Chapter 44
Osmoregulation and Excretion

Key Concepts
44.1 Osmoregulation balances the uptake and loss of water and solutes
44.2 An animal's nitrogenous wastes reflect its phylogeny and habitat
44.3 Diverse excretory systems are variations on a tubular theme
44.4 The nephron is organized for stepwise processing of blood filtrate
44.5 Hormonal circuits link kidney function, water balance, and blood pressure

Chapter Review
Animals are able to tolerate the hydration challenges in their external environment by regulating solute and water balance (osmoregulation). Animals must also dispose of nitrogenous (nitrogen-containing) wastes (excretion).

44.1 Osmoregulation balances the uptake and loss of water and solutes

Osmosis and Osmolarity Whatever an animal's habitat or nitrogenous waste product, its water gain must balance water loss.

Osmosis is the diffusion of water across a selectively permeable membrane that separates two solutions differing in osmolarity (moles of solute per liter). Osmolarity is expressed in units of milliosmoles per liter (mosm/L). Isoosmotic solutions are equal in osmolarity, and there is no net osmosis between them. There is a net flow of water from a hypoosmotic (more dilute) to a hyperosmotic (more concentrated) solution.

Osmotic Challenges Osmoconformers are isoosmotic with their surroundings. Osmoregulators regulate their internal osmolarity. Osmoregulators must get rid of excess water if they live in a hypoosmotic medium or take in water to offset osmotic loss if they inhabit a hyperosmotic environment.

Most animals are stenohaline, able to tolerate only small changes in external osmolarity. Animals that are euryhaline can survive large differences in the osmotic environment.
Most marine invertebrates are osmoconformers, whereas marine vertebrates are osmoregulators. Marine bony fishes are hypoosmotic to seawater. They gain salt by diffusion, from food, and from the large quantities of seawater they drink to replace the water they lose by osmosis through their skin and gills. Excess salt is pumped out through the gills and other ions are excreted in the scanty urine.

Sharks have an internal salt concentration lower than that of seawater. Salt tends to diffuse into the body and is excreted by the rectal glands and kidneys. A shark’s osmolarity is slightly higher than that of seawater because it maintains high concentrations of urea in its tissues, as well as trimethylamine oxide (TMAO), which protects proteins from the damaging effects of urea. Water that enters a shark’s body by osmosis or in food is disposed of in urine produced in the kidneys.

Freshwater animals constantly take in water by osmosis and lose salts by diffusion. Freshwater fishes excrete large quantities of dilute urine. Salt supplies are replaced from their food or by active uptake of ions across the gills.

Some animals are capable of anhydrobiosis, surviving dehydration, or desiccation, in a dormant state. Anhydrobiotic roundworms produce large quantities of trehalose, a disaccharide that replaces water around membranes and proteins during dehydration. Many insects survive freezing in the same manner.

Adaptations to prevent dehydration in terrestrial animals include water-impervious coverings and behavioral adaptations such as nocturnal lifestyles. Water is lost in urine and feces and through evaporation, and gained by drinking and eating moist food and by metabolic production during cellular respiration.

**Energetics of Osmoregulation** Osmoregulation is energetically costly because animals must actively transport solutes in order to maintain osmotic gradients needed to gain or lose water. The energy cost is related to the difference in osmolarity between an animal and its environment, and the body fluid composition of many animals is adapted to the salinity of their habitats.

### INTERACTIVE QUESTION 44.1

Indicate whether the following animals are isoosmotic, hyperosmotic, or hypoosmotic to their environment. Then briefly list their mechanisms of osmoregulation.

<table>
<thead>
<tr>
<th>Animal</th>
<th>Osmotic Relation to Environment</th>
<th>Osmoregulatory Mechanisms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Marine invertebrate</td>
<td>a. ISOOSMOTIC</td>
<td>b. conformer, but may regulate some salts</td>
</tr>
<tr>
<td>Shark</td>
<td>c. SLIGHTLY HYPEROSMOTIC</td>
<td>d. maintain Urea at high conc.</td>
</tr>
<tr>
<td>Marine bony fish</td>
<td>e. HYPOOSMOTIC</td>
<td>f. Drink H₂O gills pump out salt in urine</td>
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<tr>
<td>Freshwater fish</td>
<td>g. HYPEROSMOTIC</td>
<td>h. a lot of dilute urine, pump salt thru gills</td>
</tr>
<tr>
<td>Terrestrial animal</td>
<td>i. HYPEROSMOTIC</td>
<td>j. body covers, reduce evaporation, drink and eat moist food</td>
</tr>
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**Transport Epithelia in Osmoregulation** The transport of specific solutes across a transport epithelium is essential for both osmotic regulation and disposing of metabolic wastes. Transport epithelia are usually arranged in tubular networks that provide large surface areas for exchange. Nasal glands in marine birds utilize a countercurrent exchange in removing salt from the blood and producing a concentrated salt secretion.

### 44.2 An animal’s nitrogenous wastes reflect its phylogeny and habitat

**Ammonia**, a small and toxic molecule, is produced when proteins and nucleic acids are metabolized. Some animals excrete ammonia; others expend energy to convert it to less toxic wastes.

**Forms of Nitrogenous Waste** Aquatic animals can excrete nitrogenous wastes as ammonia because it is very soluble and easily permeates membranes. Many invertebrates lose ammonia across their whole body surface. In fishes, most nitrogenous wastes pass as $\text{NH}_4^+$ across the epithelia of the gills.
Mammals, most adult amphibians, sharks, and some marine bony fishes and turtles produce urea, a much less toxic compound than ammonia. Urea can be tolerated in a more concentrated form and excreted with less loss of water. Ammonia and carbon dioxide are combined in the liver to produce urea, which is then carried by the circulatory system to the kidneys. The production of urea requires energy.

Insects, land snails, and many reptiles, including birds, produce uric acid, a compound of low solubility in water that can be excreted as a semisolid with very little water loss. Its synthesis, however, is energetically expensive.

**The Influence of Evolution and Environment on Nitrogenous Wastes** The mode of reproduction seems to have determined which form of nitrogenous waste product evolved in various animal groups.

The form of nitrogenous wastes also relates to habitat. Terrestrial turtles excrete mainly uric acid, whereas aquatic turtles excrete both urea and ammonia. Some animals actually shift their nitrogenous waste product depending on environmental conditions.

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**INTERACTIVE QUESTION 44.2**

a. Which would produce more nitrogenous waste for the same size animal:

- an endotherm or an ectotherm?
- an herbivore or a carnivore?

Explain your answers.

b. Vertebrates that produce shelled eggs excrete [Urea].

Mammals produce [Uric acid].

What adaptive advantage do these types of nitrogenous wastes provide?

- Soluble and less toxic than ammonia, can be removed by mother's blood
- Takes less N to produce urea than uric acid

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**INTERACTIVE QUESTION 44.3**

Indicate whether these tubular systems function in osmoregulation, excretion, or both. If they function in osmoregulation, do they help conserve water or remove excess water that had entered by osmosis?

- Protophrenidia of freshwater planaria **osmoreg.** removes excess \( H_2O \)
- Metanephridia of earthworms **both**
- Malpighian tubules of insects **both**
- Kidneys of terrestrial mammals **both**

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**Survey of Excretory Systems** The protonephridia of flatworms are branched systems of closed tubules. Water and solutes from the interstitial fluid pass into the flame bulbs at the ends of the tubules, propelled by cilia. The processed filtrate, or urine, is excreted into the external environment. The flame-bulb system of freshwater flatworms is primarily osmoregulatory. In parasitic flatworms, however, protonephridia function mainly in excretion of nitrogenous wastes.

Metanephridia are found in most annelids. They occur in pairs in each segment of an earthworm. An open ciliated funnel collects coelomic fluid, which then moves through a folded tubule encased in capillaries. The transport epithelium of the tubule reabsorbs most solutes, which then reenter the blood. Hypoosmotic urine, carrying nitrogenous wastes and excess water absorbed by osmosis, exits to the outside.

Malpighian tubules are excretory organs in insects and other terrestrial arthropods. Transport epithelia lining these blind sacs, which open into the digestive tract, secrete solutes from the hemolymph into the tubule. The fluid passes into the rectum, where most of the solutes are pumped back into the hemolymph, and water follows by osmosis. In this water-conserving system, uric acid is eliminated as dry matter along with the feces.

The numerous excretory tubules of most vertebrates are enclosed in a network of capillaries and arranged into compact kidneys. The kidneys, their associated blood vessels, and the structures that carry urine out of the body comprise the vertebrate excretory system.

**Excretory Processes** During filtration, water and small solutes are forced out of the blood or body fluids across a transport epithelium into an excretory tubule. Two mechanisms transform this filtrate to urine: Valuable solutes are returned from the filtrate in selective reabsorption. In selective secretion, excess salts, toxins, and other solutes are added to the filtrate. The osmotic movement of water into or out of the filtrate follows the pumping of solutes.
**Solute Gradients and Water Conservation**  
The osmolarity gradient of NaCl and urea in the renal medulla is produced by the loops of Henle and collecting ducts and enables the human kidney to produce urine up to four times as concentrated as blood and normal interstitial fluid.

Filtrate leaving Bowman’s capsule has an osmolarity of about 300 mosm/L, the same as blood. Both water and salt are reabsorbed in the proximal tubule; thus, the volume decreases but the osmolarity remains the same. In the trip down the descending limb of the loop of Henle, water exits by osmosis, and the filtrate becomes more concentrated. Salt, which is now in high concentration in the filtrate, diffuses out as the filtrate moves up the salt-permeable but water-impermeable ascending limb—helping to create the osmolarity gradient.

The flow of filtrate in the loop of Henle, along with the energy-consuming active transport of NaCl from the thick segment of the ascending limb, maintains the steep osmotic gradient between the cortex and medulla. This **countercurrent multiplier system** expends energy to create the gradient of the high salt concentration.

The vasa recta also has a countercurrent flow through the loop of Henle. As the blood in these vessels moves down into the inner medulla, water leaves by osmosis and salt enters; as the blood moves back up toward the cortex, water moves back in and salt diffuses out. Thus the capillaries can carry nutrients and other supplies to the medulla without disrupting the osmolarity gradient.
MULTIPLE CHOICE: Choose the one best answer.

1. A unicellular protist may use a contractile vacuole to expel excess water. Contractile vacuoles most likely would be found in protists that are
   a. in a freshwater environment.
   b. in a marine environment.
   c. internal parasites.
   d. hypoosmotic to their environment.
   e. isoosmotic to their environment.

2. Transport epithelia are responsible for
   a. pumping water across a membrane.
   b. forming an impermeable boundary at an interface with the environment.
   c. the movement of solutes for osmoregulation or excretion.
   d. transporting urine in the ureter and urethra.
   e. the passive transport of H\(^{+}\) and HCO\(_3\)\(^{-}\) for the regulation of pH.

3. A freshwater fish would be expected to
   a. pump salt out through salt glands in the gills.
   b. produce copious quantities of dilute urine.
   c. diffuse urea across the epithelium of the gills.
   d. have scales that reduce water loss to the environment.
   e. do all of the above.

4. Which of the following is not part of the filtrate entering Bowman's capsule?
   a. water, salt, and electrolytes
   b. glucose
   c. urea
   d. plasma proteins
   e. amino acids

5. Which is the correct pathway for the passage of urine in vertebrates?
   a. collecting tubule → ureter → bladder → urethra
   b. renal vein → renal ureter → bladder → urethra
   c. nephron → urethra → bladder → ureter
   d. cortex → medulla → bladder → ureter
   e. renal pelvis → medulla → bladder → urethra

6. Aldosterone
   a. is a hormone that stimulates thirst.
   b. is secreted by the adrenal glands in response to a high osmolarity of the blood.
   c. stimulates the active reabsorption of Na\(^{+}\) in the distal tubules.
   d. causes diuresis.
   e. is converted from a blood protein by the action of renin.

7. Which of the following statements is incorrect?
   a. Long loops of Henle are associated with steep osmotic gradients and the production of hypotonic urine.
   b. Ammonia is a toxic nitrogenous waste molecule that passively diffuses out of the bodies of aquatic invertebrates.
   c. Uric acid is the form of nitrogenous waste that requires the least amount of water to excrete.
   d. In the mammalian kidney, urea diffuses out of the collecting duct and contributes to the osmotic gradient within the medulla.
   e. Uric acid is produced by a mammalian fetus and removed through the placenta to the mother's excretory system.

9. The process of reabsorption in the formation of urine ensures that
   a. excess H\(^{+}\) is removed from the blood.
   b. drugs and other poisons are removed from the blood.
   c. urine is always hypotonic to interstitial fluid.
   d. glucose, salts, and water are returned to the blood.
   e. pH is maintained with a balance of hydrogen ions and bicarbonate.

10. The peritubular capillaries
    a. form the ball of capillaries inside Bowman's capsule from which filtrate is forced by blood pressure into the renal tubule.
    b. intertwine with the proximal and distal tubules and exchange solutes with the interstitial fluid.
    c. form a countercurrent flow of blood through the medulla to supply nutrients without interfering with the osmolarity gradient.
    d. surround the collecting ducts and reabsorb water, helping to create a hypotonic urine.
    e. rejoin to form the efferent arteriole.
11. ADH and the RAAS both increase water reabsorption, but they respond to different osmoregulatory problems. Which two of the following statements are true?
   1. ADH will be released in response to high alcohol consumption.
   2. ADH is released when osmoregulatory cells in the hypothalamus sense an increase in blood osmolarity.
   3. The RAAS will increase the osmolarity of urine due to the cooperative action of renin, angiotensin II, and aldosterone.
   4. The RAAS is a response to a rise in blood pressure or volume.
   5. The RAAS is most likely to respond following an accident or severe case of diarrhea.
      a. 1 and 4
      b. 1 and 5
      c. 2 and 3
      d. 2 and 4
      e. 2 and 5

12. Which of the following sections of the mammalian nephron is incorrectly paired with its function?
   a. Bowman’s capsule and glomerulus—filtration of blood
   b. proximal tubule—secretion of ammonia and H⁺ into filtrate and transport of glucose and amino acids out of tubule
   c. descending limb of loop of Henle—diffusion of urea out of filtrate
   d. ascending limb of loop of Henle—diffusion and pumping of NaCl out of filtrate
   e. distal tubule—regulation of pH and K⁺

13. One of the advantages of the production of uric acid by birds is that uric acid
   a. has low toxicity and can be safely stored in the egg.
   b. is very soluble in water and takes very little energy to produce.
   c. contributes to the production of the egg shell and can thus serve two purposes.
   d. takes less energy to produce than urea and is nontoxic.
   e. Both a and d are correct.

14. What is the mechanism for the filtration of blood within the nephron?
   a. the active transport of Na⁺ and glucose, followed by osmosis
   b. both active and passive secretion of ions, toxins, and NH₃ into the tubule
   c. high hydrostatic pressure of blood forcing water and small molecules out of the capillary
   d. the high osmolarity of the medulla that was created by active and passive transport of salt from the tubule and passive diffusion of urea from the collecting duct
   e. a lower osmotic pressure in Bowman’s capsule compared to that in the glomerulus
Activity 44.1 What is nitrogenous waste, and how is it removed from the body?

1. Define excretion, and indicate how it differs from elimination.

   - Getting rid of waste made by cells (metabolic waste)
   - Getting rid of undigested solid waste

2. The removal of nitrogenous wastes (excess nitrogen) is a special problem in most animals.
   a. Where does the nitrogenous waste come from?

      Deamination of amino acids - occurs when excess protein is consumed or when dead or damaged cells and other substances are removed from the body.

      (Metabolism of proteins)

   b. What is it about the chemistry of nitrogen that makes it difficult for most animals to deal with?

      Amine groups easily convert to ammonia ($NH_3$) which is very soluble in $H_2O$. It is toxic! Therefore, large amounts of $H_2O$ must be available to organisms that excrete it. Terrestrial animals have limited $H_2O$ available. Therefore ammonia is converted to a less toxic form, either urea or uric acid.
3. Work through parts a and b, and then use the information you gather there to answer the question in part c.

a. Describe the composition of the newly filtered solution that enters Bowman’s capsule. Then compare it to the composition of the blood entering and leaving the glomerulus.

The solution entering Bowman’s capsule is: H₂O, salt, H₂O soluble meds, drugs, sugar, vitamins, and nitrogenous waste. The concentration of these is similar to the conc. in the blood that enters the glomerulus.

b. Starting with the solution that escapes into Bowman’s capsule from the glomerulus, describe the changes that occur in its composition as it moves through each of these regions:

i. Proximal convoluted tubule
In this region, NaCl and nutrients (for example, sugars) are actively transported out of the filtrate and into the cortex of the kidney. Bicarbonate ions, potassium ions, and water passively diffuse into the cortex. They are picked up by capillaries and returned to the blood. In this same region, excess H⁺ ions are actively transported into the tubule. Ammonia produced by the surrounding cells diffuses passively into the tubule in response to increased H⁺ concentrations and neutralizes the pH of the fluid in the tubule.

ii. Loop of Henle
In the thick segment of the ascending portion of the loop, NaCl is actively transported out of the fluid and into the medulla of the kidney. In the thin (lower) portion of the ascending loop, NaCl diffuses out of the tubule. In the descending portion of the loop, water passively diffuses out of the tubule and into the medulla of the kidney.

iii. Distal convoluted tubule
In this region, NaCl and bicarbonate ions are actively transported out of the tubule. Excess potassium ions and H⁺ ions are actively transported into the tubule. Water leaves by passive diffusion into the cortex of the kidney.

iv. Collecting duct
The cortical and outer medullary regions of the collecting duct are permeable to water but not to NaCl or urea. Excess NaCl is actively transported out of the duct into the medulla. In the lower medullary region, the duct becomes permeable to urea. If the concentration of urea in the duct is high, some passively diffuses out into the medulla. As the collecting duct passes through the high concentration of salt (and urea) in the medulla, the filtrate solution loses water passively and the filtrate becomes very concentrated.

v. Urinary bladder
The collecting ducts empty into the renal pelvis, which leads to the ureter. The fluid in the ureter can be stored in the bladder. Little change occurs in the fluid after it reaches the bladder. During periods of extended dehydration, some of the water may be removed from the bladder by passive diffusion into surrounding tissues.

c. Now explain how the general function of the kidney enables it to “remove” (a better expression would be “let out”) from the body a wide variety of unfamiliar substances (drugs, inorganic molecules, or ions of many kinds) that the body has never encountered before. After answering this, explain why “let out” from the body is a better expression than “remove.”

Let out in the glomerulus. Capillaries there contain a large # of aquaporins and hydrostatic pressure causes H₂O and H₂O soluble substances in blood to move. It’s nonselective. As it moves thru the nephron, cells actively transport needed components back into blood.
4. It is useful to consider the excretory system (along with the digestive and gas-exchange systems) as primarily involved in bulk exchange with the external environment. The excretory system could also be interpreted as a specialized part of the external surface of the organism, which in its own way encloses and modifies part of the environment. Describe how this is true for the human kidney. For example:

a. Where in the kidney does the organism end and the environment begin?

org ends at the glomerulus - route to external env. is unobstructed from Bowman's capsule to urethra

b. Are changes in the glomerular filtrate changes in the organism, changes in the environment, or both?

The filtrate in the tubule is technically in the external env.

c. What do your answers in parts a and b indicate about the possible evolutionary origins of the kidney?

Excretory systems are variations on a tubular theme.
Envacinations of the body surface may cause these tubes cells making up these tubes control what goes in the body and what doesn't

5. a. What is the difference between hydrostatic pressure and osmotic pressure?

pressure exerted by a fluid
on the walls of the container

b. Where in the human excretory system is hydrostatic pressure responsible for moving water across a membrane or layer of cells?

From glomerulus into Bowman's capsule

c. Where in the excretory system is osmotic pressure responsible for such movement?

Descending loop of Henle
Collecting duct.