Osmotic Regulation and the Urinary System
Chapter 50
Challenge Questions

• Indicate the areas of the nephron that the following hormones target, and describe when and how the hormones elicit their actions.
  – Antidiuretic hormone
  – Aldosterone
  – Atrial natriuretic hormone
Challenge Questions

• John’s doctor is concerned that John’s kidneys may not be functioning properly due to a circulatory condition. The doctor wants to determine if the blood volume flowing through the kidneys (called renal blood flow rate) is within normal range. Calculate what would be a “normal” renal blood flow rate based on the following information:
  – John weighs 90 kg. Assume a normal total blood volume is 80 mL/kg of body weight, and a normal heart pumps the total blood volume through the heart once per minute (cardiac output). Also assume that the normal renal blood flow rate is 21% of cardiac output.
Osmolarity and Osmotic Balance

• Water in a multicellular body distributed between
  – Intracellular compartment
  – Extracellular compartment

• Most vertebrates maintain homeostasis for
  – Total solute concentration of their extracellular fluids
  – Concentration of specific inorganic ions
Osmolarity and Osmotic Balance

- Important ions
  - Sodium ($\text{Na}^+$) is the major cation in extracellular fluids
  - Chloride ($\text{Cl}^-$) is the major anion
  - Divalent cations, calcium ($\text{Ca}^{2+}$) and magnesium ($\text{Mg}^{2+}$), the monovalent cation $\text{K}^+$, as well as other ions, also have important functions and are maintained at constant levels
Osmotic Pressure

• Osmotic pressure
  – Measure of a solution’s tendency to take in water by osmosis

• Osmolarity
  – Number of osmotically active moles of solute per liter of solution

• Tonicity
  – Measure of a solution’s ability to change the volume of a cell by osmosis
  – Solutions may be hypertonic, hypotonic, or isotonic
Osmolarity and Osmotic Balance

• Terrestrial vertebrates
  – Higher concentration of water than surrounding air
  – Tend to lose water by evaporation from skin and lungs
  – Urinary/osmoregulatory systems have evolved in these vertebrates that help them retain water
Nitrogenous Wastes

• Amino acids and nucleic acids are catabolized into nitrogenous wastes
  – Must be eliminated from the body
  – Ammonia, Urea, and Uric Acid

• First step is deamination
  – Removal of the amino (—NH$_2$) group
  – Combined with H$^+$ to form ammonia (NH$_3$) in the liver
    • Toxic to cells, and thus it is only safe in dilute concentrations
Nitrogenous Wastes

• Mammals also produce uric acid, but from degradation of purines, not amino acids
• Most have an enzyme called uricase, which convert uric acid into a more soluble derivative called allantoin
• Humans lack this enzyme
• Excessive accumulation of uric acid in joints causes gout
Osmoregulatory Organs

• In many animals, removal of water or salts is coupled with removal of metabolic wastes through the excretory system

• A variety of mechanisms have evolved to accomplish this
  – Single-celled protists and sponges use contractile vacuoles
  – Other multicellular animals have a system of excretory tubules to expel fluid and wastes
Osmoregulatory Organs

- Vertebrate kidneys
  - Create a tubular fluid by filtering the blood under pressure through the glomerulus
  - Filtrate contains many small molecules, in addition to water and waste products
  - Most of these molecules and water are reabsorbed into the blood
    - Selective reabsorption provides great flexibility
  - Waste products are eliminated from the body in the form of urine
Evolution of the Vertebrate Kidney

• Made up of thousands of repeating units – nephrons
• Although the same basic design has been retained in all vertebrate kidneys, a few modifications have occurred
• All vertebrates can produce a urine that is isotonic or hypotonic to blood
• Only birds and mammals can make a hypertonic urine
Organization of the vertebrate nephron
The Mammalian Kidney

• Each kidney receives blood from a renal artery
• Produces urine from this blood
• Urine drains from each kidney through a ureter into a urinary bladder
• Urine is passed out of the body through the urethra
The Mammalian Kidney

- Within the kidney, the mouth of the ureter flares open to form the renal pelvis
- Receives urine from the renal tissue
- Divided into an outer renal cortex and inner renal medulla
The Mammalian Kidney

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The Mammalian Kidney

• The kidney has three basic functions
  – Filtration
    • Fluid in the blood is filtered out of the glomerulus into the tubule system
  – Reabsorption
    • Selective movement of solutes out of the filtrate back into the blood via peritubular capillaries
  – Secretion
    • Movement of substances from the blood into the extracellular fluid, then into the filtrate in the tubular system
Excretion

Secretion from blood

Filtration

Glomerulus

Bowman's capsule

Afferent arteriole

Reabsorption to blood

Renal tubule

Efferent arteriole
The Mammalian Kidney

• Each kidney is made up of about 1 million functioning nephrons
  – Juxtamedullary nephrons have long loops that dip deeply into the medulla
  – Cortical nephrons have shorter loops
• Blood is carried by an afferent arteriole to the glomerulus
• Blood is filtered as it is forced through porous capillary walls
The Mammalian Kidney

- Blood components that are not filtered drain into an efferent arteriole, which empties into peritubular capillaries
  - Vasa recta in juxtamedullary nephrons
- Glomerular filtrate enters the first region of the nephron tubules – Bowman’s capsule
- Goes into the proximal convoluted tubule
- Then moves down the medulla and back up into cortex in the loop of Henle
The Mammalian Kidney

- After leaving the loop, the fluid is delivered to a distal convoluted tubule in the cortex
- Drains into a collecting duct
- Merges with other collecting ducts to empty its contents, now called urine, into the renal pelvis
Nephron in a mammalian kidney
Reabsorption and Secretion

• Approximately 2,000 L of blood passes through the kidneys each day
• 180 L of water leaves the blood and enters the glomerular filtrate
• Most of the water and dissolved solutes that enter the glomerular filtrate must be returned to the blood by reabsorption
• Water is reabsorbed by the proximal convoluted tubule, descending loop of Henle, and collecting duct
Reabsorption and Secretion

- Reabsorption of glucose and amino acids is driven by active transport and secondary active transport
  - Maximum rate of transport
  - Glucose remains in the urine of untreated diabetes mellitus patients

- Secretion of waste products involves transport across capillary membranes and kidney tubules into the filtrate
  - Penicillin must be administered several times a day
Excretion

• Major function of the kidney is elimination of a variety of potentially harmful substances that animals eat and drink.
• In addition, urine contains nitrogenous wastes, and may contain excess $K^+$, $H^+$, and other ions that are removed from blood.
• Kidneys are critically involved in maintaining acid–base balance of blood.
Transport in the Nephron

• Proximal convoluted tubule
  – Reabsorbs virtually all nutrient molecules in the filtrate, and two-thirds of the NaCl and water
  – Because NaCl and water are removed from the filtrate in proportionate amounts, the filtrate that remains in the tubule is still isotonic to the blood plasma
Transport in the Nephron

• Loop of Henle
  – Creates a gradient of increasing osmolarity from the cortex to the medulla
  – Actively transports $\text{Na}^+$, and $\text{Cl}^-$ follows from the ascending loop
    • Creates an osmotic gradient
  – Allows reabsorption of water from descending loop and collecting duct
  – Two limbs of the loop form a countercurrent multiplier system
    • Creates a hypertonic renal medulla
Reabsorption of salt and water in mammalian kidney
Transport in the Nephron

- Distal convoluted tubule and collecting duct
  - Filtrate that enters is hypotonic
  - Hypertonic interstitial fluid of the renal medulla pulls water out of the collecting duct and into the surrounding blood vessels
    - Permeability controlled by antidiuretic hormone (ADH)
  - Kidneys also regulate electrolyte balance in the blood by reabsorption and secretion
    - $K^+$, $H^+$, and $HCO_3^-$
Controlling salt balance
Hormones Control Osmoregulation

- Kidneys maintain relatively constant levels of blood volume, pressure, and osmolarity
- Also regulate the plasma K\(^+\) and Na\(^+\) concentrations and blood pH within narrow limits
- These homeostatic functions of kidneys are coordinated primarily by hormones
Hormones Control Osmoregulation

• Antidiuretic hormone (ADH)
  – Produced by the hypothalamus and secreted by the posterior pituitary gland
  – Stimulated by an increase in the osmolarity of blood
  – Causes walls of distal tubule and collecting ducts to become more permeable to water
    • Aquaporins
  – More ADH increases reabsorption of water
    • Makes a more concentrated urine
Antidiuretic hormone stimulates the reabsorption of water by the kidney

**Stimulus**
- Dehydration; Increased osmolarity of plasma

**Sensor**
- Osmoreceptors in hypothalamus

**Effector**
- Posterior pituitary gland
  - Increased ADH secretion

**Response**
- Increased reabsorption of water
  
**Negative feedback**

**Thirst**
- Increased water intake

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Hormones Control Osmoregulation

• Aldosterone
  – Secreted by the adrenal cortex
  – Stimulated by low levels of Na\(^+\) in the blood
  – Causes distal convoluted tubule and collecting ducts to reabsorb Na\(^+\)
  – Reabsorption of Cl\(^-\) and water follows
  – Low levels of Na\(^+\) in the blood are accompanied by a decrease in blood volume
    • Renin-angiotensin-aldosterone system is activated
Lowering blood volume activates the renin–angiotensin–aldosterone system
Hormones Control Osmoregulation

• Atrial natriuretic hormone (ANH)
  – Opposes the action of aldosterone in promoting salt and water retention
  – Secreted by the right atrium of the heart in response to an increased blood volume
  – Promotes the excretion of salt and water in the urine and lowering blood volume