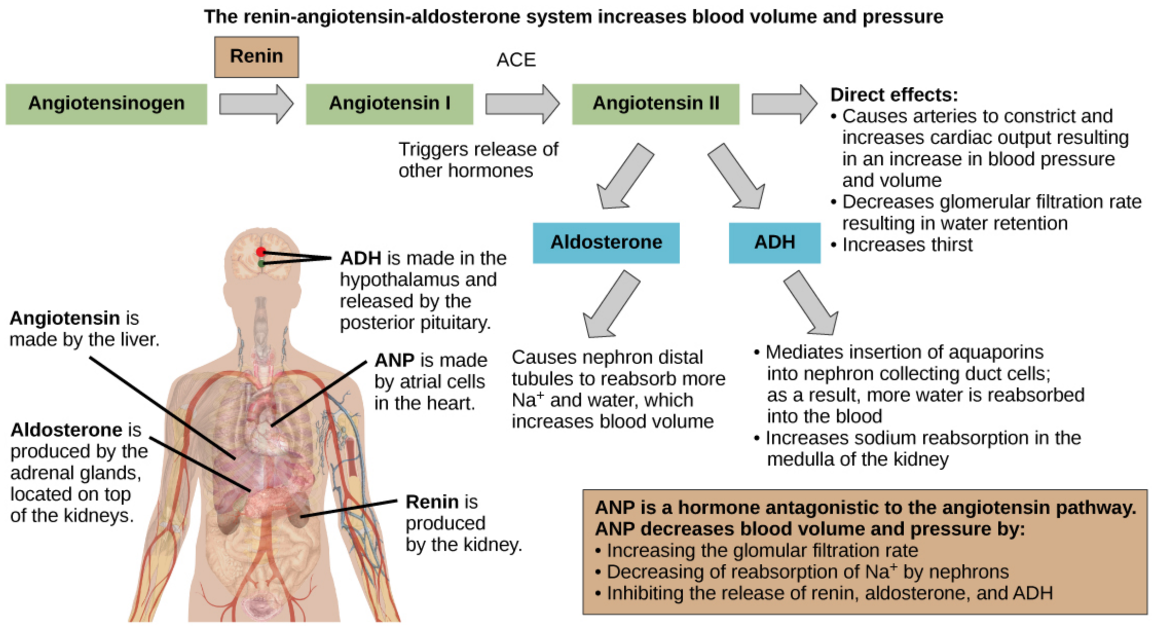


Figure 41.15 The renin-angiotensin-aldosterone system increases blood pressure and volume. The hormone ANP has antagonistic effects. (credit: modification of work by Mikael Häggström)

Mineralocorticoids

Mineralocorticoids are hormones synthesized by the adrenal cortex that affect osmotic balance. Aldosterone is a mineralocorticoid that regulates sodium levels in the blood. Almost all of the sodium in the blood is reclaimed by the renal tubules under the influence of aldosterone. Because sodium is always reabsorbed by active transport and water follows sodium to maintain osmotic balance, aldosterone manages not only sodium levels but also the water levels in body fluids. In contrast, the aldosterone also stimulates potassium secretion concurrently with sodium reabsorption. In contrast, absence of aldosterone means that no sodium gets reabsorbed in the renal tubules and all of it gets excreted in the urine. In addition, the daily dietary potassium load is not secreted and the retention of K^+ can cause a dangerous increase in plasma K^+ concentration. Patients who have Addison's disease have a failing adrenal cortex and cannot produce aldosterone. They lose sodium in their urine constantly, and if the supply is not replenished, the consequences can be fatal.

Antidiuretic Hormone

As previously discussed, antidiuretic hormone or ADH (also called **vasopressin**), as the name suggests, helps the body conserve water when body fluid volume, especially that of blood, is low. It is formed by the hypothalamus and is stored and released from the posterior pituitary. It acts by inserting aquaporins in the collecting ducts and promotes reabsorption of water. ADH also acts as a vasoconstrictor and increases blood pressure during hemorrhaging.

Atrial Natriuretic Peptide Hormone

The atrial natriuretic peptide (ANP) lowers blood pressure by acting as a **vasodilator**. It is released by cells in the atrium of the heart in response to high blood pressure and in patients with sleep apnea. ANP affects salt release, and because water passively follows salt to maintain osmotic balance, it also has a diuretic effect. ANP also prevents sodium reabsorption by the renal tubules, decreasing water reabsorption (thus acting as a diuretic) and lowering blood pressure. Its actions suppress the actions of aldosterone, ADH, and renin.

KEY TERMS

afferent arteriole arteriole that branches from the cortical radiate artery and enters the glomerulus
ammonia compound made of one nitrogen atom and three hydrogen atoms
ammonotelic describes an animal that excretes ammonia as the primary waste material
angiotensin converting enzyme (ACE) enzyme that converts angiotensin I to angiotensin II
angiotensin I product in the renin-angiotensin-aldosterone pathway
angiotensin II molecule that affects different organs to increase blood pressure
anti-diuretic hormone (ADH) hormone that prevents the loss of water
antioxidant agent that prevents cell destruction by reactive oxygen species
arcuate artery artery that branches from the interlobar artery and arches over the base of the renal pyramids
ascending limb part of the loop of Henle that ascends from the renal medulla to the renal cortex
blood urea nitrogen (BUN) estimate of urea in the blood and an indicator of kidney function
Bowman's capsule structure that encloses the glomerulus
calyx structure that connects the renal pelvis to the renal medulla
cortex (animal) outer layer of an organ like the kidney or adrenal gland
cortical nephron nephron that lies in the renal cortex
cortical radiate artery artery that radiates from the arcuate arteries into the renal cortex
countercurrent exchanger peritubular capillary network that allows exchange of solutes and water from the renal tubules
countercurrent multiplier osmotic gradient in the renal medulla that is responsible for concentration of urine
descending limb part of the loop of Henle that descends from the renal cortex into the renal medulla
distal convoluted tubule (DCT) part of the renal tubule that is the most distant from the glomerulus
efferent arteriole arteriole that exits from the glomerulus
electrolyte solute that breaks down into ions when dissolved in water
flame cell (also, protonephridia) excretory cell found in flatworms
glomerular filtration filtration of blood in the glomerular capillary network into the glomerulus
glomerular filtration rate (GFR) amount of filtrate formed by the glomerulus per minute
glomerulus (renal) part of the renal corpuscle that contains the capillary network
hilum region in the renal pelvis where blood vessels, nerves, and ureters bunch before entering or exiting the kidney
inferior vena cava one of the main veins in the human body
interlobar artery artery that branches from the segmental artery and travels in between the renal lobes
juxtaglomerular cell cell in the afferent and efferent arterioles that responds to stimuli from the macula densa
juxtamedullary nephron nephron that lies in the cortex but close to the renal medulla
kidney organ that performs excretory and osmoregulatory functions
lobes of the kidney renal pyramid along with the adjoining cortical region
loop of Henle part of the renal tubule that loops into the renal medulla
macula densa group of cells that senses changes in sodium ion concentration; present in parts of the renal tubule and collecting ducts
Malpighian tubule excretory tubules found in arthropods
medulla middle layer of an organ like the kidney or adrenal gland
microvilli cellular processes that increase the surface area of cells
molality number of moles of solute per kilogram of solvent
molarity number of moles of solute per liter of solution
mole gram equivalent of the molecular weight of a substance
nephridia excretory structures found in annelids
nephridiopore pore found at the end of nephridia
nephron functional unit of the kidney
non-electrolyte solute that does not break down into ions when dissolved in water
osmoconformer organism that changes its tonicity based on its environment
osmoregulation mechanism by which water and solute concentrations are maintained at desired levels
osmoregulator organism that maintains its tonicity irrespective of its environment
osmotic balance balance of the amount of water and salt input and output to and from a biological system without disturbing the desired osmotic pressure and solute concentration in every compartment
osmotic pressure pressure exerted on a membrane to equalize solute concentration on either side
perirenal fat capsule fat layer that suspends the kidneys
peritubular capillary network capillary network that surrounds the renal tubule after the efferent artery exits the glomerulus
proximal convoluted tubule (PCT) part of the renal tubule that lies close to the glomerulus
renal artery branch of the artery that enters the kidney
renal capsule layer that encapsulates the kidneys
renal column area of the kidney through which the

interlobar arteries travel in the process of supplying blood to the renal lobes

renal corpuscle glomerulus and the Bowman's capsule together

renal fascia connective tissue that supports the kidneys

renal pelvis region in the kidney where the calyces join the ureters

renal pyramid conical structure in the renal medulla

renal tubule tubule of the nephron that arises from the glomerulus

renal vein branch of a vein that exits the kidney and joins the inferior vena cava

renin-angiotensin-aldosterone biochemical pathway that activates angiotensin II, which increases blood pressure

segmental artery artery that branches from the renal artery

semi-permeable membrane membrane that allows only certain solutes to pass through

transport maximum maximum amount of solute that can be transported out of the renal tubules during reabsorption

tubular reabsorption reclamation of water and solutes that got filtered out in the glomerulus

tubular secretion process of secretion of wastes that do not get reabsorbed

urea cycle pathway by which ammonia is converted to urea

ureotelic describes animals that secrete urea as the primary nitrogenous waste material

ureter urine-bearing tube coming out of the kidney; carries urine to the bladder

uric acid byproduct of ammonia metabolism in birds, insects, and reptiles

urinary bladder structure that the ureters empty the urine into; stores urine

urine filtrate produced by kidneys that gets excreted out of the body

vasa recta peritubular network that surrounds the loop of Henle of the juxtamedullary nephrons

vasodilator compound that increases the diameter of blood vessels

vasopressin another name for anti-diuretic hormone

CHAPTER SUMMARY

41.1 Osmoregulation and Osmotic Balance

Solute concentrations across semi-permeable membranes influence the movement of water and solutes across the membrane. It is the number of solute molecules and not the molecular size that is important in osmosis. Osmoregulation and osmotic balance are important bodily functions, resulting in water and salt balance. Not all solutes can pass through a semi-permeable membrane. Osmosis is the movement of water across the membrane. Osmosis occurs to equalize the number of solute molecules across a semi-permeable membrane by the movement of water to the side of higher solute concentration. Facilitated diffusion utilizes protein channels to move solute molecules from areas of higher to lower concentration while active transport mechanisms are required to move solutes against concentration gradients. Osmolarity is measured in units of milliequivalents or milliosmoles, both of which take into consideration the number of solute particles and the charge on them. Fish that live in freshwater or saltwater adapt by being osmoregulators or osmoconformers.

41.2 The Kidneys and Osmoregulatory Organs

The kidneys are the main osmoregulatory organs in mammalian systems; they function to filter blood and maintain the osmolarity of body fluids at 300 mOsm. They are surrounded by three layers and are made up internally of three distinct regions—the cortex, medulla, and pelvis.

The blood vessels that transport blood into and out of the kidneys arise from and merge with the aorta and inferior vena cava, respectively. The renal arteries branch out from the aorta and enter the kidney where they further divide into segmental, interlobar, arcuate, and cortical radiate arteries.

The nephron is the functional unit of the kidney, which actively filters blood and generates urine. The nephron is made up of the renal corpuscle and renal tubule. Cortical nephrons are found in the renal cortex, while juxtamedullary nephrons are found in the renal cortex close to the renal medulla. The nephron filters and exchanges water and solutes with two sets of blood vessels and the tissue fluid in the kidneys.

There are three steps in the formation of urine: glomerular filtration, which occurs in the glomerulus; tubular reabsorption, which occurs in the renal tubules; and tubular secretion, which also occurs in the renal tubules.

41.3 Excretion Systems

Many systems have evolved for excreting wastes that are simpler than the kidney and urinary systems of vertebrate animals. The simplest system is that of contractile vacuoles present in microorganisms. Flame cells and nephridia in worms perform excretory functions and maintain osmotic balance. Some insects have evolved Malpighian tubules to excrete wastes and maintain osmotic balance.

41.4 Nitrogenous Wastes

Ammonia is the waste produced by metabolism of nitrogencontaining compounds like proteins and nucleic acids. While aquatic animals can easily excrete ammonia into their watery surroundings, terrestrial animals have evolved special mechanisms to eliminate the toxic ammonia from their systems. Urea is the major byproduct of ammonia metabolism in vertebrate animals. Uric acid is the major byproduct of ammonia metabolism in birds, terrestrial arthropods, and reptiles.

41.5 Hormonal Control of Osmoregulatory Functions

Hormonal cues help the kidneys synchronize the osmotic needs of the body. Hormones like epinephrine, norepinephrine, renin-angiotensin, aldosterone, anti-diuretic hormone, and atrial natriuretic peptide help regulate the needs of the body as well as the communication between the different organ systems.

VISUAL CONNECTION QUESTIONS

1. Figure 41.5 Which of the following statements about the kidney is false?
   a. The renal pelvis drains into the ureter.
   b. The renal pyramids are in the medulla.
   c. The cortex covers the capsule.
   d. Nephrons are in the renal cortex.

2. Figure 41.6 Which of the following statements about the nephron is false?
   a. The collecting duct empties into the distal convoluted tubule.
   b. The Bowman's capsule surrounds the glomerulus.
   c. The loop of Henle is between the proximal and distal convoluted tubules.
   d. The loop of Henle empties into the distal convoluted tubule.

3. Figure 41.8 Loop diuretics are drugs sometimes used to treat hypertension. These drugs inhibit the reabsorption of Na^+ and Cl^- ions by the ascending limb of the loop of Henle. A side effect is that they increase urination. Why do you think this is the case?

REVIEW QUESTIONS

4. When a dehydrated human patient needs to be given fluids intravenously, he or she is given:
   a. water, which is hypotonic with respect to body fluids
   b. saline at a concentration that is isotonic with respect to body fluids
   c. glucose because it is a non-electrolyte
   d. blood

5. The sodium ion is at the highest concentration in:
   a. intracellular fluid
   b. extracellular fluid
   c. blood plasma
   d. none of the above

6. Cells in a hypertonic solution tend to:
   a. shrink due to water loss
   b. swell due to water gain
   c. stay the same size due to water moving into and out of the cell at the same rate
   d. none of the above

7. The macula densa is/are:
   a. present in the renal medulla.
   b. dense tissue present in the outer layer of the kidney.
   c. cells present in the DCT and collecting tubules.
   d. present in blood capillaries.

8. The osmolarity of body fluids is maintained at ________.
   a. 100 mOsm
   b. 300 mOsm
   c. 1000 mOsm
   d. it is not constantly maintained

9. The gland located at the top of the kidney is the ________ gland.
   a. adrenal
   b. pituitary
   c. thyroid
   d. thymus

10. Active transport of K^+ in Malpighian tubules ensures that:
    a. water follows K^+ to make urine
    b. osmotic balance is maintained between waste matter and bodily fluids
    c. both a and b
    d. neither a nor b

11. Contractile vacuoles in microorganisms:
    a. exclusively perform an excretory function
    b. can perform many functions, one of which is excretion of metabolic wastes
    c. originate from the cell membrane
    d. both b and c

12. Flame cells are primitive excretory organs found in ________.
    a. arthropods
    b. annelids
    c. mammals
    d. flatworms

13. BUN is ________.
    a. blood urea nitrogen
    b. blood uric acid nitrogen
    c. an indicator of blood volume
    d. an indicator of blood pressure

14. Human beings accumulate ________ before excreting nitrogenous waste.
    a. nitrogen
    b. ammonia
    c. urea
    d. uric acid

15. Renin is made by ________.
    a. granular cells of the juxtaglomerular apparatus
    b. the kidneys
    c. the nephrons
    d. all of the above

16. Patients with Addison's disease ________.
    a. retain water
    b. retain salts
    c. lose salts and water
    d. have too much aldosterone

17. Which hormone elicits the “fight or flight” response?
    a. epinephrine
    b. mineralcorticoids
    c. anti-diuretic hormone
    d. thyroxine

CRITICAL THINKING QUESTIONS

18. Why is excretion important in order to achieve osmotic balance?
19. Why do electrolyte ions move across membranes by active transport?
20. Why are the loop of Henle and vasa recta important for the formation of concentrated urine?
21. Describe the structure of the kidney.
22. Why might specialized organs have evolved for excretion of wastes?
23. Explain two different excretory systems other than the kidneys.
24. In terms of evolution, why might the urea cycle have evolved in organisms?
25. Compare and contrast the formation of urea and uric acid.
26. Describe how hormones regulate blood pressure, blood volume, and kidney function.
27. How does the renin-angiotensin-aldosterone mechanism function? Why is it controlled by the kidneys?