Chapter 44

Osmoregulation and Excretion

PowerPoint® Lecture Presentations for

Biology

Eighth Edition

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Overview: A Balancing Act

- Physiological systems of animals operate in a fluid environment
- Relative concentrations of water and solutes must be maintained within fairly narrow limits
- **Osmoregulation** regulates solute concentrations and balances the gain and loss of water

- Freshwater animals show adaptations that reduce water uptake and conserve solutes
- Desert and marine animals face desiccating environments that can quickly deplete body water
- **Excretion** gets rid of nitrogenous metabolites and other waste products

Fig. 44-1

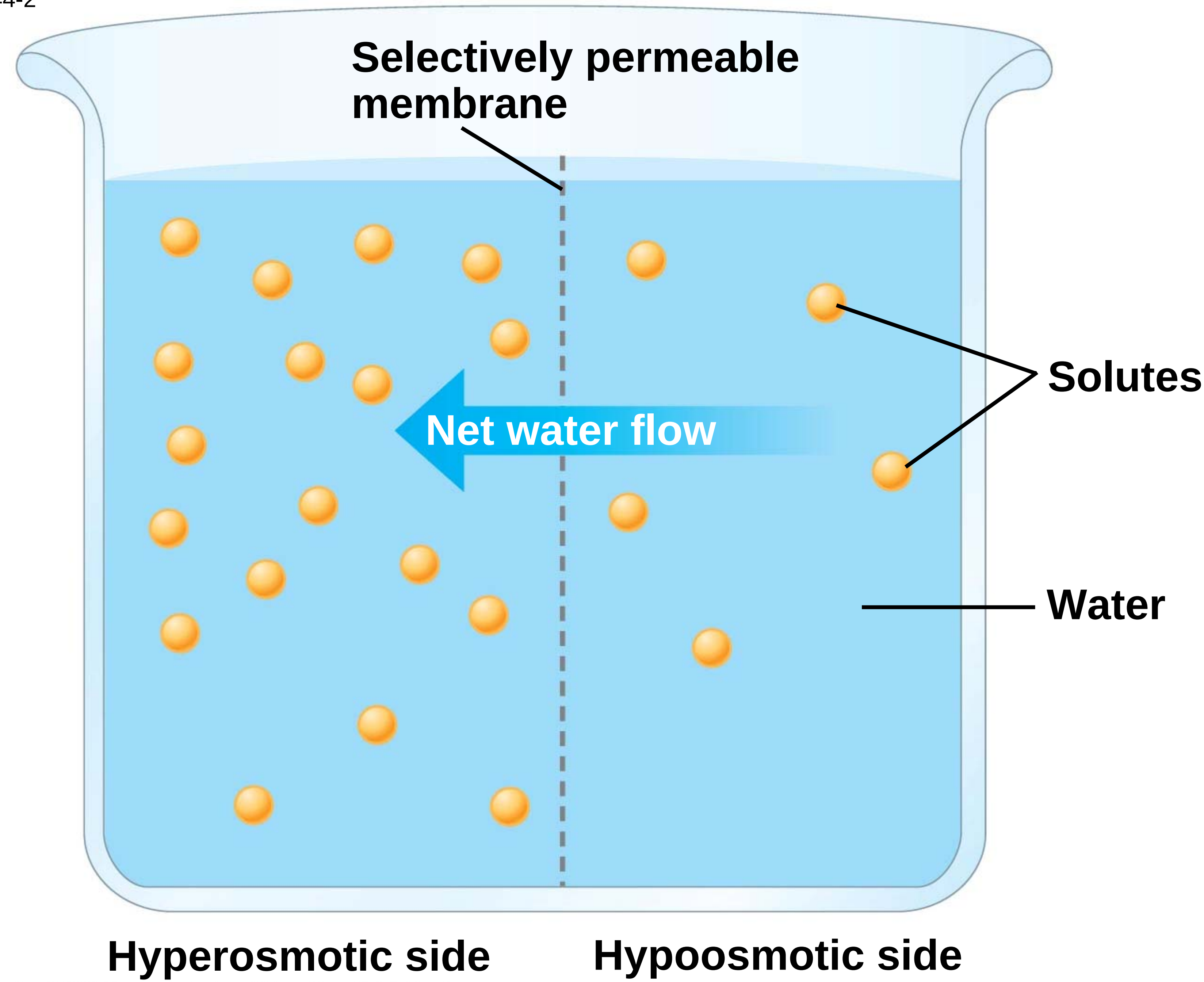
Concept 44.1: Osmoregulation balances the uptake and loss of water and solutes

- Osmoregulation is based largely on controlled movement of solutes between internal fluids and the external environment

Osmosis and Osmolarity

- Cells require a balance between osmotic gain and loss of water
- **Osmolarity**, the solute concentration of a solution, determines the movement of water across a selectively permeable membrane
- If two solutions are *isoosmotic*, the movement of water is equal in both directions
- If two solutions differ in osmolarity, the net flow of water is from the hypoosmotic to the hyperosmotic solution

Fig. 44-2



Selectively permeable membrane
Solutes
Net water flow
Water
Hyperosmotic side
Hypoosmotic side

Osmotic Challenges

- **Osmoconformers**, consisting only of some marine animals, are isoosmotic with their surroundings and do not regulate their osmolarity
- **Osmoregulators** expend energy to control water uptake and loss in a hyperosmotic or hypoosmotic environment

- Most animals are **stenohaline**; they cannot tolerate substantial changes in external osmolarity

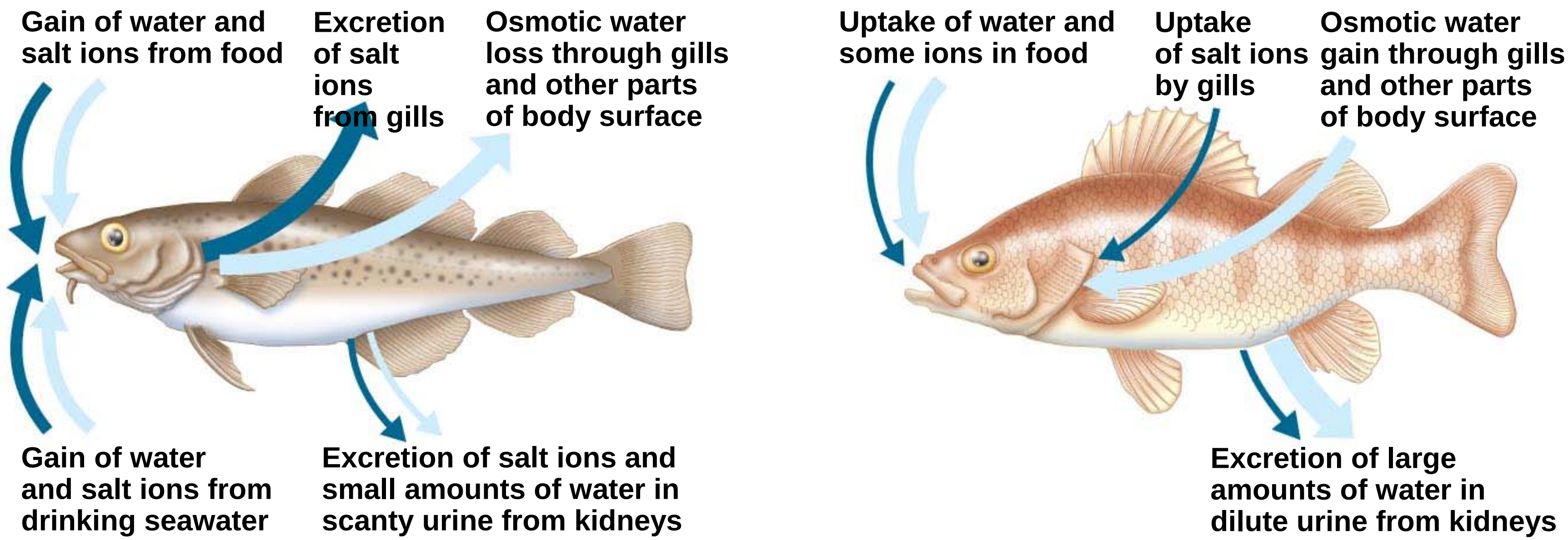
- **Euryhaline** animals can survive large fluctuations in external osmolarity

Fig. 44-3

Marine Animals

- Most marine invertebrates are osmoconformers
- Most marine vertebrates and some invertebrates are osmoregulators
- Marine bony fishes are hypoosmotic to sea water
- They lose water by osmosis and gain salt by diffusion and from food
- They balance water loss by drinking seawater and excreting salts

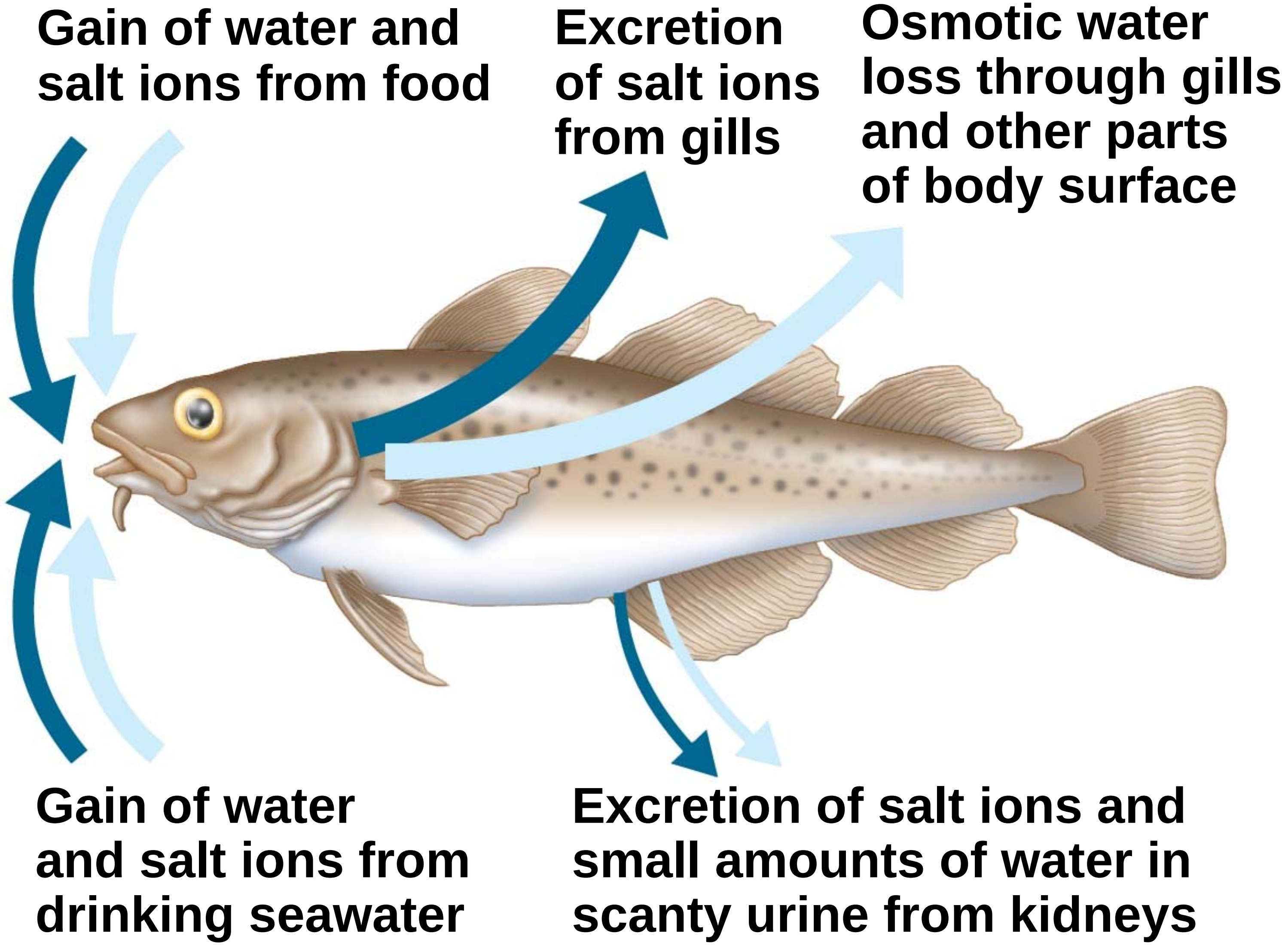
Fig. 44-4



(a) Osmoregulation in a saltwater fish

(b) Osmoregulation in a freshwater fish

Fig. 44-4a

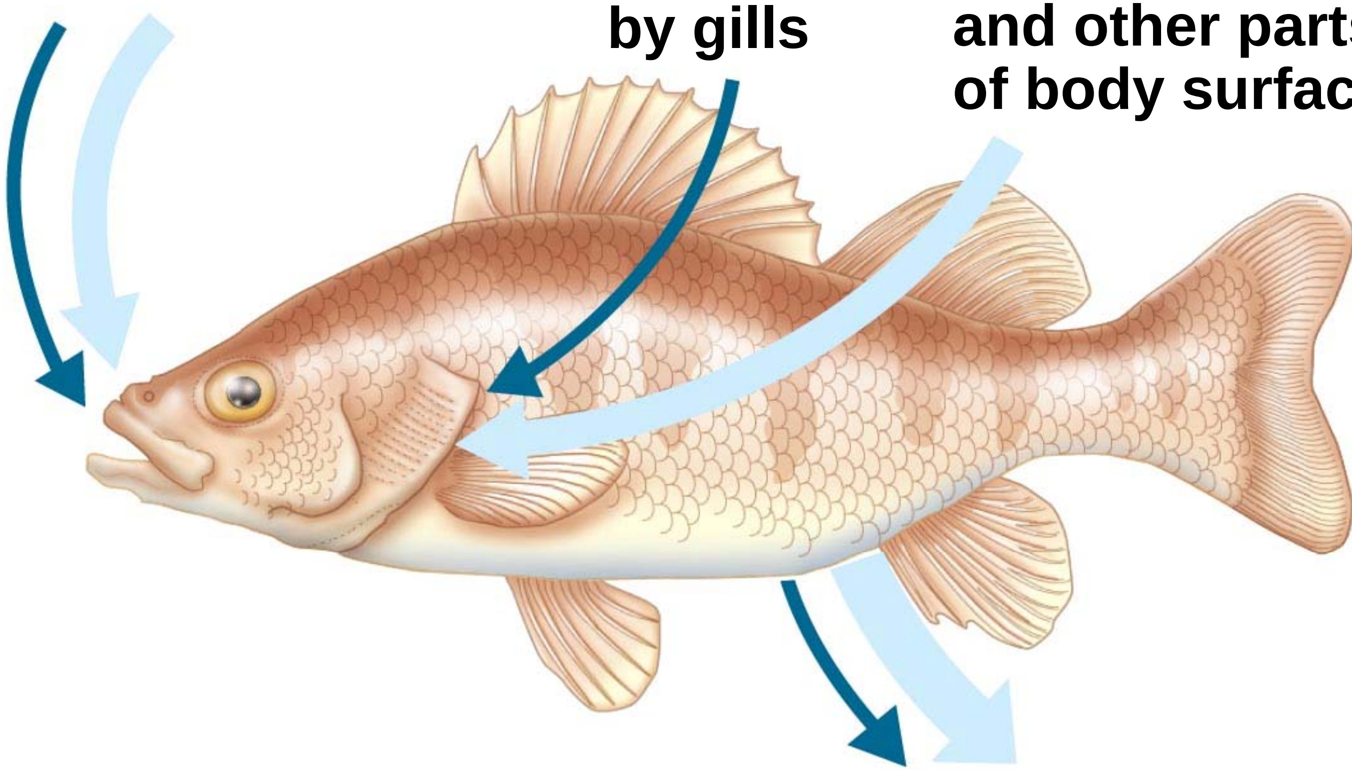


(a) Osmoregulation in a saltwater fish

Freshwater Animals

- Freshwater animals constantly take in water by osmosis from their hypoosmotic environment
- They lose salts by diffusion and maintain water balance by excreting large amounts of dilute urine
- Salts lost by diffusion are replaced in foods and by uptake across the gills

Fig. 44-4b

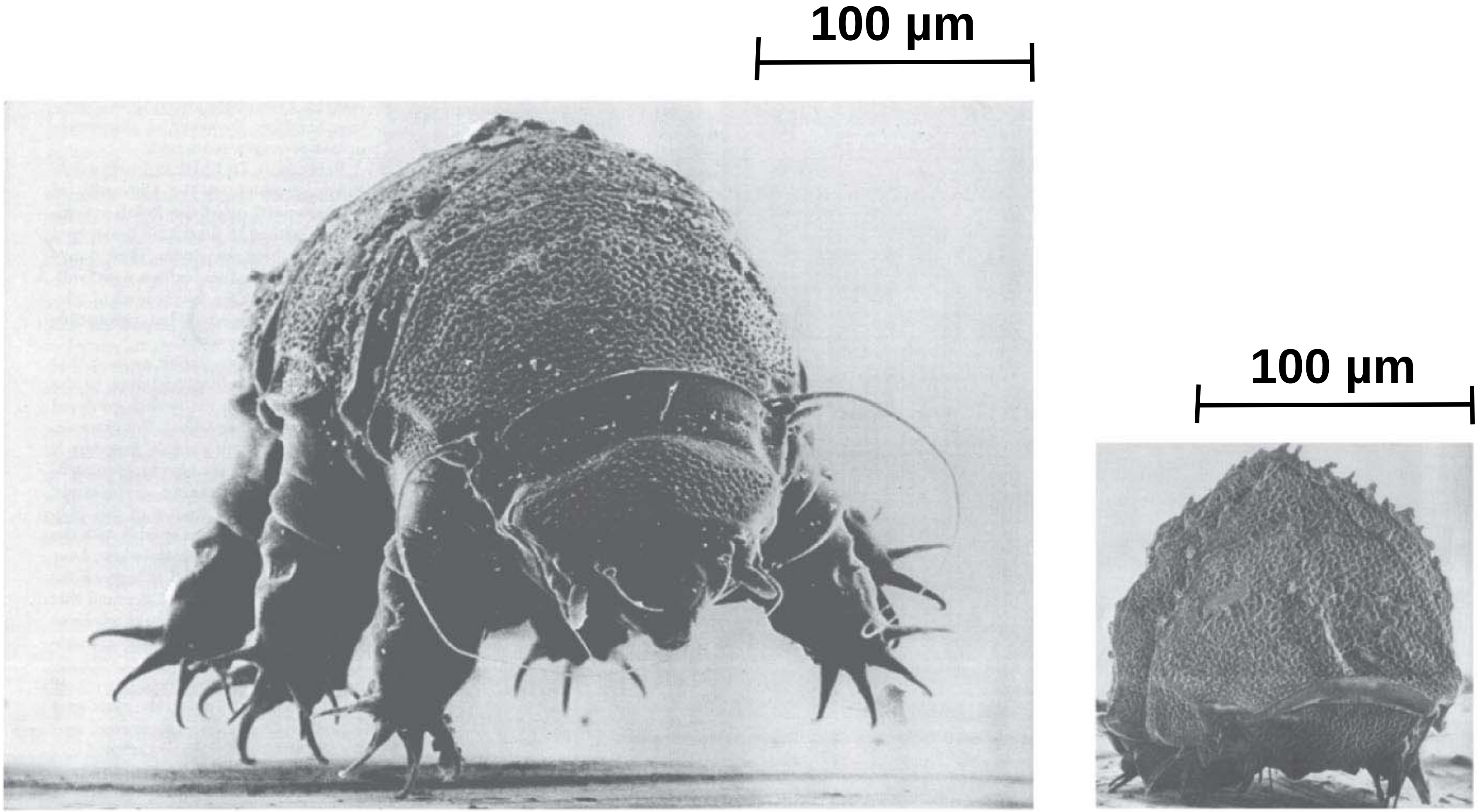


(b) Osmoregulation in a freshwater fish

Animals That Live in Temporary Waters

- Some aquatic invertebrates in temporary ponds lose almost all their body water and survive in a dormant state
- This adaptation is called **anhydrobiosis**

Fig. 44-5



(a) Hydrated tardigrade

(b) Dehydrated tardigrade

Land Animals

- Land animals manage water budgets by drinking and eating moist foods and using metabolic water
- Desert animals get major water savings from simple anatomical features and behaviors such as a nocturnal life style

Fig. 44-6

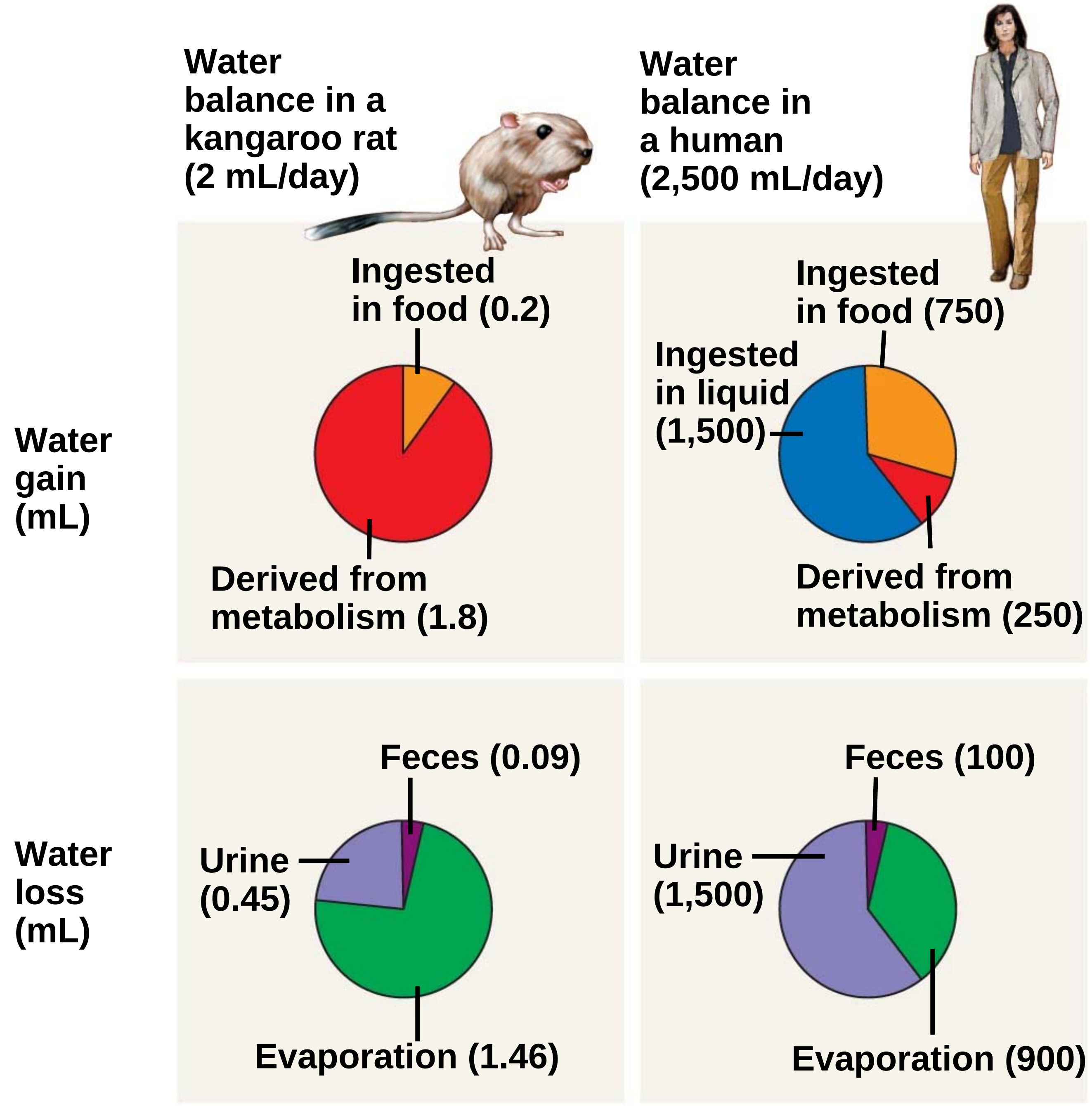

Water
balance in a
kangaroo rat
(2 mL/day)
Water
balance in
a human
(2,500 mL/day)
Water
gain
(mL)
Ingested
in food (0.2)
Derived from
metabolism (1.8)
Ingested
in food (750)
Ingested
in liquid
(1,500)
Derived from
metabolism (250)
Water
loss
(mL)
Feces (0.09)
Urine
(0.45)
Evaporation (1.46)
Feces (100)
Urine
(1,500)
Evaporation (900)

Fig. 44-6a

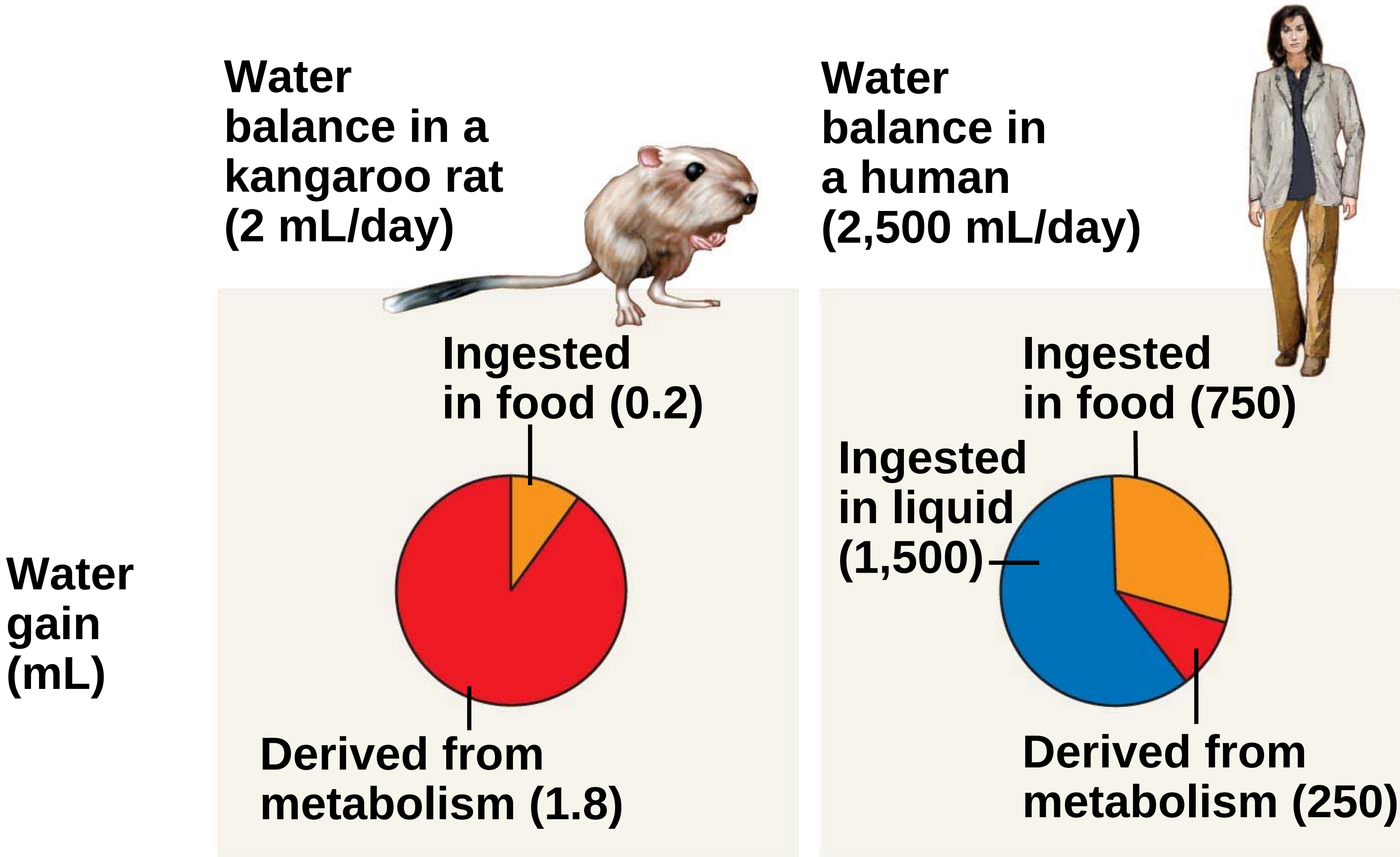
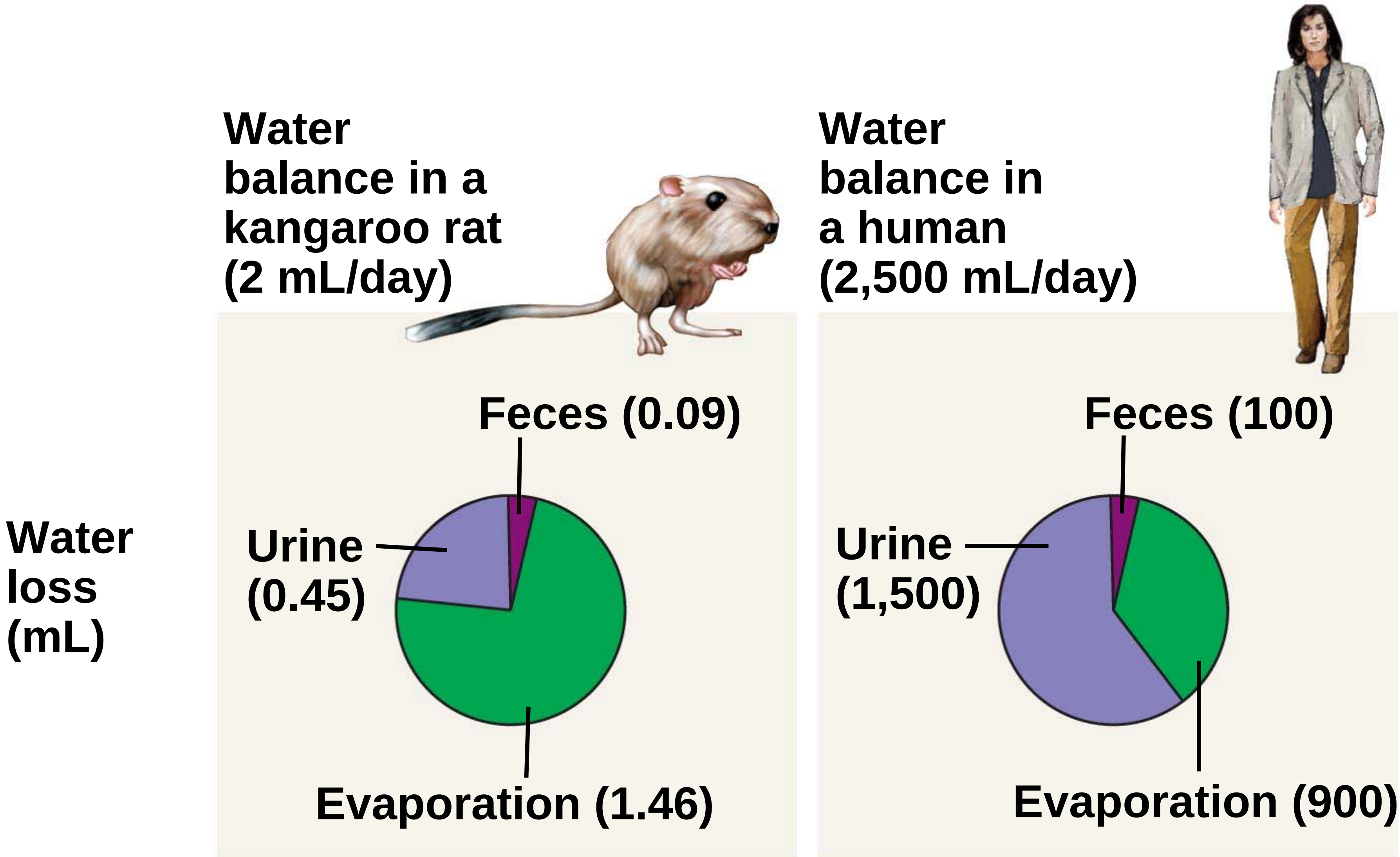

Water
gain
(mL)
Water
balance in a
kangaroo rat
(2 mL/day)
Ingested
in food (0.2)
Derived from
metabolism (1.8)
Water
balance in
a human
(2,500 mL/day)
Ingested
in food (750)
Ingested
in liquid
(1,500)
Derived from
metabolism (250)

Fig. 44-6b


Water balance in a kangaroo rat (2 mL/day)
Water balance in a human (2,500 mL/day)
Water loss (mL)
Feces (0.09)
Urine (0.45)
Evaporation (1.46)
Feces (100)
Urine (1,500)
Evaporation (900)

Energetics of Osmoregulation

- Osmoregulators must expend energy to maintain osmotic gradients

Transport Epithelia in Osmoregulation

- Animals regulate the composition of body fluid that bathes their cells
- **Transport epithelia** are specialized epithelial cells that regulate solute movement
- They are essential components of osmotic regulation and metabolic waste disposal
- They are arranged in complex tubular networks
- An example is in salt glands of marine birds, which remove excess sodium chloride from the blood

Fig. 44-7

EXPERIMENT

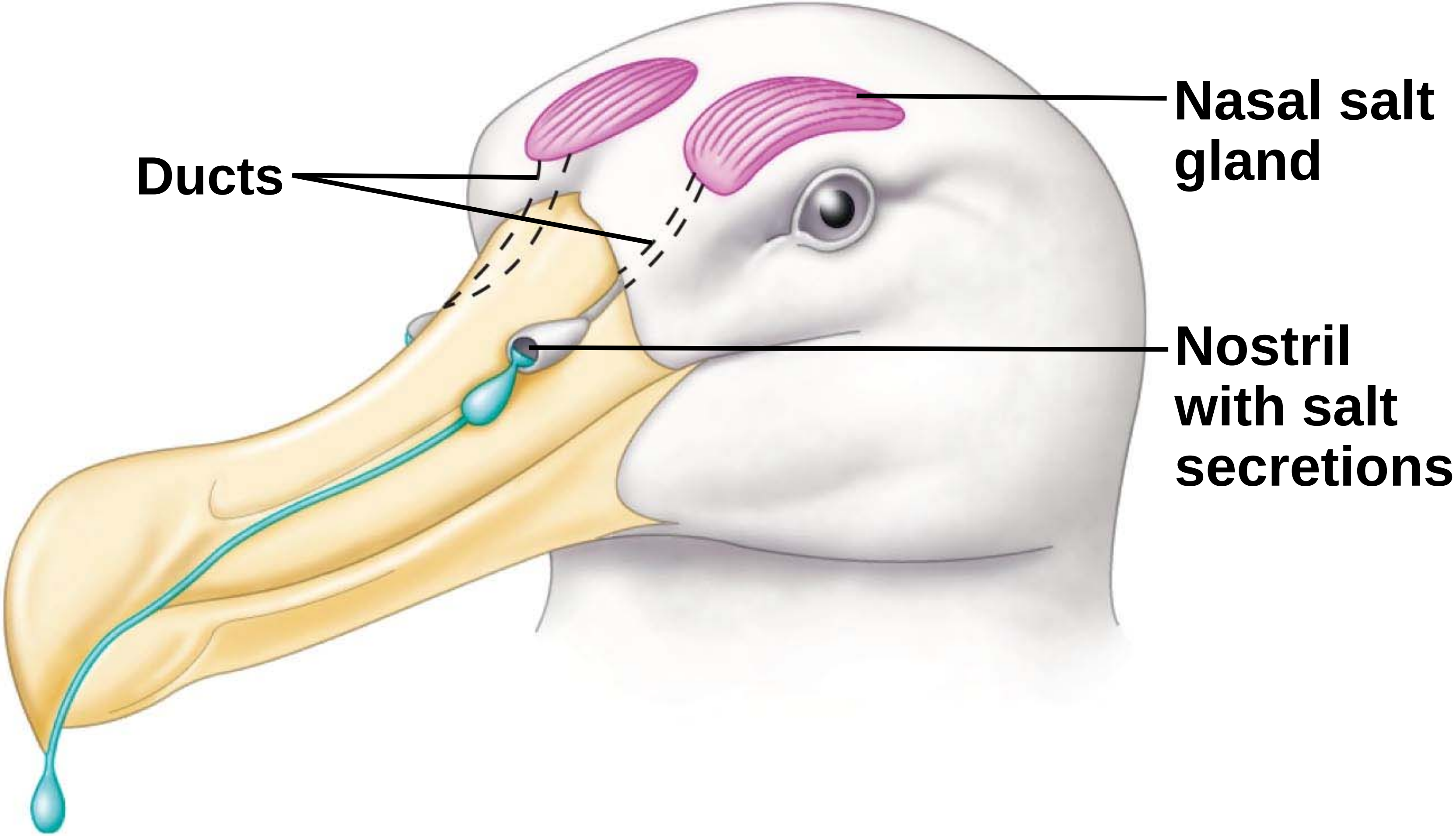
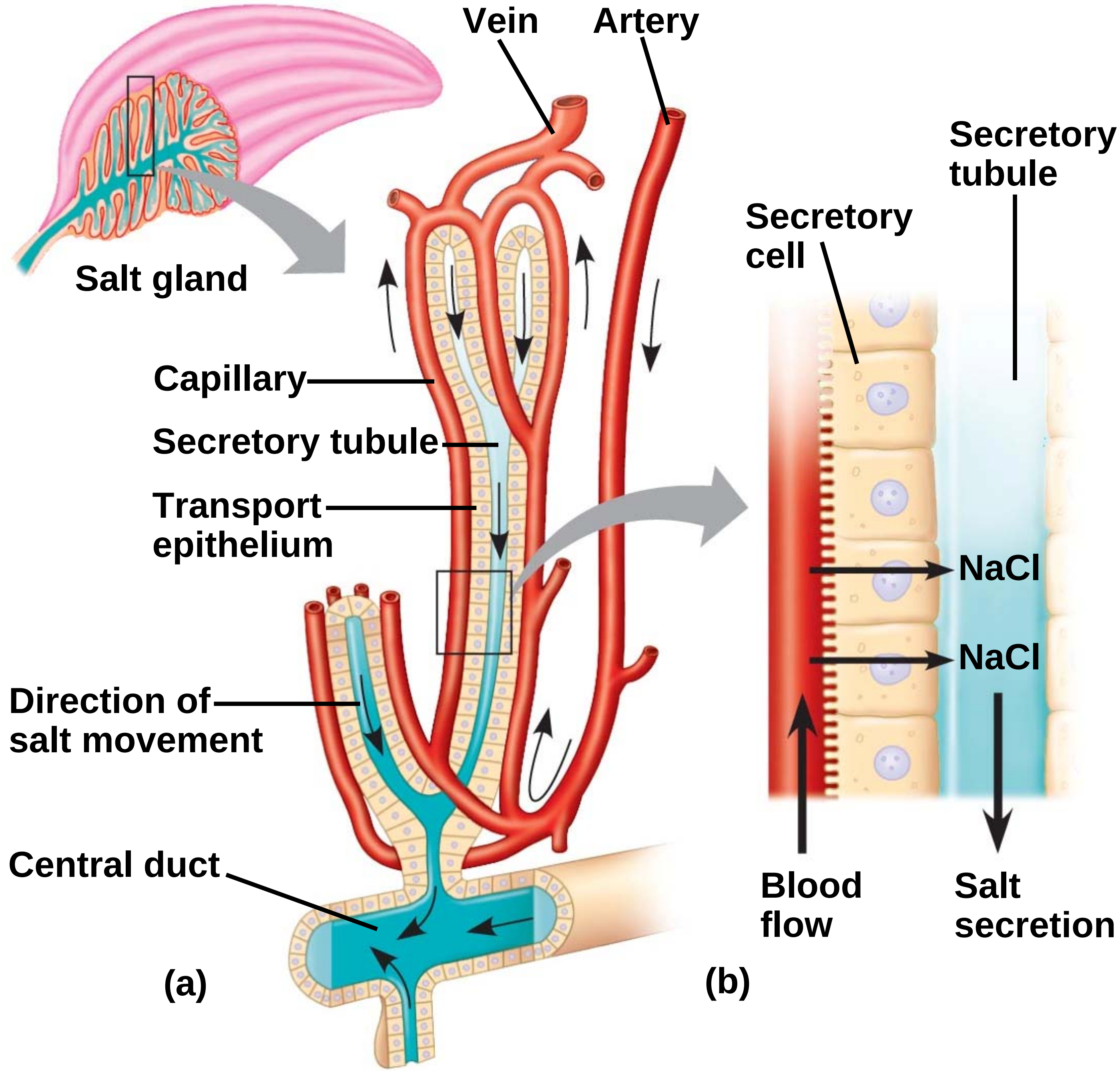


Fig. 44-8

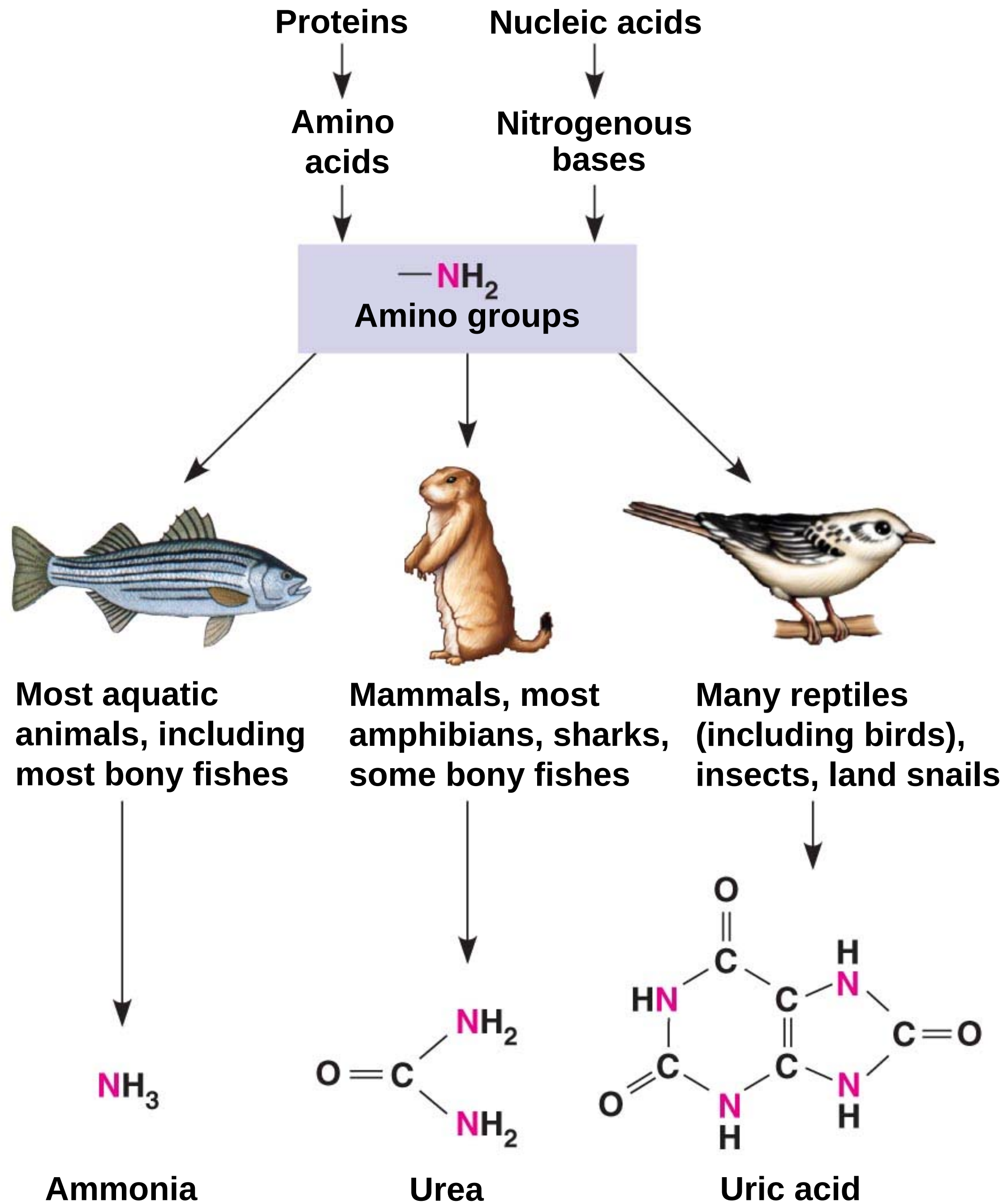


Vein
Artery
Salt gland
Capillary
Secretory tubule
Transport epithelium
Direction of salt movement
Central duct
(a)
Secretory tubule
Secretory cell
NaCl
NaCl
Blood flow
Salt secretion
(b)

Concept 44.2: An animal's nitrogenous wastes reflect its phylogeny and habitat

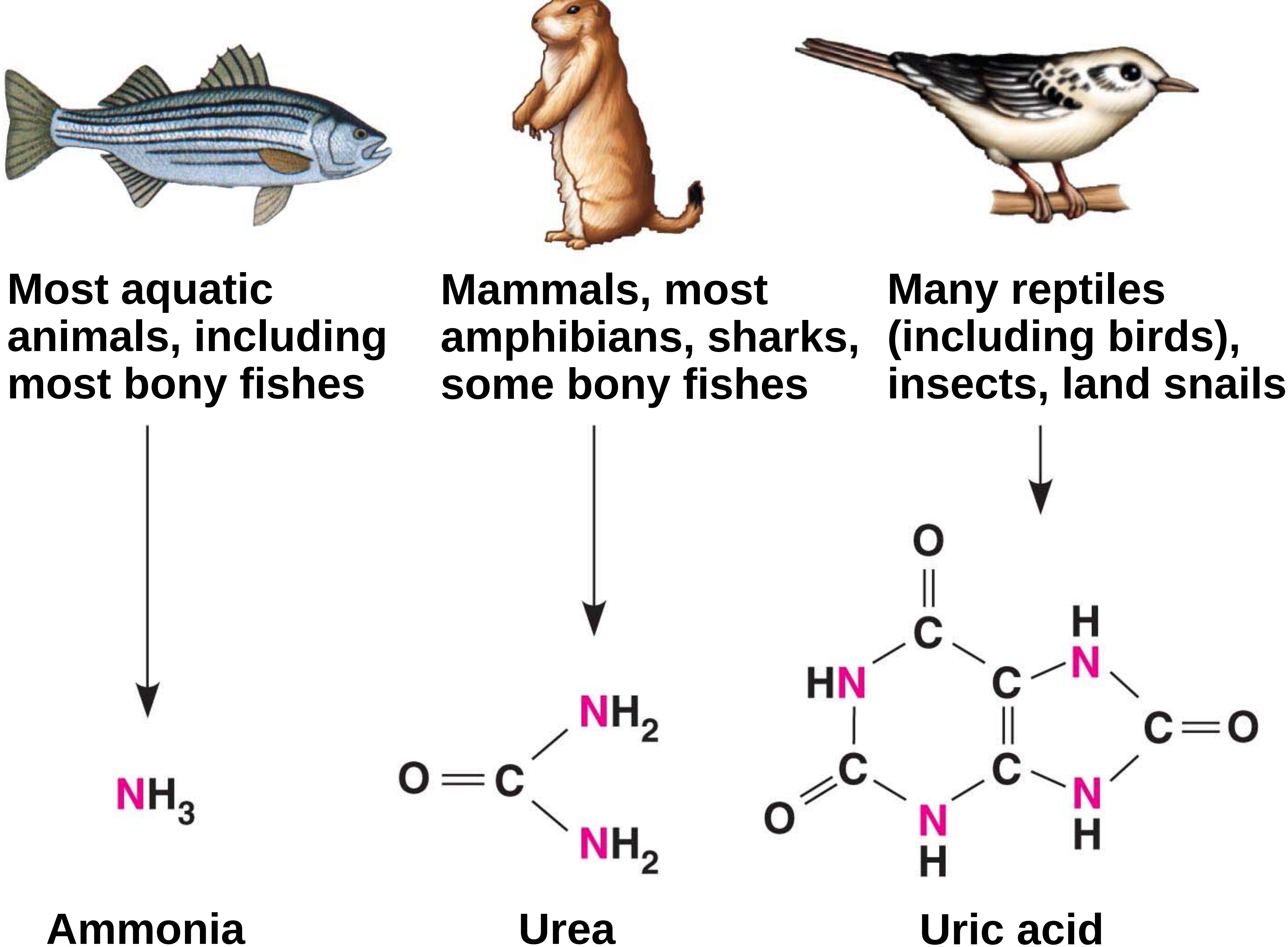
- The type and quantity of an animal's waste products may greatly affect its water balance
- Among the most important wastes are nitrogenous breakdown products of proteins and nucleic acids
- Some animals convert toxic **ammonia** (NH_3) to less toxic compounds prior to excretion

Fig. 44-9



Proteins
Nucleic acids
Amino acids
Nitrogenous bases
—NH2
Amino groups
Most aquatic animals, including most bony fishes
Mammals, most amphibians, sharks, some bony fishes
Many reptiles (including birds), insects, land snails
NH3
Ammonia
Urea
Uric acid

Fig. 44-9a


Most aquatic animals, including most bony fishes
Mammals, most amphibians, sharks, some bony fishes
Many reptiles (including birds), insects, land snails
NH3
NH2
O = C
NH2
O
C
HN
C
H
N
C = O
C
C
O
N
H
N
H
Ammonia
Urea
Uric acid

Forms of Nitrogenous Wastes

- Different animals excrete nitrogenous wastes in different forms: ammonia, urea, or uric acid

Ammonia

- Animals that excrete nitrogenous wastes as ammonia need lots of water
- They release ammonia across the whole body surface or through gills

Urea

- The liver of mammals and most adult amphibians converts ammonia to less toxic **urea**
- The circulatory system carries urea to the kidneys, where it is excreted
- Conversion of ammonia to urea is energetically expensive; excretion of urea requires less water than ammonia

Uric Acid

- Insects, land snails, and many reptiles, including birds, mainly excrete **uric acid**
- Uric acid is largely insoluble in water and can be secreted as a paste with little water loss
- Uric acid is more energetically expensive to produce than urea

The Influence of Evolution and Environment on Nitrogenous Wastes

- The kinds of nitrogenous wastes excreted depend on an animal’s evolutionary history and habitat
- The amount of nitrogenous waste is coupled to the animal’s energy budget

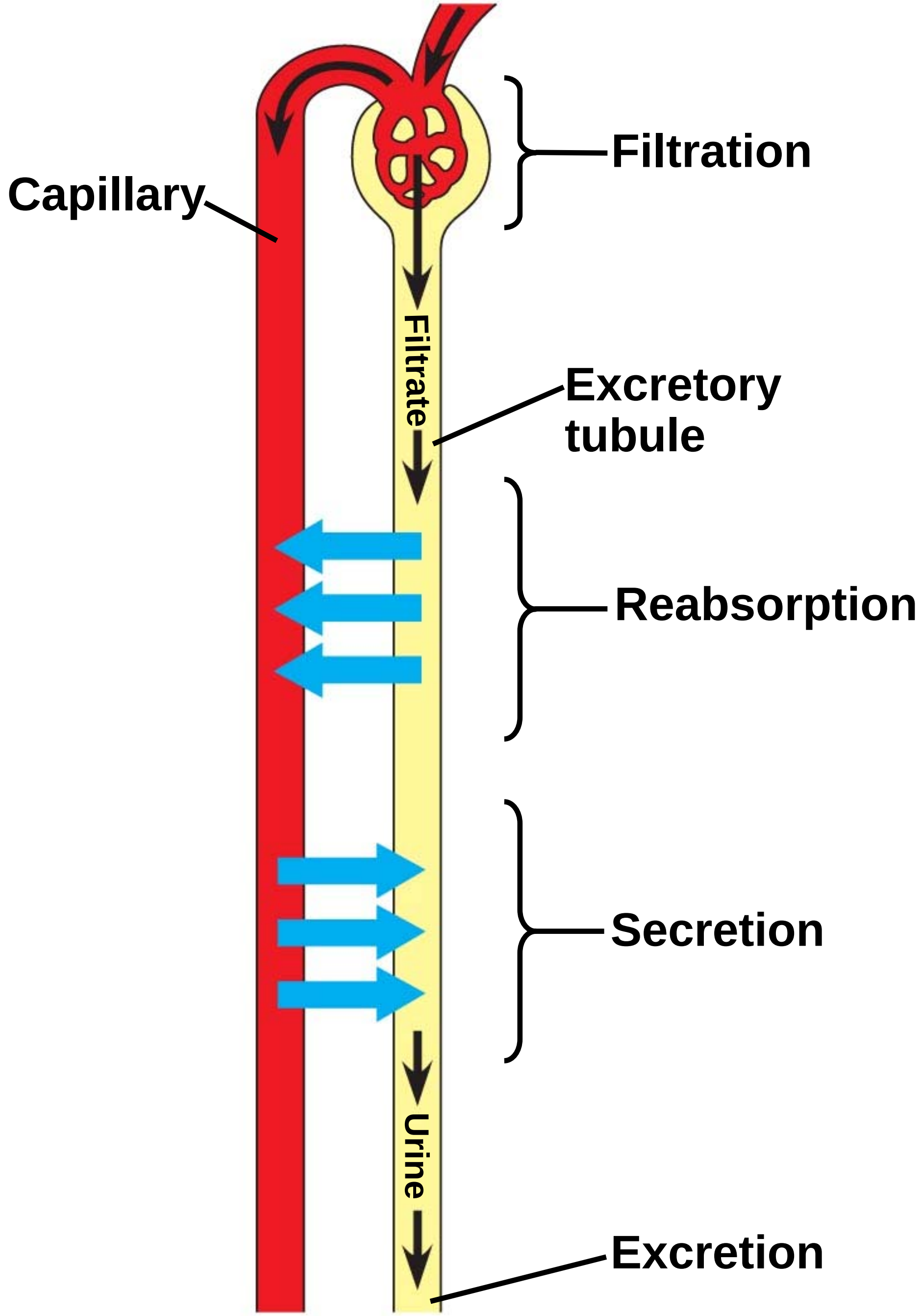
Concept 44.3: Diverse excretory systems are variations on a tubular theme

- Excretory systems regulate solute movement between internal fluids and the external environment

Excretory Processes

- Most excretory systems produce urine by refining a **filtrate** derived from body fluids
- Key functions of most excretory systems:
  - **Filtration**: pressure-filtering of body fluids
  - **Reabsorption**: reclaiming valuable solutes
  - **Secretion**: adding toxins and other solutes from the body fluids to the filtrate
  - Excretion: removing the filtrate from the system

Fig. 44-10



Capillary
Filtration
Filtrate
Excretory tubule
Reabsorption
Secretion
Urine
Excretion

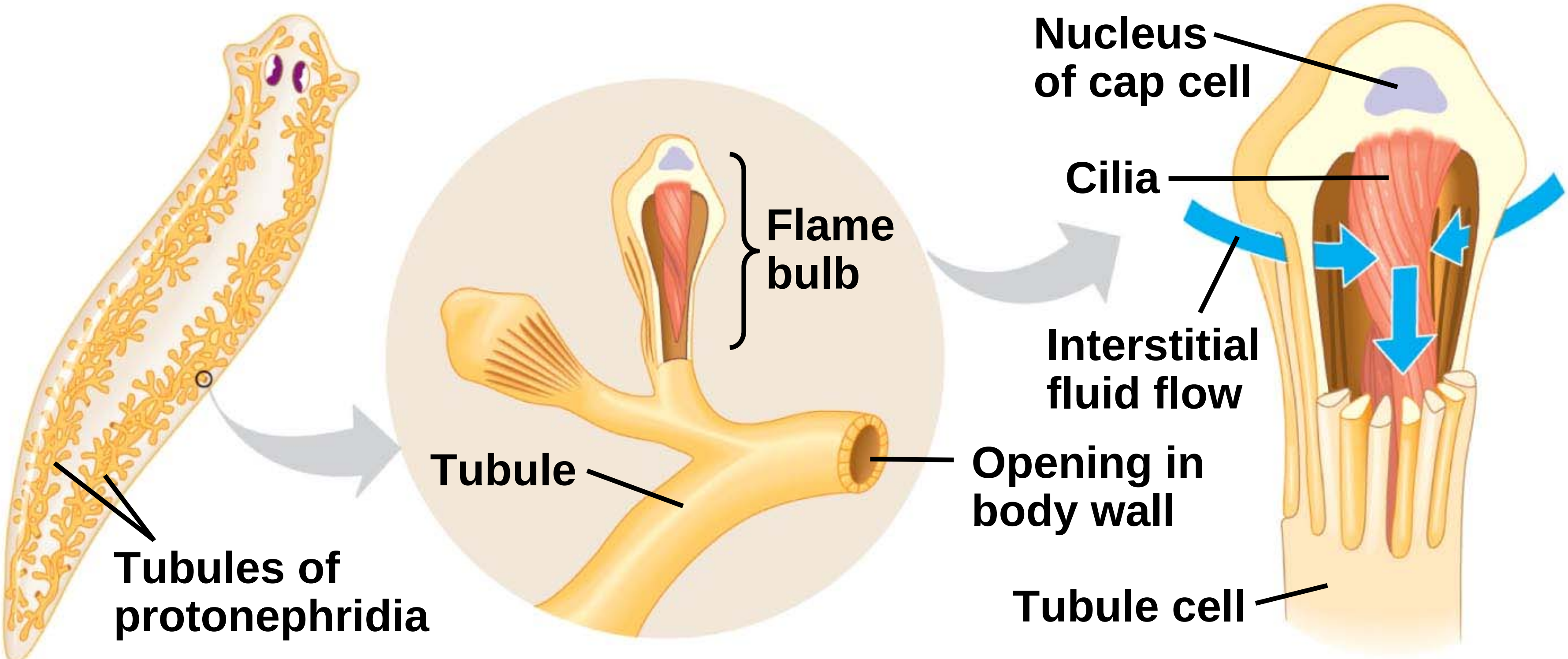
Survey of Excretory Systems

- Systems that perform basic excretory functions vary widely among animal groups
- They usually involve a complex network of tubules

Protonephridia

- A **protonephridium** is a network of dead-end tubules connected to external openings
- The smallest branches of the network are capped by a cellular unit called a flame bulb
- These tubules excrete a dilute fluid and function in osmoregulation

Fig. 44-11

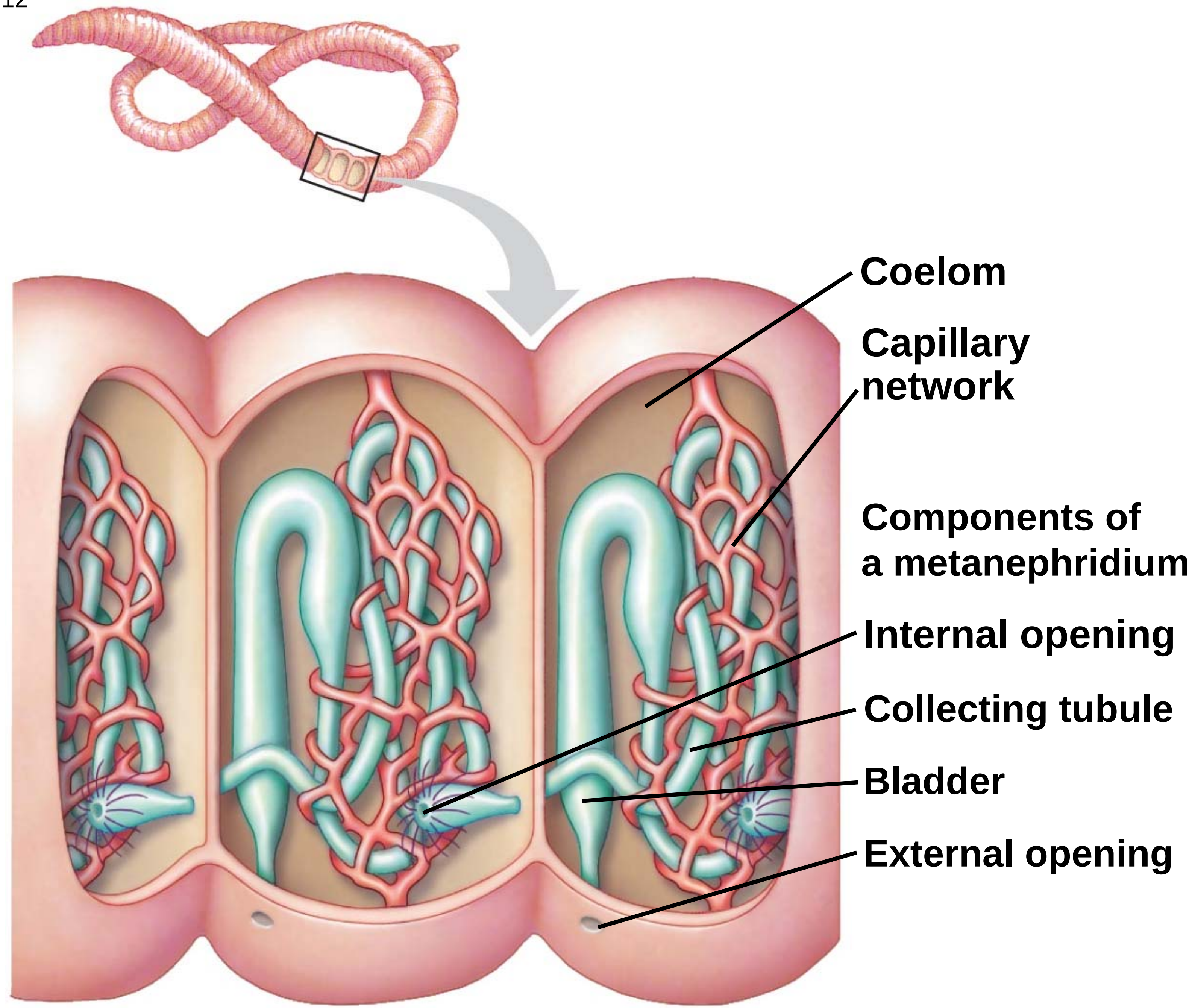


Nucleus of cap cell
Cilia
Flame bulb
Interstitial fluid flow
Tubule
Opening in body wall
Tubules of protonephridia
Tubule cell

Metanephridia

- Each segment of an earthworm has a pair of open-ended **metanephridia**
- Metanephridia consist of tubules that collect coelomic fluid and produce dilute urine for excretion

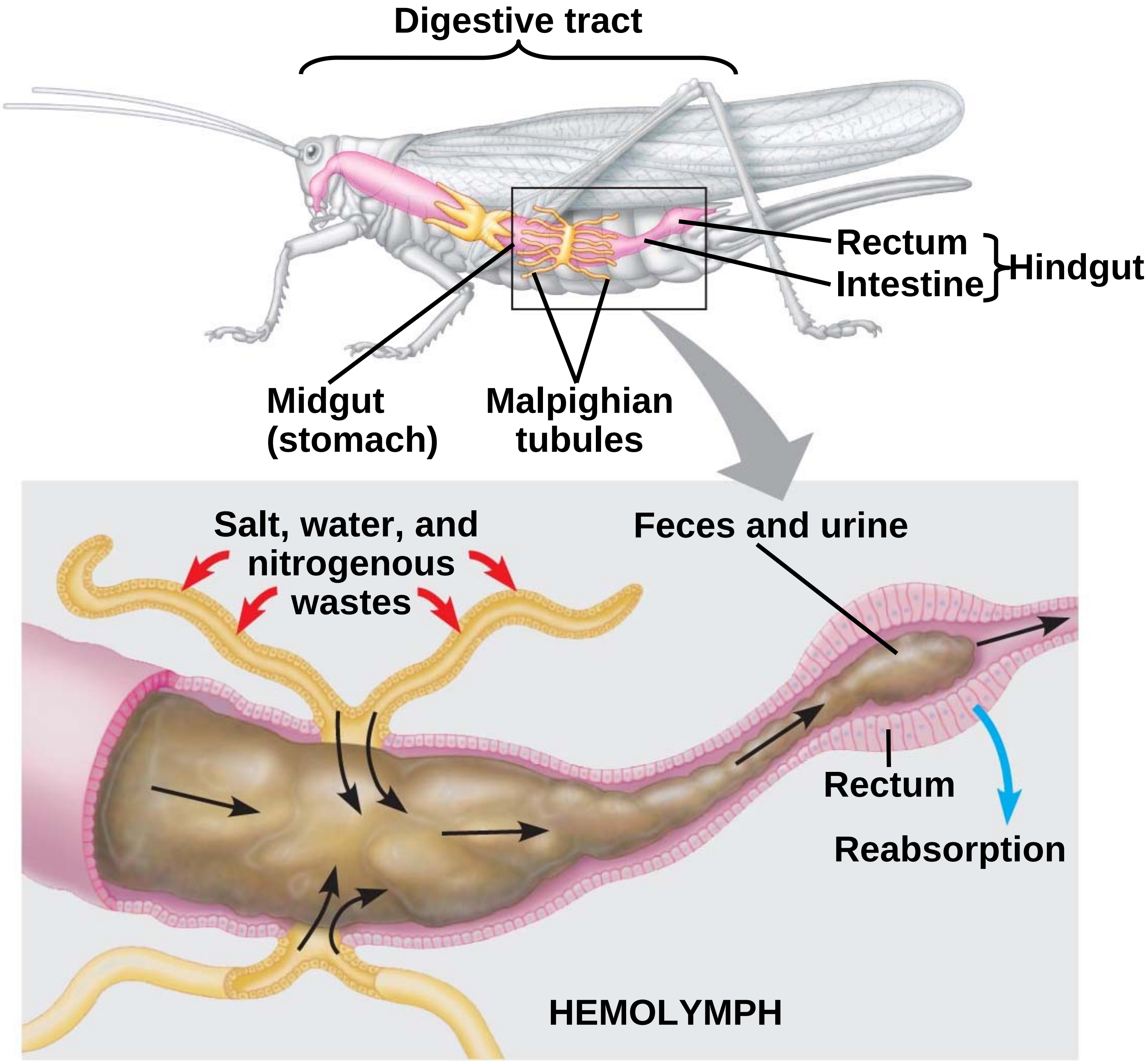
Fig. 44-12


Coelom
Capillary network
Components of a metanephridium:
Internal opening
Collecting tubule
Bladder
External opening

Malpighian Tubules

- In insects and other terrestrial arthropods, **Malpighian tubules** remove nitrogenous wastes from hemolymph and function in osmoregulation
- Insects produce a relatively dry waste matter, an important adaptation to terrestrial life

Fig. 44-13


Digestive tract
Rectum
Intestine
Hindgut
Midgut
(stomach)
Malpighian
tubules
Salt, water, and
nitrogenous
wastes
Feces and urine
Rectum
Reabsorption
HEMOLYMPH

Kidneys

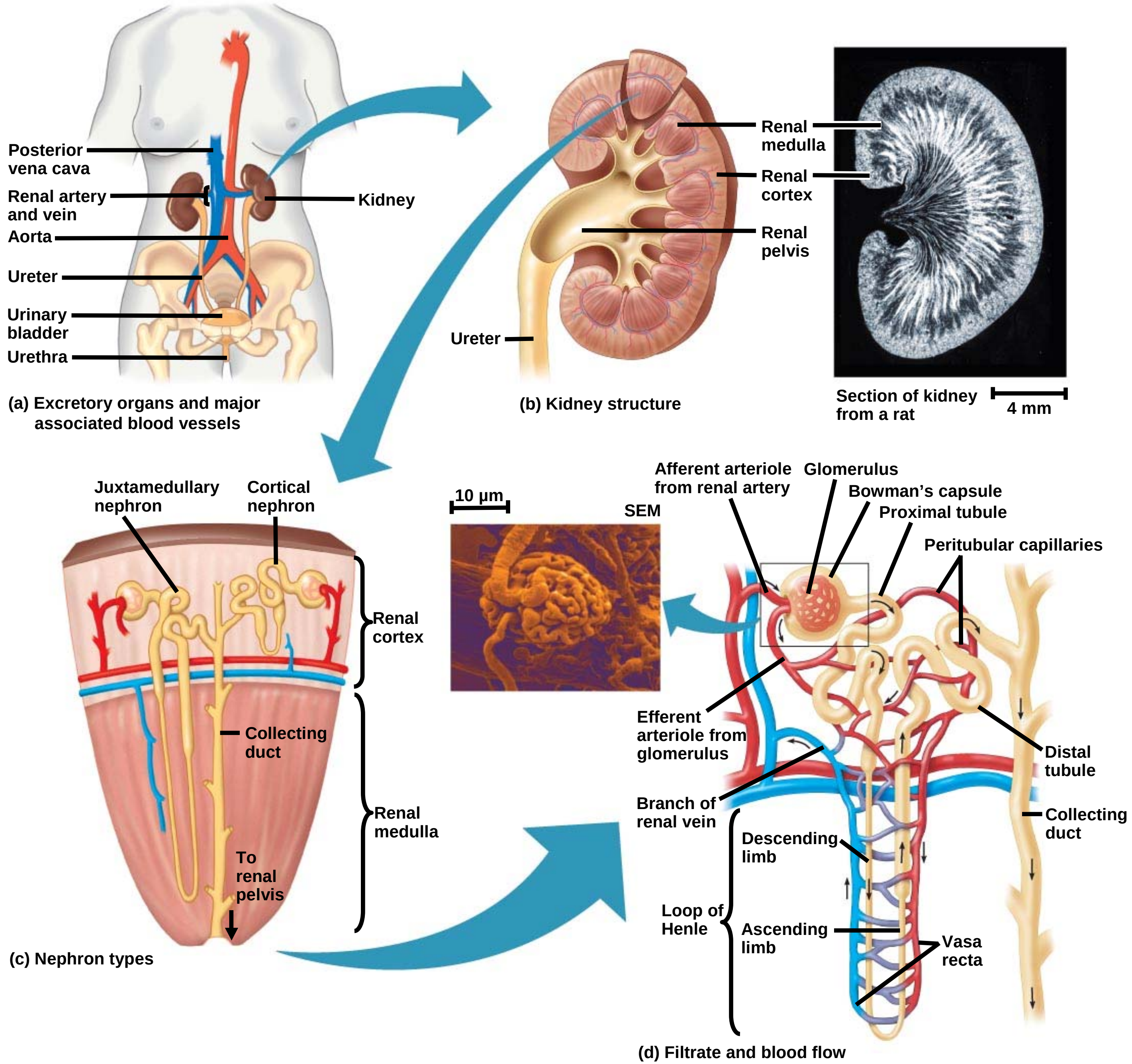
- Kidneys, the excretory organs of vertebrates, function in both excretion and osmoregulation

Structure of the Mammalian Excretory System

- The mammalian excretory system centers on paired kidneys, which are also the principal site of water balance and salt regulation
- Each kidney is supplied with blood by a **renal artery** and drained by a **renal vein**
- Urine exits each kidney through a duct called the **ureter**
- Both ureters drain into a common **urinary bladder**, and urine is expelled through a **urethra**

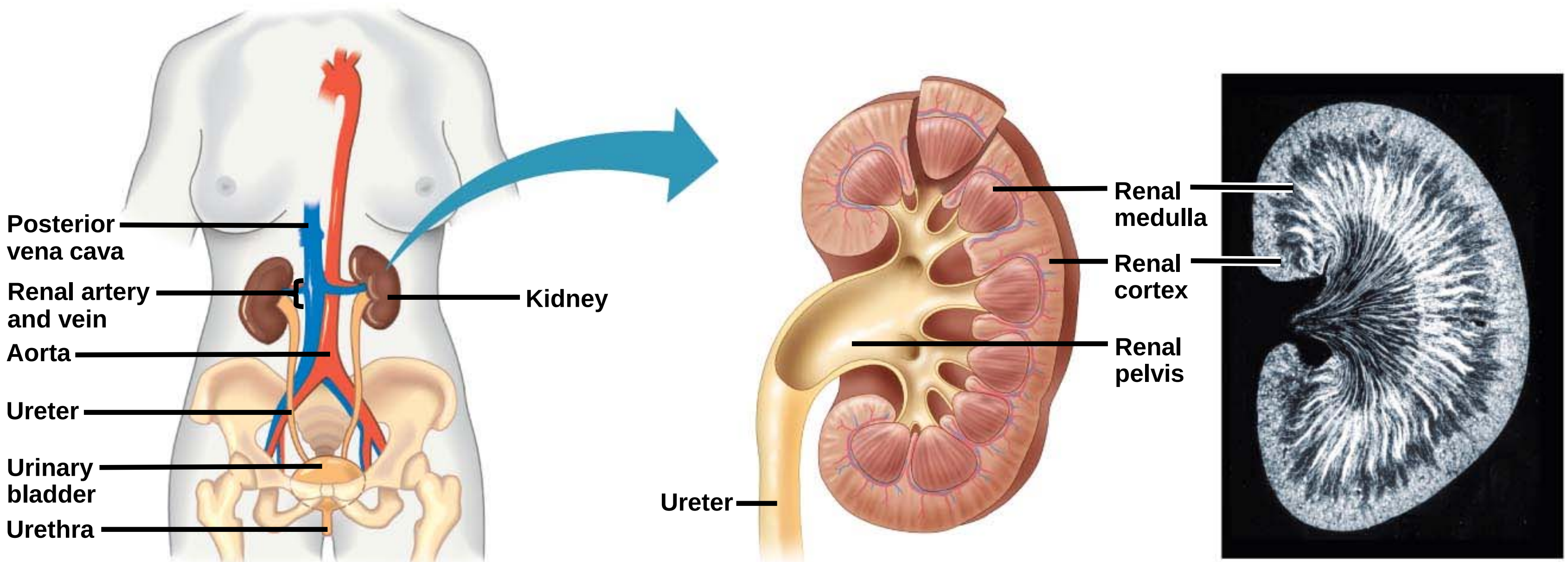
PLAY Animation: Nephron Introduction

Fig. 44-14



Posterior vena cava
Renal artery and vein
Aorta
Ureter
Urinary bladder
Urethra
Kidney
(a) Excretory organs and major associated blood vessels
Renal medulla
Renal cortex
Renal pelvis
Ureter
(b) Kidney structure
Section of kidney from a rat
4 mm
Juxtamedullary nephron
Cortical nephron
Renal cortex
Collecting duct
Renal medulla
To renal pelvis
(c) Nephron types
10 µm
SEM
Afferent arteriole from renal artery
Glomerulus
Bowman's capsule
Proximal tubule
Peritubular capillaries
Efferent arteriole from glomerulus
Branch of renal vein
Distal tubule
Collecting duct
Descending limb
Loop of Henle
Ascending limb
Vasa recta
(d) Filtrate and blood flow

Fig. 44-14ab



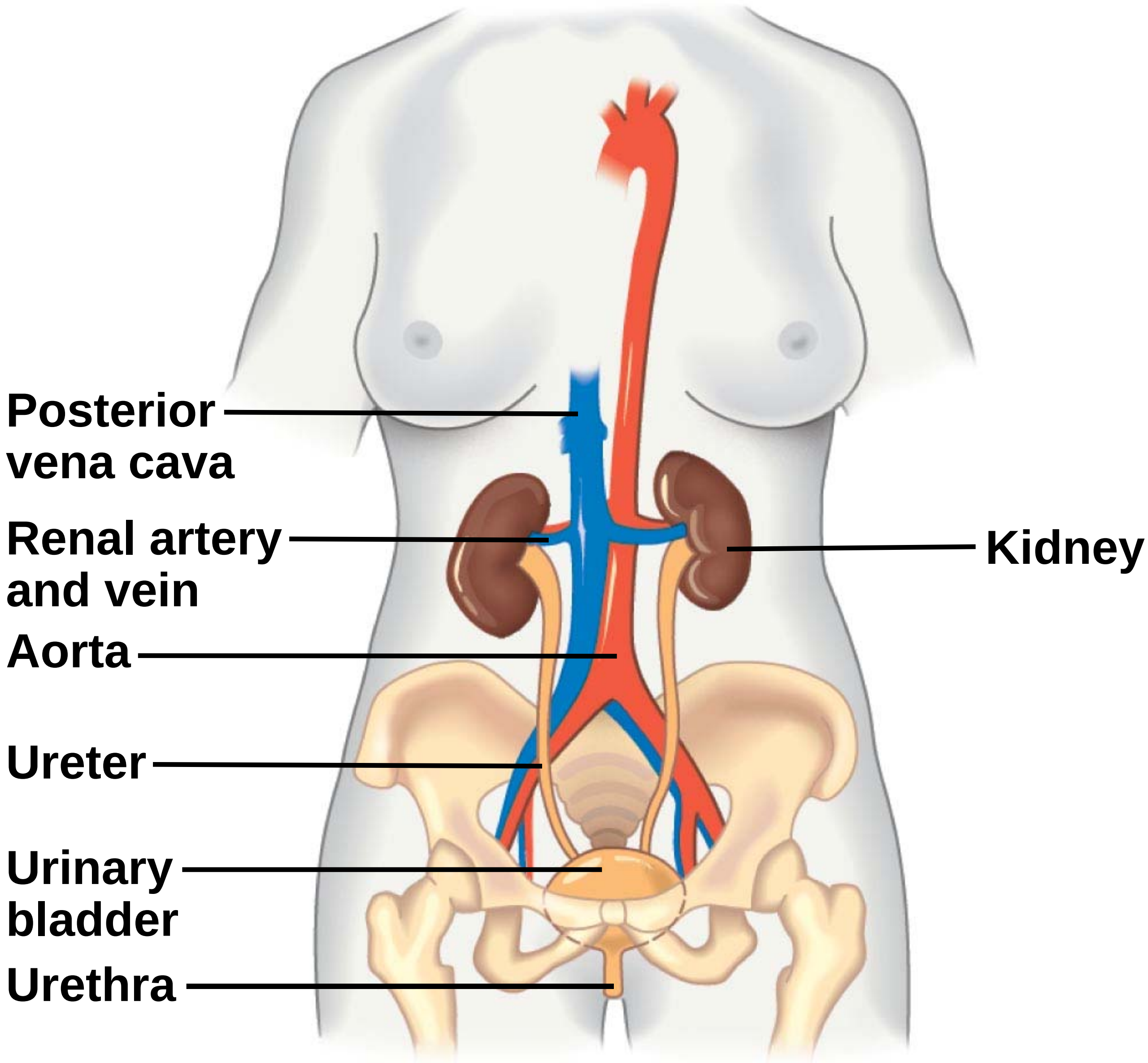
(a) Excretory organs and major associated blood vessels

(b) Kidney structure

Section of kidney from a rat

4 mm

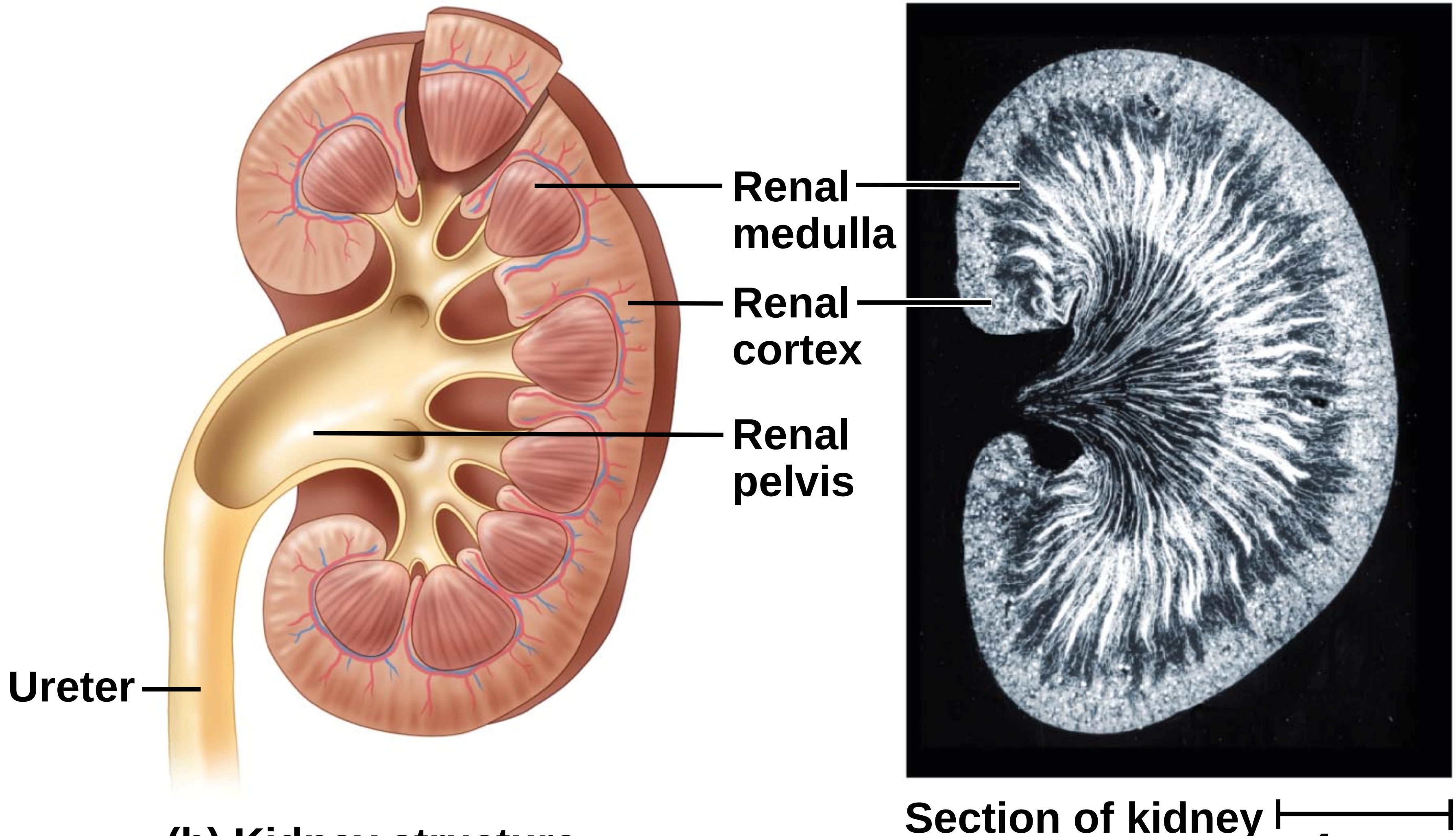
Fig. 44-14a



(a) Excretory organs and major associated blood vessels

- The mammalian kidney has two distinct regions: an outer **renal cortex** and an inner **renal medulla**

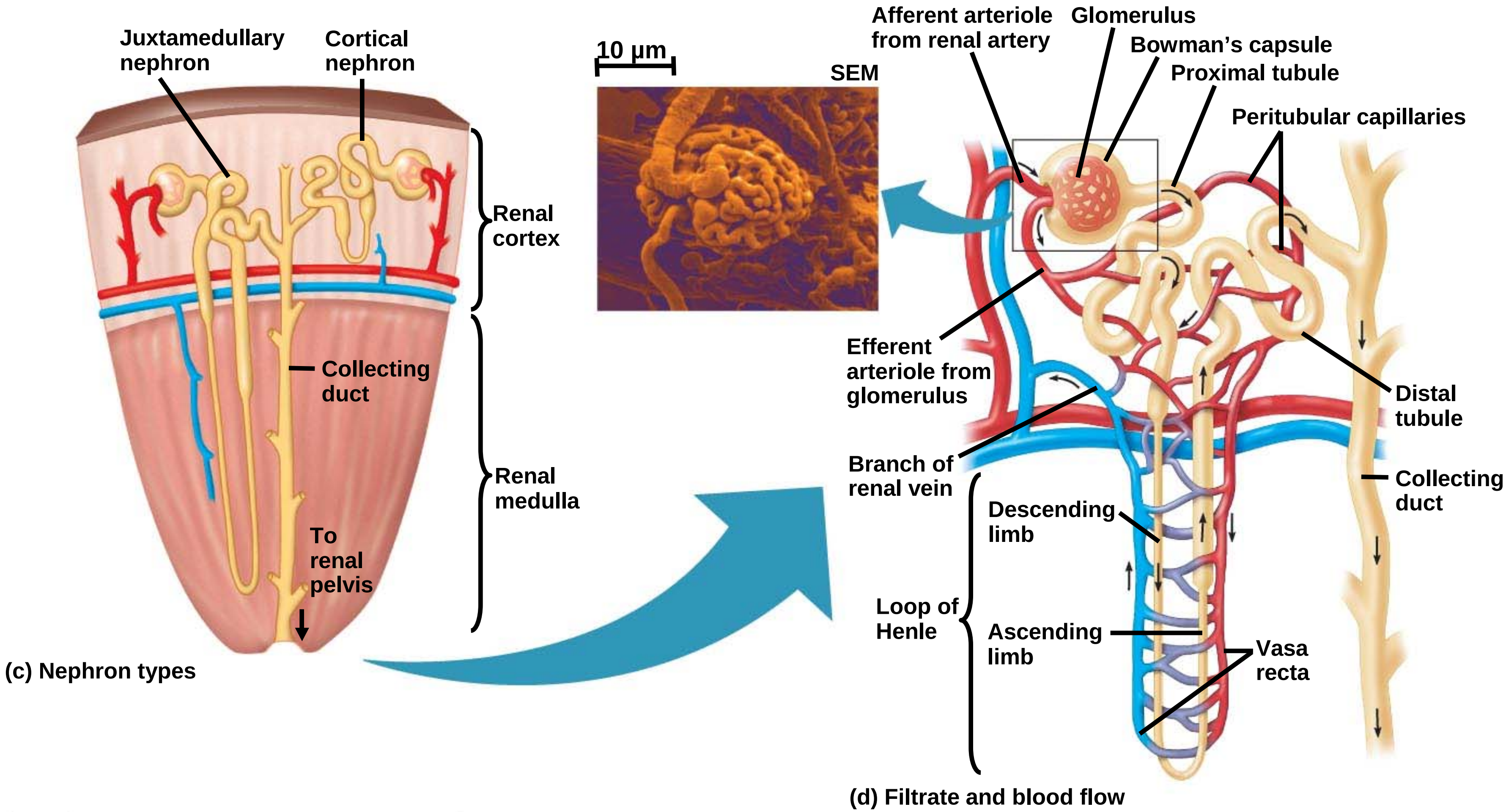
Fig. 44-14b



(b) Kidney structure

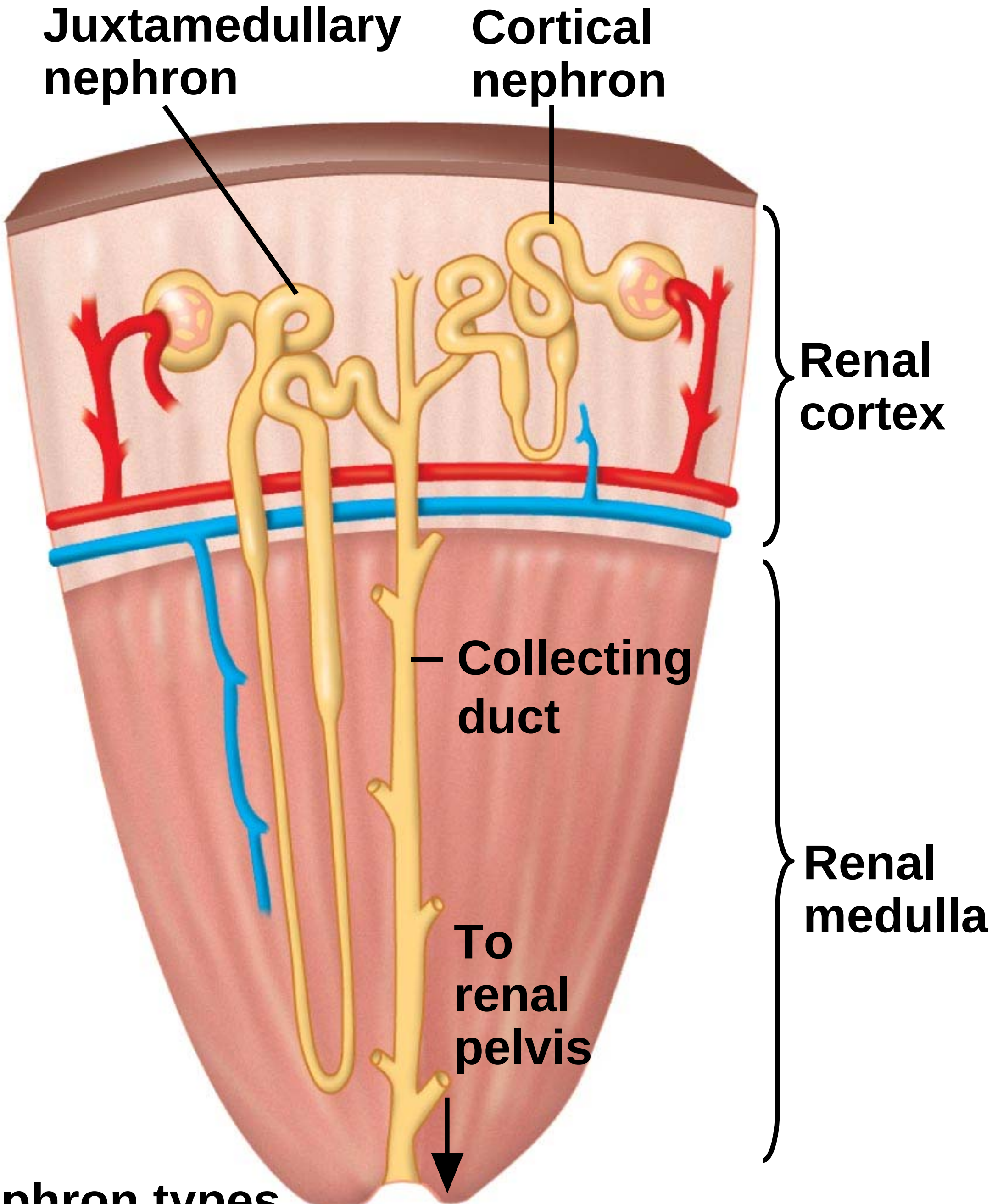
Section of kidney from a rat

Fig. 44-14cd


Juxtamedullary nephron
Cortical nephron
Renal cortex
Collecting duct
Renal medulla
To renal pelvis
(c) Nephron types
10 µm
SEM
Afferent arteriole from renal artery
Glomerulus
Bowman's capsule
Proximal tubule
Peritubular capillaries
Efferent arteriole from glomerulus
Branch of renal vein
Distal tubule
Collecting duct
Descending limb
Loop of Henle
Ascending limb
Vasa recta
(d) Filtrate and blood flow

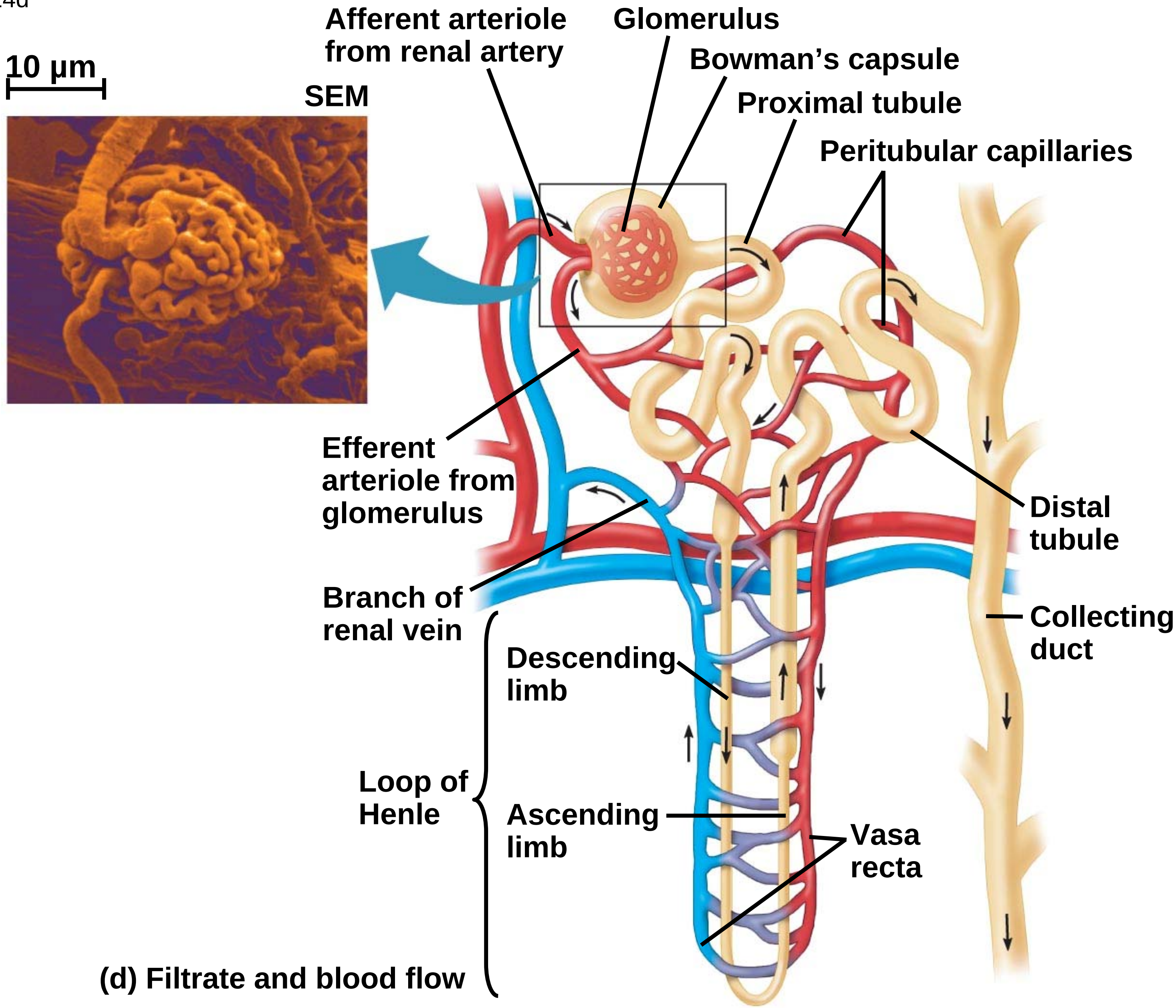
- The **nephron**, the functional unit of the vertebrate kidney, consists of a single long tubule and a ball of capillaries called the **glomerulus**
- **Bowman's capsule** surrounds and receives filtrate from the glomerulus

Fig. 44-14c



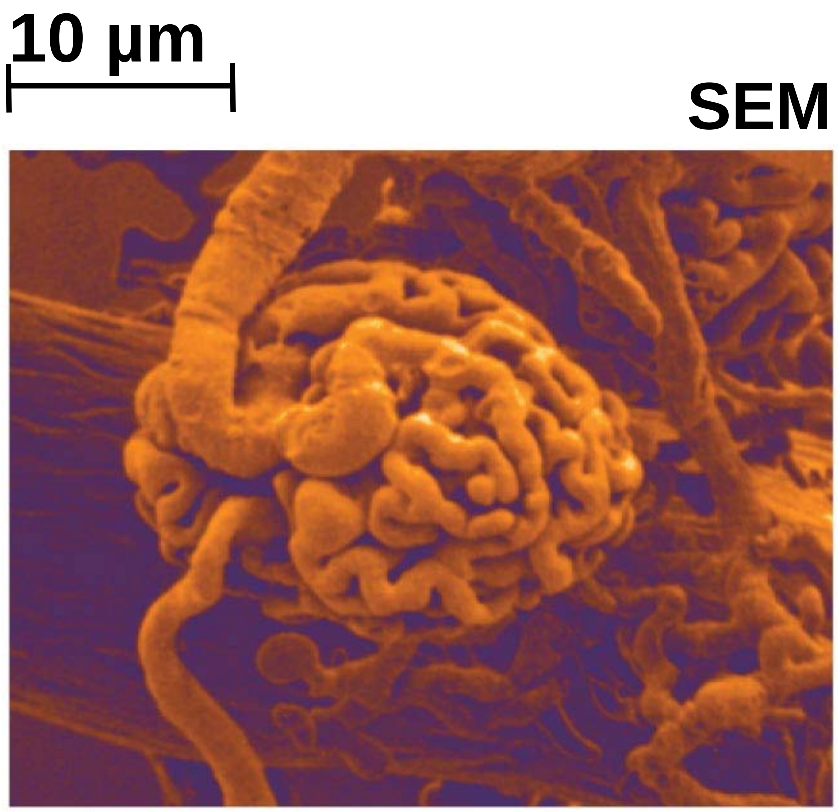
(c) Nephron types

Fig. 44-14d



(d) Filtrate and blood flow

Fig. 44-14e



Filtration of the Blood

- Filtration occurs as blood pressure forces fluid from the blood in the glomerulus into the lumen of Bowman's capsule
- Filtration of small molecules is nonselective
- The filtrate contains salts, glucose, amino acids, vitamins, nitrogenous wastes, and other small molecules

Pathway of the Filtrate

- From Bowman’s capsule, the filtrate passes through three regions of the nephron: the **proximal tubule**, the **loop of Henle**, and the **distal tubule**
- Fluid from several nephrons flows into a **collecting duct**, all of which lead to the **renal pelvis**, which is drained by the ureter
- **Cortical nephrons** are confined to the renal cortex, while **juxtamedullary nephrons** have loops of Henle that descend into the renal medulla

Blood Vessels Associated with the Nephrons

- Each nephron is supplied with blood by an **afferent arteriole**, a branch of the renal artery that divides into the capillaries
- The capillaries converge as they leave the glomerulus, forming an **efferent arteriole**
- The vessels divide again, forming the **peritubular capillaries**, which surround the proximal and distal tubules

- **Vasa recta** are capillaries that serve the loop of Henle
- The vasa recta and the loop of Henle function as a countercurrent system

Concept 44.4: The nephron is organized for stepwise processing of blood filtrate

- The mammalian kidney conserves water by producing urine that is much more concentrated than body fluids

From Blood Filtrate to Urine: *A Closer Look*

Proximal Tubule

- Reabsorption of ions, water, and nutrients takes place in the proximal tubule
- Molecules are transported actively and passively from the filtrate into the interstitial fluid and then capillaries
- Some toxic materials are secreted into the filtrate
- The filtrate volume decreases

PLAY **Animation: Bowman's Capsule and Proximal Tubule**

Descending Limb of the Loop of Henle

- Reabsorption of water continues through channels formed by **aquaporin** proteins
- Movement is driven by the high osmolarity of the interstitial fluid, which is hyperosmotic to the filtrate
- The filtrate becomes increasingly concentrated

Ascending Limb of the Loop of Henle

- In the ascending limb of the loop of Henle, salt but not water is able to diffuse from the tubule into the interstitial fluid
- The filtrate becomes increasingly dilute

Distal Tubule

- The distal tubule regulates the K^+ and NaCl concentrations of body fluids
- The controlled movement of ions contributes to pH regulation

PLAY

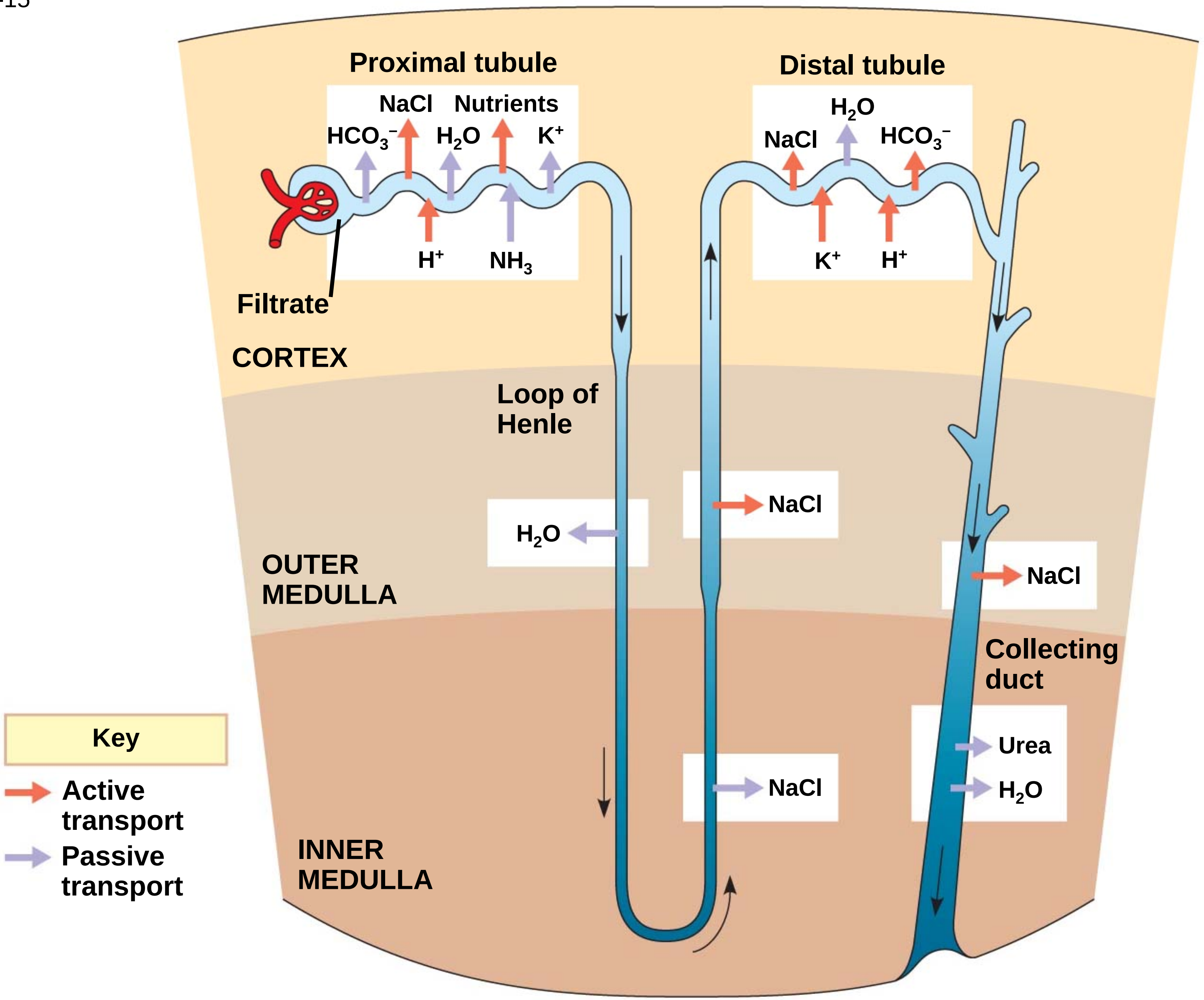
Animation: Loop of Henle and Distal Tubule

Collecting Duct

- The collecting duct carries filtrate through the medulla to the renal pelvis
- Water is lost as well as some salt and urea, and the filtrate becomes more concentrated
- Urine is hyperosmotic to body fluids

PLAY Animation: Collecting Duct

Fig. 44-15



Proximal tubule
NaCl
Nutrients
HCO_3^-
H_2O
K^+
H^+
NH_3
Filtrate
Distal tubule
H_2O
NaCl
HCO_3^-
K^+
H^+
CORTEX
Loop of Henle
H_2O
NaCl
OUTER MEDULLA
NaCl
Collecting duct
Urea
H_2O
NaCl
INNER MEDULLA
Key
Active transport
Passive transport

Solute Gradients and Water Conservation

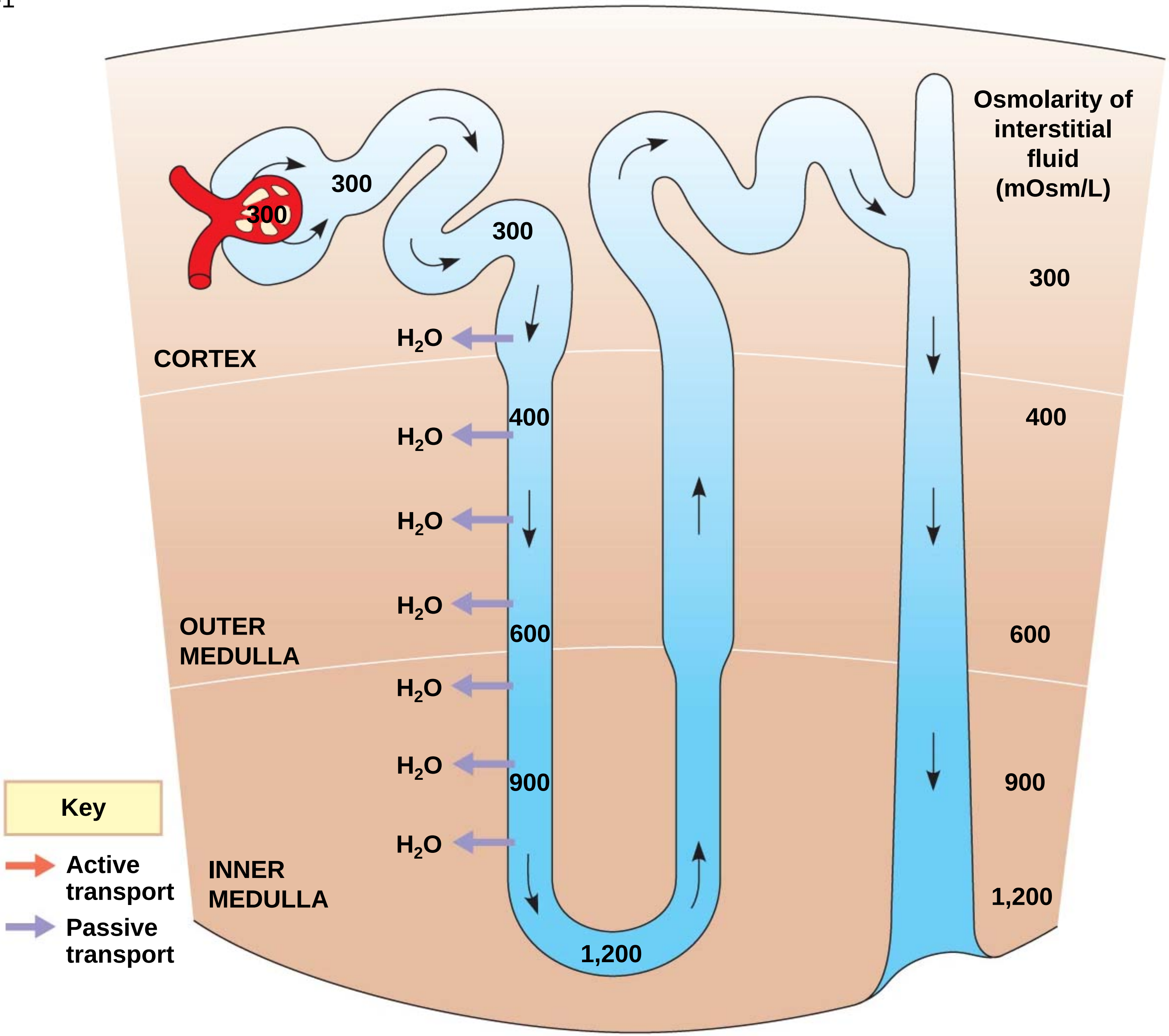
- Urine is much more concentrated than blood
- The cooperative action and precise arrangement of the loops of Henle and collecting ducts are largely responsible for the osmotic gradient that concentrates the urine
- NaCl and urea contribute to the osmolarity of the interstitial fluid, which causes reabsorption of water in the kidney and concentrates the urine

The Two-Solute Model

- In the proximal tubule, filtrate volume decreases, but its osmolarity remains the same
- The **countercurrent multiplier system** involving the loop of Henle maintains a high salt concentration in the kidney
- This system allows the vasa recta to supply the kidney with nutrients, without interfering with the osmolarity gradient
- Considerable energy is expended to maintain the osmotic gradient between the medulla and cortex

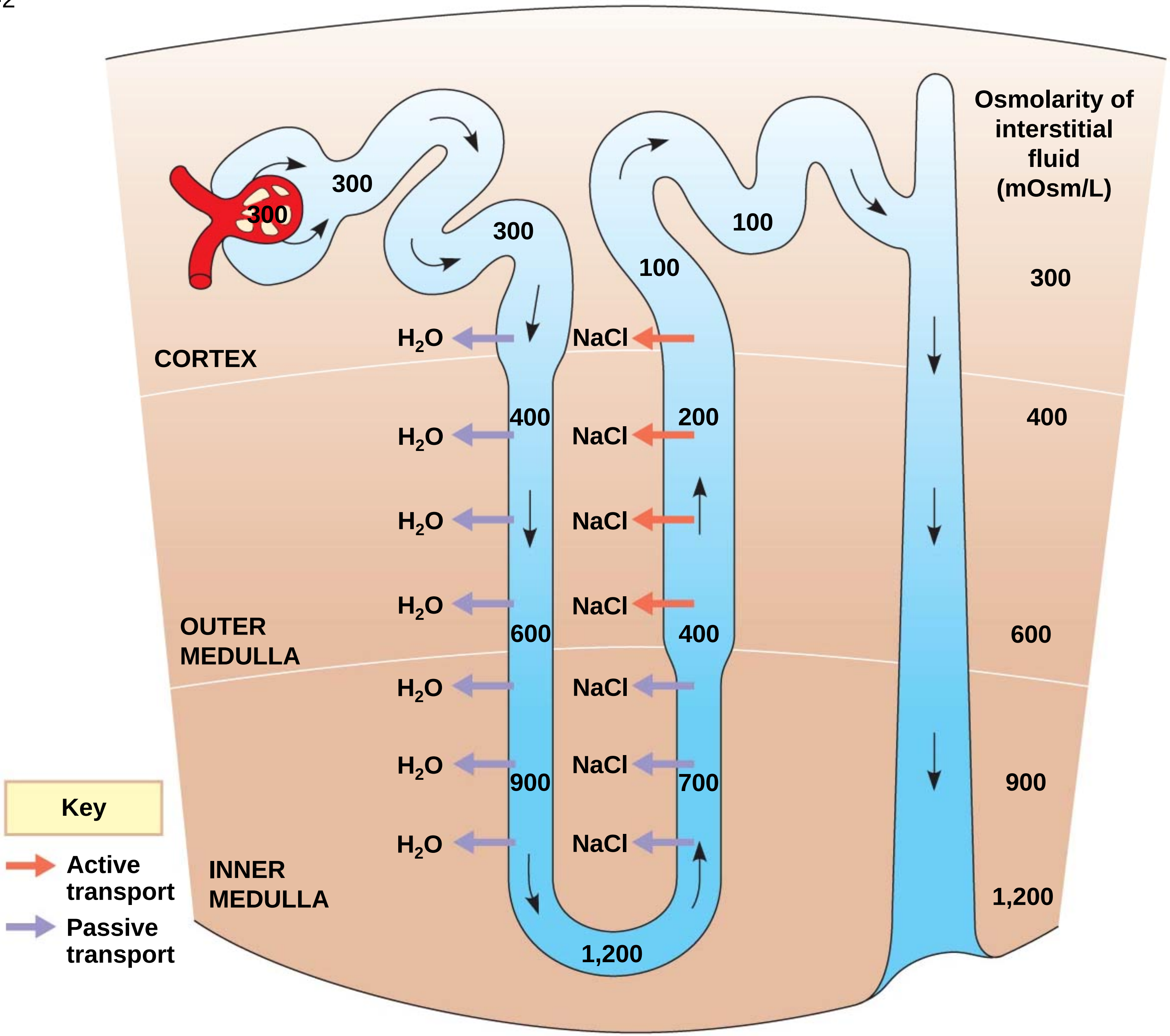
- The collecting duct conducts filtrate through the osmolarity gradient, and more water exits the filtrate by osmosis
- Urea diffuses out of the collecting duct as it traverses the inner medulla
- Urea and NaCl form the osmotic gradient that enables the kidney to produce urine that is hyperosmotic to the blood

Fig. 44-16-1



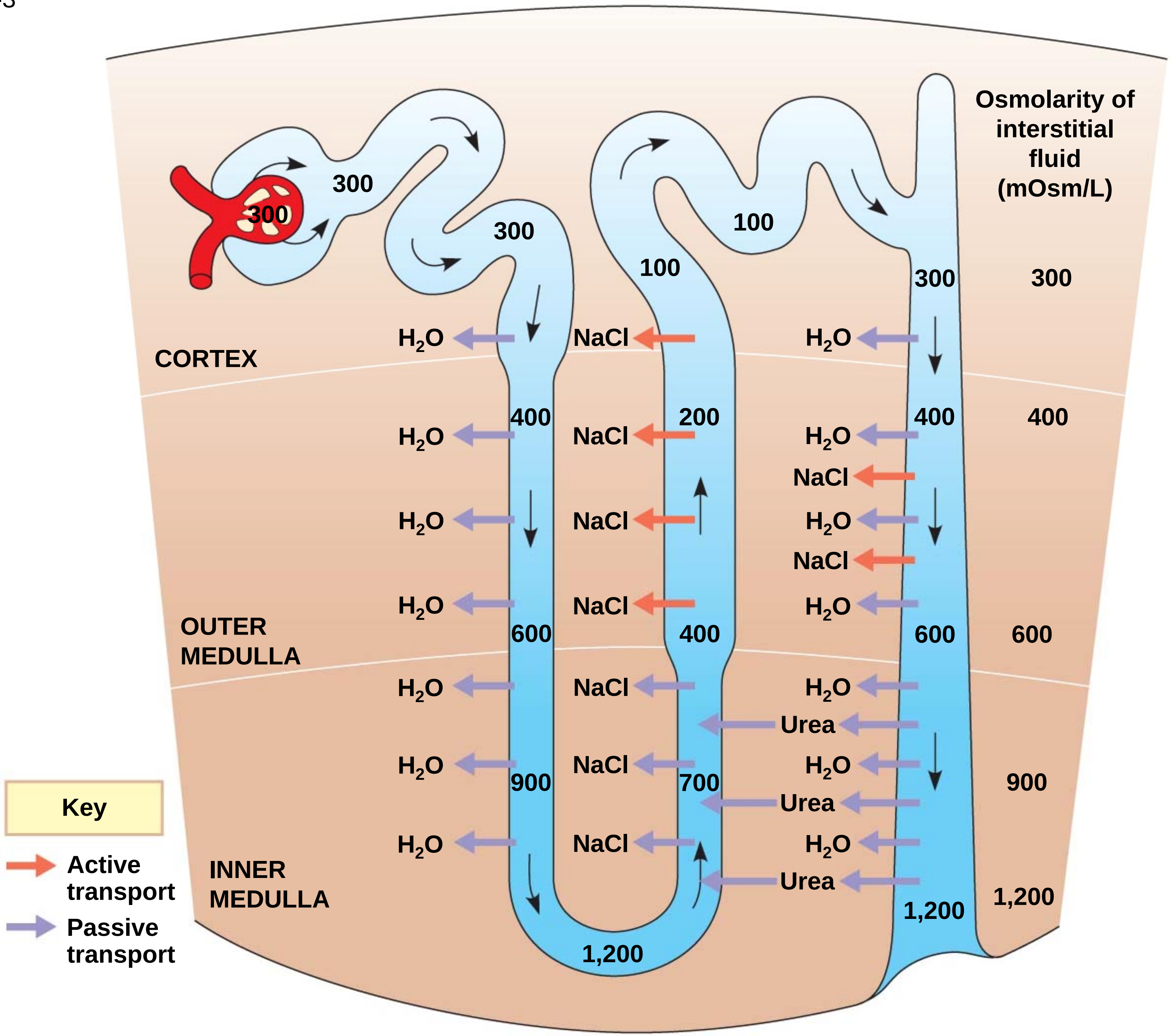
Osmolarity of interstitial fluid (mOsm/L)
300
300
300
300
CORTEX
H_2O
400
400
H_2O
H_2O
H_2O
OUTER MEDULLA
600
600
H_2O
H_2O
900
900
H_2O
INNER MEDULLA
1,200
1,200
Key
Active transport
Passive transport

Fig. 44-16-2



Osmolarity of interstitial fluid (mOsm/L)
300
300
300
100
100
300
CORTEX
H2O
NaCl
400
200
400
H2O
NaCl
H2O
NaCl
H2O
NaCl
OUTER MEDULLA
600
400
600
H2O
NaCl
H2O
NaCl
900
700
900
H2O
NaCl
INNER MEDULLA
1,200
1,200
Key
Active transport
Passive transport

Fig. 44-16-3



300
300
300
100
100
300
Osmolarity of interstitial fluid (mOsm/L)
300
CORTEX
H2O
NaCl
H2O
400
200
400
400
H2O
NaCl
H2O
NaCl
H2O
NaCl
H2O
NaCl
H2O
OUTER MEDULLA
600
400
600
600
H2O
NaCl
H2O
Urea
H2O
NaCl
H2O
900
700
900
Urea
H2O
NaCl
H2O
Urea
INNER MEDULLA
1,200
1,200
1,200
Key
Active transport
Passive transport

Adaptations of the Vertebrate Kidney to Diverse Environments

- The form and function of nephrons in various vertebrate classes are related to requirements for osmoregulation in the animal's habitat

Mammals

- The juxtamedullary nephron contributes to water conservation in terrestrial animals
- Mammals that inhabit dry environments have long loops of Henle, while those in fresh water have relatively short loops

Birds and Other Reptiles

- Birds have shorter loops of Henle but conserve water by excreting uric acid instead of urea
- Other reptiles have only cortical nephrons but also excrete nitrogenous waste as uric acid

Fig. 44-17

Freshwater Fishes and Amphibians

- Freshwater fishes conserve salt in their distal tubules and excrete large volumes of dilute urine
- Kidney function in amphibians is similar to freshwater fishes
- Amphibians conserve water on land by reabsorbing water from the urinary bladder

Marine Bony Fishes

- Marine bony fishes are hypoosmotic compared with their environment and excrete very little urine

Concept 44.5: Hormonal circuits link kidney function, water balance, and blood pressure

- Mammals control the volume and osmolarity of urine
- The kidneys of the South American vampire bat can produce either very dilute or very concentrated urine
- This allows the bats to reduce their body weight rapidly or digest large amounts of protein while conserving water

Fig. 44-18

Antidiuretic Hormone

- The osmolarity of the urine is regulated by nervous and hormonal control of water and salt reabsorption in the kidneys
- **Antidiuretic hormone (ADH)** increases water reabsorption in the distal tubules and collecting ducts of the kidney
- An increase in osmolarity triggers the release of ADH, which helps to conserve water

PLAY Animation: Effect of ADH

Fig. 44-19

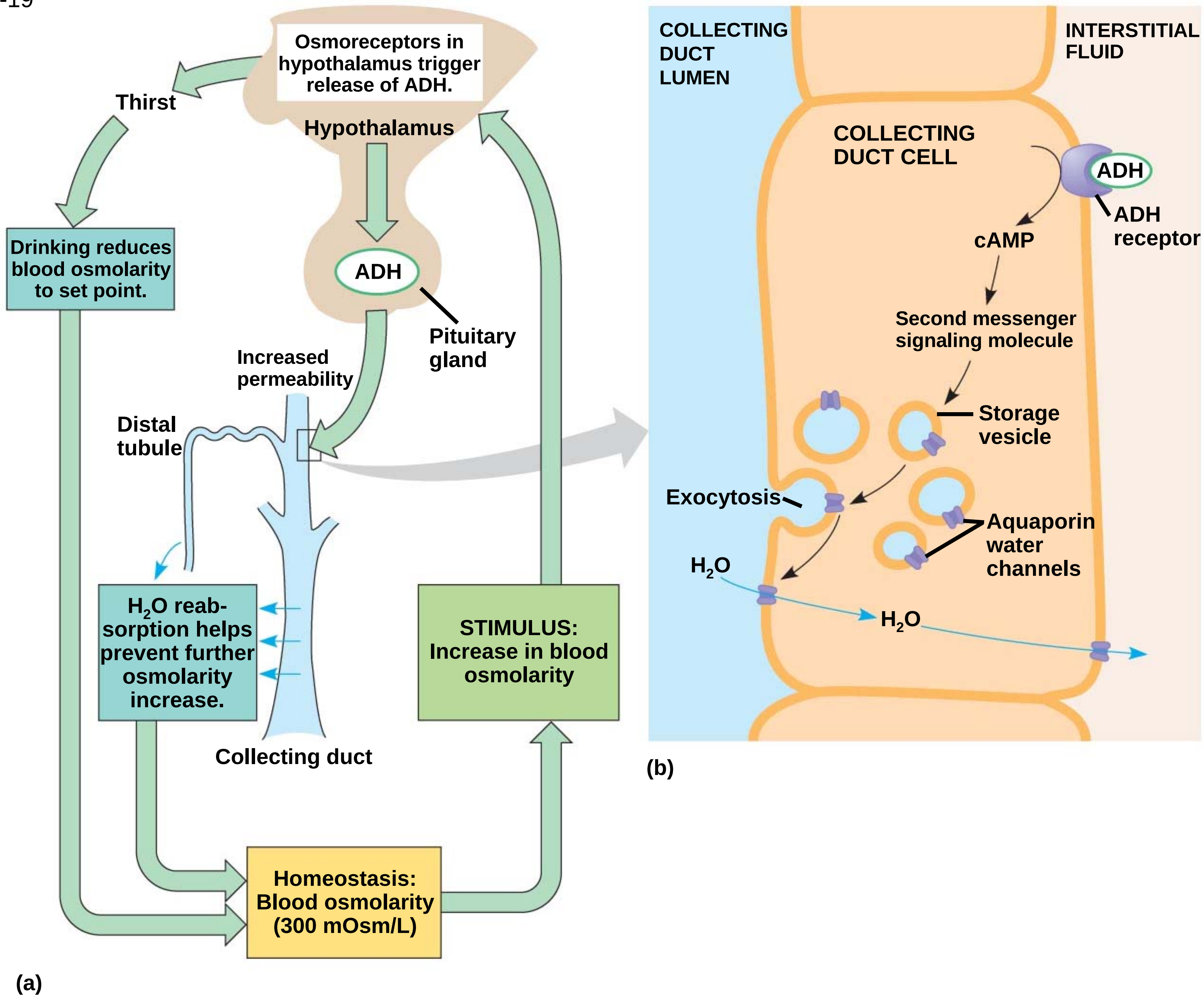
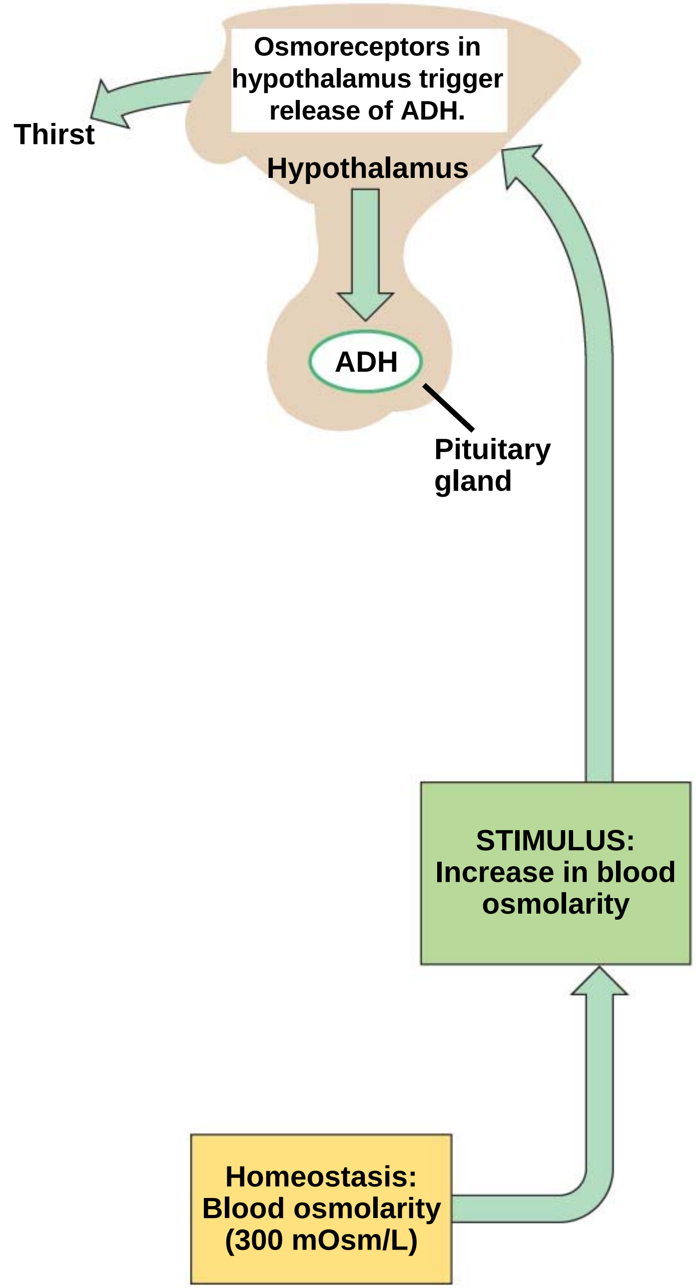

Osmoreceptors in hypothalamus trigger release of ADH.
Thirst
Hypothalamus
Drinking reduces blood osmolarity to set point.
ADH
Pituitary gland
Increased permeability
Distal tubule
H2O reab-sorption helps prevent further osmolarity increase.
STIMULUS: Increase in blood osmolarity
Collecting duct
Homeostasis: Blood osmolarity (300 mOsm/L)
(a)
COLLECTING DUCT LUMEN
INTERSTITIAL FLUID
COLLECTING DUCT CELL
ADH
ADH receptor
cAMP
Second messenger signaling molecule
Storage vesicle
Exocytosis
Aquaporin water channels
H2O
H2O
(b)

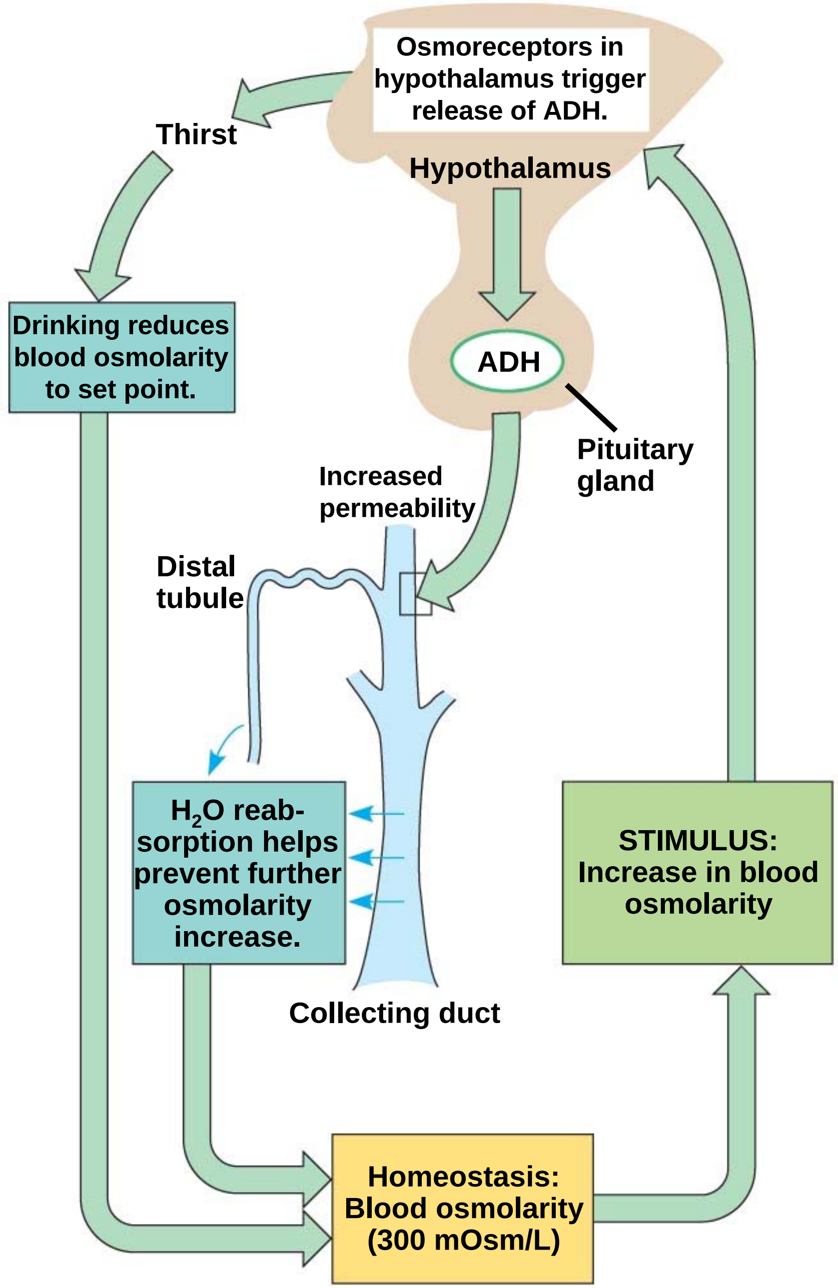
Fig. 44-19a-1



Osmoreceptors in hypothalamus trigger release of ADH.
Thirst
Hypothalamus
ADH
Pituitary gland
STIMULUS: Increase in blood osmolarity
Homeostasis: Blood osmolarity (300 mOsm/L)

(a)

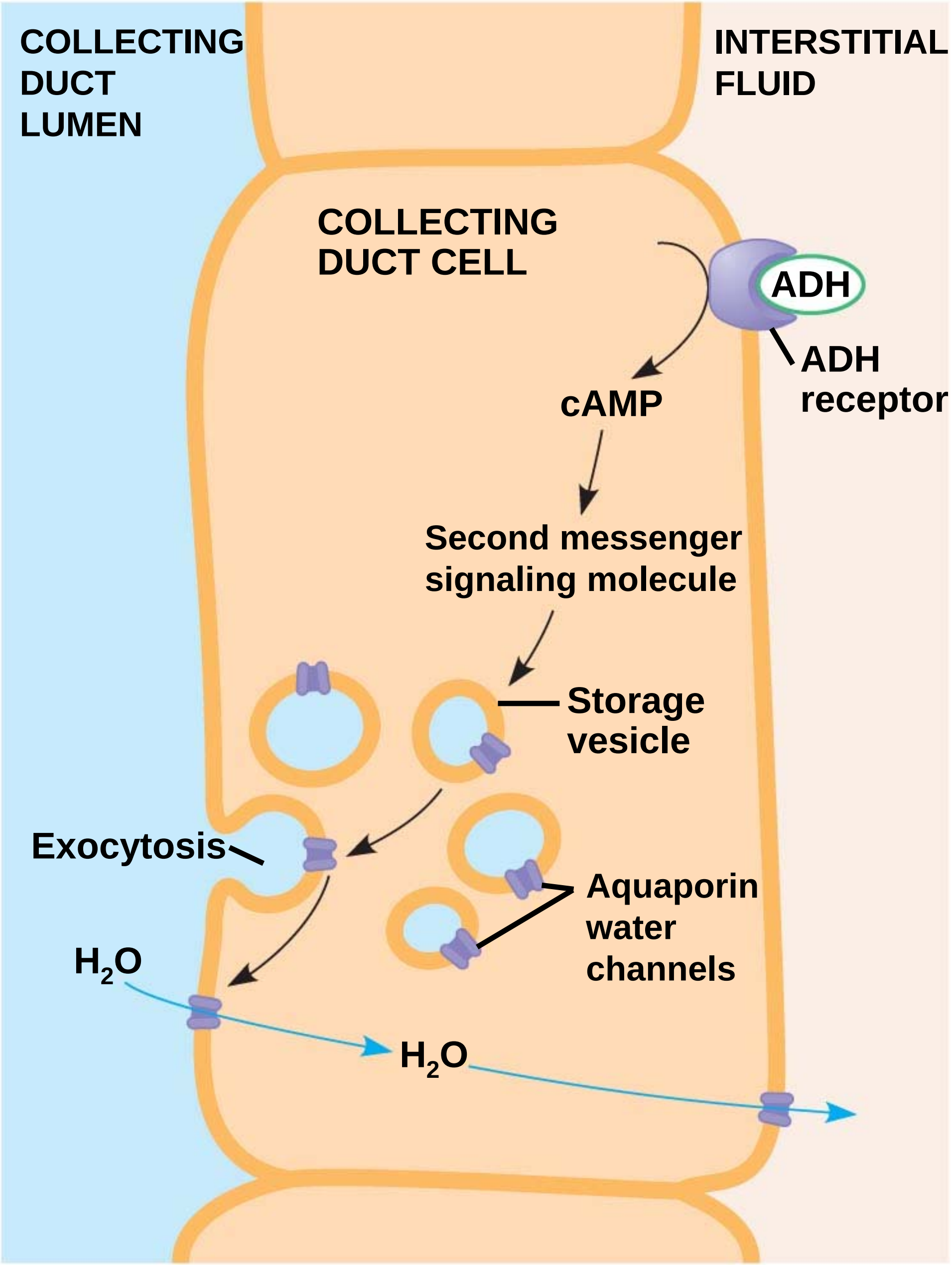
Fig. 44-19a-2



Osmoreceptors in hypothalamus trigger release of ADH.
Thirst
Hypothalamus
Drinking reduces blood osmolarity to set point.
ADH
Pituitary gland
Increased permeability
Distal tubule
H_2O reab-sorption helps prevent further osmolarity increase.
STIMULUS: Increase in blood osmolarity
Collecting duct
Homeostasis: Blood osmolarity (300 mOsm/L)

(a)

Fig. 44-19b

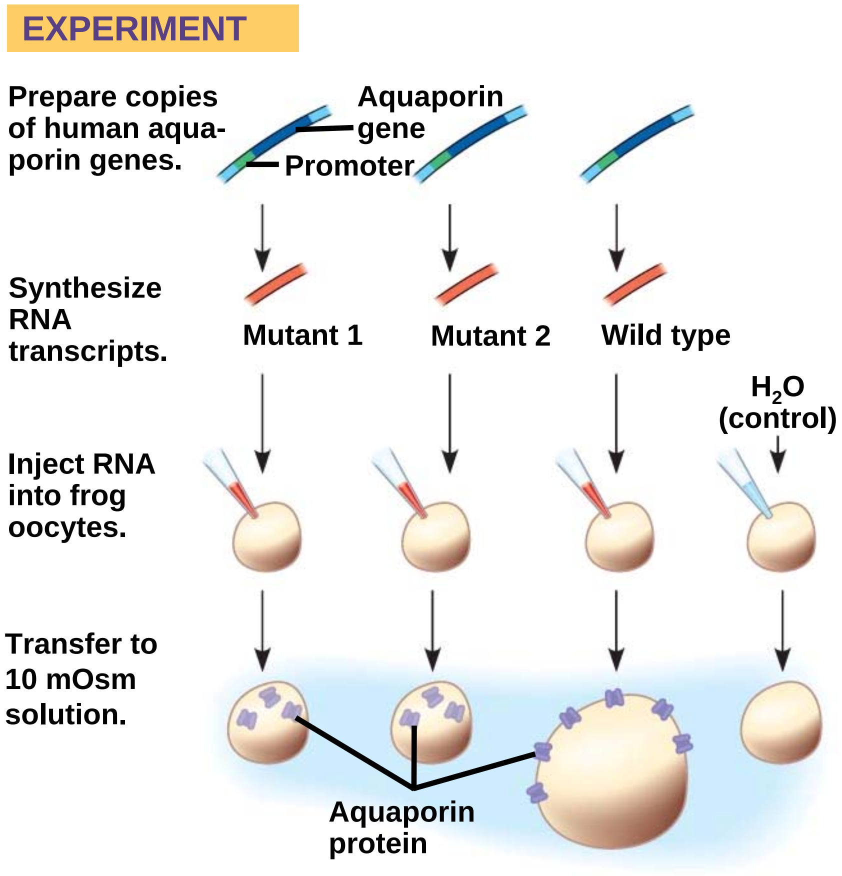


COLLECTING DUCT LUMEN
INTERSTITIAL FLUID
COLLECTING DUCT CELL
ADH
ADH receptor
cAMP
Second messenger signaling molecule
Storage vesicle
Exocytosis
Aquaporin water channels
H_2O
H_2O

(b)

- Mutation in ADH production causes severe dehydration and results in diabetes insipidus
- Alcohol is a diuretic as it inhibits the release of ADH

Fig. 44-20



RESULTS

Injected RNA	Permeability (µm/s)
Wild-type aquaporin	196
None	20
Aquaporin mutant 1	17
Aquaporin mutant 2	18

Fig. 44-20a

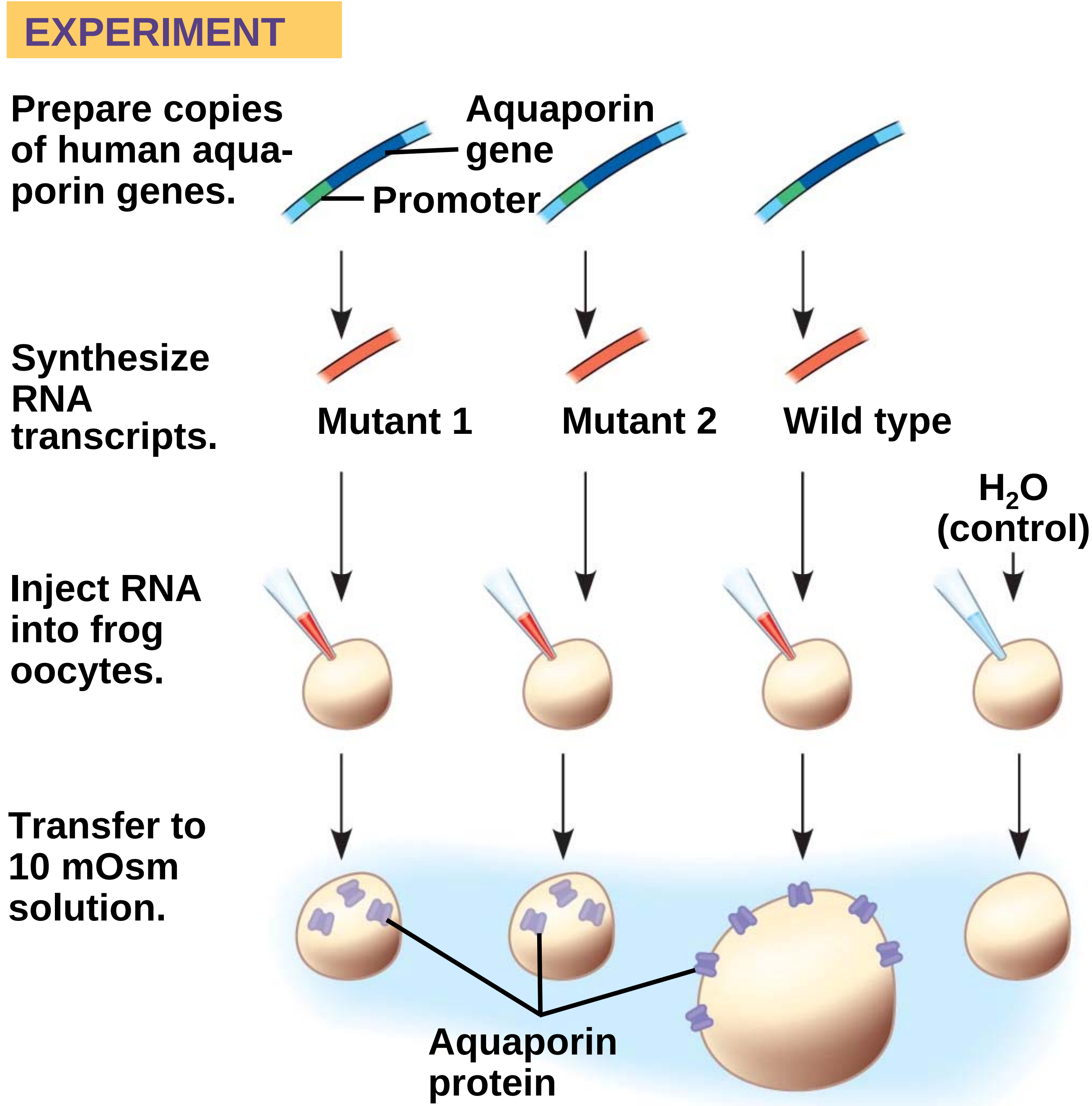

EXPERIMENT
Prepare copies of human aqua-porin genes.
Aquaporin gene
Promoter
Synthesize RNA transcripts.
Mutant 1
Mutant 2
Wild type
H_2O (control)
Inject RNA into frog oocytes.
Transfer to 10 mOsm solution.
Aquaporin protein

Fig. 44-20b

RESULTS

Injected RNA	Permeability (µm/s)
Wild-type aquaporin	196
None	20
Aquaporin mutant 1	17
Aquaporin mutant 2	18

The Renin-Angiotensin-Aldosterone System

- The **renin-angiotensin-aldosterone system (RAAS)** is part of a complex feedback circuit that functions in homeostasis
- A drop in blood pressure near the glomerulus causes the **juxtaglomerular apparatus (JGA)** to release the enzyme renin
- Renin triggers the formation of the peptide **angiotensin II**

- Angiotensin II
  - Raises blood pressure and decreases blood flow to the kidneys
  - Stimulates the release of the hormone **aldosterone**, which increases blood volume and pressure

Fig. 44-21-1

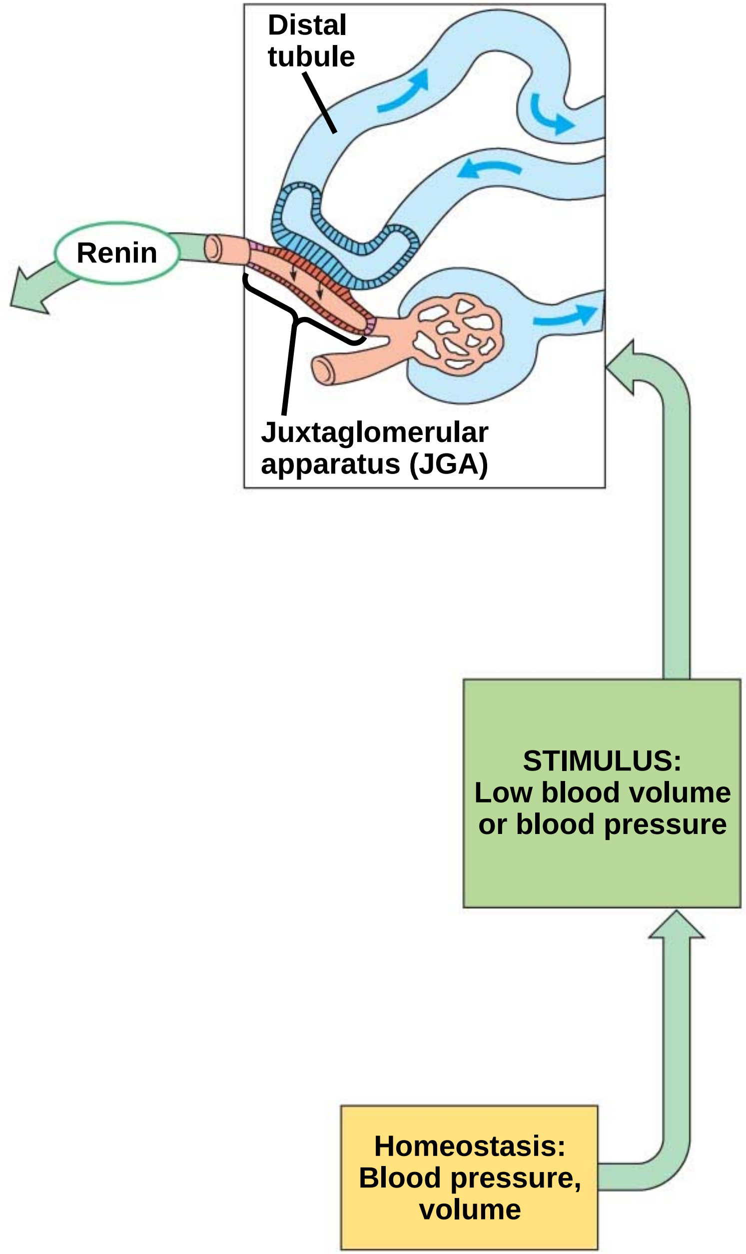

Distal tubule
Renin
Juxtaglomerular apparatus (JGA)
STIMULUS:
Low blood volume or blood pressure
Homeostasis:
Blood pressure, volume

Fig. 44-21-2

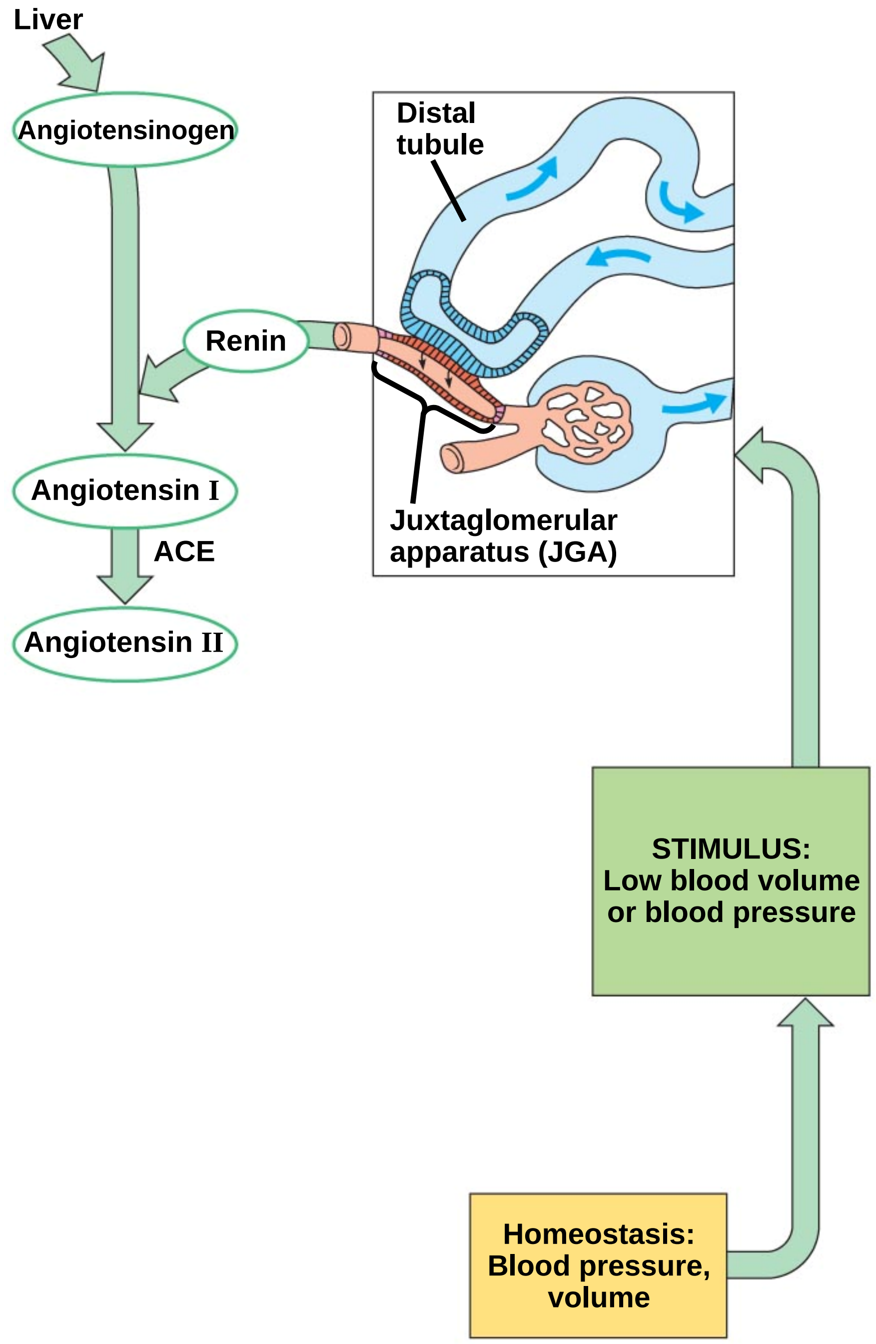
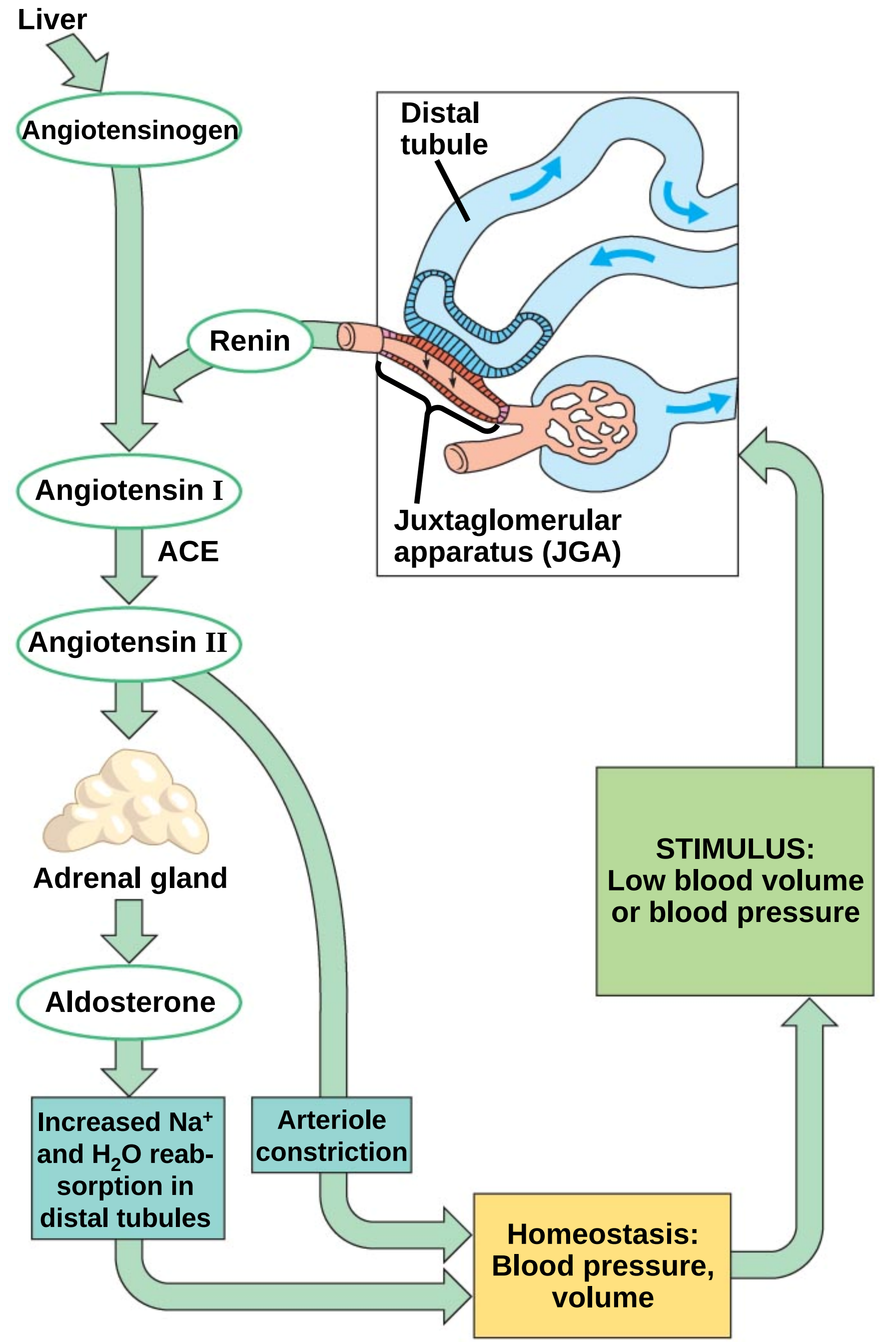

Liver
Angiotensinogen
Renin
Angiotensin I
ACE
Angiotensin II
Distal
tubule
Juxtaglomerular
apparatus (JGA)
STIMULUS:
Low blood volume
or blood pressure
Homeostasis:
Blood pressure,
volume

Fig. 44-21-3


Liver
Angiotensinogen
Distal tubule
Renin
Angiotensin I
ACE
Juxtaglomerular apparatus (JGA)
Angiotensin II
Adrenal gland
STIMULUS: Low blood volume or blood pressure
Aldosterone
Increased Na^+ and H_2O reab-sorption in distal tubules
Arteriole constriction
Homeostasis: Blood pressure, volume

Homeostatic Regulation of the Kidney

- ADH and RAAS both increase water reabsorption, but only RAAS will respond to a decrease in blood volume
- Another hormone, **atrial natriuretic peptide (ANP)**, opposes the RAAS
- ANP is released in response to an increase in blood volume and pressure and inhibits the release of renin

Fig. 44-UN1

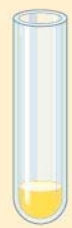
Animal	Inflow/Outflow	Urine
Freshwater fish	Does not drink water Salt in (active trans-port by gills) H_2O in  Salt out	 ▶ Large volume of urine ▶ Urine is less concentrated than body fluids
Bony marine fish	Drinks water Salt in H_2O out  Salt out (active transport by gills)	 ▶ Small volume of urine ▶ Urine is slightly less concentrated than body fluids
Terrestrial vertebrate	Drinks water Salt in (by mouth)  H_2O and salt out	 ▶ Moderate volume of urine ▶ Urine is more concentrated than body fluids

Fig. 44-UN1a

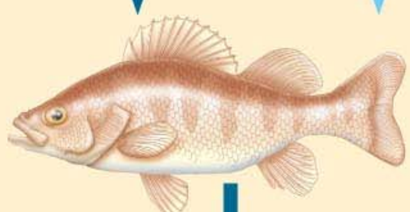
Animal	Inflow/Outflow	Urine
Freshwater fish	Does not drink water Salt in (active transport by gills) H_2O in  Salt out	 ▶ Large volume of urine ▶ Urine is less concentrated than body fluids

Fig. 44-UN1b

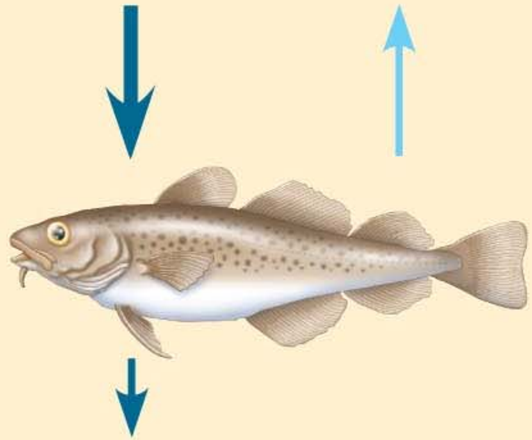
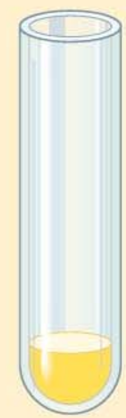
Animal	Inflow/Outflow	Urine
Bony marine fish	Drinks water Salt in H_2O out  Salt out (active transport by gills)	 ▶ Small volume of urine ▶ Urine is slightly less concentrated than body fluids

Fig. 44-UN1c

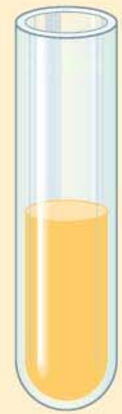
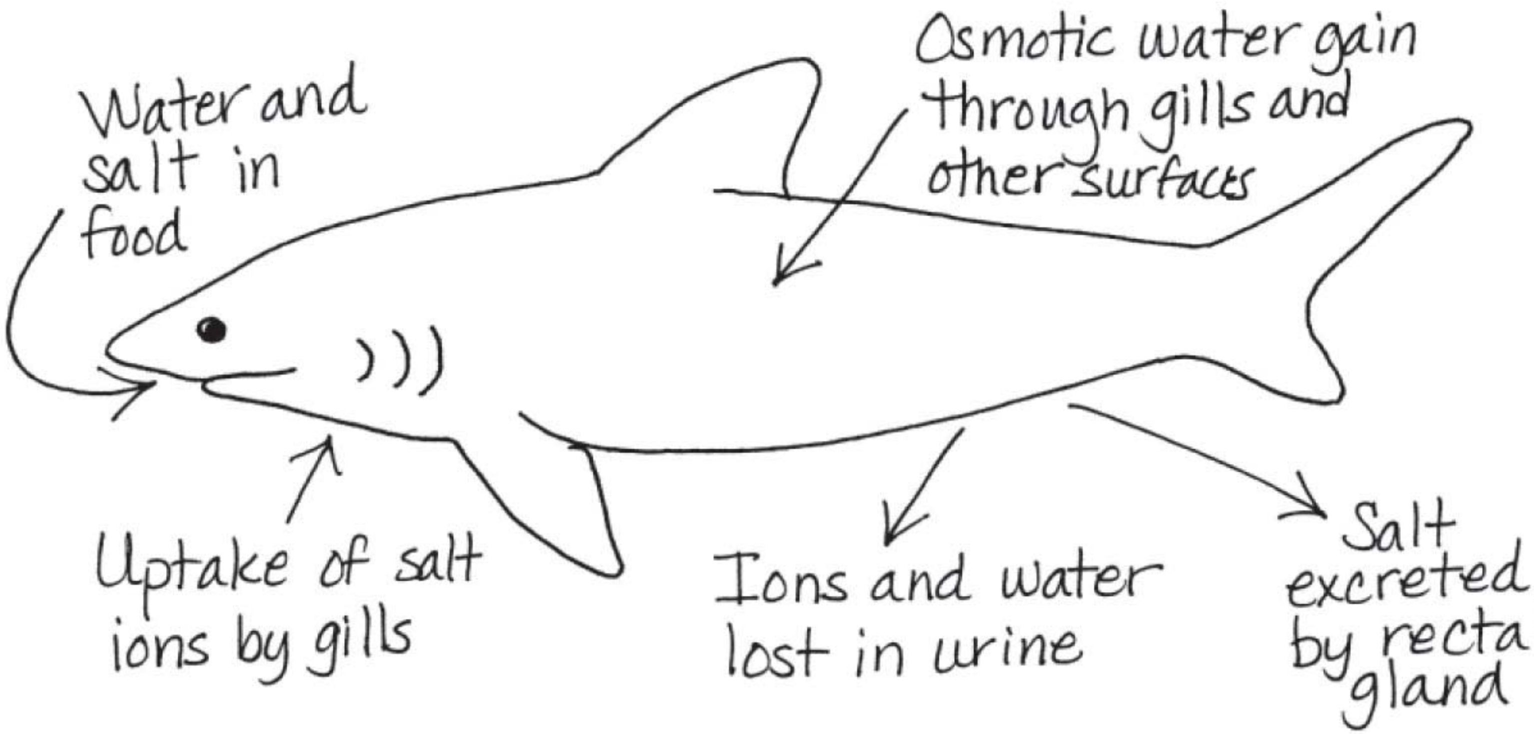
Animal	Inflow/Outflow	Urine
Terrestrial vertebrate	Drinks water Salt in (by mouth)  H_2O and salt out	 ▶ Moderate volume of urine ▶ Urine is more concentrated than body fluids

Fig. 44-UN2



Water and salt in food
Osmotic water gain through gills and other surfaces
Uptake of salt ions by gills
Ions and water lost in urine
Salt excreted by rectal gland

You should now be able to:

1. Distinguish between the following terms: isoosmotic, hyperosmotic, and hypoosmotic; osmoregulators and osmoconformers; stenohaline and euryhaline animals
2. Define osmoregulation, excretion, anhydrobiosis
3. Compare the osmoregulatory challenges of freshwater and marine animals
4. Describe some of the factors that affect the energetic cost of osmoregulation

5. Describe and compare the protonephridial, metanephridial, and Malpighian tubule excretory systems
6. Using a diagram, identify and describe the function of each region of the nephron
7. Explain how the loop of Henle enhances water conservation
8. Describe the nervous and hormonal controls involved in the regulation of kidney function