Chapter 36: Body Fluid Regulation and Excretory Systems

AP Curriculum Alignment

The excretory system is not one of the major systems on which the AP curriculum focuses. The effect of decreased ADH is illustrative example of Big Idea 2 that is covered in Chapter 36 and helps students understand the extent of hormonal regulation on human bodies. The production and elimination of nitrogen wastes is also an illustrative example that is fully explained in Chapter 36 along with the energy and water requirements for the process in the production of different types of nitrogen wastes.

The excretory system does interact with other bodily systems to enable life to continue within an organism. The excretion of wastes is an illustrative example from Big Idea 4 that is explained in Chapter 36.

<table>
<thead>
<tr>
<th>ALIGNMENT OF CONTENT TO THE CURRICULUM FRAMEWORK</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Big Idea 2: Biological systems utilize free energy and molecular building blocks to grow, to reproduce, and to maintain dynamic homeostasis.</strong></td>
</tr>
<tr>
<td><strong>Enduring understanding (EU) 2.C:</strong> Organisms use feedback mechanisms to regulate growth and reproduction, and to maintain dynamic homeostasis.</td>
</tr>
<tr>
<td><strong>Essential knowledge (EK) 2.C.1:</strong> Organisms use feedback mechanisms to maintain their internal environments and respond to external environmental changes.</td>
</tr>
<tr>
<td>c. Alteration in the mechanisms of feedback often results in deleterious consequences.</td>
</tr>
<tr>
<td>To foster student understanding of this concept, instructors can choose an illustrative example such as:</td>
</tr>
<tr>
<td>• Diabetes mellitus in response to decreased insulin</td>
</tr>
<tr>
<td>• Dehydration in response to decreased antidiuretic hormone (ADH)</td>
</tr>
<tr>
<td>• Graves’ disease (hyperthyroidism)</td>
</tr>
<tr>
<td>• Blood clotting</td>
</tr>
<tr>
<td><strong>Enduring understanding (EU) 2.D:</strong> Growth and dynamic homeostasis of a biological system are influenced by changes in the system’s environment.</td>
</tr>
<tr>
<td><strong>Essential knowledge (EK) 2.D.2:</strong> Homeostatic mechanisms reflect both common ancestry and divergence due to adaptation in different environments.</td>
</tr>
<tr>
<td>b. Organisms have various mechanisms for obtaining nutrients and eliminating wastes.</td>
</tr>
<tr>
<td>To foster student understanding of this concept, instructors can choose an illustrative example such as:</td>
</tr>
<tr>
<td>• Gas exchange in aquatic and terrestrial plants</td>
</tr>
<tr>
<td>• Digestive mechanisms in animals such as food vacuoles, gastrovascular cavities, one-way digestive systems</td>
</tr>
<tr>
<td>• Respiratory systems of aquatic and terrestrial animals</td>
</tr>
<tr>
<td>• Nitrogenous waste production and elimination in aquatic and terrestrial animals</td>
</tr>
</tbody>
</table>
c. Homeostatic control systems in species of microbes, plants and animals support common ancestry.

*To foster student understanding of this concept, instructors can choose an illustrative example such as the comparison of:*

- Excretory systems in flatworms, earthworms and vertebrates
- Osmoregulation in bacteria, fish and protists
- Osmoregulation in aquatic and terrestrial plants
- Circulatory systems in fish, amphibians and mammals
- Thermoregulation in aquatic and terrestrial animals (countercurrent exchange mechanisms)

**Essential knowledge (EK) 2.D.3:** Biological systems are affected by disruptions to their dynamic homeostasis.

a. Disruptions at the molecular and cellular levels affect the health of the organism.

*To foster student understanding of this concept, instructors can choose an illustrative example such as:*

- Physiological responses to toxic substances
- Dehydration
- Immunological responses to pathogens, toxins and allergens

**Big Idea 4:** Biological systems interact, and these systems and their interactions possess complex properties.

**Enduring understanding (EU) 4.A:** Interactions within biological systems lead to complex properties.

**Essential knowledge 4.A.4:** Organisms exhibit complex properties due to interactions between their constituent parts.

a. Interactions and coordination between organs provide essential biological activities.

*To foster student understanding of this concept, instructors can choose an illustrative example such as:*

- Stomach and small intestines
- Kidney and bladder
- Root, stem and leaf

**Enduring understanding (EU) 4.B:** Competition and cooperation are important aspects of biological systems.

**Essential knowledge (EK) 4.B.2:** Cooperative interactions within organisms promote efficiency in the use of energy and matter.

2. Within multicellular organisms, specialization of organs contributes to the overall functioning of the organism.

*To foster student understanding of this concept, instructors can choose an illustrative example such as:*

- Exchange of gases
- Circulation of fluids
- Digestion of food
- Excretion of wastes
Concepts covered in Chapter 36 also align to the learning objectives that provide a foundation for the course, an inquiry–based laboratory experience, class activities, and AP exam questions. Each learning objective (LO) merges required content with one or more of the seven *science practices* (SP), and one activity or lab can encompass several learning objectives. The learning objectives and science practices from the Curriculum Framework that pertain to body fluid regulation and excretory systems are shown in the table below. Note that other learning objectives may apply as well.

| LO 2.25 | The student can construct explanations based on scientific evidence that homeostatic mechanisms reflect continuity due to common ancestry and/or divergence due to adaptation in different environments. |
| LO 2.26 | The student is able to analyze data to identify phylogenetic patterns or relationships, showing that homeostatic mechanisms reflect both continuity due to common ancestry and change due to evolution in different environments. |
| LO 2.27 | The student is able to connect differences in the environment with the evolution of homeostatic mechanisms. |
| LO 2.28 | The student is able to use representations or models to analyze quantitatively and qualitatively the effects of disruptions to dynamic homeostasis in biological systems. |
| LO 4.8  | The student is able to evaluate scientific questions concerning organisms that exhibit complex properties due to the interaction of their constituent parts. |
| LO 4.9  | The student is able to predict the effects of a change in a component(s) of a biological system on the functionality of an organism(s). |
| LO 4.10 | The student is able to refine representations and models to illustrate biocomplexity due to interactions of the constituent parts. |
| LO 4.18 | The student is able to use representations and models to analyze how cooperative interactions within organisms promote efficiency in the use of energy and matter. |

### Key Concepts Summary

**Evolution of excretory systems**

- Nitrogen wastes are excreted from animals in the form of ammonia, uric acid, or urea, with each requiring specific amount of water and energy to produce.
- Most invertebrates have tubular excretory organs that regulate the water–salt balance of the body and excrete metabolic wastes into the environment.
  - In planaria, the beating of flame–cell cilia propels fluid through the excretory tubules and out of the body.
  - Every segment of an earthworm contains a pair of excretory structures called nephridia.
  - In aquatic crustaceans nitrogenous wastes are generally removed by diffusion across the gills.
- In most vertebrates, the kidneys are the most important organs involved in
osmoregulation.
- The kidneys produce urine, a liquid that contains a number of different metabolic wastes.
- The concentration of the urine produced by an animal varies depending on its environment, as well as on factors such as water and salt intake.
  - The total concentration of the various ions in the blood of sharks, rays, and skates is less than that in seawater.
  - Excess salts are secreted by the kidneys and by an excretory organ, the rectal gland.
  - Marine bony fishes must avoid the tendency to become dehydrated; the gills actively transport salt into the environment.
  - Freshwater fishes tend to gain water by osmosis across the gills and the body surface and a consequence, these fishes never drink water and eliminate excess water by producing large quantities of dilute (hypotonic) urine.
- The need for water conservation by terrestrial animals is taken care of by the evolution of the kidney which can produce concentrated urine.
- Most terrestrial animals need to drink water at least occasionally to make up for the water lost from the skin and respiratory passages and through urination.
- In sea birds, salt-excreting glands are located near the eyes.

### Human excretory system
- The major excretory organs of humans are the kidneys.
- Each human kidney is connected to a ureter, a duct that takes urine from the kidney to the urinary bladder, where it is stored until it is voided from the body through the single urethra.
- Each kidney is composed of over 1 million tiny tubules called nephrons that remove urea and return nutrients to the blood.
- The kidneys are organs of homeostasis for four main reasons:
  - The kidneys excrete metabolic wastes, such as urea, which is the primary nitrogenous waste of humans.
  - They maintain the water–salt balance, which in turn affects blood volume and blood pressure.
  - Kidneys maintain the acid–base balance and therefore the pH balance.
  - They secrete hormones.
- The bicarbonate (HCO₃⁻) buffer system and breathing work together to help maintain the pH of the blood. Central to the mechanism is the following reaction, which you have seen before:
  \[
  \text{H}^+ + \text{HCO}_3^- \rightarrow \text{H}_2\text{CO}_3 \rightarrow \text{H}_2\text{O} + \text{CO}_2
  \]
  The excretion of carbon dioxide (CO₂) by the lungs helps keep the pH within normal limits, because when carbon dioxide is exhaled, this reaction is pushed to the right and hydrogen ions are tied up in water.
- The kidneys are slower–acting than the buffer/breathing mechanism, but they have a more powerful effect on pH.
Key Terms

afferent arteriole  
eddythropoietin  
tubule

aldosterone  
excretion  	renin

ammonia  	glomerular capsule  
tubular reabsorption

antidiuretic hormone  
glomerular filtration  
tubular secretion
(ADH)

aquaporins  
glomerulus  
urea

Atrial natriuretic hormone  
kidneys  
ureter
(ANH)

collecting duct  
loop of the nephron  
urethra

distal convoluted tubule  
nephrons  
uric acid

Teaching Strategies

Class time: Two 45–minute class periods

Day 1: Lecture on bodily fluid regulation and excretory systems – 45 minutes

Day 2: Activity 1, design a creature – 45 minutes

Suggested Approaches

Activity 1 below taps the creative abilities of your students to increase their learning. After reviewing the many examples of different types of excretory systems that exist in animals, students will filter through that information to produce the excretory system of their own designed creature.

Student Misconceptions and Pitfalls

Students get confused about the excretory system and believe that the excretory system is responsible for the production of feces. They have a hard time understanding the concept that a buildup of nitrogen wastes within an animal is toxic.
Suggested Activities

Activity 1: Design a Creature

Divide students into groups of 4 or 5. Have each group design and draw a creature using the criteria below:

1. Creature’s habitat, including biome

2. Creature’s method of getting energy: respiration, fermentation, or photosynthesis — and an explanation of how that method works. Identify your creature as a producer or consumer; predator or prey species; where it is on the food pyramid. Draw its food web. Construct a food chain for one item of the creature’s diet.

3. Special behavior of the creature.

4. Special interactions it may have with its fellow species mates. Include type of population structure.

5. Describe the excretory system of your creature. Explain how this system interacts with the other systems of your creature.

6. Present your creature to the class.
Student Edition Chapter Review Answers

Answers to Assess Questions

1. d; 2. a; 3. d; 4. c; 5. d; 6. c; 7. c; 8. c; 9. d; 10. a. glomerular capsule; b. proximal convoluted tubule; c. loop of the nephron; d. descending limb; e. ascending limb; f. distal convoluted tubule; g. collecting duct; h. renal artery; i. afferent arteriole; j. glomerulus; k. efferent arteriole; l. peritubular capillary network; m. renal vein

Answers to Applying the Big Ideas Questions

1. Homeostatic mechanisms reflect adaptation in different environments across vertebrate animals. Proper salt balance has a critical effect on cellular functions, and many adaptations have evolved to maintain it.
   
   (a) **Describe** the osmoregulation of excretory systems of aquatic animals and those of terrestrial organisms.
   
   (b) **Explain** how each is an adaptation for its environment.

<table>
<thead>
<tr>
<th>Essential Knowledge</th>
<th>2.D.2: Homeostatic mechanisms reflect both common ancestry and divergence due to adaptation in different environments.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Science Practice</td>
<td>7.1: The student can connect phenomena and models across spatial and temporal scales.</td>
</tr>
<tr>
<td>Learning Objective</td>
<td>2.27: The student is able to connect differences in the environment with the evolution of homeostatic mechanisms.</td>
</tr>
</tbody>
</table>

4 points maximum.

Connections drawn between osmoregulation of organisms and their environment may include:

<table>
<thead>
<tr>
<th>Descriptions of excretory systems (1 point each):</th>
<th>Explanation of adaptation (1 point each):</th>
</tr>
</thead>
<tbody>
<tr>
<td>Most fishes and other aquatic animals excrete ammonia as their nitrogenous waste. Marine and freshwater bony fishes use different mechanisms to osmoregulate their body fluids, including using their gills.</td>
<td>• Ammonia requires less energy to produce than the waste of terrestrial animals, but requires more water to excrete – which is available in abundance in the aquatic environment.</td>
</tr>
<tr>
<td></td>
<td>• Some marine animals have developed specialized glands for excreting excess</td>
</tr>
</tbody>
</table>
Vertebrates in both aquatic and terrestrial environments have kidneys. Kidneys perform several functions critical to homeostasis, including maintaining the balance between water and several types of salts.

- Freshwater species tend to gain water by osmosis, so these species never drink water, and eliminate excess water by producing large quantities of dilute (hypotonic) urine.

Most terrestrial animals excrete urea or uric acid as their nitrogenous waste.

- Urea and uric acid require more energy to produce than the waste of aquatic animals, but requires less water to excrete, which helps to prevent dehydration. The development of a kidney also prevents dehydration as it produces a concentrated (hypotonic) urine.

2. Within multicellular organisms, specialization of organs contributes to the overall functioning of the organism. Within vertebrates, kidneys, circulatory system, and other organs work together to promote efficiency in excreting waste and maintaining homeostasis.
   (a) **Draw** a model representing the connections between the kidneys and at least TWO other organs or systems of the body. Label the organs, and include descriptions of their contributing functions.
   (b) **Answer** the following question: how would the body be impacted in the case of kidney failure in each of the connections you drew in part (a)?

<table>
<thead>
<tr>
<th>Essential Knowledge</th>
<th>4.B.2: Cooperative interactions within organisms promote efficiency in the use of energy and matter.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Science Practice</td>
<td>1.4: The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.</td>
</tr>
<tr>
<td>Learning Objective</td>
<td>4.18: The student is able to use representations and models to analyze how cooperative interactions within organisms promote efficiency in the use of energy and matter.</td>
</tr>
</tbody>
</table>
3 points maximum.

Note: Examples for models may include images similar in structure to Figure 36.6 of the human urinary system, Figure 36.9 of the Processes in urine formation, or Figure 36.11 of the renin–angiotensin–aldosterone system. Models and explanations of their contributions may include:

<table>
<thead>
<tr>
<th>Labeled drawings (1 point each):</th>
<th>Consequence of kidney failure (1 point each):</th>
</tr>
</thead>
<tbody>
<tr>
<td>In the urinary system, <strong>kidneys</strong> produce urine, <strong>ureters</strong> transport the urine, the <strong>bladder</strong> stores the urine, and the urethra passes urine to the outside. They work together to filter a large amount of water and solutes out of the blood (then reabsorb the water and materials needed to conserve) and excrete out of the body the waste.</td>
<td>With the loss of kidney function, waste would no longer be removed from the blood. Holding in solutes would also cause the body to hold in too much fluid, leading to swelling due to electrolyte imbalance and other issues. Changes will occur in urination frequency.</td>
</tr>
</tbody>
</table>

The **nephrons** of kidneys are closely associated with **capillaries** of the circulatory system in order to filter water and solutes in and out of the blood stream. Kidneys produce hormones and enzymes that contribute to the water/salt and pH balance in blood. The **pituitary gland** interacts with the kidneys through hormones to stimulate the retention or loss of water, and the **adrenal cortex** is stimulated by signals from products of the kidneys and the **liver** to increase blood pressure. With the loss of kidney function, anemia can result in the blood, calcium can be drawn from bones, blood pressure can falter, and heart disease can occur.

Drawings should include **labels** and directional arrows, as well as be legible and clear as to the inclusion of each part.
Answers to Applying the Science Practices Questions

1. urine

2. The body sweats to cool itself and maintain a constant temperature. During rigorous exercise, the body sweats heavily to counteract the heat generated in the muscles.

3. 

<table>
<thead>
<tr>
<th>Source</th>
<th>Normal Temps</th>
<th>High Temps</th>
<th>Rigorous Exercise</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urine</td>
<td>62%</td>
<td>39%</td>
<td>12%</td>
</tr>
<tr>
<td>Sweat</td>
<td>19%</td>
<td>51%</td>
<td>78%</td>
</tr>
<tr>
<td>Lungs</td>
<td>19%</td>
<td>10%</td>
<td>10%</td>
</tr>
</tbody>
</table>
Additional Questions for AP Practice

1. Indicate the amount of energy required (relatively) to product the various nitrogen wastes.

2. Explain the human kidney’s ability to control blood pH.
Grid—In Questions

1. Ammonia can be toxic to fishes above concentrations of 1 mg/L. If there are 20 fish in a 1,000 L tank, and each fish produces 5 mg of ammonia per day, assuming that the ammonia concentrations only increase, how long would it be before you would need to change the water in the tank?
Answers to Additional Questions for AP Practice

1. *The formation of ammonia requires little to no energy.* Production of urea requires the expenditure of energy because it is produced in the liver by a set of energy–requiring enzymatic reactions, known as the urea cycle. Uric acid is synthesized by a long, complex series of enzymatic reactions that requires the expenditure of even more energy than does urea synthesis.

2. *If the blood is acidic, hydrogen ions are excreted and bicarbonate ions are reabsorbed.* If the blood is basic, hydrogen ions are not excreted and bicarbonate ions are not reabsorbed. The fact that urine is typically acidic (pH about 6) shows that usually an excess of hydrogen ions are excreted.

Answers to Grid–In Questions

1. 10; \( \frac{5 \text{ mg per fish}}{\text{day}} \times 20 \text{ fish} = \frac{100 \text{ mg}}{\text{day}} \)

\[
\frac{1 \text{ mg}}{L} \times 1000 L \times \frac{\text{day}}{100 \text{ mg}} = 10 \text{ days}
\]