CHAPTER 38 BODY FLUID REGULATION AND EXCRETION

Chapter Outline

38.1 Body Fluid Regulation

A. Water and Ion Balance
   1. The excretory system regulates body fluid concentrations by regulating the water and ions in body fluids.
   2. The regulation depends on the concentration of mineral ions (i.e., Na^+, Cl^-, K^+, and HCO_3^-).
   3. Body fluids gain mineral ions when animals eat food and drink fluids; the body then loses ions by excretion.
   4. Water enters animals when they eat foods, by metabolism where cellular respiration produces water, and when they drink water.
   5. Water is lost by evaporation from skin and lungs, through feces, and by excretion.
   6. To be in balance, the water entering the body must equal the water lost.
   7. If osmolarity differs between two regions, water moves into the region with the higher amount of solutes.
   8. Marine environments are high in salt and promote the loss of water and the gain of ions by drinking water.
   9. Fresh water promotes a gain of water by osmosis and a loss of ions as this excess water is excreted.
   10. Terrestrial animals tend to lose both water and ions to the environment.

B. Aquatic Animals
   1. Cartilage Fishes and Marine Invertebrates
      a. Sharks and rays are nearly isotonic with seawater.
      b. Yet they do not contain the same amount of salt as seawater.
      c. Their blood has high concentrations of urea to match the tonicity of seawater; for some reason this is not toxic to them.
   2. Marine Bony Fishes
      a. Bony fishes have a moderate salt level compared to seawater, their common ancestor probably evolved in freshwater.
      b. Marine bony fishes constantly drink seawater; they are prone to water loss and could become dehydrated.
      c. Marine bony fishes swallow water equal to 1% of their weight every hour to counteract dehydration.
      d. This provides the marine fish with water but also with excess salt.
      e. To remove excess salt, they actively transport Na^+ and Cl^- ions (salt) at the gills.
   3. Freshwater Bony Fishes
      a. The body fluids of freshwater bony fish are hypertonic to freshwater; they passively gain water.
      b. Freshwater fishes never drink water.
      c. They take in salts at the gills and pass large quantities of dilute, hypotonic urine.
      d. They discharge a quantity of urine equal to one-third their body weight each day.
      e. Because this causes them to lose salts, they actively import Na^+ and Cl^- ions into the blood at the gills.
   4. Some fish can move between marine and freshwater environments.
      a. Salmon begin their life in freshwater streams, mature in ocean and return to freshwater to breed.
      b. Salmon alter their behavior and gill and kidney functions in response to osmotic changes.

C. Terrestrial Animals
   1. Some terrestrial animals near oceans are able to drink seawater despite its high osmolarity.
   2. Such birds and reptiles have a **nasal salt gland** that excretes concentrated salt solution.
   3. Water Loss Prevention
      a. Some animals excrete a rather insoluble nitrogenous waste.
      b. Animal skin is adapted to moist (moist, thin, permeable) or dry (dry, thick, impermeable)

        environments.
    c. Some animals have other unique adaptations to prevent water loss.
    d. The camel and kangaroo rat have convoluted nasal passages that absorb moisture from exhaled air.
4. Most terrestrial animals must drink fresh water often; however, the kangaroo rat completely avoids drinking water.
    a. It forms a very concentrated urine.
    b. It defecates fecal matter that is almost completely dry.
    c. It meets its water requirements with the metabolic water derived from aerobic respiration.

38.2 Nitrogenous Waste Products

A. Eliminating Nitrogenous Wastes
    1. The breakdown of nucleic acids and amino acids results in nitrogenous wastes.
    2. Amino acids derived from protein synthesize body proteins or nitrogen-containing molecules.
    3. Unused amino acids are oxidized to generate energy or are stored as fats or carbohydrates.
    4. In both cases, **amino groups** (—NH_2) must be removed.
    5. Nitrogenous wastes are excreted as ammonia, urea, or uric acid, depending on animal.
    6. The removal of amino groups requires a fairly constant amount of energy that differs for each conversion.

B. Excreting Ammonia
    1. Amino groups removed from amino acids form **ammonia** (NH_3) by adding a third hydrogen ion (H^+).
    2. This requires little or no energy.
    3. Ammonia is quite toxic but it is water soluble; it requires the most water to wash it away from the body.
    4. Bony fishes, aquatic invertebrates, and amphibians excrete this ammonia through gills and the skin surfaces.

C. Excreting Urea
    1. Terrestrial amphibians and mammals usually excrete **urea** as their main nitrogenous waste.
    2. Urea is much less toxic than ammonia; excreted in a moderately concentrated solution, it also conserves body water.
    3. Production of urea requires energy; it is produced in the liver as a product of the energy-requiring **urea cycle**.
    4. In the urea cycle, carrier molecules take up carbon dioxide and two molecules of ammonia, finally releasing urea.

D. Excreting Uric Acid
    1. Insects, reptiles, and birds excrete **uric acid** as their main nitrogenous waste.
    2. Uric acid is not very toxic and is poorly soluble in water; uric acid is readily concentrated for water conservation.
    3. In reptiles and birds, a dilute solution of uric acid passes from the kidneys to the **cloaca,** a common reservoir for products of the digestive, urinary, and reproductive systems.
    4. After any water is absorbed by the cloaca, the uric acid passes out with the feces.
    5. Reptiles and bird embryos are enclosed in eggshells; the uric acid that builds up is nontoxic in storage.
    6. Uric acid is synthesized by enzymatic reactions using even more ATP than urea synthesis.
    7. Therefore, there is a trade-off between water conservation and energy expenditure.

38.3 Organs of Excretion

A. Most animals have tubular organs to regulate salt-water balance and excrete metabolic wastes.

B. Flame Cells in Planarians
    1. Planaria have two strands of branching excretory tubules that open to the outside through excretory pores.
    2. Located along the tubules are **flame cells** containing tufts of cilia that appear to flicker.
    3. The cilia beat back-and-forth propelling a hypotonic fluid through canals emptying at the body surface.
    4. This system functions in excess water excretion, osmotic regulation, and the excretion of wastes.

C. Nephridia in Earthworms
   1. An earthworm's body is divided into segments and nearly every segment has a pair of **nephridia**.
   2. A **nephridium** is a tubule with a ciliated opening, the **nephridiostome**, and an excretory **nephridiopore**.
   3. Fluid from the body cavity is propelled through this tubule by cilia.
   4. Certain substances are reabsorbed and carried away by the network of capillaries surrounding the tubules.
   5. The nephridia form urine that contains only metabolic wastes, salts, and water.
   6. Each day, an earthworm produces urine equal to 60% of its body weight, enough water that it can safely excrete ammonia.

D. Malpighian Tubules in Insects
   1. Insects have a unique excretory system consisting of long, thin Malpighian tubules attached to the gut.
   2. **Malpighian tubules** take up metabolic wastes and water from the hemolymph' these follow the salt gradient established by active transport of K^+ ions.
   3. At the rectum, water and other useful substances are reabsorbed.
   4. Uric acid remains and eventually passes out the anus.
   5. Insects that live in the water or that eat large quantities of moist food reabsorb very little water.
   6. Insects in dry climates reabsorb most of the water and excrete a dry, semisolid mass of uric acid.

38.4 Urinary System in Humans

A. The **human urinary system** is an organ system with four parts.
   1. The human **kidneys** are two bean-shaped, reddish brown organs, each about the size of a fist.
      a. They are to the side of the vertebral column, below the diaphragm, and partly protected by the lower rib cage.
      b. The kidneys are the sites of **urine** formation.
   2. Each kidney is connected to a **ureter**; each conducts urine from a kidney to **urinary bladder**.
   3. **Urinary bladder** stores urine from kidneys until it is voided from body through **urethra**.
   4. A single **urethra** conducts urine from the urinary bladder to exterior of the body.
   5. Male urethra runs through penis and conducts semen; in females, it opens ventral to vaginal opening.

B. Kidneys
   1. If the kidney is sectioned longitudinally, three major regions can be distinguished.
      a. The **renal cortex** is the thin, outer region of a kidney and it appears granular.
      b. The **renal medulla** consists of the striped, pyramid-shaped regions that lie on the inner side of the cortex.
      c. The **renal pelvis** is the innermost hollow chamber of the kidney.
   2. Each human kidney is composed of about one million tiny tubules called **nephrons**.
   3. Some nephrons are located primarily in cortex but others dip down into the medulla.

C. Nephrons
   1. Each nephron is comprised of several parts.
   2. The end of a nephron pushes in to form a cuplike structure called the **glomerular capsule**.
      a. The outer layer is composed of simple squamous epithelium.
      b. The inner layer is made of specialized cells that allow easy passage of molecules.
   3. Nearest the glomerular capsule is the **proximal convoluted tubule** lined by cells with many mitochondria and tightly packed microvilli.
   4. Simple squamous epithelium forms the **loop of the nephron**, the middle portion of the nephron tubule with a descending and ascending limb.
   5. The **distal convoluted tubule** is the distal portion of the nephron tubule; several join to deliver the urine into **collecting ducts**.
   6. The loop of nephron and the collecting duct give pyramids of the medulla their striped appearance.
   7. Each nephron has its own blood supply.
      a. The renal artery branches into smaller arteries, which then branch into **afferent arterioles**, one for each nephron.
      b. Each **afferent arteriole** divides to form a capillary bed or glomerulus.
      c. The glomerular capillaries drain into an **efferent arteriole** which branches into a peritubular network.
      d. The peritubular capillaries drain into a venule; the venules from many nephrons drain into a small vein; small veins join to form the **renal vein**, a vessel that enters the inferior vena cava.

D. Urine Formation
    1. Urine production requires three distinct processes.
    2. **Glomerular filtration** occurs at glomerular capsule.
    3. **Tubular reabsorption** occurs at proximal convoluted tubule.
    4. **Tubular secretion** occurs at distal convoluted tubule.

E. Glomerular Filtration
    1. When blood enters the glomerulus, blood pressure moves small molecules from the glomerulus across the inner membrane of the glomerular capsule into the lumen of the glomerular capsule; this is **pressure filtration**.
    2. The glomerular walls are 100 times more permeable than the walls of most capillaries.
    3. Molecules that leave the blood and enter the glomerular capsules are **glomerular filtrate**.
    4. Plasma proteins and blood cells are too large to be part of the glomerular filtrate.
    5. Failure to restore fluids would soon cause death from loss of water, nutrients, and low blood pressure.

F. Tubular Reabsorption
    1. **Tubular reabsorption** of fluids from the nephron back to the blood occurs through the walls of the proximal convoluted tubule.
    2. Reabsorption recovers much of the glomerular filtrate.
        a. The osmolarity of the blood equals the filtrate so osmosis of water does not occur.
        b. Sodium ions are actively reabsorbed, pulling along chlorine.
        c. This changes the osmolarity of the blood so that water moves passively from the tubule back to the blood.
        d. About 60–70% of salt and water are reabsorbed at the proximal convoluted tubule.
    3. Cells of the proximal convoluted tubule have numerous microvilli increasing surface area for absorption, and numerous mitochondria, which supply the energy needed for active transport.
    4. Only molecules with carrier molecules are reabsorbed.
    5. If there is more glucose, for example, than carriers, excess glucose will appear in the urine.
    6. In diabetes mellitus, there is a too much glucose because the liver fails to store glucose as glycogen.

G. Tubular Secretion
    1. **Tubular secretion** moves substances from the blood to the tubular lumen by other than glomerular filtration.
    2. Secretion back into the filtrate is primarily associated with the distal convoluted tubule.
    3. This helps rid the body of potentially harmful compounds that were not filtered into the glomerular capsule.
    4. Uric acid, hydrogen ions, ammonia, and penicillin are eliminated this way.

H. Maintaining the Water-Salt Balance
    1. The long loop of nephron is comprised of a **descending limb** (going down) and an **ascending limb** (going up).
    2. Salt (NaCl) passively diffuses out of the lower portion of the ascending limb, but the upper, thick portion of the limb actively transports salt out into the tissue of the outer renal medulla.
    3. Less salt is available for transport from the tubule as fluid moves up the thick portion of the ascending limb; the ascending limb is impermeable to water.
    4. Urea leaks from the lower portion of the collecting ducts causing the concentrations in the lower medulla to be highest.
    5. Because of the solute concentration gradient within the renal medulla, water leaves descending limb of loop of nephron along its length.
    6. The decreasing water concentration in the descending limb encounters an increasing solute concentration; this is a countercurrent mechanism.
    7. Fluid received by a collecting duct from the distal convoluted tubule is isotonic to cells of cortex; as this fluid passes through the renal medulla, water diffuses out of the collecting duct into the renal medulla.
    8. The urine finally delivered to the renal pelvis is usually hypertonic to the blood plasma.
    9. **Antidiuretic hormone (ADH)** is released from posterior lobe of pituitary.
        a. ADH acts on the collecting ducts by increasing its permeability to H_2O, thereby increasing H_2O retention.
        b. When ADH is released, more water is reabsorbed and there is less urine.
        c. When ADH is not released, more water is excreted and more urine forms.

d. If an individual does not drink, the pituitary releases ADH; if hydrated, ADH is not released.
e. Diuresis means increased urine; antidiuresis means a decreased amount of urine.

10. Reabsorption of Salt
    a. Usually more than 99% of the sodium filtered out at the glomerulus is returned to the blood.
    b. Most is reabsorbed at the proximal tubule, 25% is extruded by the ascending limb of the loop of nephron and the rest is from the distal convoluted tubule and collecting duct.
11. **Aldosterone** is a hormone secreted by the adrenal cortex.
    a. It acts on the distal convoluted tubules to increase the reabsorption of Na^+ and the excretion of K^+.
    b. Increased Na^+ in the blood causes water to be reabsorbed, increasing blood volume and pressure.
    c. Aldosterone production is triggered by the **renin-angiotensin-aldosterone system**.
    d. Blood pressure is constantly monitored within the **juxtaglomerular apparatus.**
    e. If the blood pressure is insufficient to promote glomerular filtration, the afferent arteriole cells secrete **renin**.
    f. Renin catalyzes the conversion of **angiotensinogen** (a protein produced by liver) into **angiotensin I**.
    g. Later, angiotensin I is converted to **angiotensin II** by **angiotensin-converting enzyme**.
    h. Angiotensin II stimulates cells in the adrenal cortex to produce aldosterone.
    i. Angiotensin II increases the blood pressure as a vasoconstrictor.
12. **Atrial natriuretic hormone (ANH)** is produced by the atria of heart when cardiac cells stretch.
    a. When blood pressure rises, the heart produces ANH to inhibit the secretion of renin and the release of ADH.
    c. Therefore, this hormone decreases blood volume and pressure.

I. Maintaining the Acid-Base Balance
1. The bicarbonate buffer system and breathing work together to maintain blood pH.
2. The excretion of H^+ ions and NH_3, and reabsorption of bicarbonate ions (HCO_3^-) is adjusted.
    a. If the blood is basic, fewer hydrogen ions are excreted and fewer sodium and bicarbonate ions are reabsorbed.

$$H^+ + HCO_3^- \iff H_2CO_3 \iff H_2O + CO_2$$

    b. If the blood is acidic, H^+ ions are excreted with ammonia, while Na^+ and HCO_3^- ions are reabsorbed; Na^+ ions promote formation of hydroxide ions and bicarbonate takes up H^+ ions when carbonic acid is formed.

$$NH_3 + H^+ \rightarrow NH_4^+$$

    c. Ammonia is produced in the tubule cells by deamination of amino acids.
3. Reabsorption or excretion of ions by the kidneys is a homeostatic function that maintains the pH of the blood and osmolarity.