Maintaining the Internal Environment

Chapter 41
Kidneys rid the body of excess water, excess or harmful solutes, and drugs – physicians routinely check urine to monitor their patient’s health.
41.1 Maintenance of Extracellular Fluid

- All animals constantly acquire and lose water and solutes, and produce metabolic wastes.

- Excretory organs keep the volume and the composition of their internal environment – the extracellular fluid – stable.
Fluid Distribution in the Human Body

- Intracellular Fluid (28 liters)
- Extracellular Fluid (ECF) (15 liters)

Human Body Fluids (43 liters)
plasma

lymph, cerebrospinal fluid, mucus, and other fluids

interstitial fluid

Intracellular Fluid (28 liters)

Extracellular Fluid (ECF) (15 liters)

Human Body Fluids (43 liters)

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Fig. 41-2, p. 722
41.2 How Do Invertebrates Maintain Fluid Balance?

- Sponges
  - Simple animals with no excretory organs
  - Wastes diffuse out across the body wall
  - Excess water is expelled by contractile vacuoles
How Invertebrates Maintain Fluid Balance

- Flatworms and earthworms
  - Tubular excretory organs deliver fluid with dissolved ammonia to a pore at the body surface
  - **Flame cells** in flatworms
  - **Nephridia** in earthworms
Planarian Flame Cells

Pair of highly branched tubules that adjust water and solute levels in body.

Nucleus

Cilia

Fluid filters through membrane folds

Flame cell

Opening at body surface
Fig. 41-3, p. 722

pair of highly branched tubules that adjust water and solute levels in body

nucleus

cilia

fluid filters through membrane folds

flame cell

opening at body surface

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Earthworm Nephridia

- Funnel where coelomic fluid enters the nephridium (coded green)
- Pore where ammonia-rich fluid leaves the body
- One body segment of an earthworm

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funnel where coelomic fluid enters the nephridium (coded green)

pore where ammonia-rich fluid leaves the body

one body segment of an earthworm

body wall
storage bladder
loops where blood vessels take up solutes
funnel where coelomic fluid enters the nephridium (coded green)

pore where ammonia-rich fluid leaves the body

body wall

storage bladder

loops where blood vessels take up solutes

one body segment of an earthworm

Fig. 41-4b, p. 723
How Invertebrates Maintain Fluid Balance

- Insects
  - Insects convert ammonia to **uric acid**, which **Malpighian tubules** deliver to the gut
  - Excreting uric acid rather than ammonia reduces water loss
Malpighian Tubules

- Malpighian tubule
- Portion of the gut
Malpighian tubule

Portion of the gut
Vertebrates have a **urinary system** that filters water, metabolic wastes and toxins out of the blood, and reclaims water and certain solutes.

All vertebrates have paired **kidneys** – excretory organs that filter blood and adjust the level of solutes.
Interactions with Other Organ Systems

- **Digestive System**: food, water intake, nutrients, water, salts, elimination of food residues
- **Respiratory System**: oxygen intake, oxygen, carbon dioxide, elimination of carbon dioxide
- **Circulatory System**: rapid transport to and from all living cells
- **Urinary System**: water, solutes, elimination of excess water, salts, wastes
food, water intake

Digestive System

nutrients, water, salts

oxygen intake

Respiratory System

carbon dioxide

Circulatory System

oxygen

rapid transport to and from all living cells

carbon dioxide

Urinary System

water, solutes

elimination of excess water, salts, wastes

elimination of food residues

Fig. 41-6, p. 724
Bony fishes have body fluid that is saltier than freshwater, but less salty than seawater

- Marine fish drink water, pump excess salt out through gills, and produce small amounts of urine
- Freshwater fish do not drink, and produce large amounts of dilute urine
Fluid and Solute Balance in Bony Fishes

a. Marine bony fish; body fluids are less salty than the surrounding water; they are hypotonic.

b. Freshwater bony fish; body fluids are saltier than the surrounding water; they are hypertonic.
a Marine bony fish; body fluids are less salty than the surrounding water; they are hypotonic.
a Marine bony fish: Body fluids are less salty than the surrounding water; they are hypotonic.
b Freshwater bony fish; body fluids are saltier than the surrounding water; they are hypertonic.
b  Freshwater bony fish: Body fluids are less salty than freshwater bony fish; body fluids are saltier than the surrounding water; they are hypertonic. Surrounding water; they are hypertonic.
Fluid Balance in Amphibians

- Amphibians in freshwater adjust their internal solute concentration by pumping solutes in across their skin.

- Amphibians on land conserve water by excreting uric acid.
Fluid Balance in Reptiles and Birds

- Waterproof skin and highly efficient kidneys help adapt amniotes to land

- Reptiles and birds conserve water by converting ammonia to uric acid, which reduces the amount of water required for excretion
Mammals excrete urea, which requires 20 to 30 times more water to excrete than uric acid.

Some mammals are adapted to habitats where fresh water is scarce:
- The kangaroo rat has highly efficient kidneys and other adaptations that conserve water.
- Marine mammals have large kidneys that make and excrete urine that is saltier than seawater.
Water Balance in Mammals

- Water intake must balance water losses
Animals continually produce metabolic wastes

They continually gain and lose water and solutes; yet overall composition and volume of extracellular fluid must be kept within a narrow range

Most animals have organs that accomplish this task
41.4 The Human Urinary System

- Kidneys filter blood and form urine
  - Fibrous outer layer (renal capsule)
  - Two inner zones: renal cortex and renal medulla

- The body reclaims most of the filtrate; urine flows through ureters into a bladder that stores it

- Urine flows out of the body through the urethra
The Human Urinary System

**Kidney** (one of a pair)
Blood-filtering organ; filters water, all solutes except proteins from blood; reclaims only amounts body requires, excretes rest as urine

**Ureter** (one of a pair)
Channel for urine flow from one kidney to urinary bladder

**Urinary Bladder**
Stretchable urine storage container

**Urethra**
Urine flow channel between urinary bladder and body surface

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Urethra
Urine flow channel between urinary bladder and body surface
Animation: Human urinary system
Animation: Human kidney
Nephrons – Functional Units of the Kidney

- **Nephron**
  - A microscopic tube with a wall one cell thick
  - Begins in the cortex, where it folds to form a cup-shaped **Bowman’s capsule**
  - Enters the medulla as a **proximal tubule**, turns at the **loop of Henle**, reenters the cortex as a **distal tubule** which drains into a **collecting duct**
Blood Vessels Around Nephrons

- Renal arteries branch into afferent arterioles, which branch into a capillary bed (*glomerulus*) inside a Bowman’s capsule, which filters blood.

- Efferent arterioles branch into *peritubular capillaries* around the nephron, which converge into venules and veins leaving the kidney.
A Nephron and its Blood Vessels

A  Bowman's capsule and tubular regions of one nephron, cutaway view

B  Arterioles and the two sets of blood capillaries associated with the nephron
Bowman’s capsule (red)

proximal tubule (orange)

distal tubule (brown)

Renal Cortex

Renal Medulla

loop of Henle (yellow)

collecting duct (tan)
glomerular capillaries inside Bowman’s capsule

peritubular capillaries threading around tubular nephron regions
efferent arteriole
afferent arteriole

glomerular capillaries inside Bowman’s capsule

peritubular capillaries threading around tubular nephron regions
Animation: Urine formation
The human urinary system consists of two kidneys, two ureters, a bladder, and a urethra

Inside a kidney, millions of nephrons filter water and solutes from the blood; most of this filtrate is returned to the blood

Water and solutes not returned leave the body as urine
41.5 How Urine Forms

- **Urine**
  - Water and solutes filtered from blood and not returned to it, plus unwanted solutes secreted from blood into the nephron’s tubular regions

- Urine forms by three physiological processes: glomerular filtration, tubular reabsorption, and tubular secretion
Glomerular Filtration

- Occurs at glomerular capillaries in Bowman’s capsule

- The force of the beating heart drives protein-free plasma out of glomerular capillaries and into the nephron’s tubular portion as filtrate
Glomerular Filtration

glomerulus inside Bowman’s capsule

efferent arteriole (to peritubular capillaries)

afferent arteriole (from renal artery)

outer wall of Bowman’s capsule

filtrate (to proximal tubule)
Tubular Reabsorption

- Occurs all along a nephron’s tubular parts

- Nearly all the water and solutes that leave the blood as filtrate later leave the tubule and return to the blood in peritubular capillaries
Tubular Reabsorption

- lumen of tubule
- wall of tubule
- interstitial fluid
- peritubular capillary

- Na+, glucose
- Cl⁻
- H₂O

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Tubular Secretion

- Starts at the proximal tubule and continues all along a nephron’s tubular parts

- Urine forms from water and solutes that remain in the tubule, and solutes secreted into the tubule along its length
Tubular Secretion

- Lumen of tubule
- Wall of tubule
- Interstitial fluid
- Peritubular capillary

- \( H^+ \) from the wall of the tubule

- \( K^+ \) from the wall of the tubule

- Urea from the wall of the tubule

- \( H^+ \) from the peritubular capillary

- \( K^+ \) from the peritubular capillary

- Urea from the peritubular capillary

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Concentrating the Urine

- Concentration of urine flowing down through the loop of Henle sets up a solute concentration gradient in surrounding interstitial fluid of the renal medulla.

- This gradient allows urine to become concentrated as it flows through the collecting duct to the renal pelvis.
Concentrating the Urine

- $\text{H}_2\text{O}$
- $\text{Na}^+$
- $\text{Cl}^-$

renal medulla saltiest near turn
Urine Formation

- Glomerular capillaries
- Proximal tubule
- Distal tubule
- Cortex
- Medulla
- Peritubular capillaries
- Loop of Henle

Increasing solute concentration
Fig. 41-11, p. 728

The diagram illustrates the flow of urine and solute concentration through different parts of the nephron. The glomerular capillaries are located at the beginning of the nephron, where blood is filtered to produce filtrate. The filtrate then passes through the proximal tubule, where reabsorption of water and solutes occurs, leading to an increasing solute concentration. The loop of Henle is a critical part of the nephron where water is reabsorbed, creating a countercurrent mechanism for urine concentration. The distal tubule allows for further regulation of solute and water balance, leading to the formation of concentrated urine. The peritubular capillaries carry blood to and from the renal tubules, with an increasing solute concentration as they pass through the medulla. The urine outflow from the collecting duct enters the renal pelvis, completing the urinary excretory process.
Animation: Structure of the glomerulus
Animation: Tubular reabsorption
Animation: Diffusion, osmosis, and countercurrent flow
# Processes of Urine Formation

<table>
<thead>
<tr>
<th>Process</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glomerular filtration</td>
<td>Pressure generated by heartbeats drives water and small solutes (not proteins) out of leaky glomerular capillaries and into Bowman’s capsule, the entrance to the nephron.</td>
</tr>
<tr>
<td>Tubular reabsorption</td>
<td>Most water and solutes in the filtrate move from a nephron’s tubular portions, into interstitial fluid around the nephron, then into blood inside the peritubular capillaries.</td>
</tr>
<tr>
<td>Tubular secretion</td>
<td>Urea, H⁺, and some other solutes move out of peritubular capillaries, into interstitial fluid, then into the filtrate inside the nephron for excretion in urine.</td>
</tr>
</tbody>
</table>
41.6 Regulation of Water Intake and Urine Formation

- **Thirst center**
  - When you don’t drink enough water, you make less saliva; a dry mouth signals a region of the hypothalamus (thirst center) which notifies your cerebral cortex that you need to search for water.
  - Hormonal controls act to conserve water already in the body.
Effects of Antidiuretic Hormone

- **Antidiuretic hormone (ADH)**
  - Released by the pituitary when sodium levels rise
  - Increases water reabsorption by stimulating insertion of aquaporins into plasma membranes of distal tubules and collecting ducts
  - Concentrates urine
Feedback Control of ADH Secretion

**Stimulus**

a. Water loss lowers the blood volume. Sensory receptors in the hypothalamus detect a big deviation from the set point.

b. The hypothalamus stimulates the pituitary gland to step up its secretion of ADH.

c. ADH circulates in blood, reaches nephrons in the kidneys. By acting on cells of distal tubules and collecting ducts, it makes the tube walls more permeable to water.

**Response**

f. Sensory receptors in the hypothalamus detect the increase in blood volume. Signals calling for ADH secretion slow down.

e. The blood volume rises.

d. More water is reabsorbed by peritubular capillaries around the nephrons, so less water is lost in urine.
Effects of Aldosterone

- **Aldosterone**
  - Released by the adrenal cortex
  - Increases salt reabsorption in collection ducts; water follows by osmosis; urine is concentrated

- Decrease in volume of extracellular fluid stimulates arterioles in nephrons to release renin
  - Renin converts angiotensinogen to angiotensin I, converted to angiotensin II, which acts on the adrenal cortex to secrete aldosterone
Atrial natriuretic peptide (ANP)

- Released by muscle cells in the heart’s atria when high blood volume causes walls to stretch
- Directly inhibits secretion of aldosterone by acting on adrenal cortex
- Indirectly inhibits secretion of aldosterone by inhibiting renin release
- Increases glomerular filtration rate, makes urine more dilute
Hormonal Disorders and Fluid Balance

- **Diabetes insipidus**
  - Pituitary gland secretes too little ADH, receptors don’t respond, or aquaporins are impaired

- **ADH oversecretion**
  - Some cancers, infections, antidepressants

- **Aldosterone oversecretion**
  - Adrenal gland tumors
41.7 Acid–Base Balance

- Normal pH of extracellular fluid is 7.35 to 7.45
- Kidneys, buffering systems, and respiratory system work together to maintain the acid-base balance (H⁺ concentration) within a tight range
- Kidneys are the only organs that can selectively rid the body of H⁺ ions
Acid-Base Balance

- A bicarbonate-carbonic acid **buffer system** minimizes pH changes by binding excess $H^+$

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

- Kidneys adjust blood pH by bicarbonate reabsorption and $H^+$ secretion

- Respiration adjusts blood pH by removing $CO_2$
Most kidney problems occur as complications of diabetes mellitus or high blood pressure.

Infections, toxins, drugs, and high-protein diets can also damage kidneys.

Kidney failure can be treated with dialysis, but only a kidney transplant can fully restore function.
Kidney Dialysis

- **Kidney dialysis** temporarily restores proper solute balance in a person with kidney failure.

- Hemodialysis pumps blood through a machine that cleans blood and adjusts solutes.

- In peritoneal dialysis, a dialysis solution is pumped into the peritoneal cavity at night and removed in the morning.
Two Types of Kidney Dialysis

A. Hemodialysis

Tubes carry blood from a patient’s body through a filter with dialysis solution that contains the proper concentrations of salts. Wastes diffuse from the blood into the solution and cleansed, solute-balanced blood returns to the body.

B. Peritoneal dialysis

Dialysis solution is pumped into a patient’s abdominal cavity. Wastes diffuse across the lining of the cavity into the solution, which is then drained out.
**A Hemodialysis**

Tubes carry blood from a patient’s body through a filter with dialysis solution that contains the proper concentrations of salts. Wastes diffuse from the blood into the solution and cleansed, solute-balanced blood returns to the body.

**B Peritoneal dialysis**

Dialysis solution is pumped into a patient’s abdominal cavity. Wastes diffuse across the lining of the cavity into the solution, which is then drained out.
Kidney Transplants

- A single kidney is adequate to maintain health.
- Transplants of kidneys from living donors, usually a relative, are more successful than kidneys donated after death.
- More than 40,000 people remain on waiting lists because of a shortage of donated kidneys.
What Kidneys Do

- **Urine forms by filtration, reabsorption, and secretion**

- **Its content is adjusted continually by hormonal and behavioral responses to shifts in the internal environment**

- **Hormones, as well as a thirst mechanism, influence whether urine is concentrated or dilute**
Maintaining the body’s core temperature is another aspect of homeostasis.

Some animals expend more energy than others to keep their body warm.
Internal core temperature is stable only when metabolic heat produced and heat gained from the environment balance heat lost to the environment.

Change in body heat = 

heat produced + heat gained – heat lost
How Core Temperature Can Change

- **Thermal radiation**
  - Heat is emitted into space surrounding an object

- **Conduction**
  - Heat is transferred by direct contact

- **Convection**
  - Heat is transferred by movement of air or water

- **Evaporation**
  - Heat is lost when liquid is converted to a gas
Ectotherms, Endotherms, and Heterotherms

- **Ectotherms** (fishes, amphibians, reptiles)
  - Body temperature changes with the environment
  - Regulated by altering position, not metabolism

- **Endotherms** (most birds and mammals)
  - Body temperature maintained by metabolic heat

- **Heterotherms** (some birds and mammals)
  - Can maintain or decrease core temperature
Ectotherm and Endotherm
41.10 Temperature Regulation in Mammals

- The hypothalamus is the body’s thermostat
  - Thermoreceptors detect temperature shifts and signal the hypothalamus, which prompts adjustments that maintain core temperature

- A variety of mechanisms help mammals keep their core temperature from fluctuating with that of the environment
Responses to Heat Stress

- Mammals counter heat stress by increasing blood flow to skin, sweating and panting (evaporation), and by reducing their activity level.

- Fever
  - An increase in body temperature regulated by the hypothalamus, usually a response to infection.

- Failure to control body heat results in rising core temperature (hyperthermia) which can be fatal.
Short-Term Adaptation to Heat Stress

- In dromedary camels, a hypothalamic mechanism allows core temperature to rise during hot hours of the day, then cool at night.
Responses to Cold Stress

- Mammals respond to cold with reduced blood flow to skin, fluffing up fur or hair, increased muscle activity, and increased heat production.

- Failure to protect against cold can result in falling core temperature (hypothermia) which alters brain function, and can be fatal.
Increasing Metabolic Heat Production

- **Shivering response**
  - With prolonged cold exposure, the hypothalamus commands skeletal muscles to increase heat production by contracting 10 to 20 times/second

- **Nonshivering heat production**
  - Long-term or severe cold increases thyroid activity and raises metabolic rate; reactions in cells of brown adipose tissue release energy as heat
Two Responses to Cold Stress
## Impact of Increases in Cold Stress

<table>
<thead>
<tr>
<th>Core Temperature</th>
<th>Physiological Responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>36°–34°C (about 95°F)</td>
<td>Shivering response; faster breathing, metabolic heat output. Peripheral vasoconstriction, more blood deeper in body. Dizziness, nausea.</td>
</tr>
<tr>
<td>33°–32°C (about 91°F)</td>
<td>Shivering response ends. Metabolic heat output declines.</td>
</tr>
<tr>
<td>26°–24°C (about 77°F)</td>
<td>Ventricular fibrillation sets in (Section 37.9). Death follows.</td>
</tr>
</tbody>
</table>
# Heat and Cold Stress Compared

<table>
<thead>
<tr>
<th>Stimulus</th>
<th>Main Responses</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat stress</td>
<td>Widening of blood vessels in skin; behavioral adjustments; in some species, sweating, panting</td>
<td>Dissipation of heat from body</td>
</tr>
<tr>
<td></td>
<td>Decreased muscle action</td>
<td>Heat production decreases</td>
</tr>
<tr>
<td>Cold stress</td>
<td>Narrowing of blood vessels in skin; behavioral adjustments (e.g., minimizing surface parts exposed)</td>
<td>Conservation of body heat</td>
</tr>
<tr>
<td></td>
<td>Increased muscle action; shivering; nonshivering heat production</td>
<td>Heat production increases</td>
</tr>
</tbody>
</table>
Heat losses to the environment and heat gains from the environment and from metabolic activity determine an animal’s body temperature.

Adaptations in body form and behavior help maintain core temperature within a tolerable range.
Animation: Endotherms and ectotherms
Animation: Hormone-induced adjustments
Animation: Human thermoregulation
Animation: Kidney dialysis
Animation: Reabsorption and secretion
Animation: Water and solute balance
Video: Truth in a test tube