Chapter 42

Circulation and Gas Exchange

PowerPoint® Lecture Presentations for

Biology

Eighth Edition

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Overview: Trading Places

- Every organism must exchange materials with its environment
- Exchanges ultimately occur at the cellular level
- In unicellular organisms, these exchanges occur directly with the environment

- For most cells making up multicellular organisms, direct exchange with the environment is not possible
- Gills are an example of a specialized exchange system in animals
- Internal transport and gas exchange are functionally related in most animals

Fig. 42-1

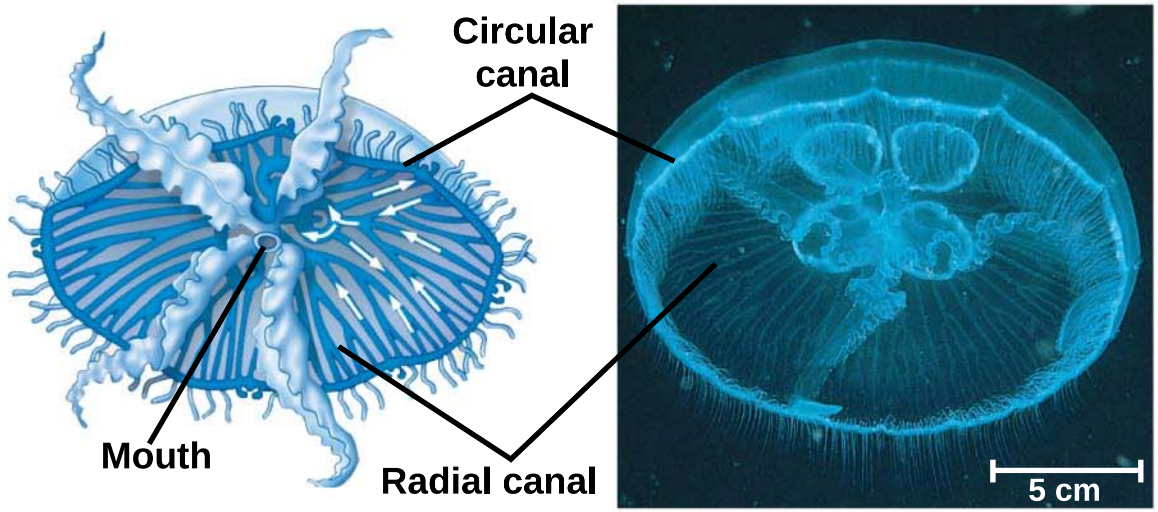
Concept 42.1: Circulatory systems link exchange surfaces with cells throughout the body

- In small and/or thin animals, cells can exchange materials directly with the surrounding medium
- In most animals, transport systems connect the organs of exchange with the body cells
- Most complex animals have internal transport systems that circulate fluid

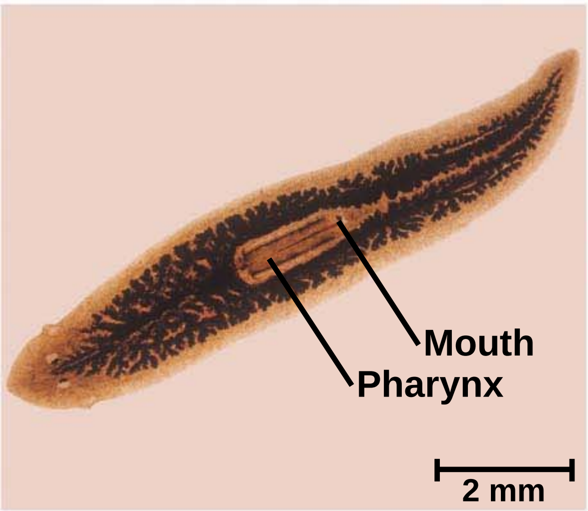
Gastrovascular Cavities

- Simple animals, such as cnidarians, have a body wall that is only two cells thick and that encloses a gastrovascular cavity
- This cavity functions in both digestion and distribution of substances throughout the body
- Some cnidarians, such as jellies, have elaborate gastrovascular cavities
- Flatworms have a gastrovascular cavity and a large surface area to volume ratio

Fig. 42-2

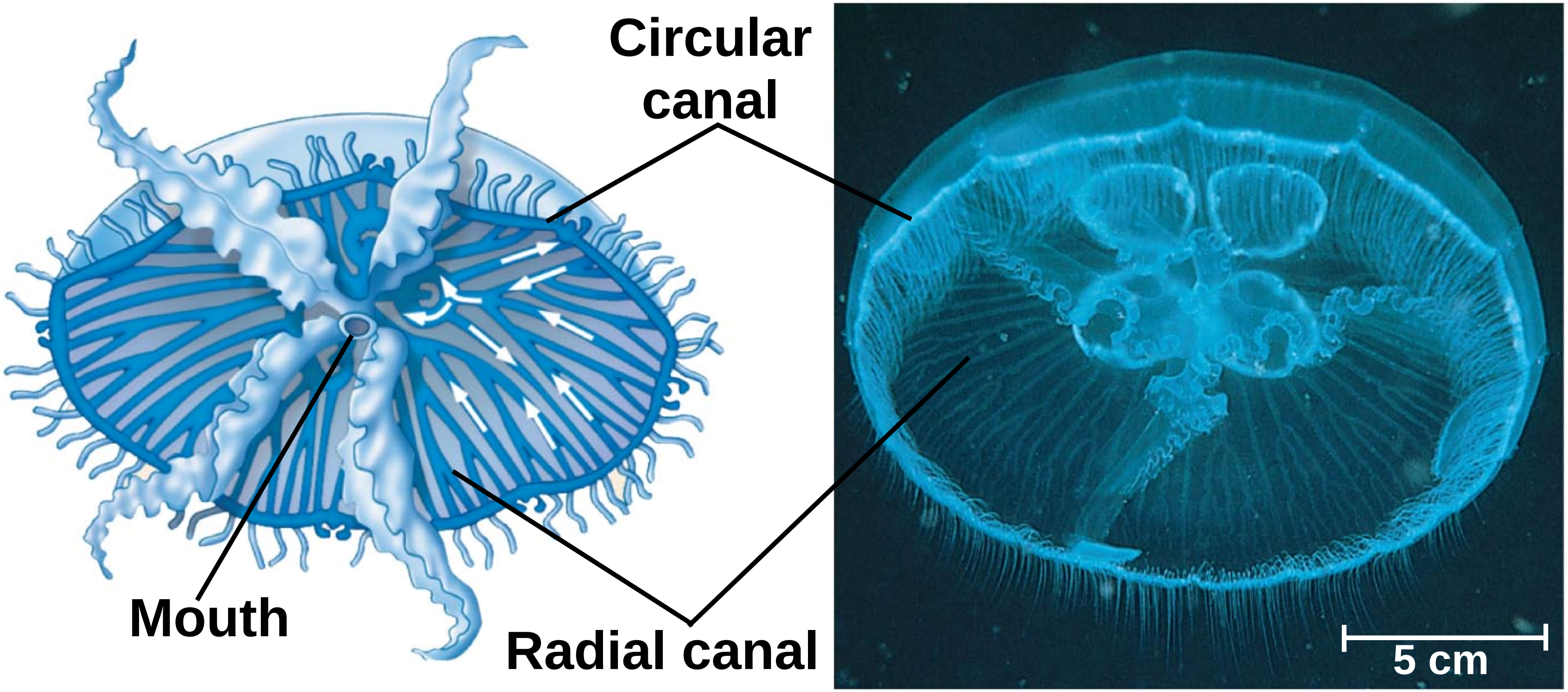


(a) The moon jelly *Aurelia*, a cnidarian



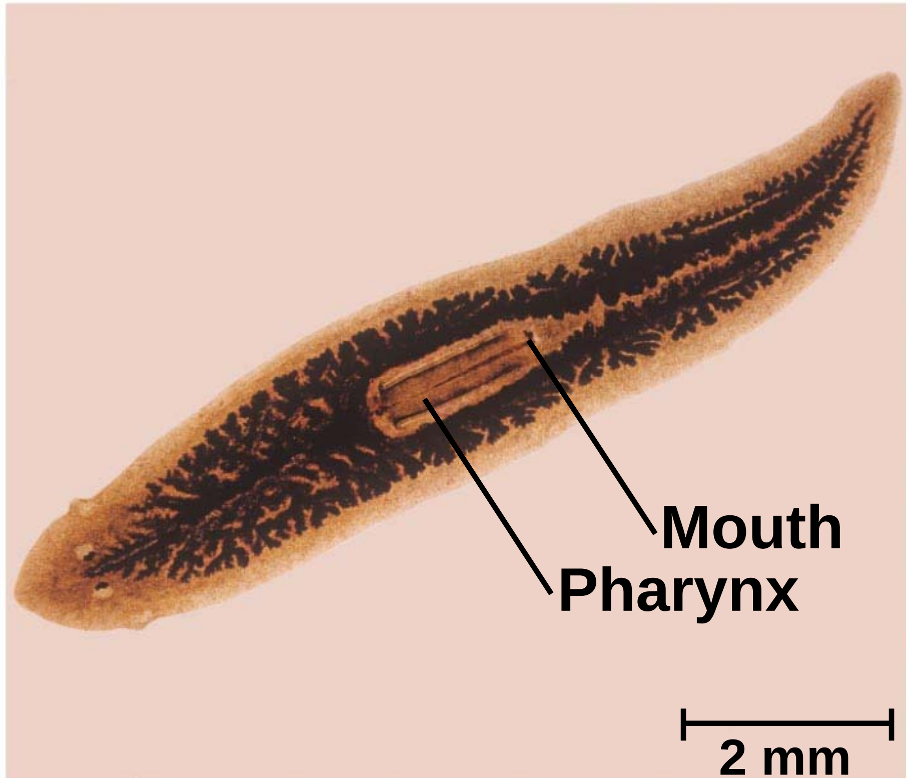
(b) The planarian *Dugesia*, a flatworm

Fig. 42-2a



(a) The moon jelly *Aurelia*, a cnidarian

Fig. 42-2b



(b) The planarian *Dugesia*, a flatworm

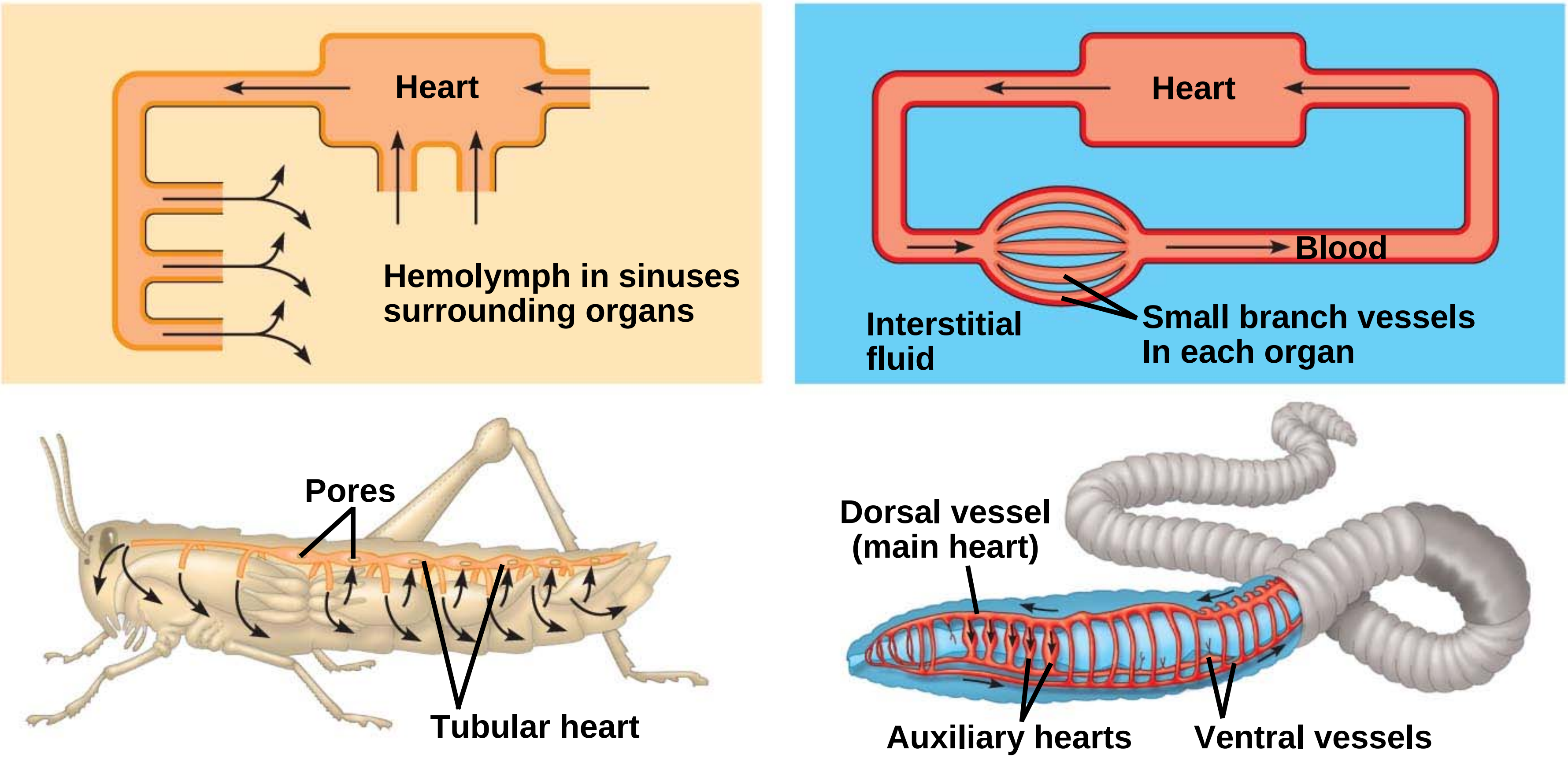
Open and Closed Circulatory Systems

- More complex animals have either open or closed circulatory systems
- Both systems have three basic components:
  - A circulatory fluid (blood or hemolymph)
  - A set of tubes (blood vessels)
  - A muscular pump (the **heart**)

- In insects, other arthropods, and most molluscs, blood bathes the organs directly in an **open circulatory system**
- In an open circulatory system, there is no distinction between blood and interstitial fluid, and this general body fluid is more correctly called **hemolymph**

- In a **closed circulatory system**, blood is confined to vessels and is distinct from the interstitial fluid
- Closed systems are more efficient at transporting circulatory fluids to tissues and cells

Fig. 42-3



(a) An open circulatory system

(b) A closed circulatory system

Organization of Vertebrate Circulatory Systems

- Humans and other vertebrates have a closed circulatory system, often called the **cardiovascular system**
- The three main types of blood vessels are arteries, veins, and capillaries

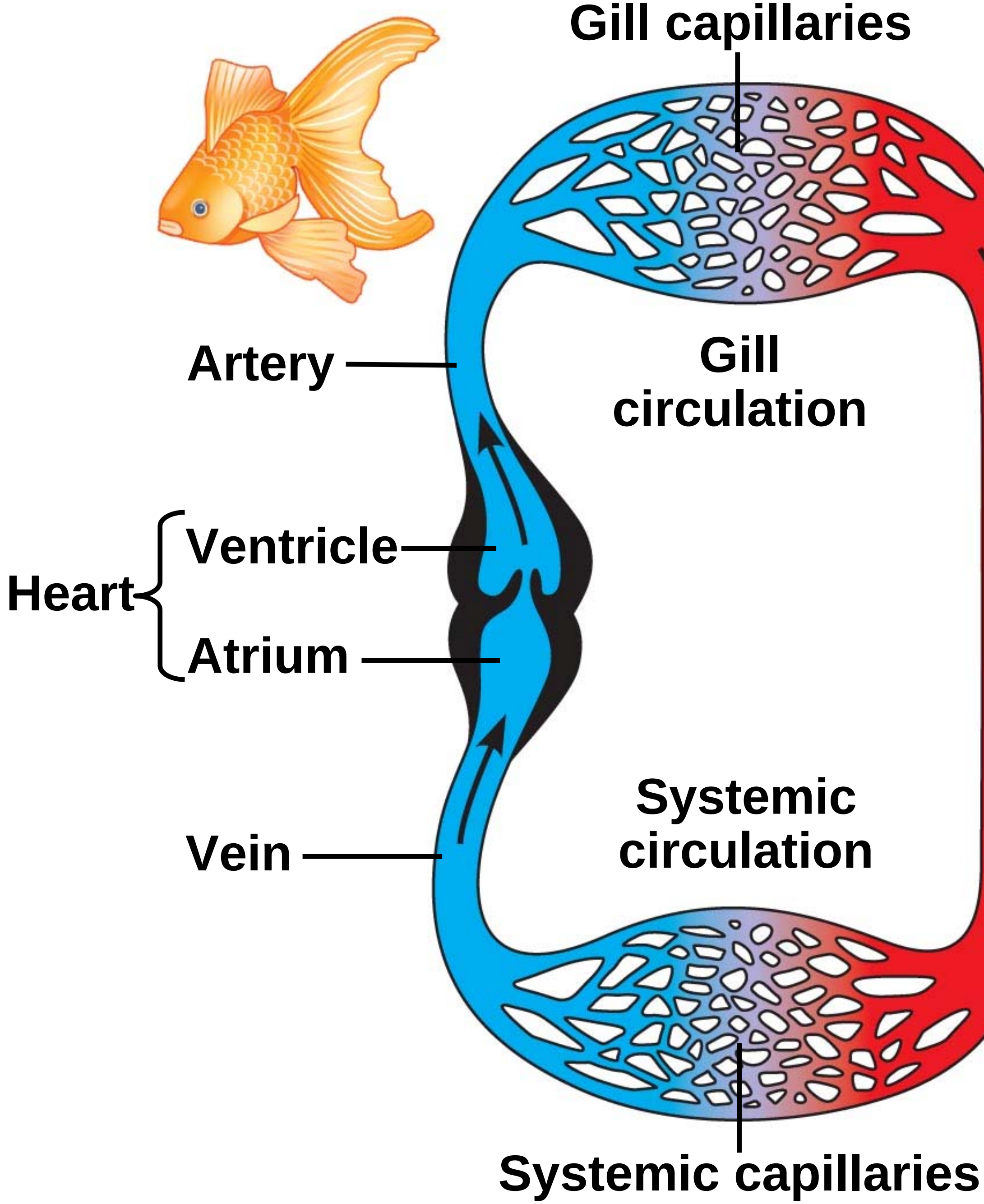
- **Arteries** branch into **arterioles** and carry blood to **capillaries**
- Networks of capillaries called **capillary beds** are the sites of chemical exchange between the blood and interstitial fluid
- **Venules** converge into **veins** and return blood from capillaries to the heart

- Vertebrate hearts contain two or more chambers
- Blood enters through an **atrium** and is pumped out through a **ventricle**

Single Circulation

- Bony fishes, rays, and sharks have **single circulation** with a two-chambered heart
- In single circulation, blood leaving the heart passes through two capillary beds before returning

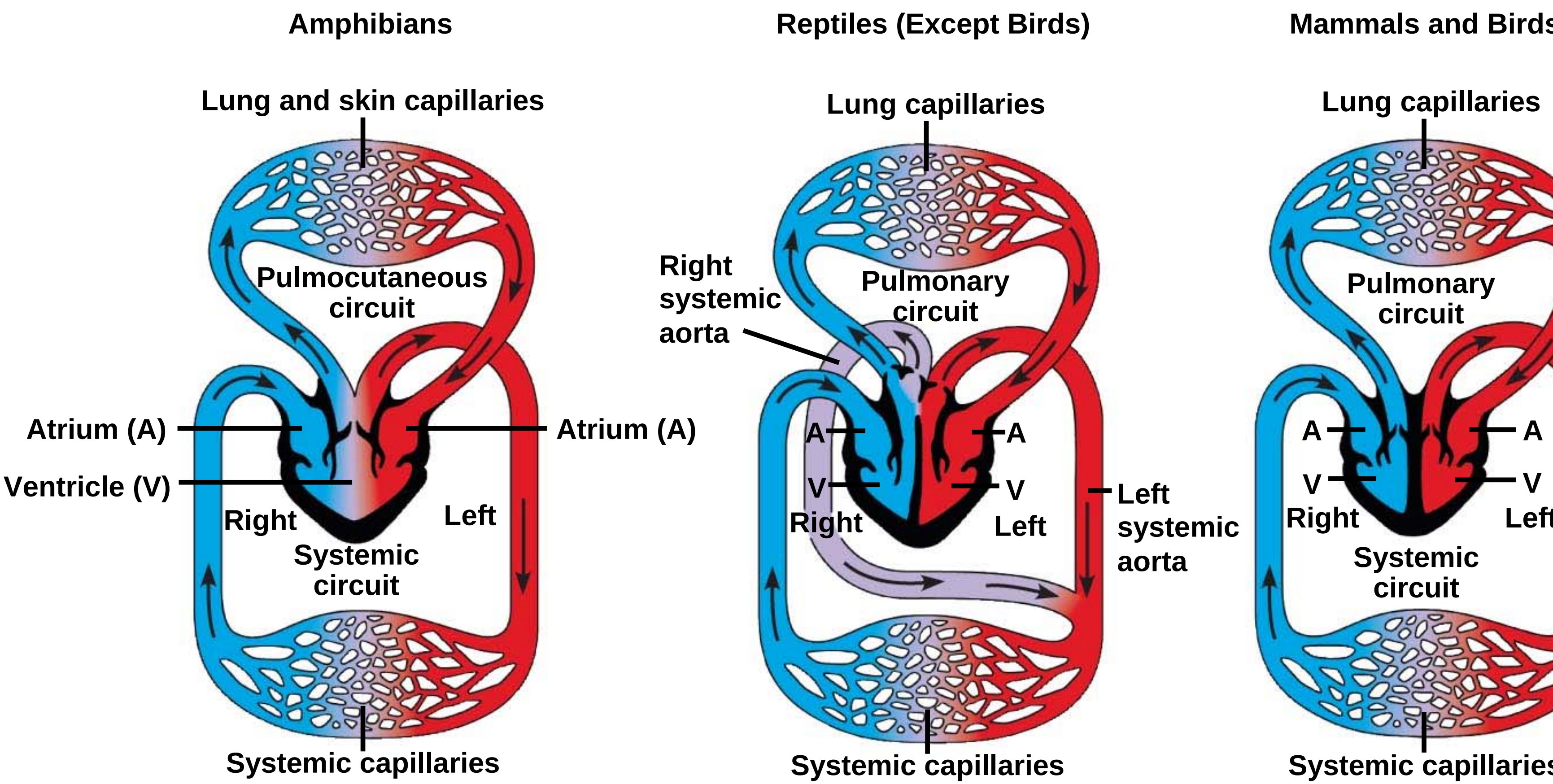
Fig. 42-4


Gill capillaries
Artery
Gill
circulation
Heart
Ventricle
Atrium
Vein
Systemic
circulation
Systemic capillaries

Double Circulation

- Amphibian, reptiles, and mammals have **double circulation**
- Oxygen-poor and oxygen-rich blood are pumped separately from the right and left sides of the heart

Fig. 42-5



Amphibians
Lung and skin capillaries
Pulmocutaneous circuit
Atrium (A)
Atrium (A)
Ventricle (V)
Right
Left
Systemic circuit
Systemic capillaries
Reptiles (Except Birds)
Lung capillaries
Right systemic aorta
Pulmonary circuit
A
A
V
V
Right
Left
Left systemic aorta
Systemic capillaries
Mammals and Birds
Lung capillaries
Pulmonary circuit
A
A
V
V
Right
Left
Systemic circuit
Systemic capillaries

- In reptiles and mammals, oxygen-poor blood flows through the **pulmonary circuit** to pick up oxygen through the lungs
- In amphibians, oxygen-poor blood flows through a **pulmocutaneous circuit** to pick up oxygen through the lungs and skin
- Oxygen-rich blood delivers oxygen through the **systemic circuit**
- Double circulation maintains higher blood pressure in the organs than does single circulation

Adaptations of Double Circulatory Systems

- Hearts vary in different vertebrate groups

Amphibians

- Frogs and other amphibians have a three-chambered heart: two atria and one ventricle
- The ventricle pumps blood into a forked artery that splits the ventricle’s output into the pulmocutaneous circuit and the systemic circuit
- Underwater, blood flow to the lungs is nearly shut off

Reptiles (Except Birds)

- Turtles, snakes, and lizards have a three-chambered heart: two atria and one ventricle
- In alligators, caimans, and other crocodilians a septum divides the ventricle
- Reptiles have double circulation, with a pulmonary circuit (lungs) and a systemic circuit

Mammals and Birds

- Mammals and birds have a four-chambered heart with two atria and two ventricles
- The left side of the heart pumps and receives only oxygen-rich blood, while the right side receives and pumps only oxygen-poor blood
- Mammals and birds are endotherms and require more O_2 than ectotherms

Concept 42.2: Coordinated cycles of heart contraction drive double circulation in mammals

- The mammalian cardiovascular system meets the body's continuous demand for O_2

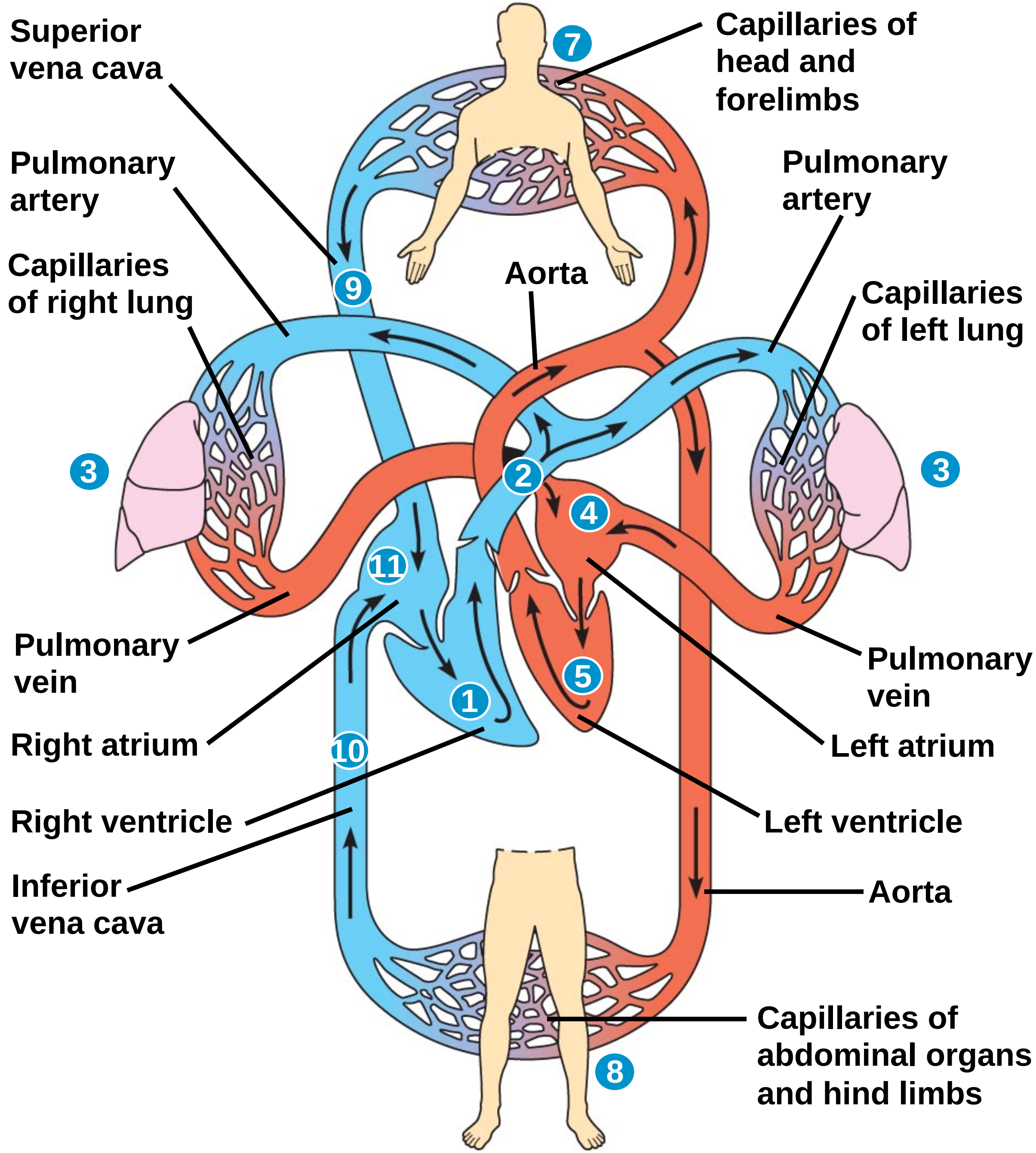
Mammalian Circulation

- Blood begins its flow with the right ventricle pumping blood to the lungs
- In the lungs, the blood loads O_2 and unloads CO_2
- Oxygen-rich blood from the lungs enters the heart at the left atrium and is pumped through the aorta to the body tissues by the left ventricle
- The aorta provides blood to the heart through the coronary arteries

- Blood returns to the heart through the superior vena cava (blood from head, neck, and forelimbs) and inferior vena cava (blood from trunk and hind limbs)
- The superior vena cava and inferior vena cava flow into the right atrium

PLAY **Animation: Path of Blood Flow in Mammals**

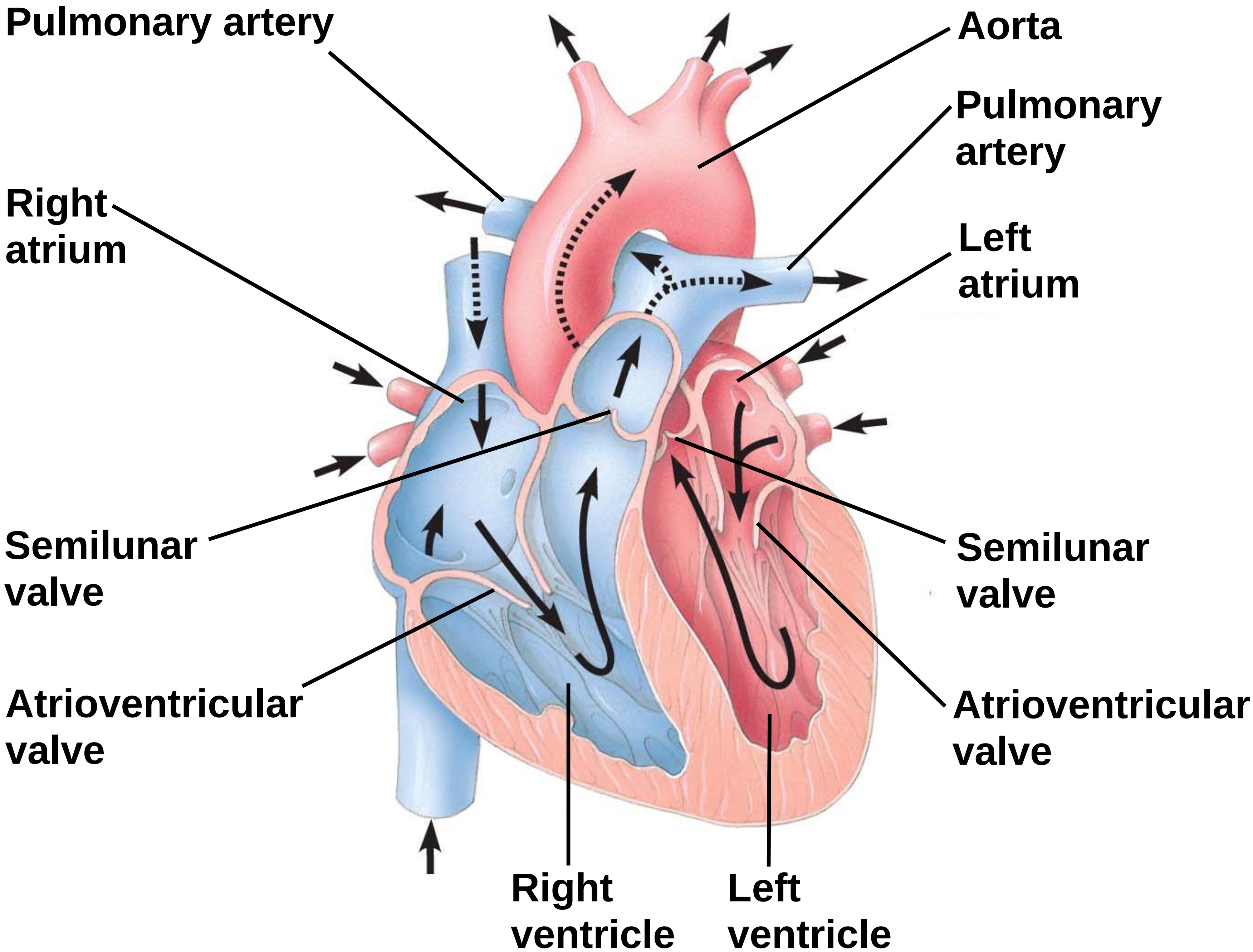
Fig. 42-6


Superior vena cava
Pulmonary artery
Capillaries of right lung
Capillaries of head and forelimbs
Pulmonary artery
Aorta
Capillaries of left lung
Pulmonary vein
Right atrium
Right ventricle
Inferior vena cava
Pulmonary vein
Left atrium
Left ventricle
Aorta
Capillaries of abdominal organs and hind limbs
1
2
3
3
4
5
7
8
9
10
11

The Mammalian Heart: *A Closer Look*

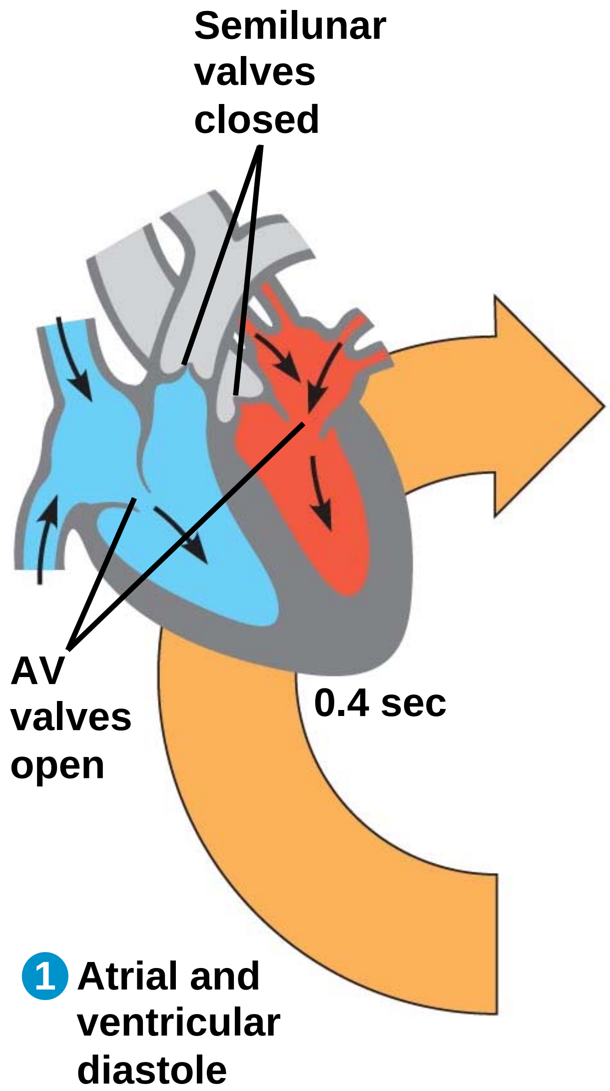
- A closer look at the mammalian heart provides a better understanding of double circulation

Fig. 42-7


Pulmonary artery
Aorta
Pulmonary
artery
Right
atrium
Left
atrium
Semilunar
valve
Semilunar
valve
Atrioventricular
valve
Atrioventricular
valve
Right
ventricle
Left
ventricle

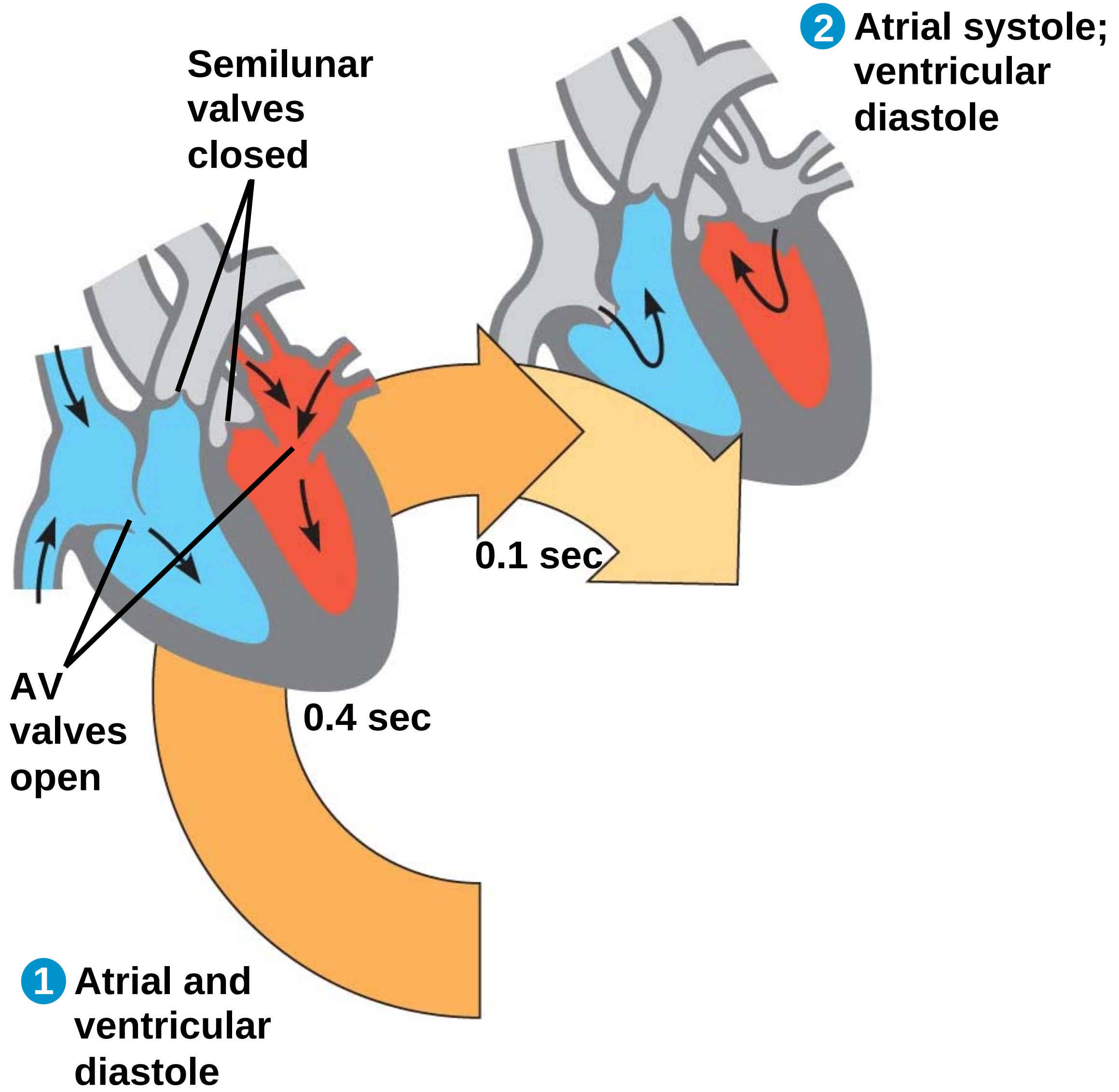
- The heart contracts and relaxes in a rhythmic cycle called the **cardiac cycle**
- The contraction, or pumping, phase is called **systole**
- The relaxation, or filling, phase is called **diastole**

Fig. 42-8-1



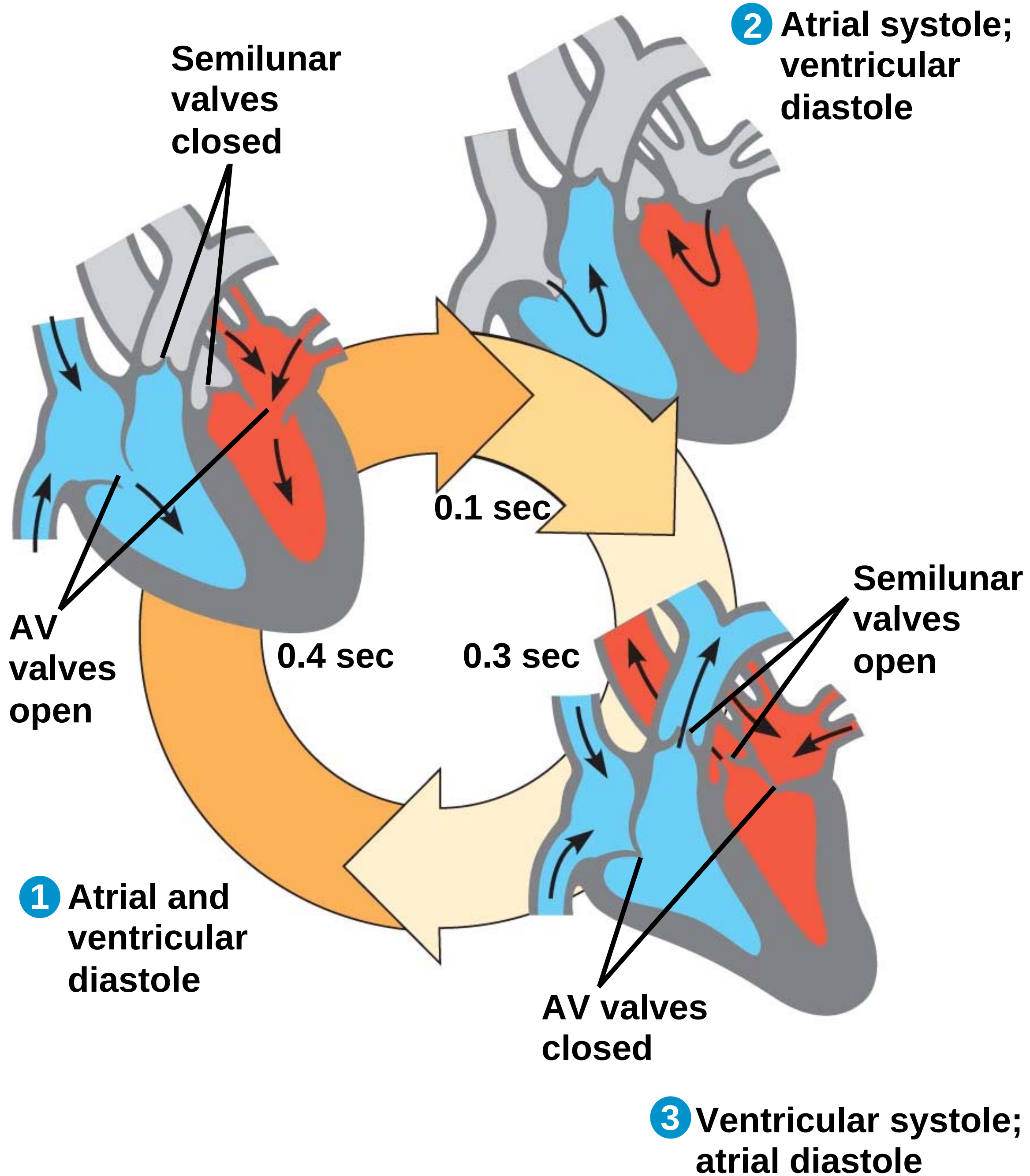
Semilunar valves closed
AV valves open
0.4 sec
1 Atrial and ventricular diastole

Fig. 42-8-2



Semilunar valves closed
2 Atrial systole; ventricular diastole
0.1 sec
0.4 sec
AV valves open
1 Atrial and ventricular diastole

Fig. 42-8



Semilunar valves closed
AV valves open
0.4 sec
1 Atrial and ventricular diastole
2 Atrial systole; ventricular diastole
0.1 sec
0.3 sec
Semilunar valves open
AV valves closed
3 Ventricular systole; atrial diastole

- The **heart rate**, also called the pulse, is the number of beats per minute
- The **stroke volume** is the amount of blood pumped in a single contraction
- The **cardiac output** is the volume of blood pumped into the systemic circulation per minute and depends on both the heart rate and stroke volume

- Four valves prevent backflow of blood in the heart
- The **atrioventricular (AV) valves** separate each atrium and ventricle
- The **semilunar valves** control blood flow to the aorta and the pulmonary artery

- The “lub-dup” sound of a heart beat is caused by the recoil of blood against the AV valves (lub) then against the semilunar (dup) valves
- Backflow of blood through a defective valve causes a **heart murmur**

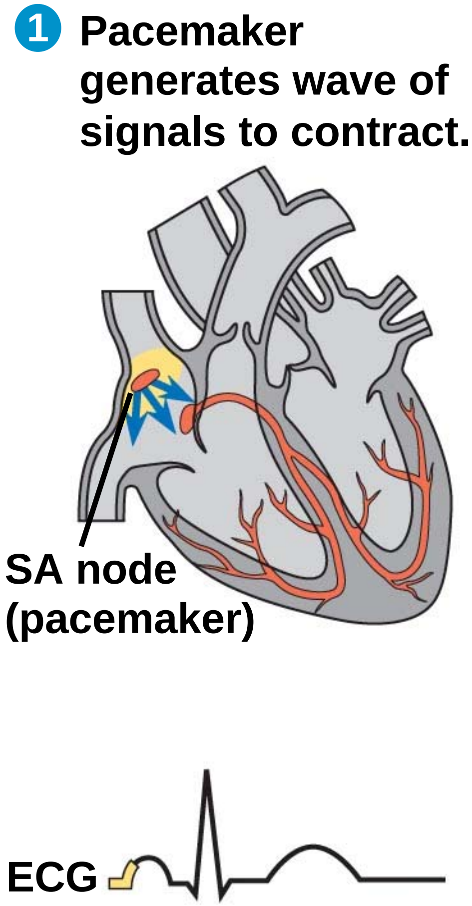
Maintaining the Heart's Rhythmic Beat

- Some cardiac muscle cells are self-excitable, meaning they contract without any signal from the nervous system

- The **sinoatrial (SA) node**, or *pacemaker*, sets the rate and timing at which cardiac muscle cells contract
- Impulses from the SA node travel to the **atrioventricular (AV) node**
- At the AV node, the impulses are delayed and then travel to the Purkinje fibers that make the ventricles contract

- Impulses that travel during the cardiac cycle can be recorded as an **electrocardiogram** (**ECG** or **EKG**)

Fig. 42-9-1



1 Pacemaker generates wave of signals to contract.
SA node (pacemaker)
ECG

2 Signals are delayed at AV node.

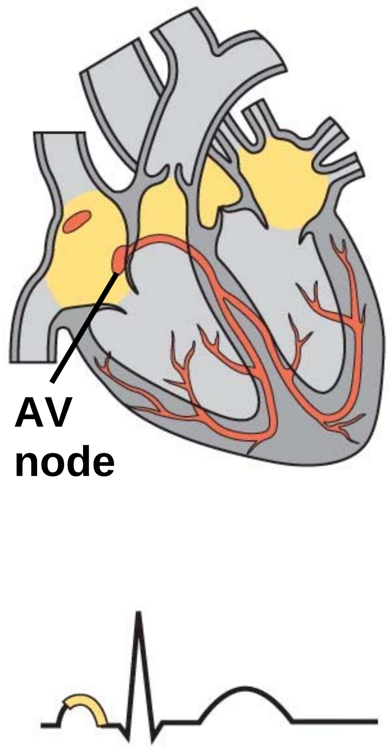


Fig. 42-9-3

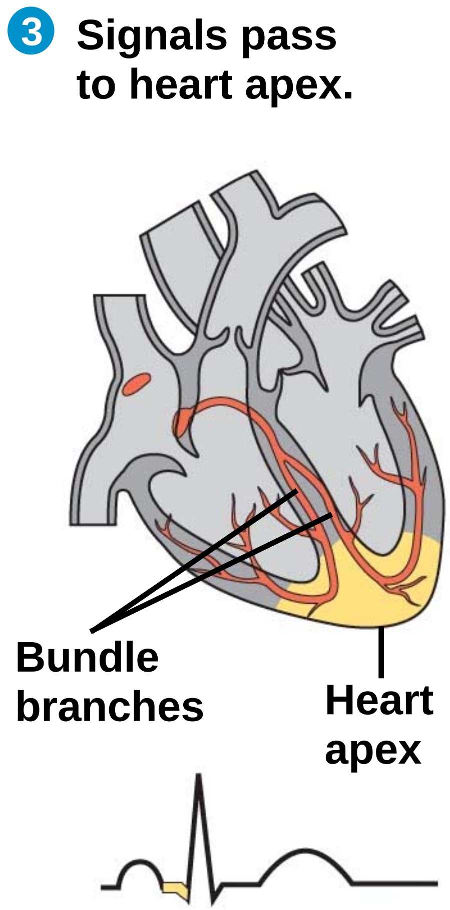


Fig. 42-9-4

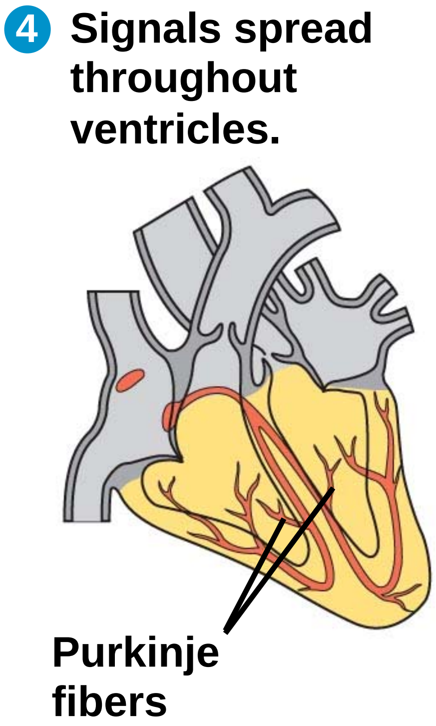
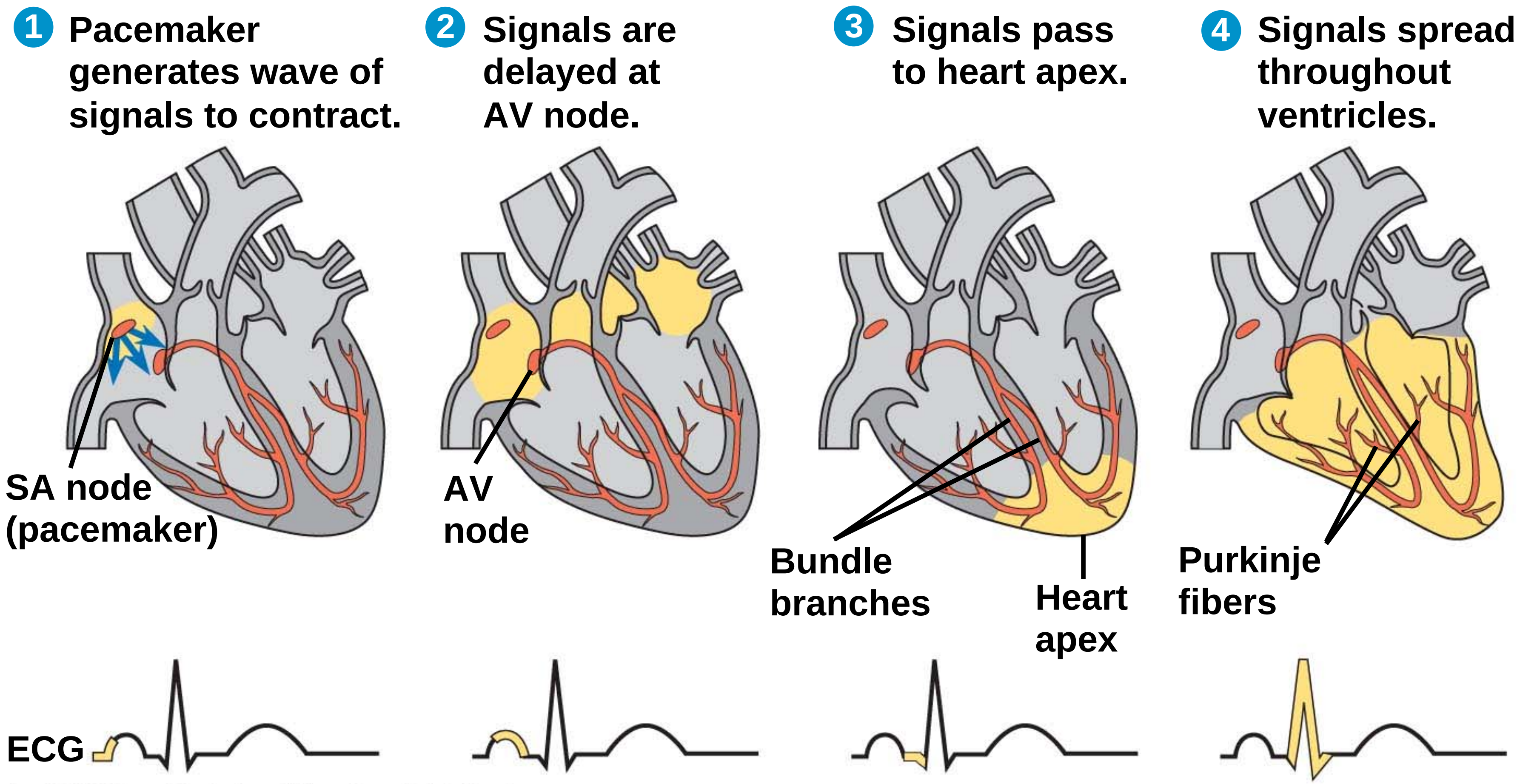


Fig. 42-9-5



1 Pacemaker generates wave of signals to contract.
2 Signals are delayed at AV node.
3 Signals pass to heart apex.
4 Signals spread throughout ventricles.
SA node (pacemaker)
AV node
Bundle branches
Heart apex
Purkinje fibers
ECG

- The pacemaker is influenced by nerves, hormones, body temperature, and exercise

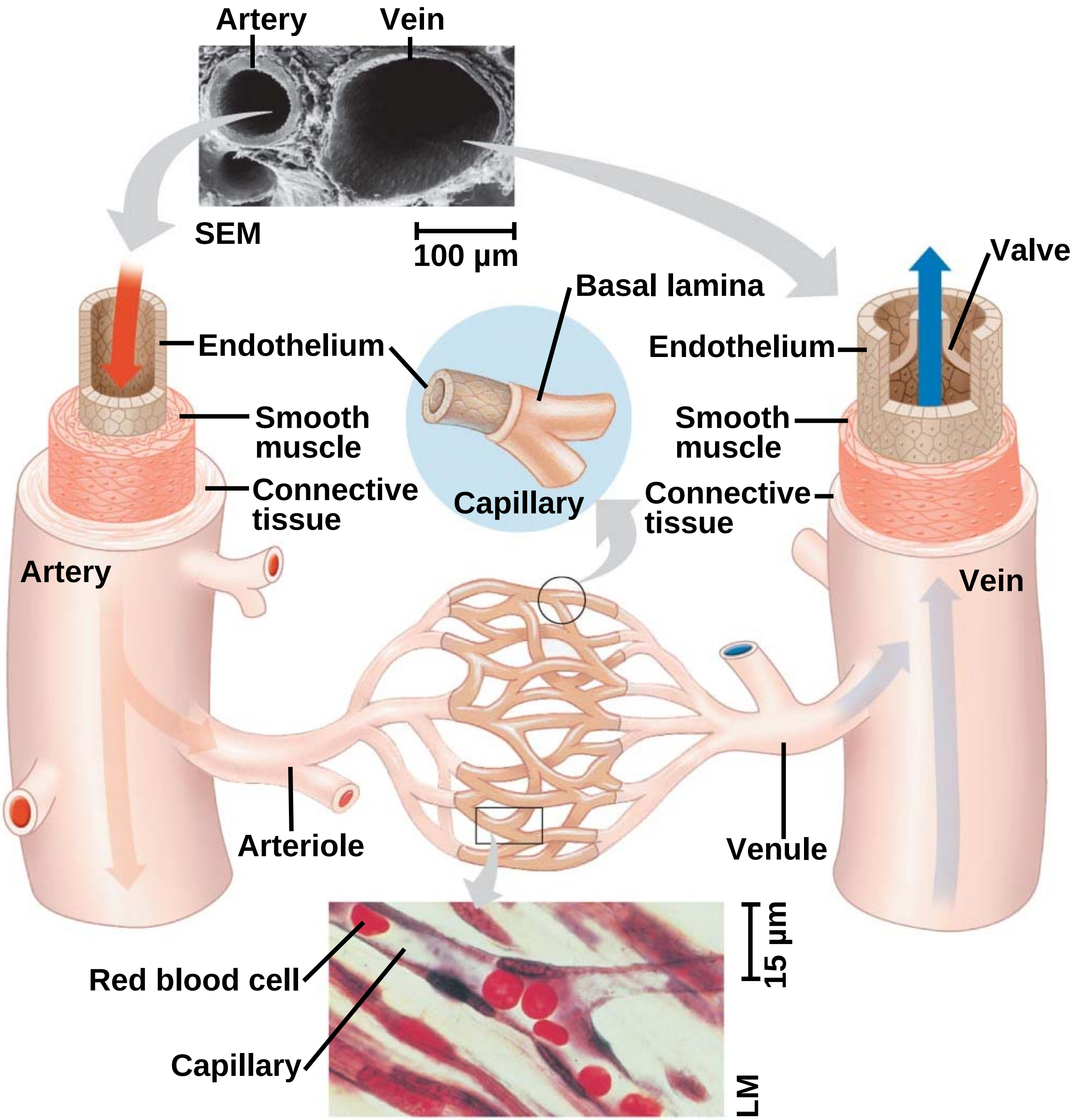
Concept 42.3: Patterns of blood pressure and flow reflect the structure and arrangement of blood vessels

- The physical principles that govern movement of water in plumbing systems also influence the functioning of animal circulatory systems

Blood Vessel Structure and Function

- The epithelial layer that lines blood vessels is called the **endothelium**

Fig. 42-10



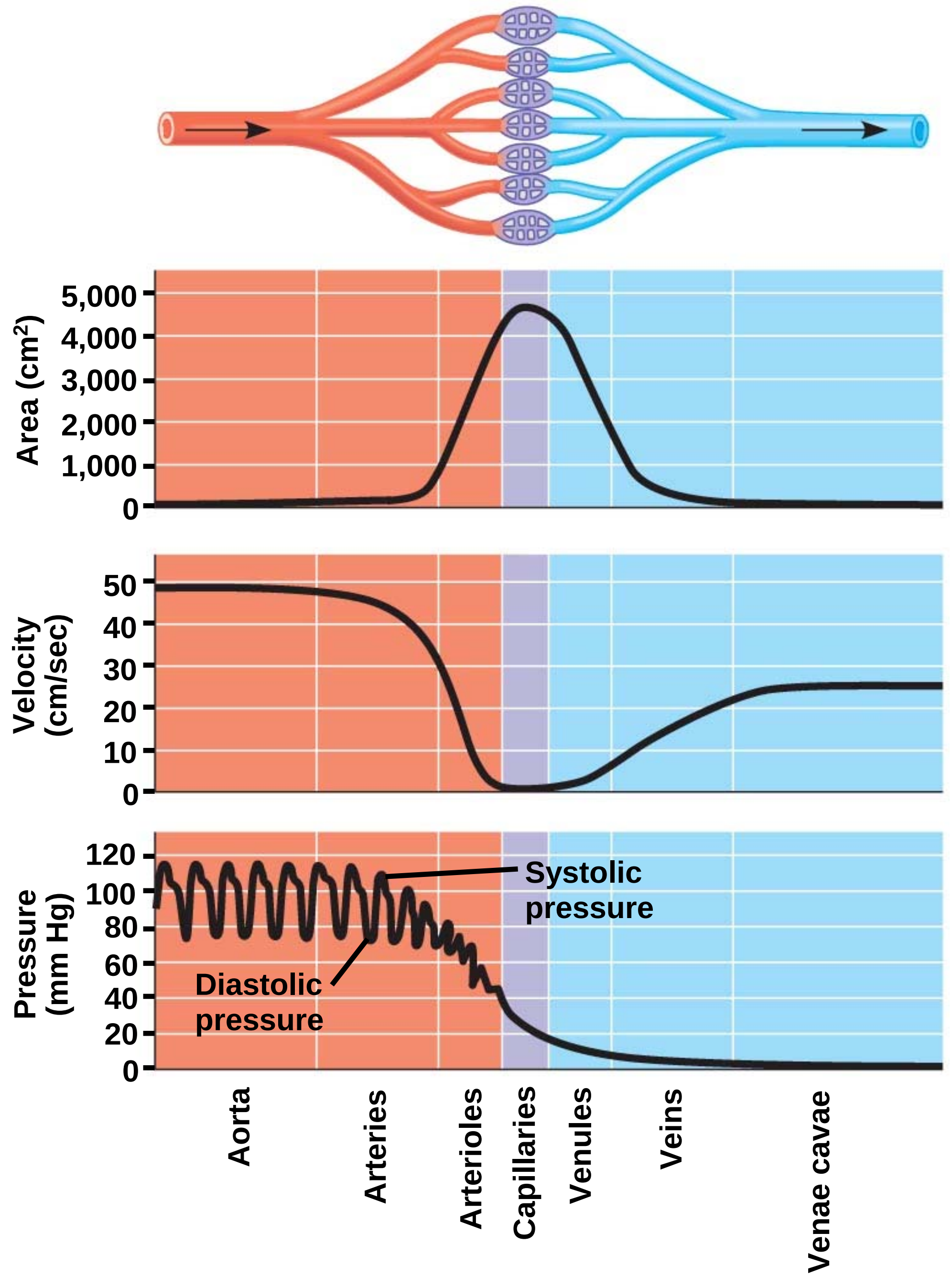
Artery
Vein
SEM
100 µm
Valve
Basal lamina
Endothelium
Smooth muscle
Connective tissue
Capillary
Endothelium
Smooth muscle
Connective tissue
Artery
Vein
Arteriole
Venule
15 µm
Red blood cell
Capillary
LM

- Capillaries have thin walls, the endothelium plus its basement membrane, to facilitate the exchange of materials
- Arteries and veins have an endothelium, smooth muscle, and connective tissue
- Arteries have thicker walls than veins to accommodate the high pressure of blood pumped from the heart
- In the thinner-walled veins, blood flows back to the heart mainly as a result of muscle action

Blood Flow Velocity

- Physical laws governing movement of fluids through pipes affect blood flow and blood pressure
- Velocity of blood flow is slowest in the capillary beds, as a result of the high resistance and large total cross-sectional area
- Blood flow in capillaries is necessarily slow for exchange of materials

Fig. 42-11



Area (cm²)
5,000
4,000
3,000
2,000
1,000
0
Velocity (cm/sec)
50
40
30
20
10
0
Pressure (mm Hg)
120
100
80
60
40
20
0
Systolic pressure
Diastolic pressure
Aorta
Arteries
Arterioles
Capillaries
Venules
Veins
Venae cavae

Blood Pressure

- Blood pressure is the hydrostatic pressure that blood exerts against the wall of a vessel
- In rigid vessels blood pressure is maintained; less rigid vessels deform and blood pressure is lost

Changes in Blood Pressure During the Cardiac Cycle

- **Systolic pressure** is the pressure in the arteries during ventricular systole; it is the highest pressure in the arteries
- **Diastolic pressure** is the pressure in the arteries during diastole; it is lower than systolic pressure
- A **pulse** is the rhythmic bulging of artery walls with each heartbeat

Regulation of Blood Pressure

- Blood pressure is determined by cardiac output and peripheral resistance due to constriction of arterioles
- **Vasoconstriction** is the contraction of smooth muscle in arteriole walls; it increases blood pressure
- **Vasodilation** is the relaxation of smooth muscles in the arterioles; it causes blood pressure to fall

- Vasoconstriction and vasodilation help maintain adequate blood flow as the body’s demands change
- The peptide **endothelin** is an important inducer of vasoconstriction

Fig. 42-12

RESULTS

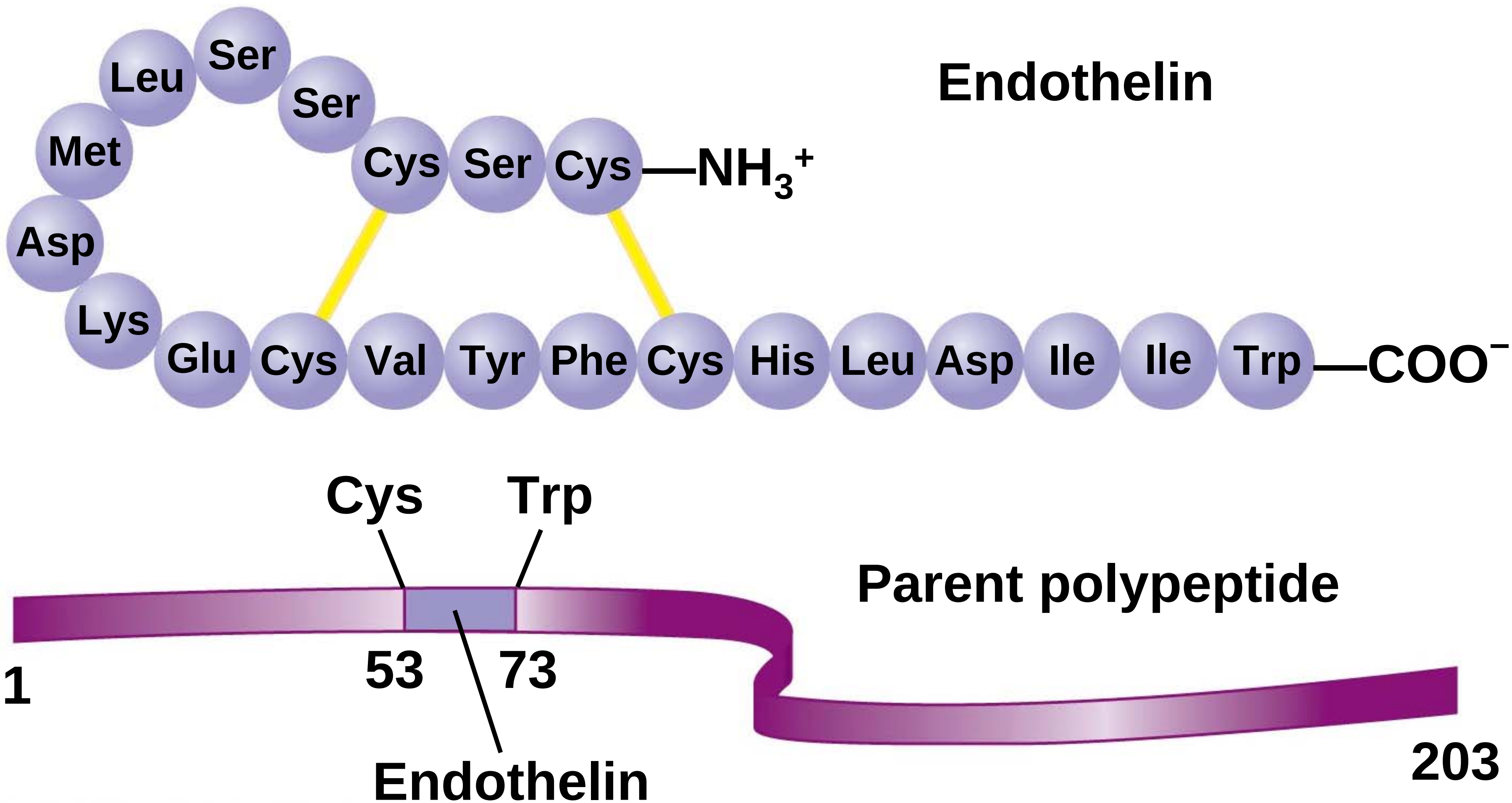


Fig. 42-12a

RESULTS

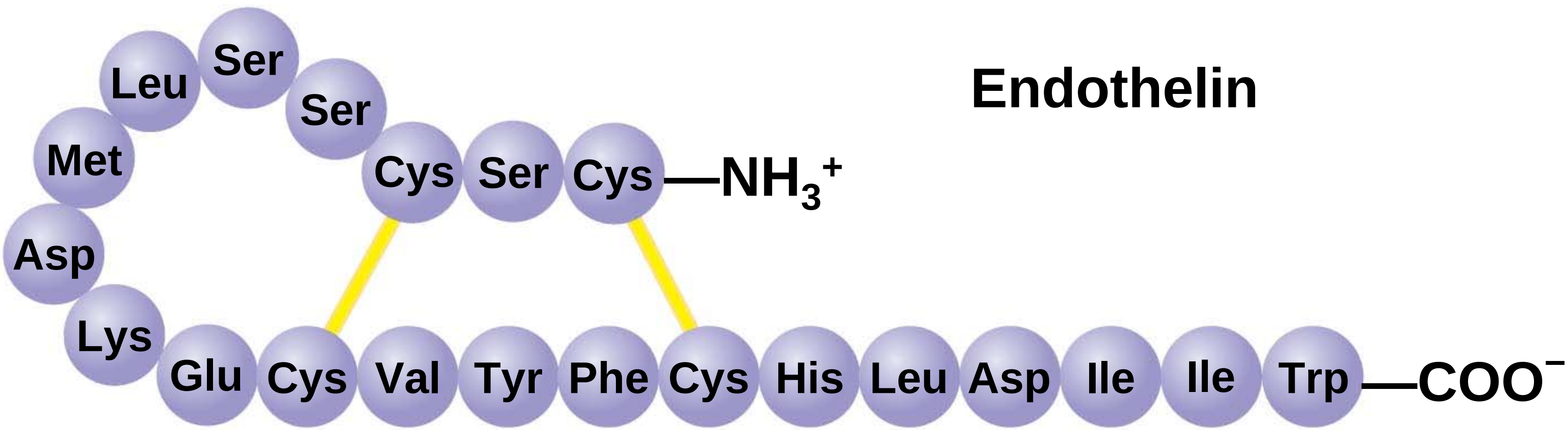
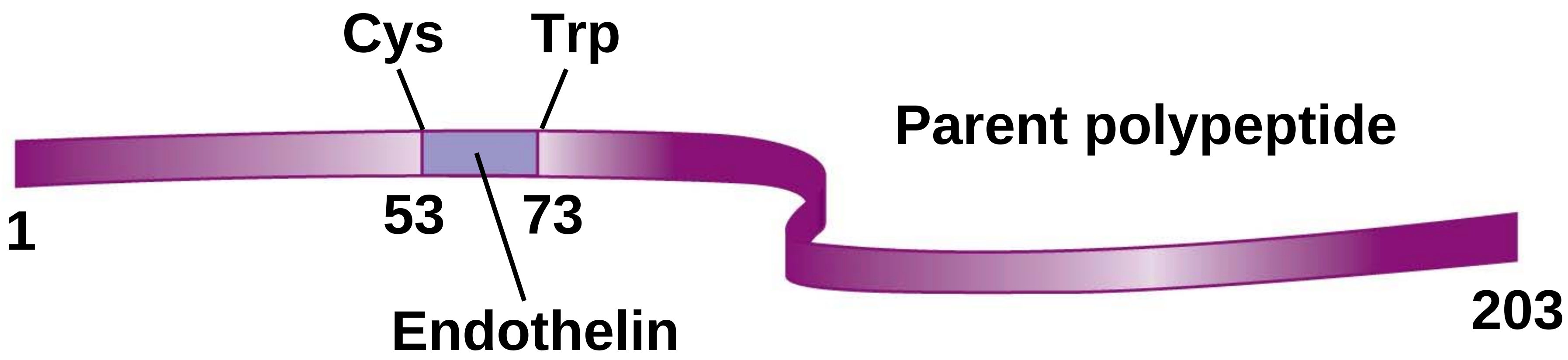


Fig. 42-12b

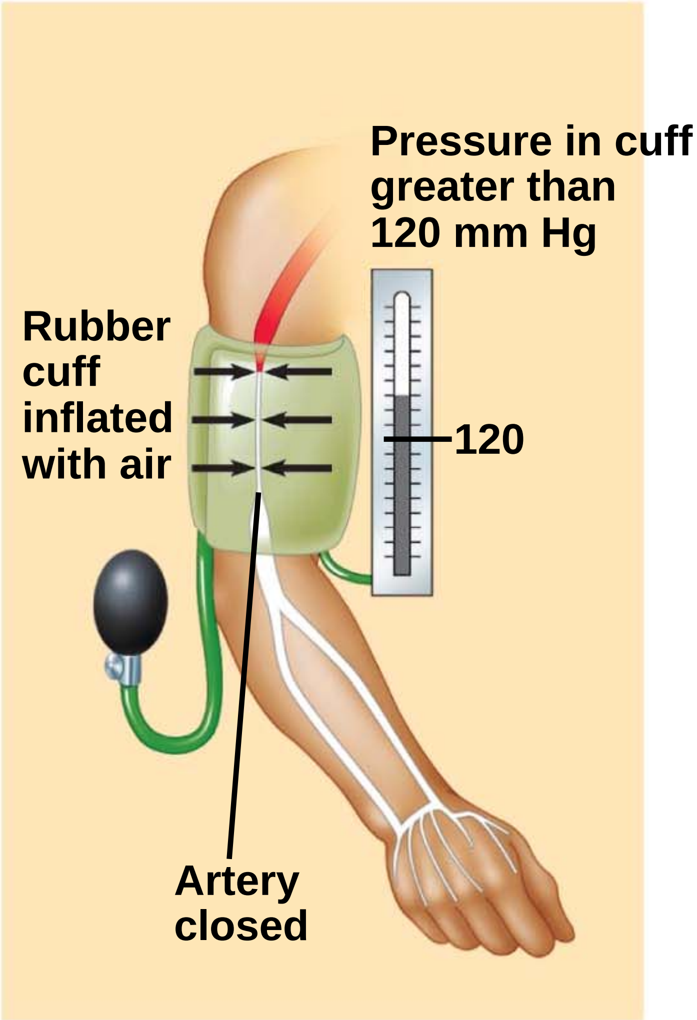
RESULTS



Blood Pressure and Gravity

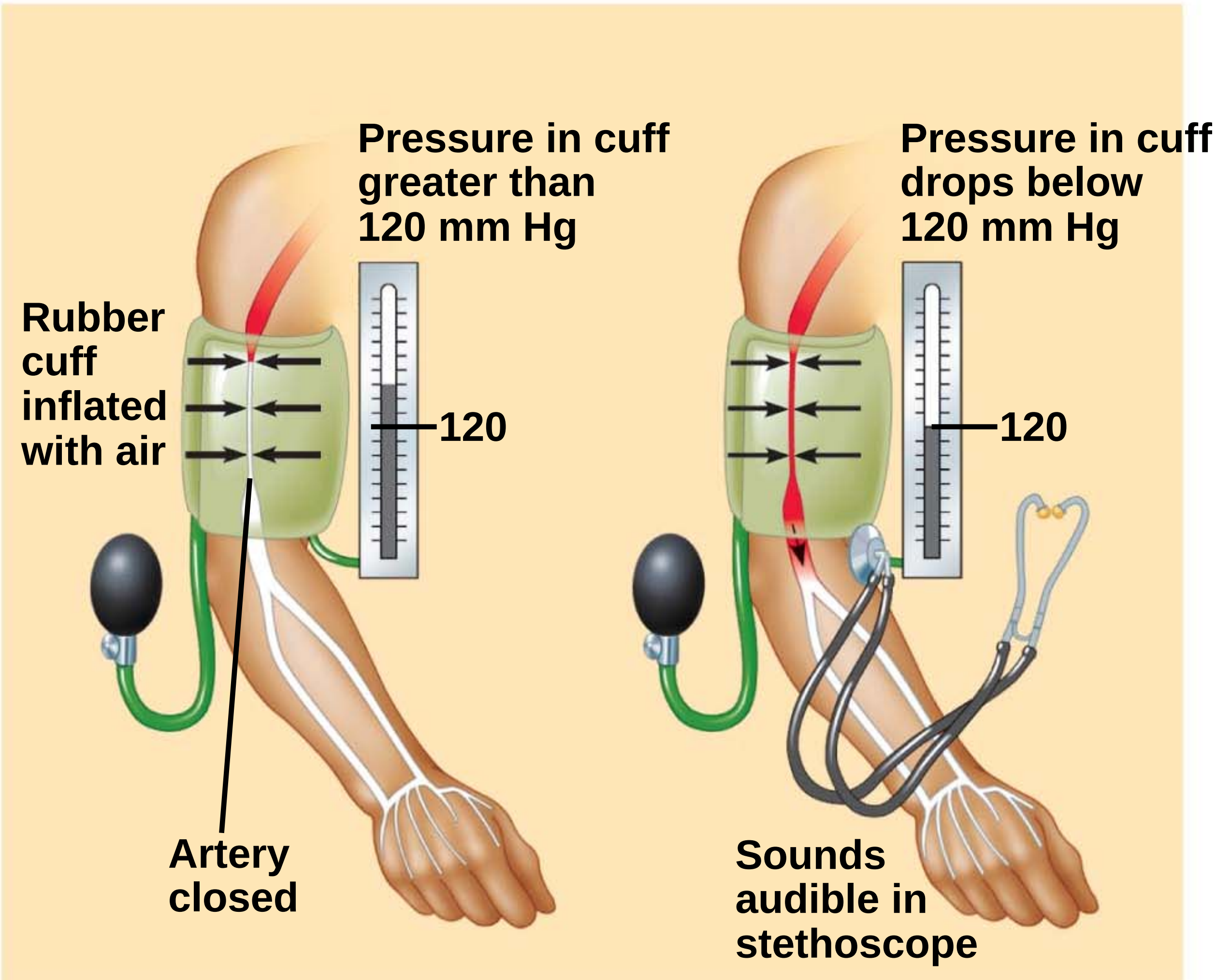
- Blood pressure is generally measured for an artery in the arm at the same height as the heart
- Blood pressure for a healthy 20 year old at rest is 120 mm Hg at systole and 70 mm Hg at diastole

Fig. 42-13-1



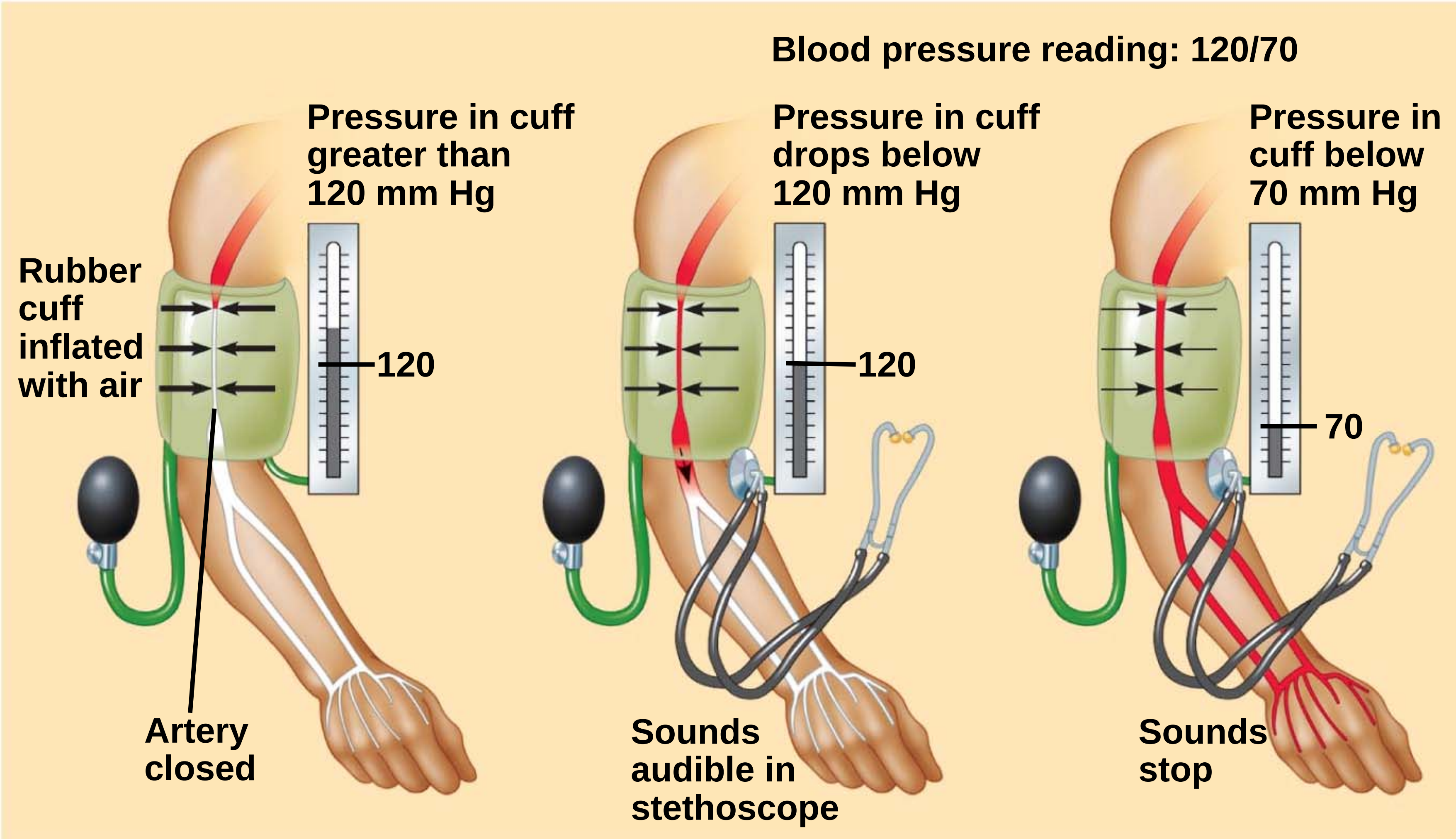
Pressure in cuff greater than 120 mm Hg
Rubber cuff inflated with air
120
Artery closed

Fig. 42-13-2



Pressure in cuff greater than 120 mm Hg
Rubber cuff inflated with air
120
Artery closed
Pressure in cuff drops below 120 mm Hg
120
Sounds audible in stethoscope

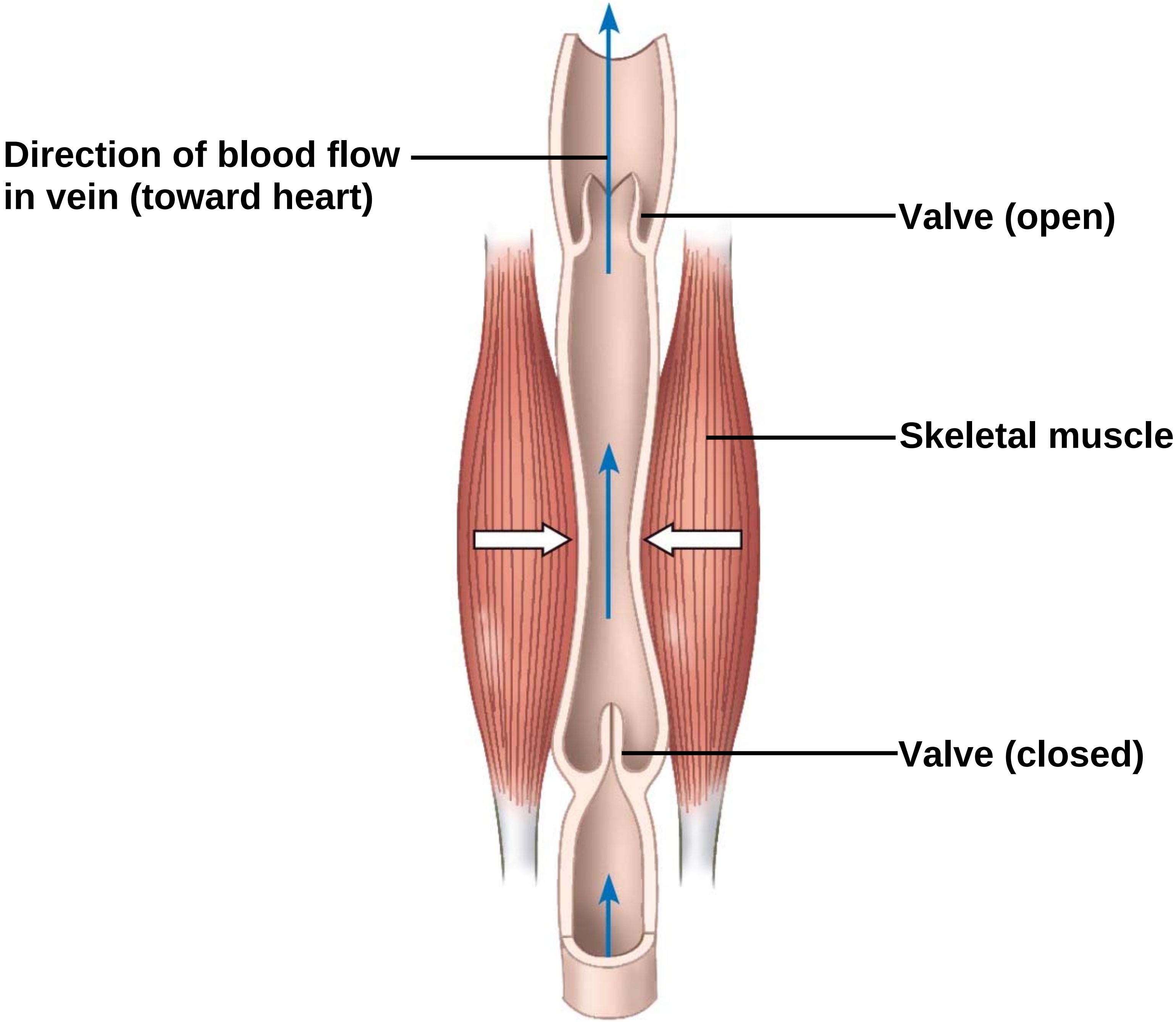
Fig. 42-13-3



Blood pressure reading: 120/70
Pressure in cuff greater than 120 mm Hg
Rubber cuff inflated with air
120
Artery closed
Pressure in cuff drops below 120 mm Hg
120
Sounds audible in stethoscope
Pressure in cuff below 70 mm Hg
70
Sounds stop

- Fainting is caused by inadequate blood flow to the head
- Animals with longer necks require a higher systolic pressure to pump blood a greater distance against gravity
- Blood is moved through veins by smooth muscle contraction, skeletal muscle contraction, and expansion of the vena cava with inhalation
- One-way valves in veins prevent backflow of blood

Fig. 42-14

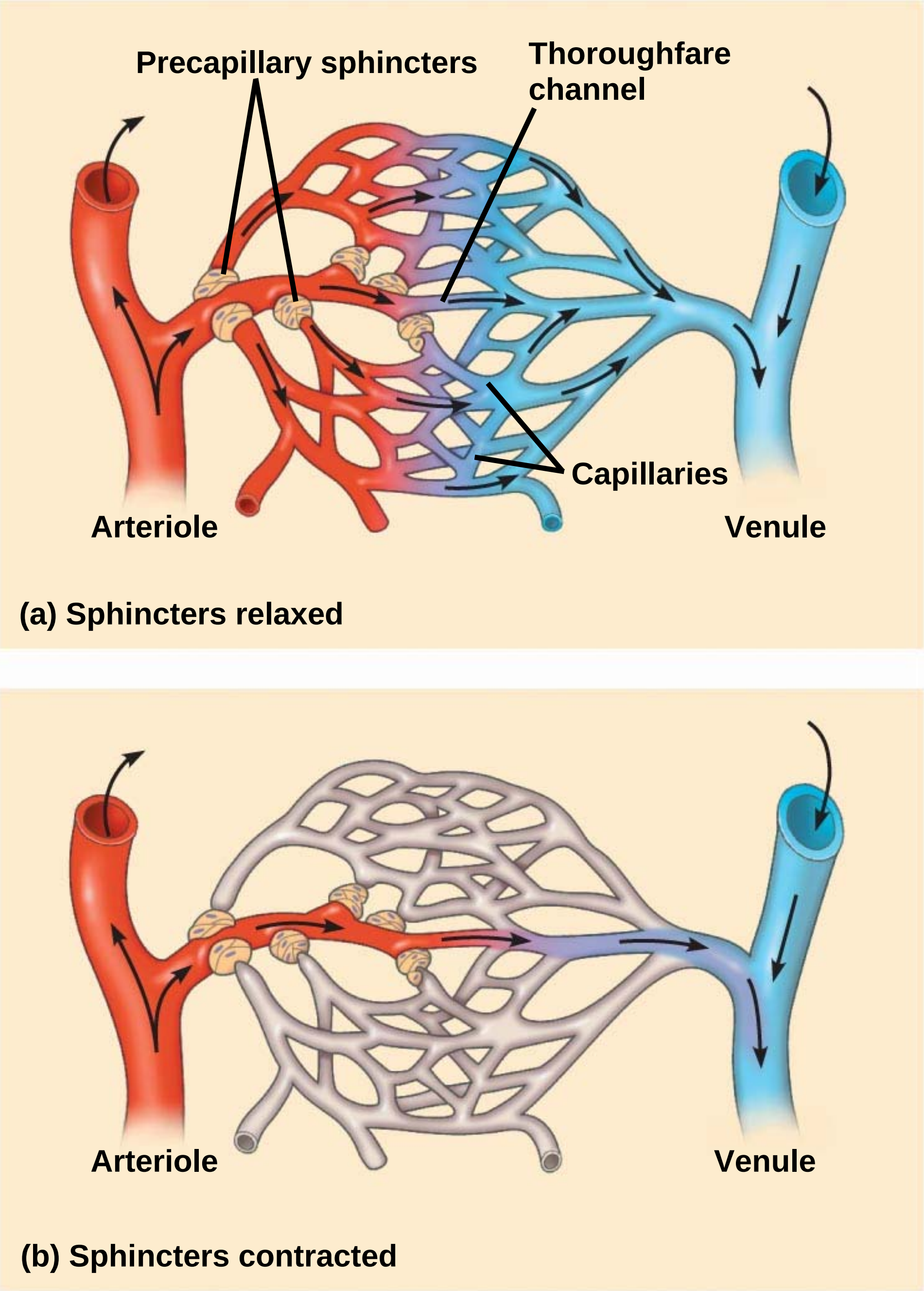

Direction of blood flow
in vein (toward heart)
Valve (open)
Skeletal muscle
Valve (closed)

Capillary Function

- Capillaries in major organs are usually filled to capacity
- Blood supply varies in many other sites

- Two mechanisms regulate distribution of blood in capillary beds:
  - Contraction of the smooth muscle layer in the wall of an arteriole constricts the vessel
  - Precapillary sphincters control flow of blood between arterioles and venules

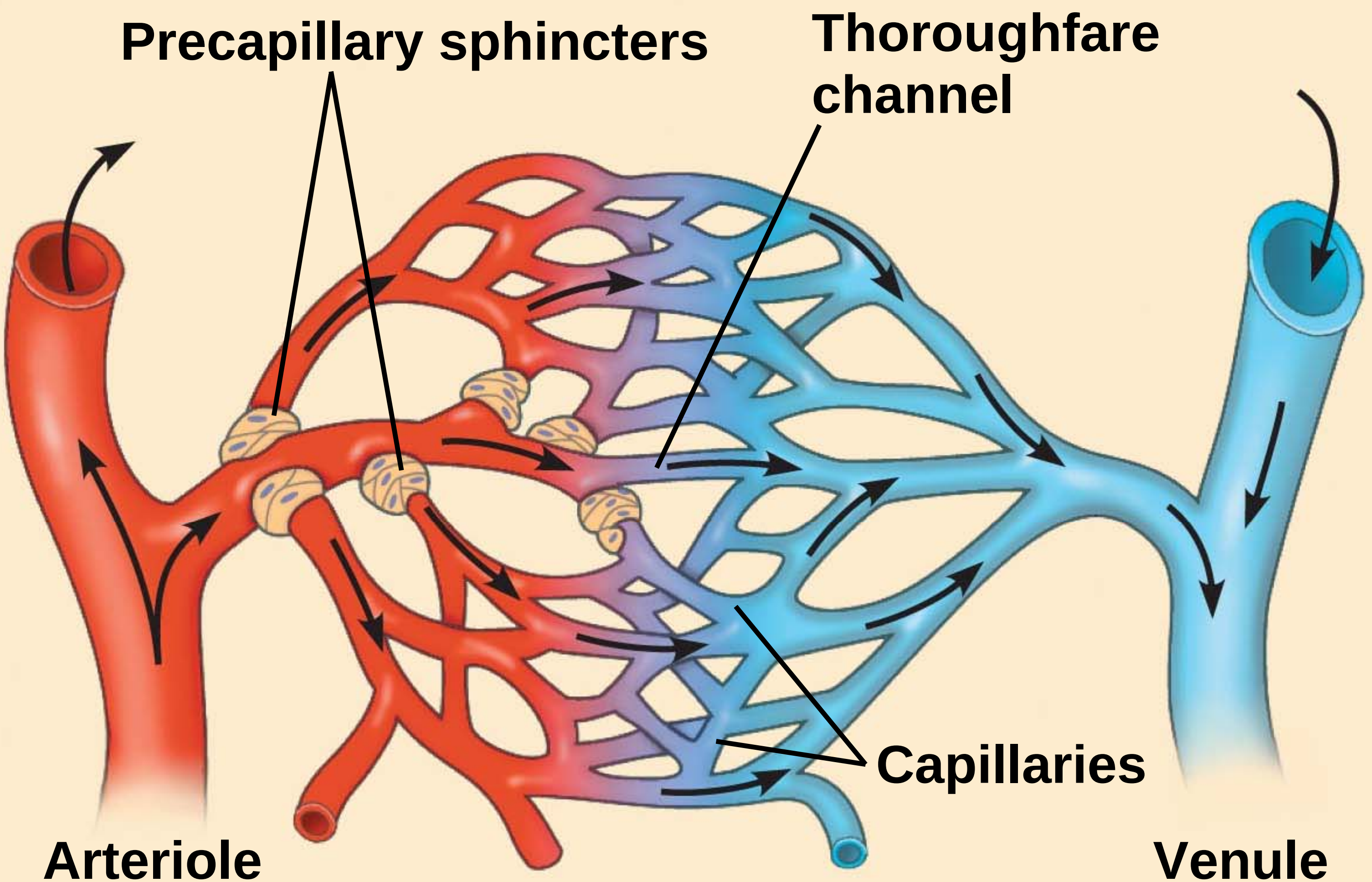
Fig. 42-15



(a) Sphincters relaxed

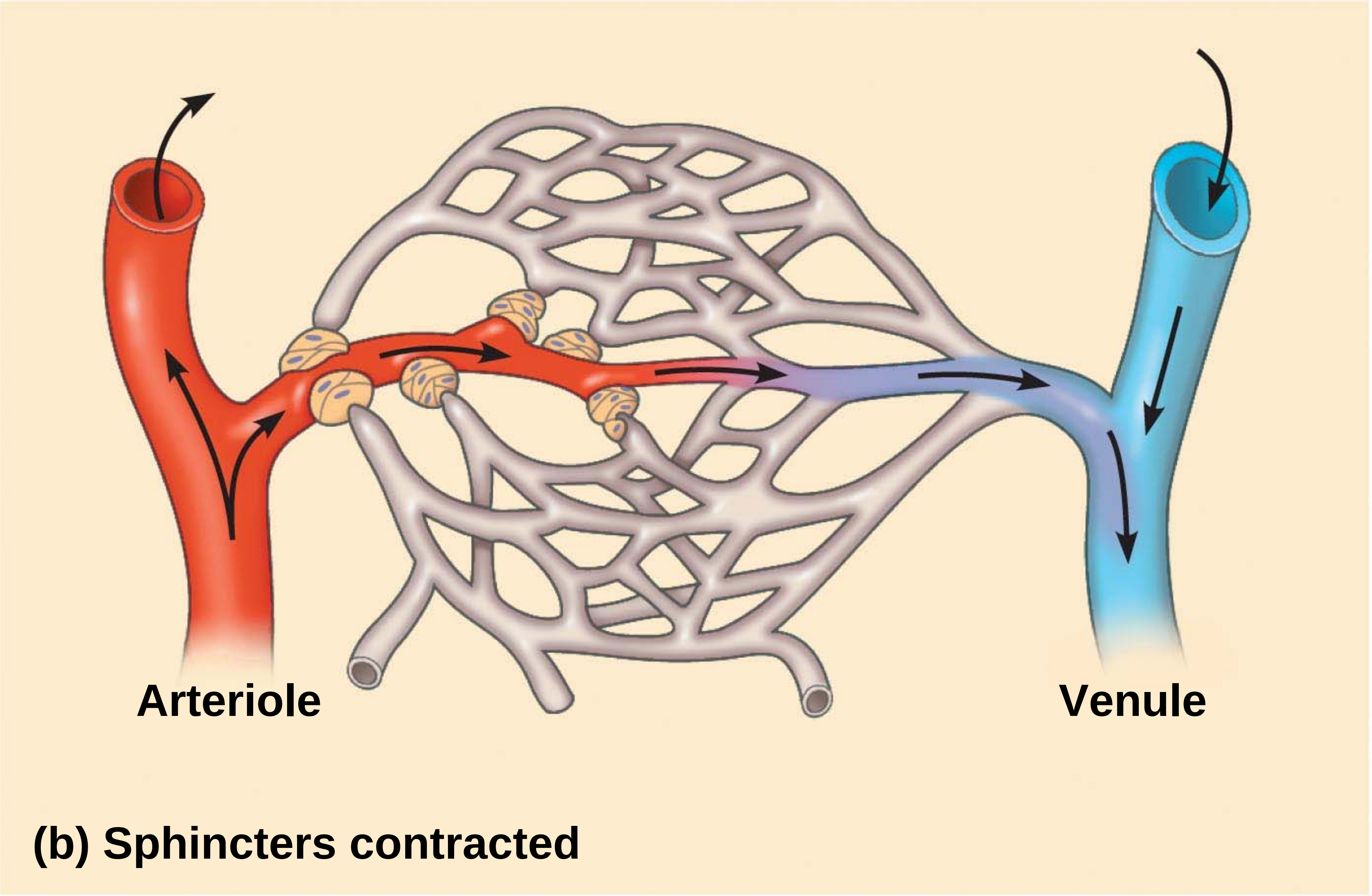
(b) Sphincters contracted

Fig. 42-15a



(a) Sphincters relaxed

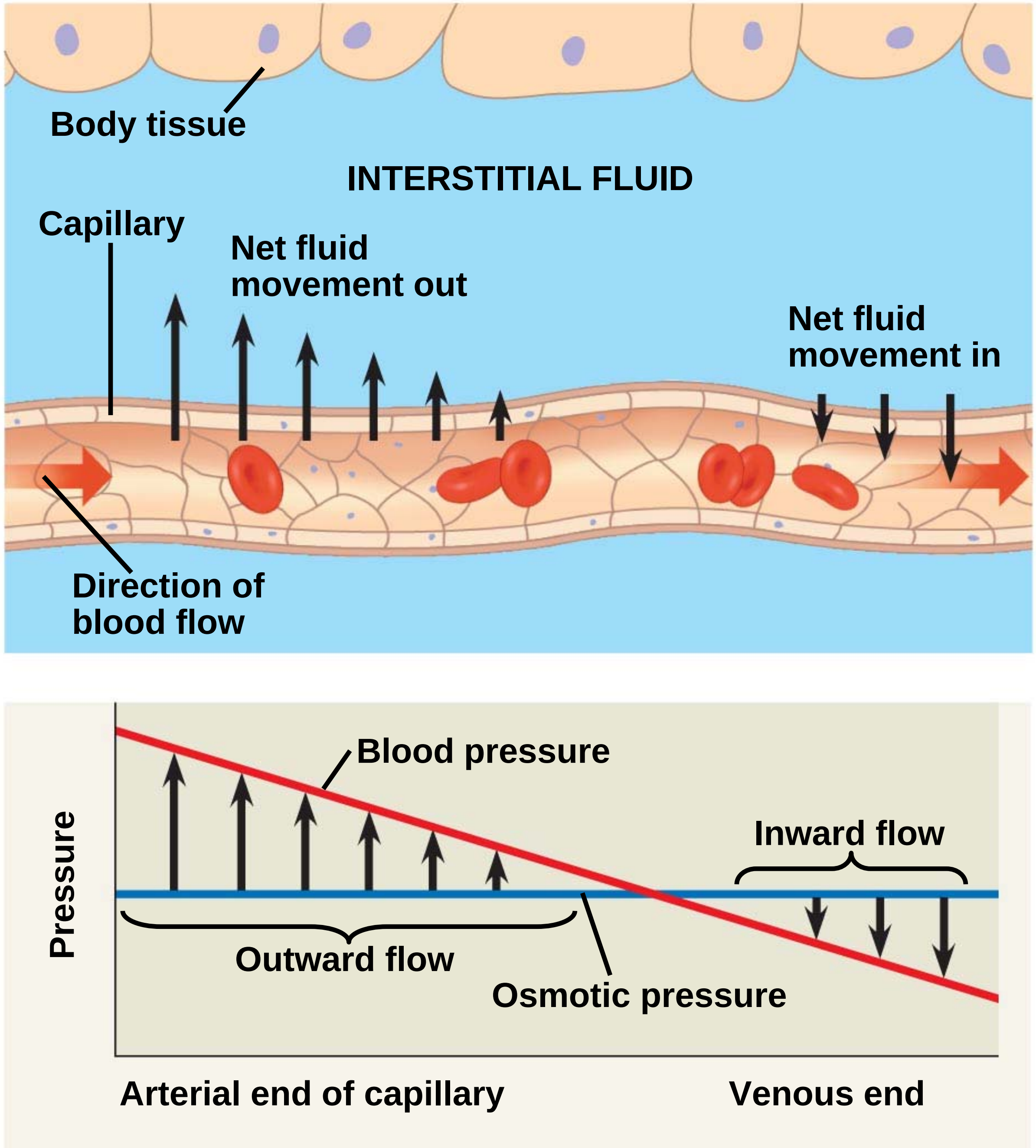
Fig. 42-15b



(b) Sphincters contracted

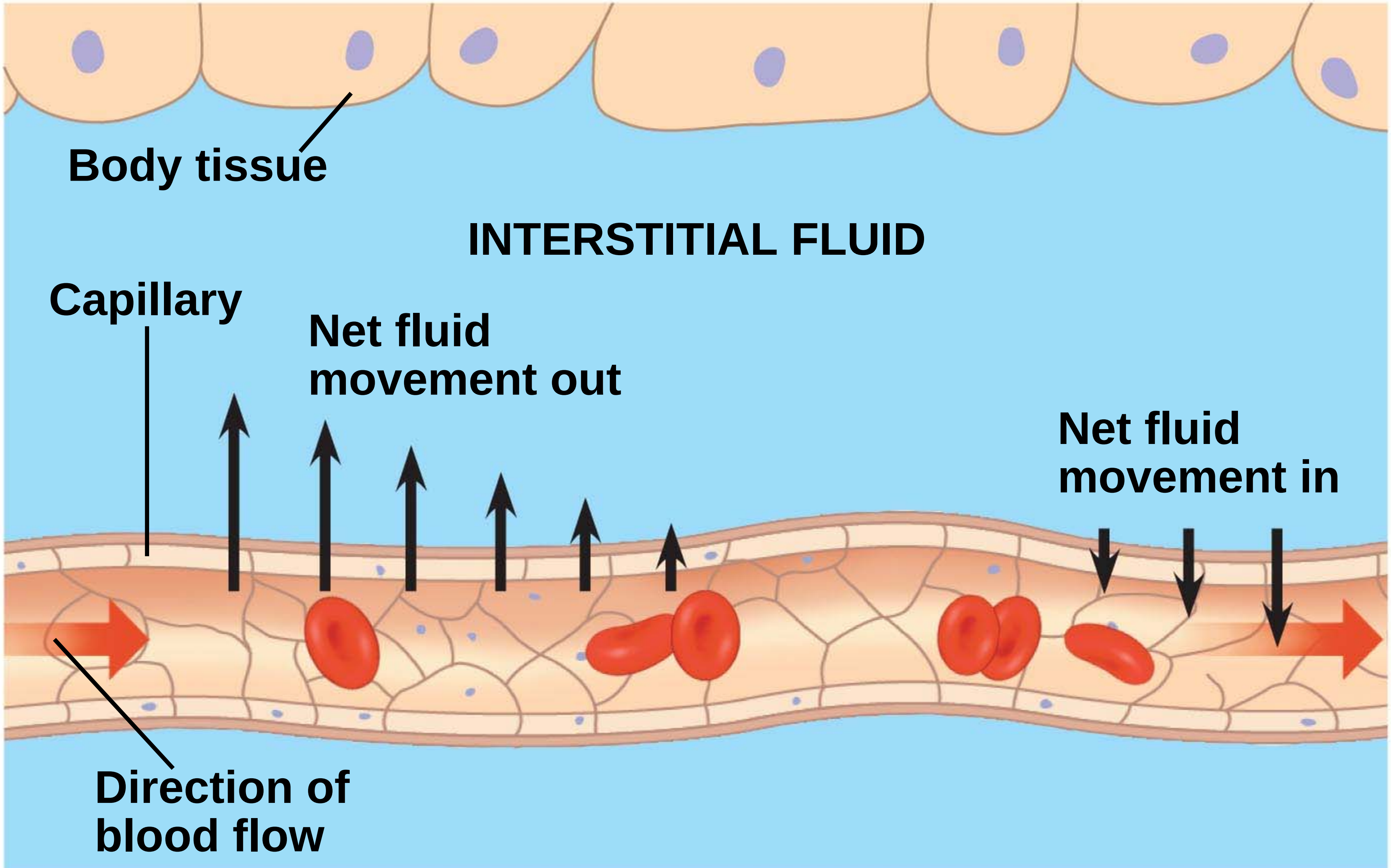
- The critical exchange of substances between the blood and interstitial fluid takes place across the thin endothelial walls of the capillaries
- The difference between blood pressure and osmotic pressure drives fluids out of capillaries at the arteriole end and into capillaries at the venule end

Fig. 42-16



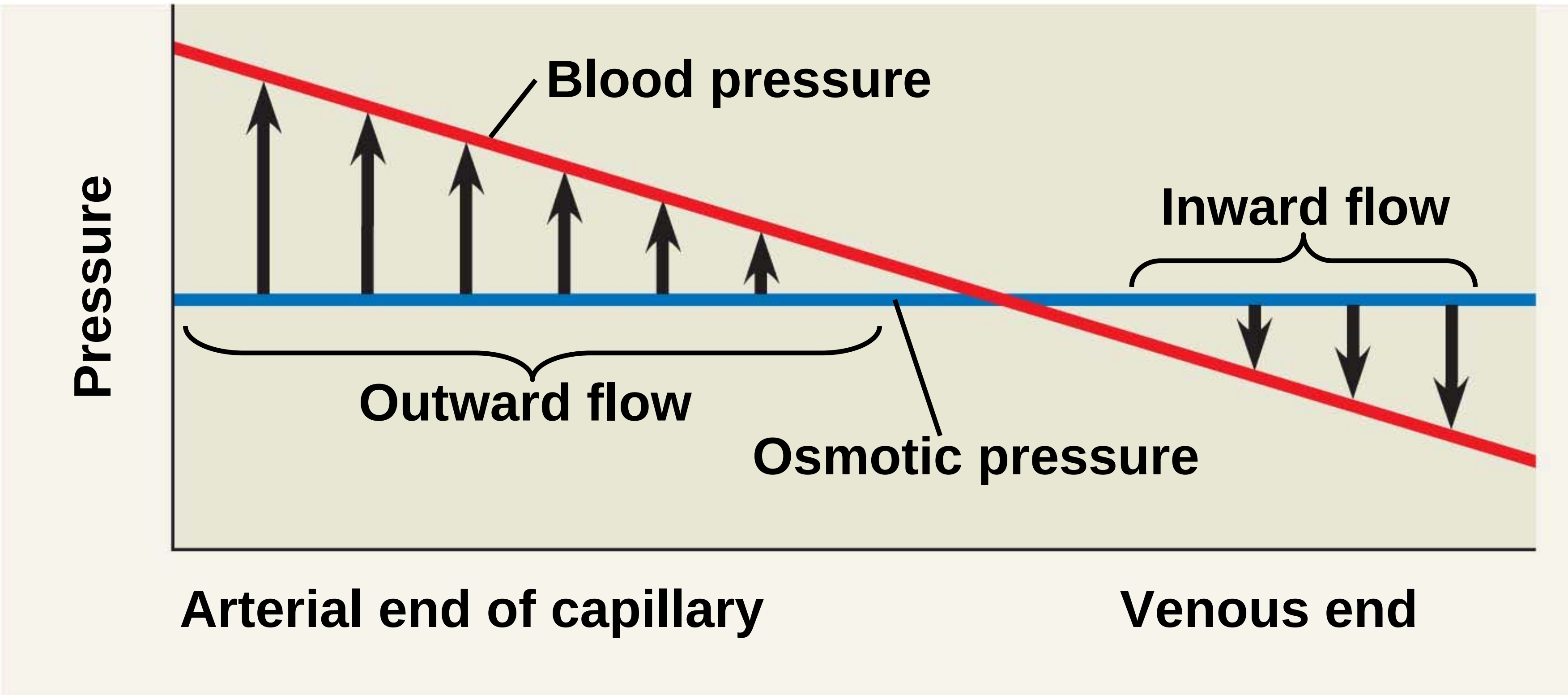
Body tissue
INTERSTITIAL FLUID
Capillary
Net fluid movement out
Net fluid movement in
Direction of blood flow
Blood pressure
Inward flow
Pressure
Outward flow
Osmotic pressure
Arterial end of capillary
Venous end

Fig. 42-16a



Body tissue
INTERSTITIAL FLUID
Capillary
Net fluid movement out
Net fluid movement in
Direction of blood flow

Fig. 42-16b



Blood pressure
Inward flow
Pressure
Outward flow
Osmotic pressure
Arterial end of capillary
Venous end

Fluid Return by the Lymphatic System

- The **lymphatic system** returns fluid that leaks out in the capillary beds
- This system aids in body defense
- Fluid, called **lymph**, reenters the circulation directly at the venous end of the capillary bed and indirectly through the lymphatic system
- The lymphatic system drains into veins in the neck

- **Lymph nodes** are organs that filter lymph and play an important role in the body's defense
- Edema is swelling caused by disruptions in the flow of lymph

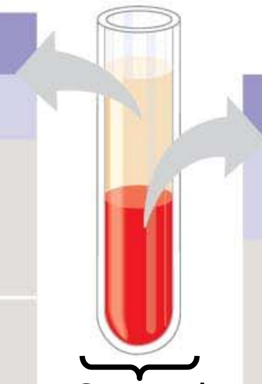
Concept 42.4: Blood components function in exchange, transport, and defense

- In invertebrates with open circulation, blood (hemolymph) is not different from interstitial fluid
- Blood in the circulatory systems of vertebrates is a specialized connective tissue

Blood Composition and Function

- Blood consists of several kinds of cells suspended in a liquid matrix called **plasma**
- The cellular elements occupy about 45% of the volume of blood

Fig. 42-17



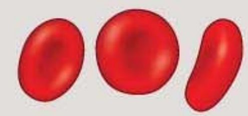
Separated blood elements

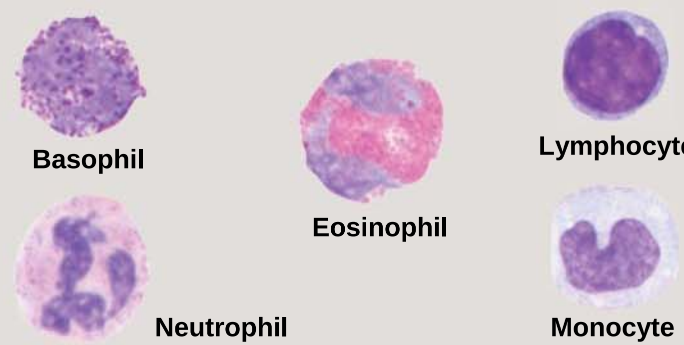
Plasma 55%

Constituent	Major functions
Water	Solvent for carrying other substances
Ions (blood electrolytes) Sodium Potassium Calcium Magnesium Chloride Bicarbonate	Osmotic balance, pH buffering, and regulation of membrane permeability
Plasma proteins	
Albumin	Osmotic balance pH buffering
Fibrinogen	Clotting
Immunoglobulins (antibodies)	Defense
Substances transported by blood Nutrients (such as glucose, fatty acids, vitamins) Waste products of metabolism Respiratory gases (O_2 and CO_2) Hormones	

Cellular elements 45%

Cell type	Number per µL (mm^3) of blood	Functions
Erythrocytes (red blood cells)	5–6 million	Transport oxygen and help transport carbon dioxide
Leukocytes (white blood cells)	5,000–10,000	Defense and immunity
Platelets	250,000–400,000	Blood clotting





Plasma

- Blood plasma is about 90% water
- Among its solutes are inorganic salts in the form of dissolved ions, sometimes called electrolytes
- Another important class of solutes is the plasma proteins, which influence blood pH, osmotic pressure, and viscosity
- Various plasma proteins function in lipid transport, immunity, and blood clotting

Cellular Elements

- Suspended in blood plasma are two types of cells:
  - Red blood cells (erythrocytes) transport oxygen
  - White blood cells (leukocytes) function in defense
- **Platelets**, a third cellular element, are fragments of cells that are involved in clotting

Erythrocytes

- Red blood cells, or **erythrocytes**, are by far the most numerous blood cells
- They transport oxygen throughout the body
- They contain **hemoglobin**, the iron-containing protein that transports oxygen

Leukocytes

- There are five major types of white blood cells, or **leukocytes**: monocytes, neutrophils, basophils, eosinophils, and lymphocytes
- They function in defense by phagocytizing bacteria and debris or by producing antibodies
- They are found both in and outside of the circulatory system

Platelets

- Platelets are fragments of cells and function in blood clotting

Blood Clotting

- When the endothelium of a blood vessel is damaged, the clotting mechanism begins
- A cascade of complex reactions converts fibrinogen to **fibrin**, forming a clot
- A blood clot formed within a blood vessel is called a **thrombus** and can block blood flow

Fig. 42-18-1

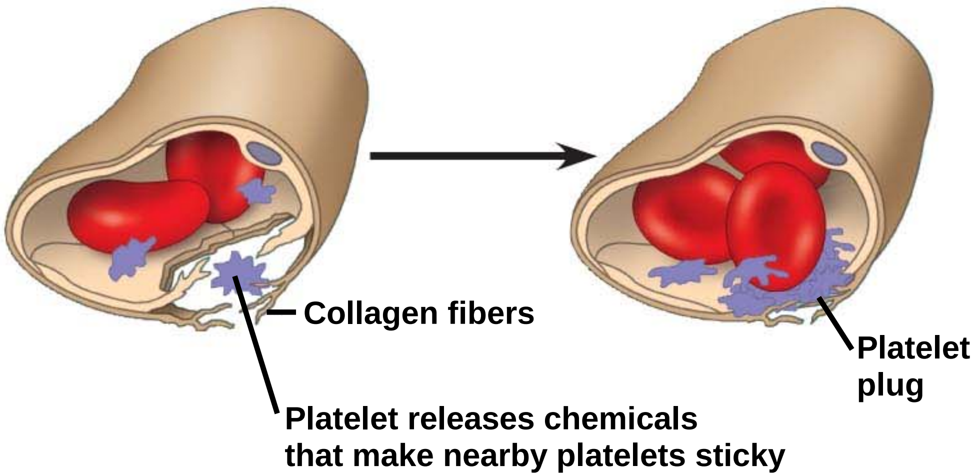

Collagen fibers
Platelet plug
Platelet releases chemicals that make nearby platelets sticky

Fig. 42-18-2

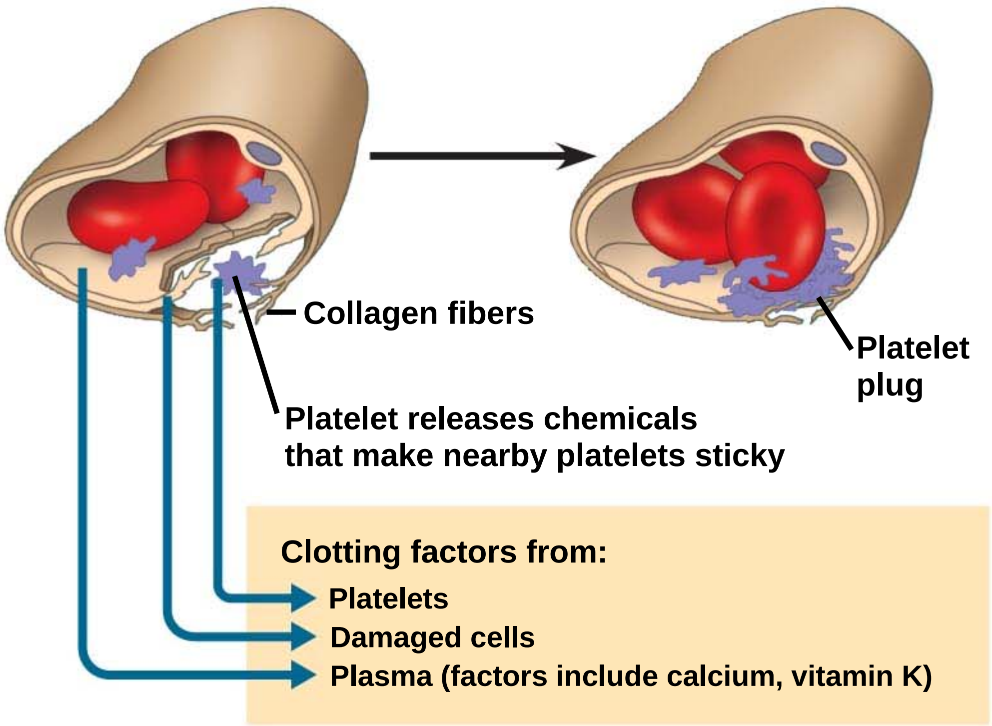
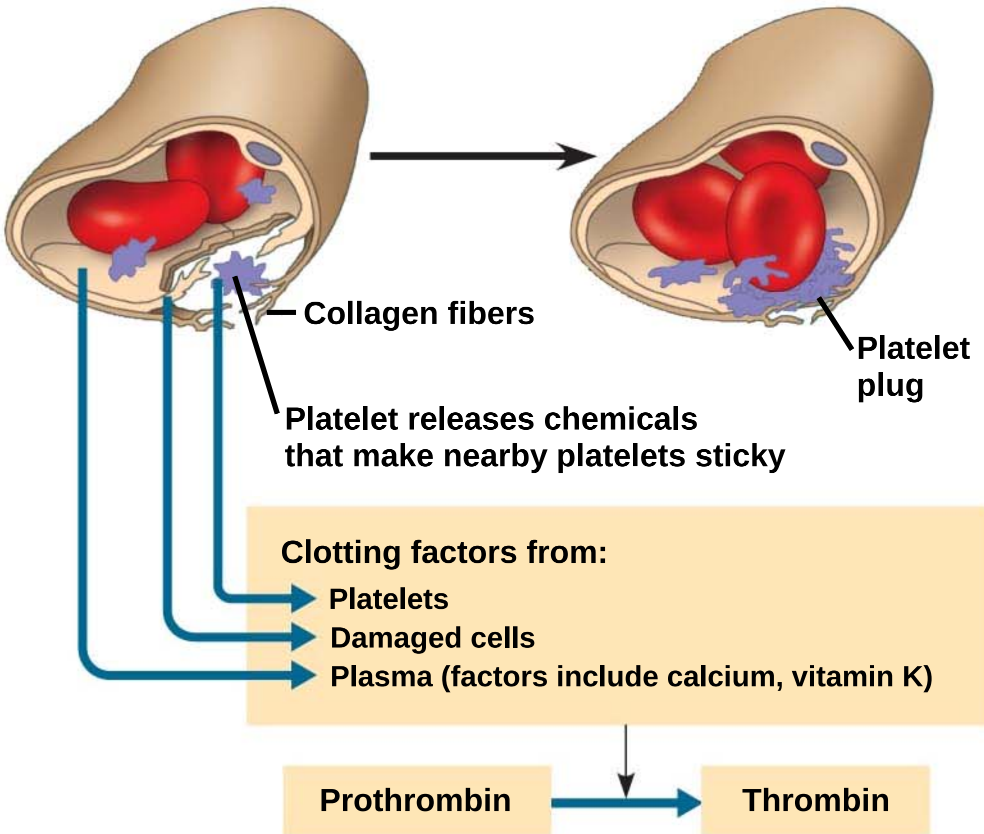
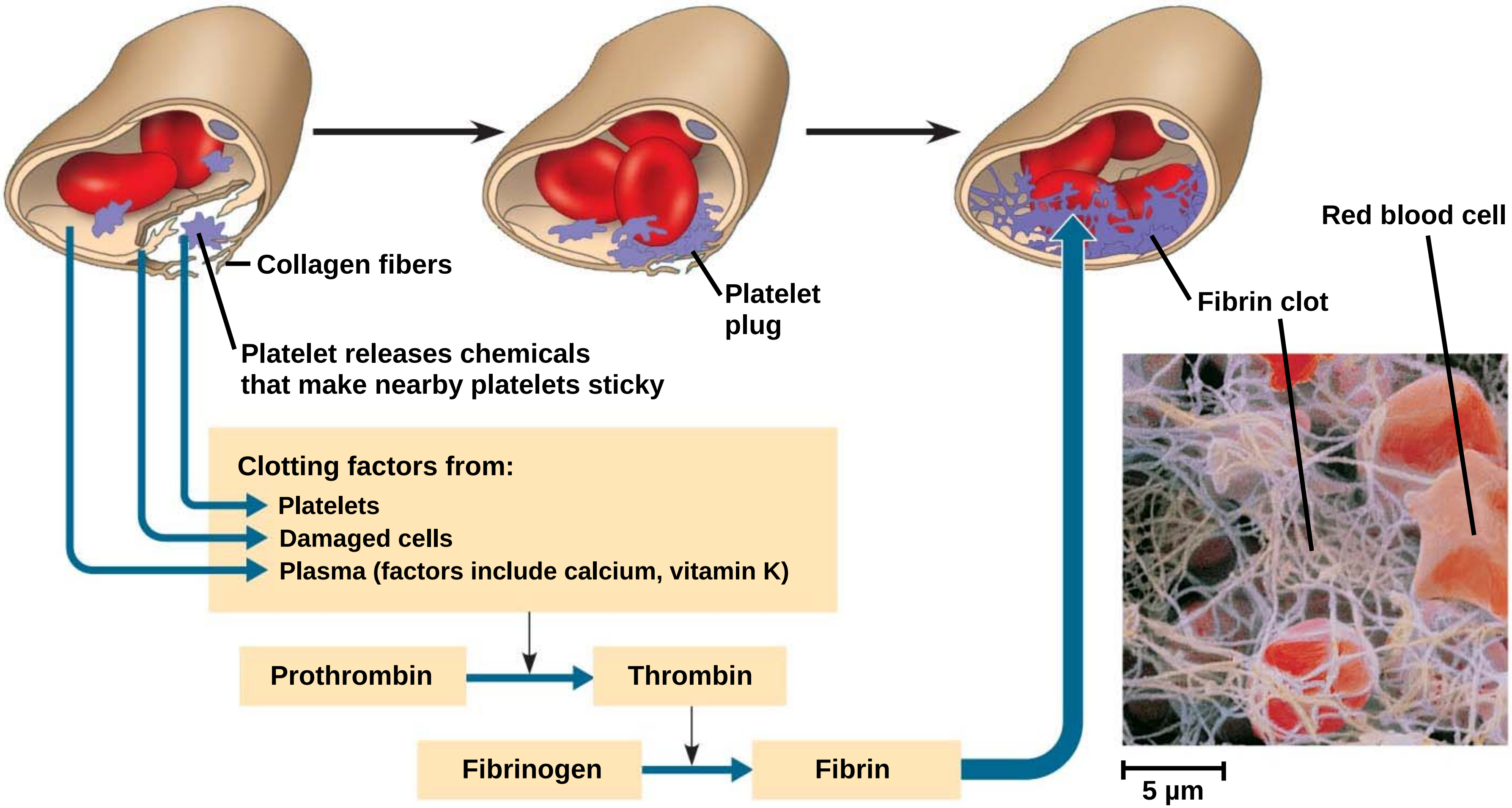

Collagen fibers
Platelet plug
Platelet releases chemicals
that make nearby platelets sticky
Clotting factors from:
Platelets
Damaged cells
Plasma (factors include calcium, vitamin K)

Fig. 42-18-3



Collagen fibers
Platelet plug
Platelet releases chemicals that make nearby platelets sticky
Clotting factors from:
Platelets
Damaged cells
Plasma (factors include calcium, vitamin K)
Prothrombin
Thrombin

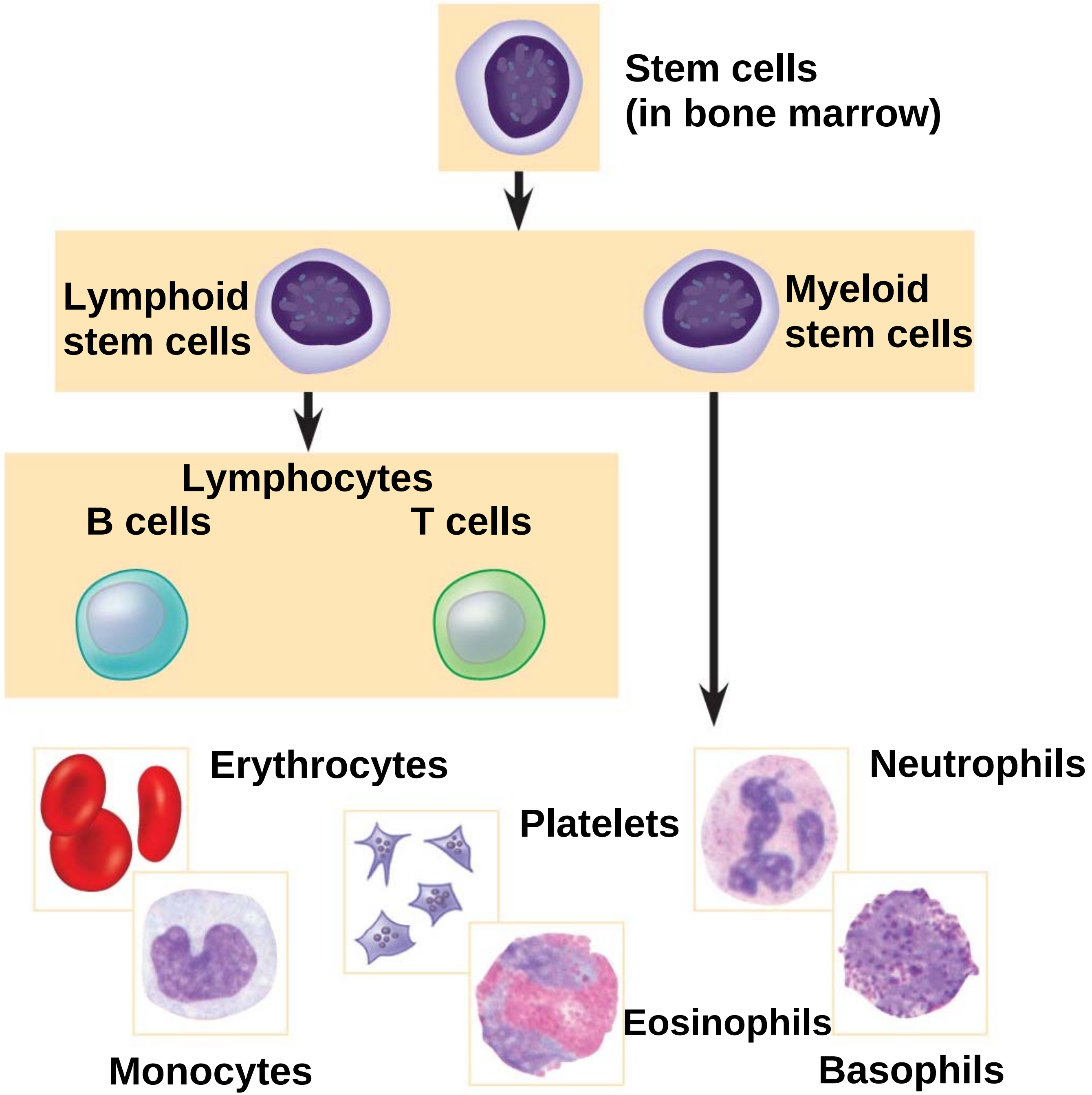
Fig. 42-18-4


Collagen fibers
Platelet releases chemicals
that make nearby platelets sticky
Platelet
plug
Fibrin clot
Red blood cell
Clotting factors from:
Platelets
Damaged cells
Plasma (factors include calcium, vitamin K)
Prothrombin
Thrombin
Fibrinogen
Fibrin
5 μm

Stem Cells and the Replacement of Cellular Elements

- The cellular elements of blood wear out and are replaced constantly throughout a person's life
- Erythrocytes, leukocytes, and platelets all develop from a common source of **stem cells** in the red marrow of bones
- The hormone **erythropoietin (EPO)** stimulates erythrocyte production when oxygen delivery is low

Fig. 42-19


Stem cells
(in bone marrow)
Lymphoid
stem cells
Myeloid
stem cells
Lymphocytes
B cells
T cells
Erythrocytes
Neutrophils
Platelets
Eosinophils
Monocytes
Basophils

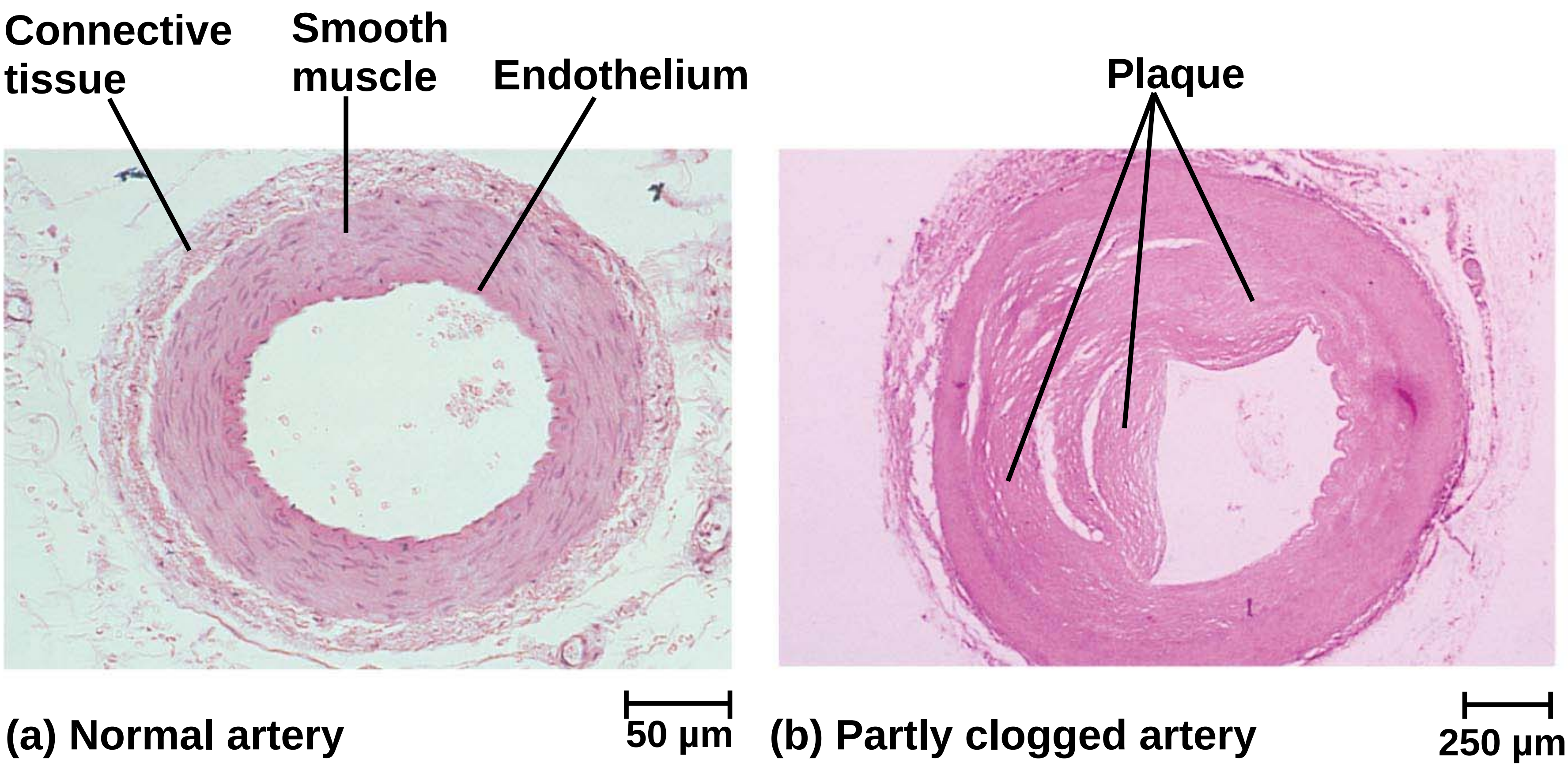
Cardiovascular Disease

- Cardiovascular diseases are disorders of the heart and the blood vessels
- They account for more than half the deaths in the United States

Atherosclerosis

- One type of cardiovascular disease, **atherosclerosis**, is caused by the buildup of plaque deposits within arteries

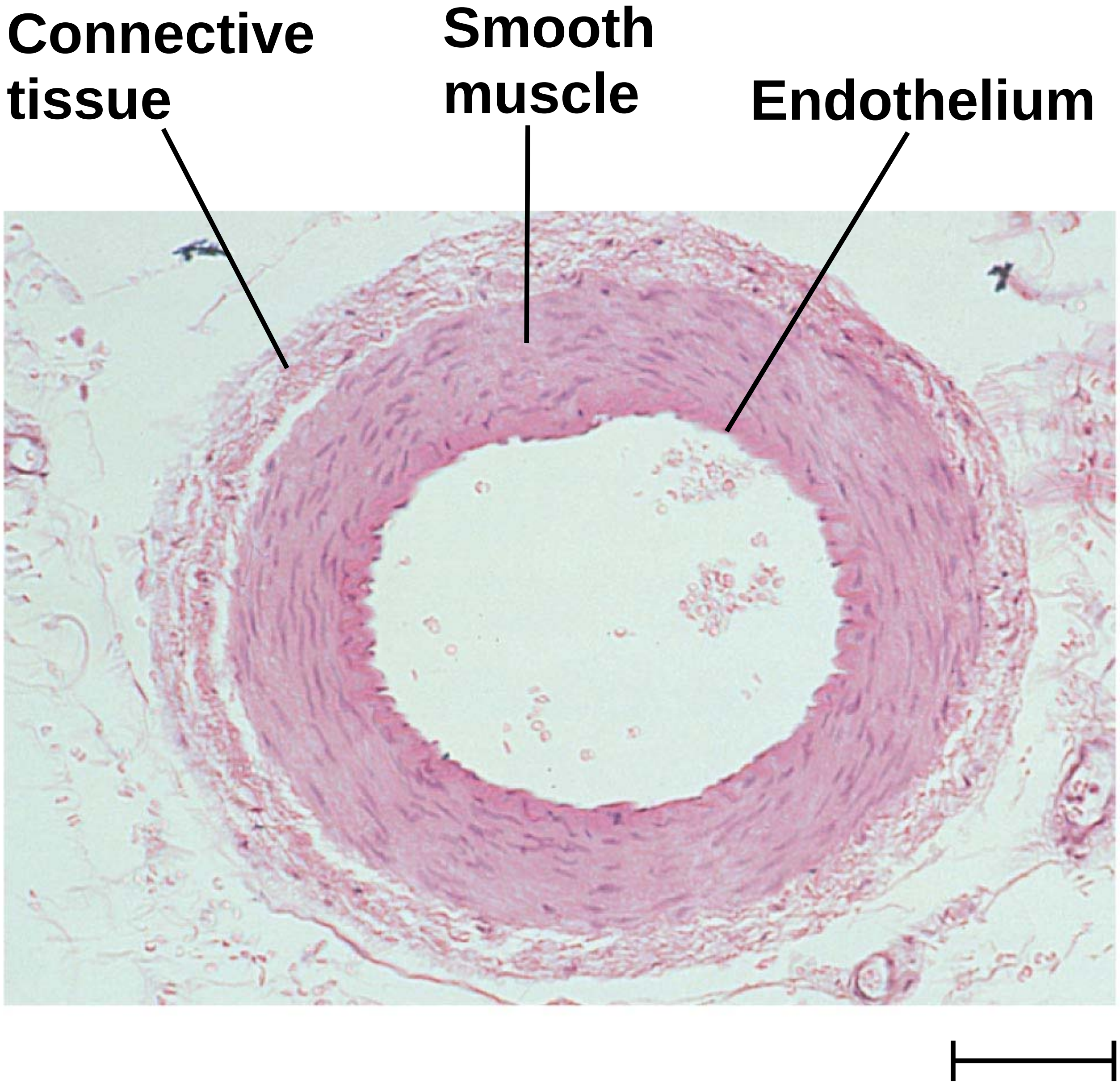
Fig. 42-20



(a) Normal artery

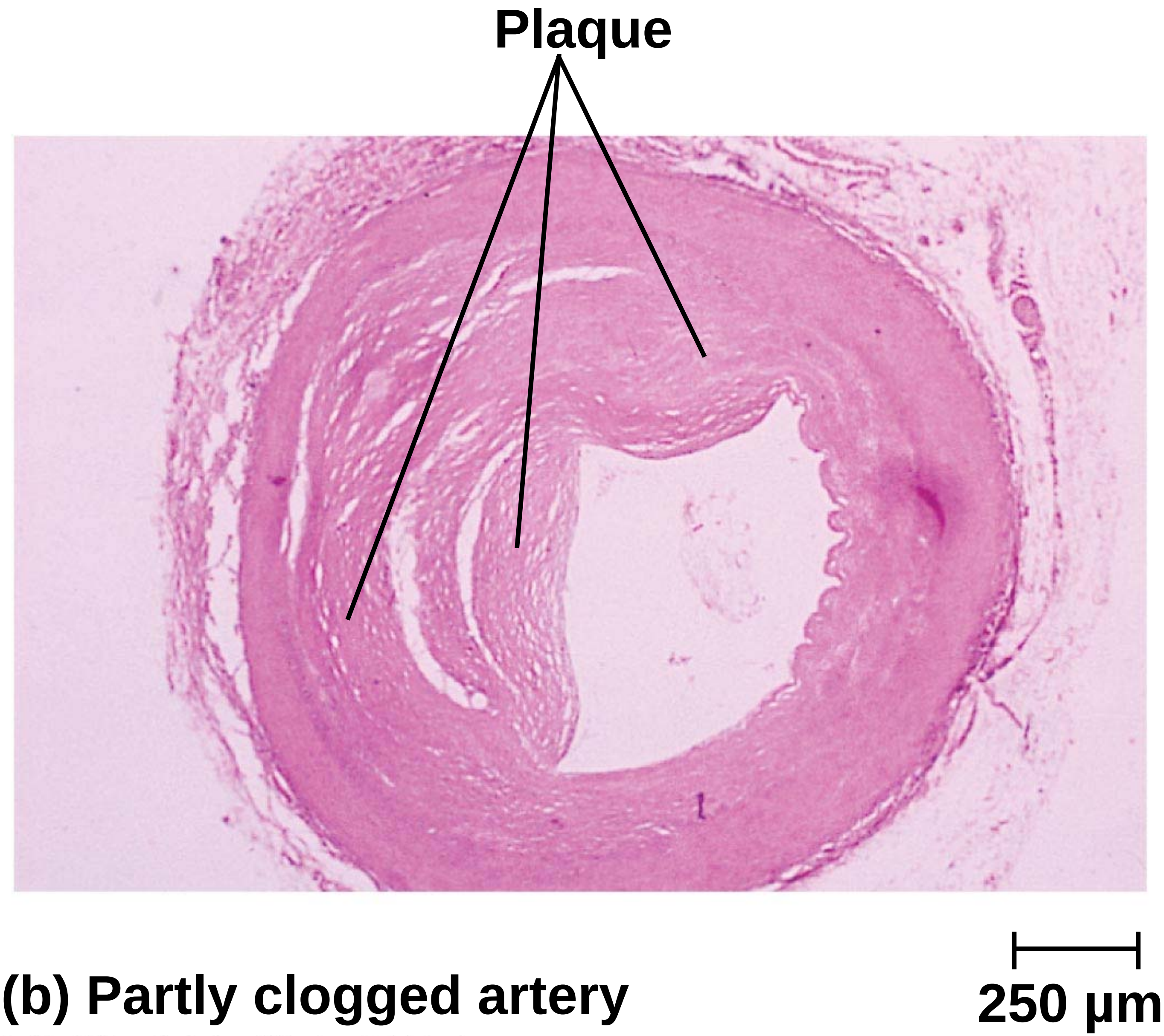
(b) Partly clogged artery

Fig. 42-20a



(a) Normal artery

Fig. 42-20b



(b) Partly clogged artery

Heart Attacks and Stroke

- A **heart attack** is the death of cardiac muscle tissue resulting from blockage of one or more coronary arteries

- A **stroke** is the death of nervous tissue in the brain, usually resulting from rupture or blockage of arteries in the head

Treatment and Diagnosis of Cardiovascular Disease

- Cholesterol is a major contributor to atherosclerosis
- **Low-density lipoproteins (LDLs)** are associated with plaque formation; these are “bad cholesterol”
- **High-density lipoproteins (HDLs)** reduce the deposition of cholesterol; these are “good cholesterol”
- The proportion of LDL relative to HDL can be decreased by exercise, not smoking, and avoiding foods with *trans* fats

- **Hypertension**, or high blood pressure, promotes atherosclerosis and increases the risk of heart attack and stroke
- Hypertension can be reduced by dietary changes, exercise, and/or medication

Concept 42.5: Gas exchange occurs across specialized respiratory surfaces

- **Gas exchange** supplies oxygen for cellular respiration and disposes of carbon dioxide

Partial Pressure Gradients in Gas Exchange

- Gases diffuse down pressure gradients in the lungs and other organs as a result of differences in partial pressure

- **Partial pressure** is the pressure exerted by a particular gas in a mixture of gases

- A gas diffuses from a region of higher partial pressure to a region of lower partial pressure
- In the lungs and tissues, O_2 and CO_2 diffuse from where their partial pressures are higher to where they are lower

Respiratory Media

- Animals can use air or water as a source of O_2, or respiratory medium
- In a given volume, there is less O_2 available in water than in air
- Obtaining O_2 from water requires greater efficiency than air breathing

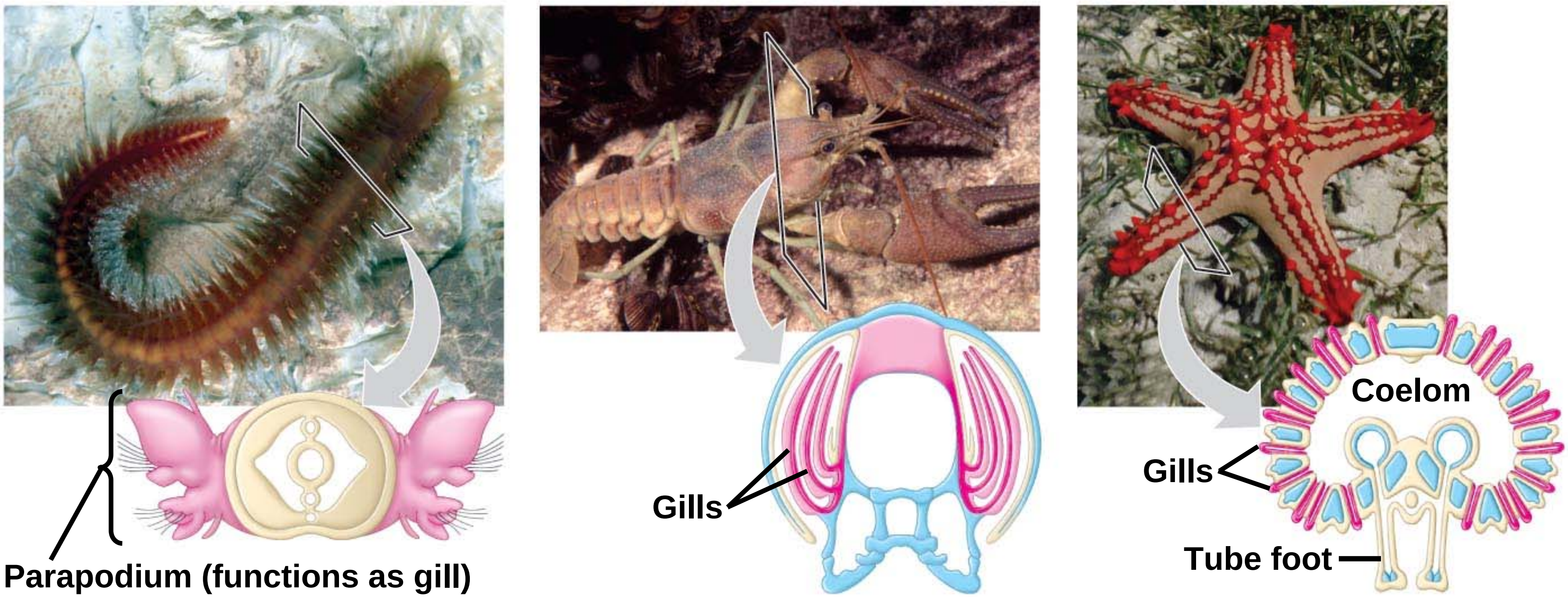
Respiratory Surfaces

- Animals require large, moist respiratory surfaces for exchange of gases between their cells and the respiratory medium, either air or water
- Gas exchange across respiratory surfaces takes place by diffusion
- Respiratory surfaces vary by animal and can include the outer surface, skin, gills, tracheae, and lungs

Gills in Aquatic Animals

- Gills are outfoldings of the body that create a large surface area for gas exchange

Fig. 42-21

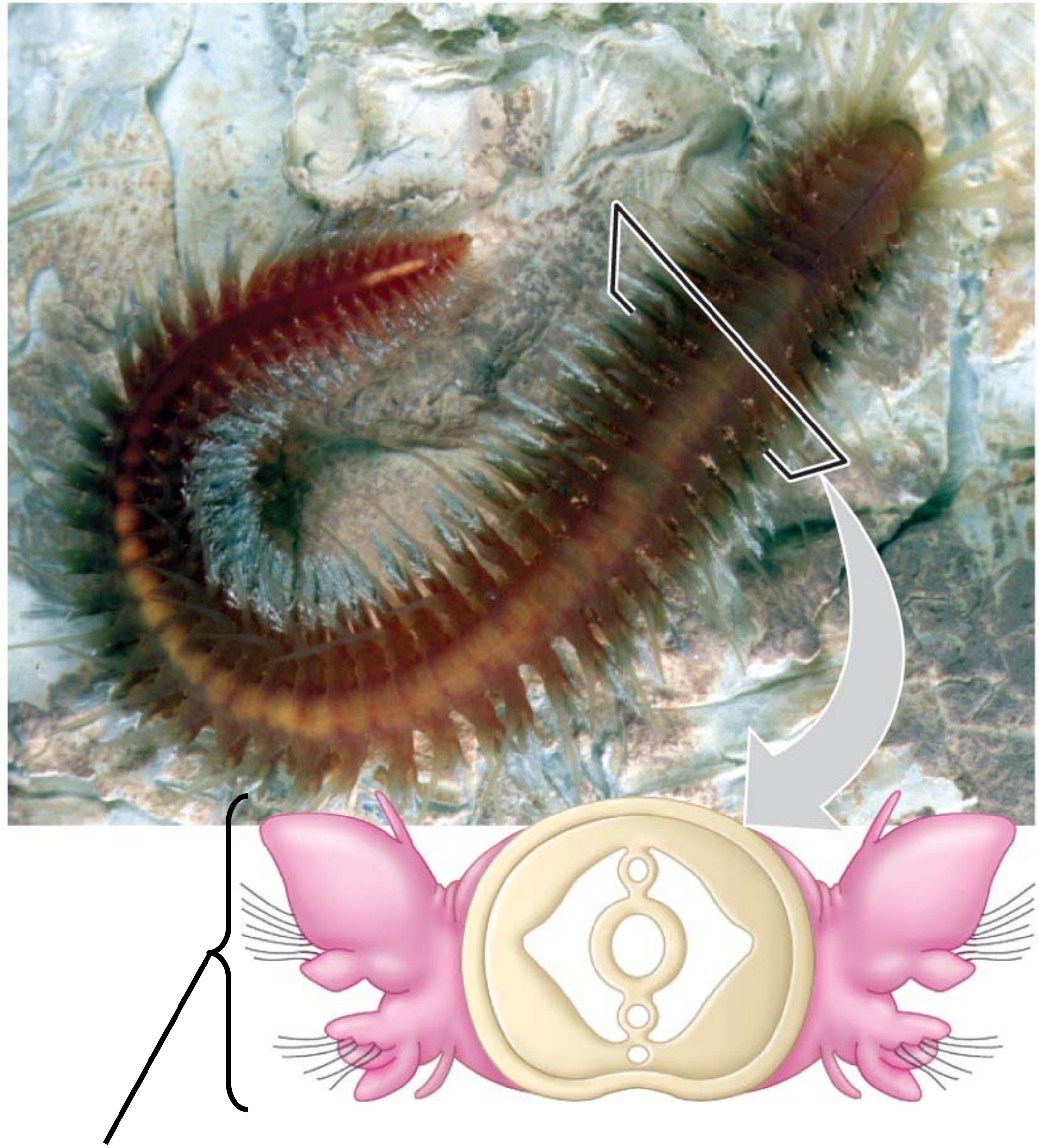


(a) Marine worm

(b) Crayfish

(c) Sea star

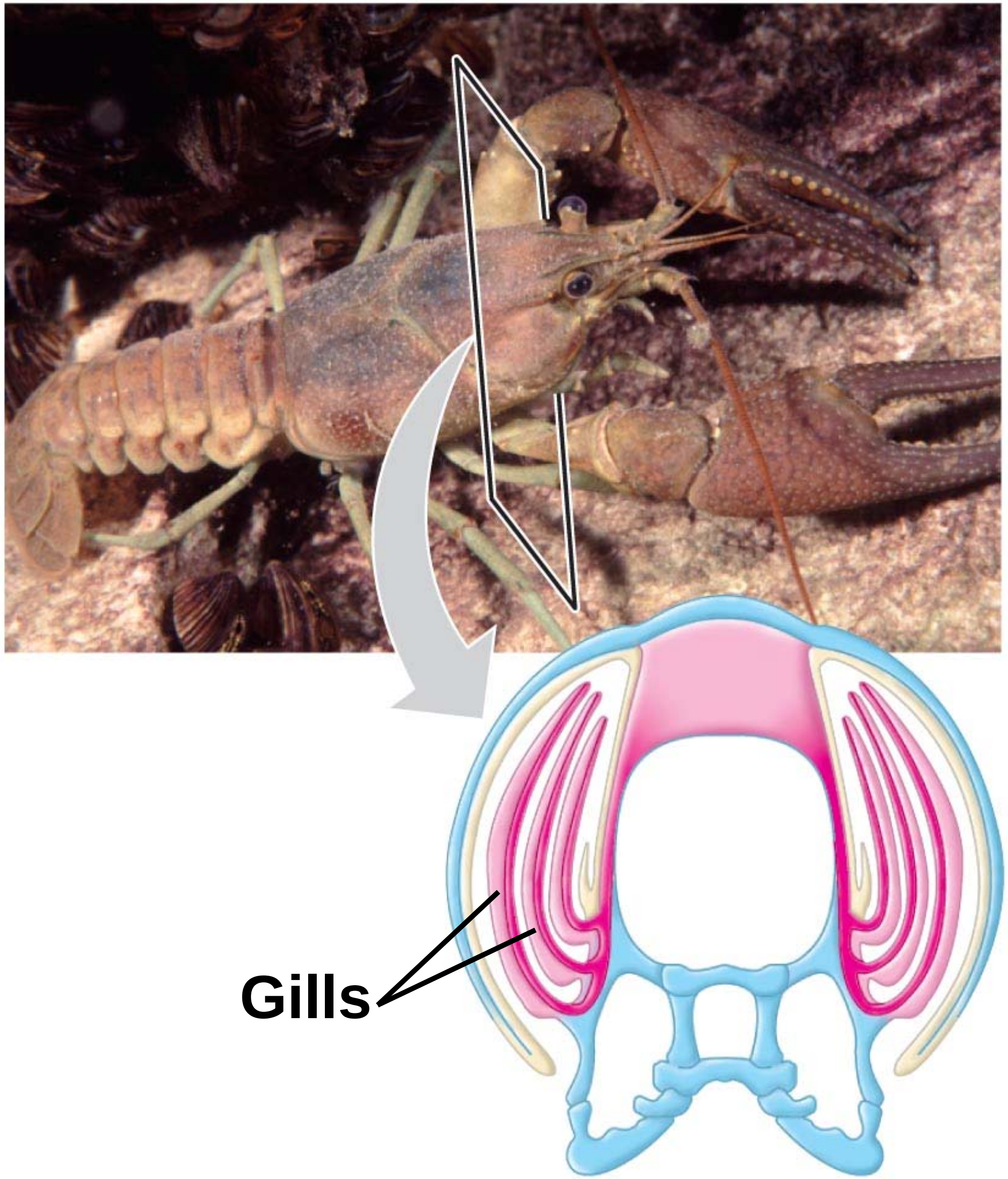
Fig. 42-21a



Parapodium (functions as gill)

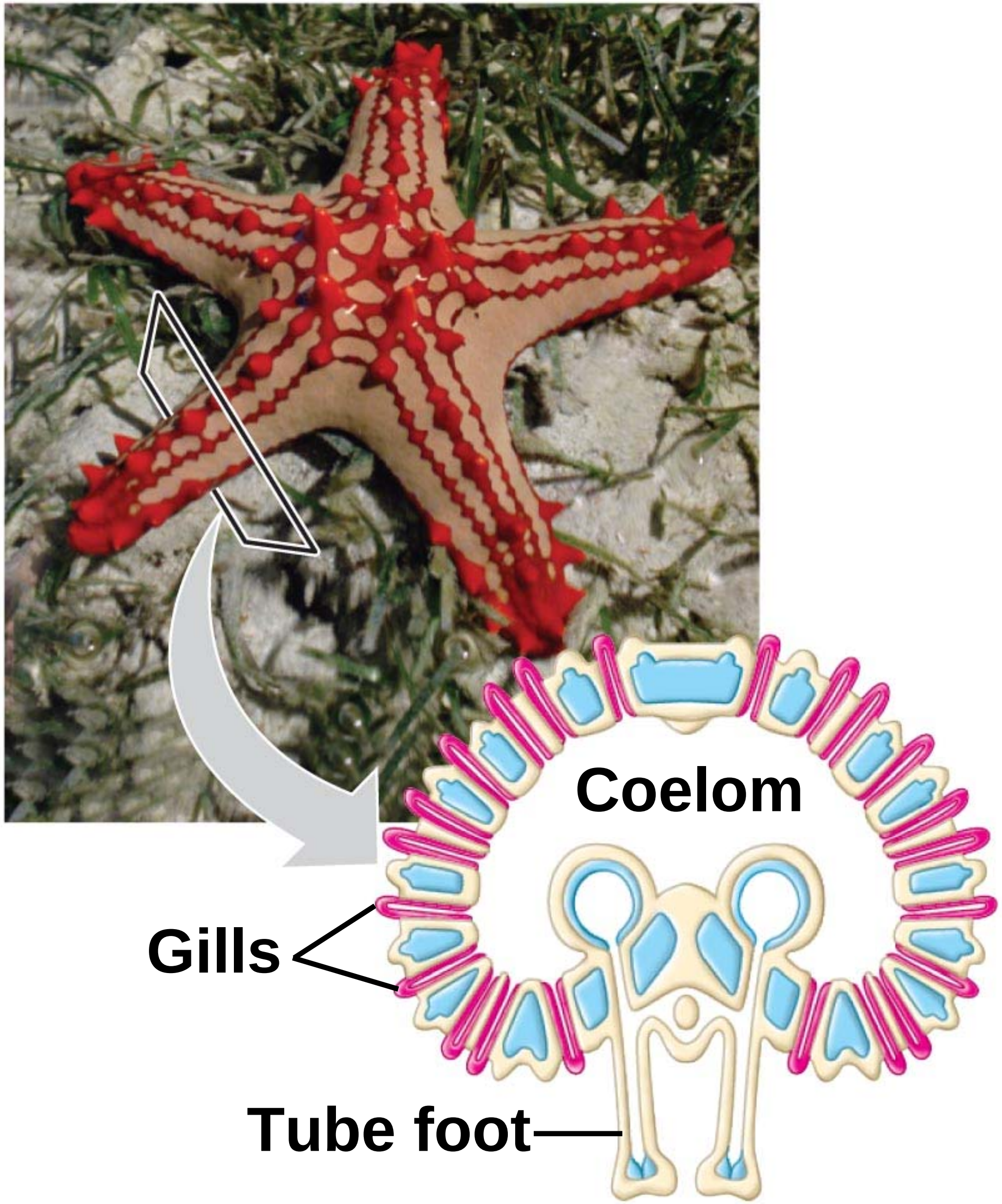
(a) Marine worm

Fig. 42-21b



(b) Crayfish

Fig. 42-21c



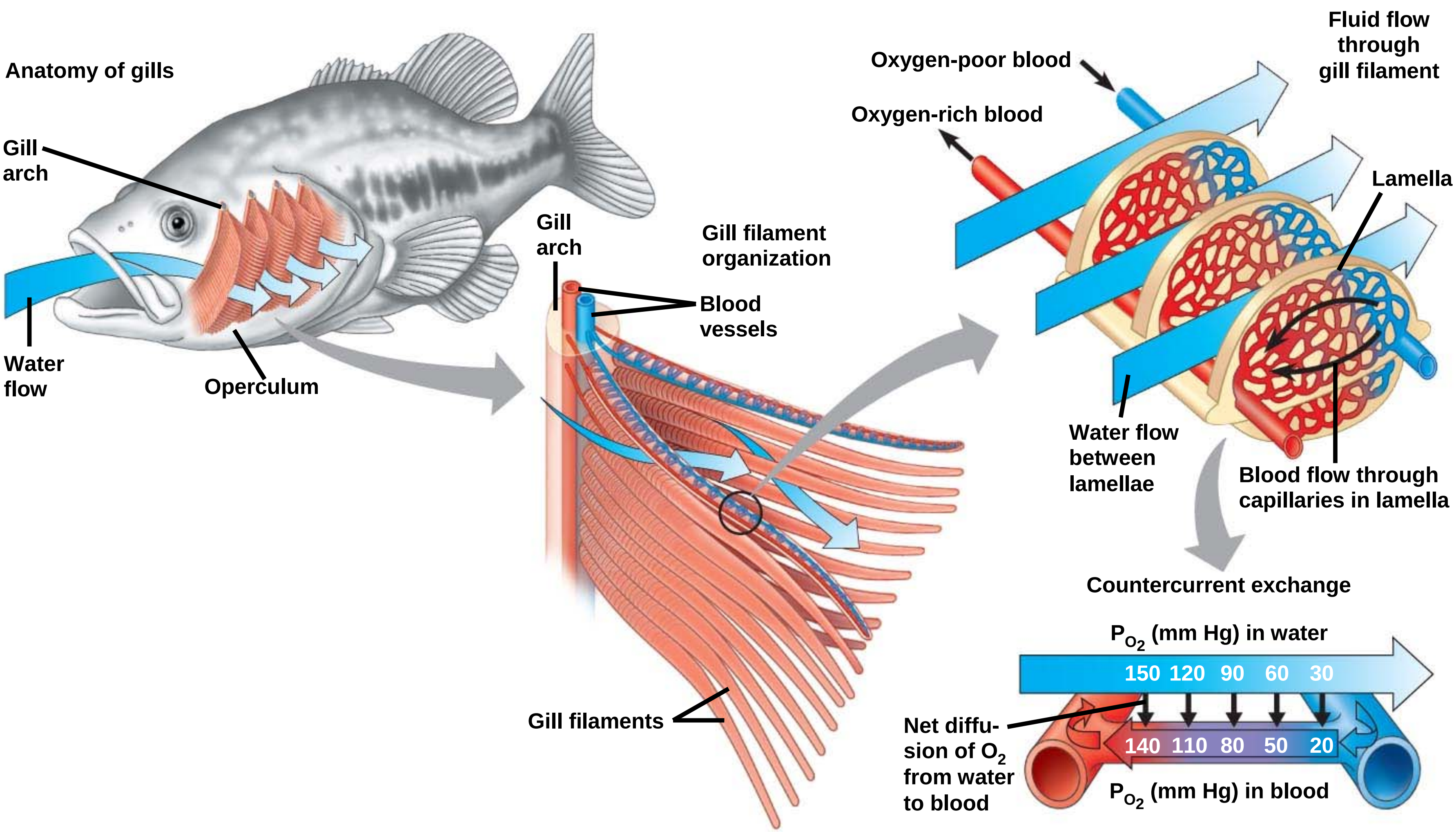
(c) Sea star

- **Ventilation** moves the respiratory medium over the respiratory surface

- Aquatic animals move through water or move water over their gills for ventilation

- Fish gills use a **countercurrent exchange** system, where blood flows in the opposite direction to water passing over the gills; blood is always less saturated with O_2 than the water it meets

Fig. 42-22

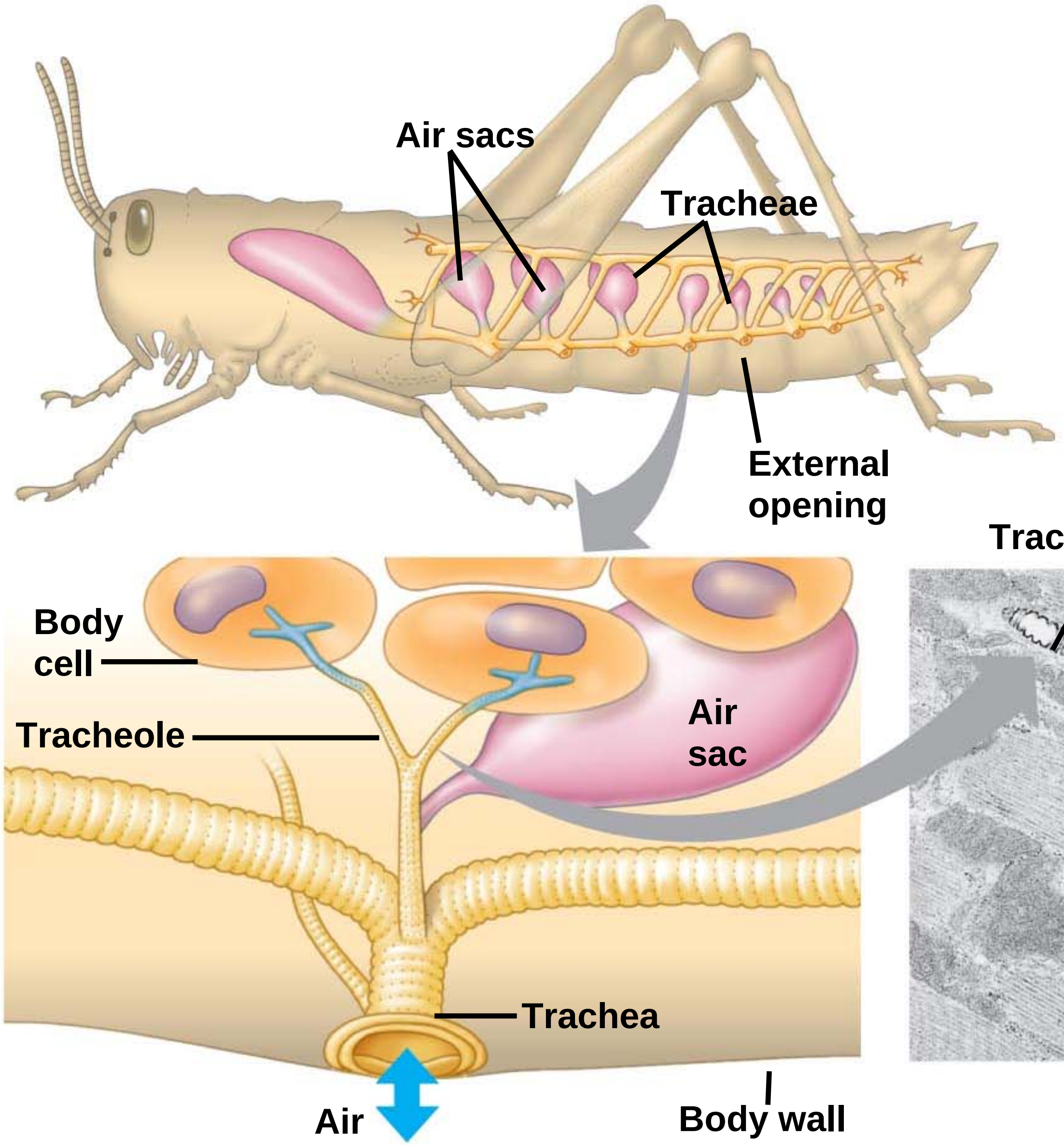


Anatomy of gills
Gill arch
Water flow
Operculum
Gill arch
Gill filament organization
Blood vessels
Gill filaments
Oxygen-poor blood
Oxygen-rich blood
Fluid flow through gill filament
Lamella
Water flow between lamellae
Blood flow through capillaries in lamella
Countercurrent exchange
P_{O_2} (mm Hg) in water
150 120 90 60 30
Net diffusion of O_2 from water to blood
140 110 80 50 20
P_{O_2} (mm Hg) in blood

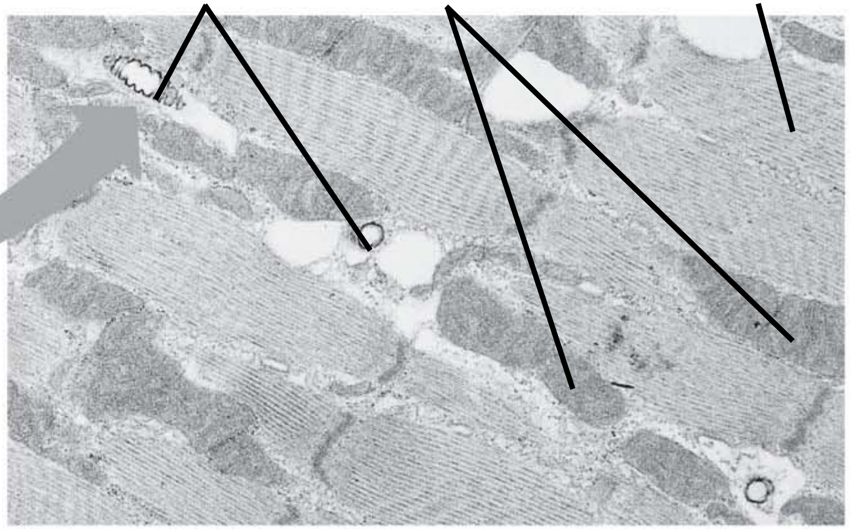
Tracheal Systems in Insects

- The **tracheal system** of insects consists of tiny branching tubes that penetrate the body
- The tracheal tubes supply O_2 directly to body cells
- The respiratory and circulatory systems are separate
- Larger insects must ventilate their tracheal system to meet O_2 demands

Fig. 42-23



Air sacs
Tracheae
External opening
Body cell
Tracheole
Air sac
Trachea
Air
Body wall



Tracheoles
Mitochondria
Muscle fiber
2.5 µm

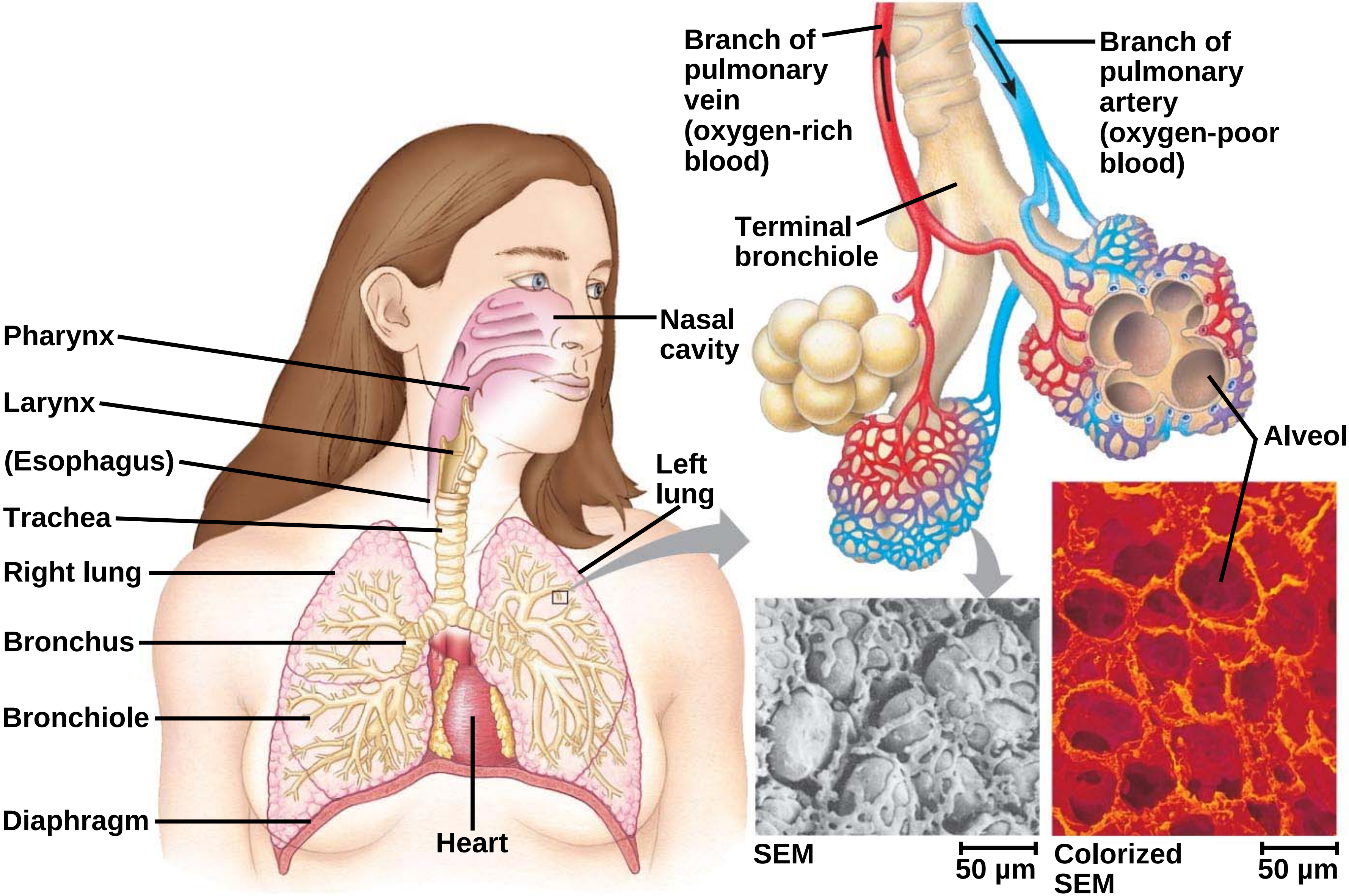
Lungs

- **Lungs** are an infolding of the body surface
- The circulatory system (open or closed) transports gases between the lungs and the rest of the body
- The size and complexity of lungs correlate with an animal’s metabolic rate

Mammalian Respiratory Systems: A Closer Look

- A system of branching ducts conveys air to the lungs
- Air inhaled through the nostrils passes through the pharynx via the **larynx**, **trachea**, **bronchi**, **bronchioles**, and **alveoli**, where gas exchange occurs
- Exhaled air passes over the **vocal cords** to create sounds
- Secretions called **surfactants** coat the surface of the alveoli

Fig. 42-24



Branch of pulmonary vein (oxygen-rich blood)
Branch of pulmonary artery (oxygen-poor blood)
Terminal bronchiole
Nasal cavity
Pharynx
Larynx
(Esophagus)
Trachea
Right lung
Bronchus
Bronchiole
Diaphragm
Heart
Left lung
Alveoli
SEM
50 µm
Colorized SEM
50 µm

Concept 42.6: Breathing ventilates the lungs

- The process that ventilates the lungs is **breathing**, the alternate inhalation and exhalation of air

How an Amphibian Breathes

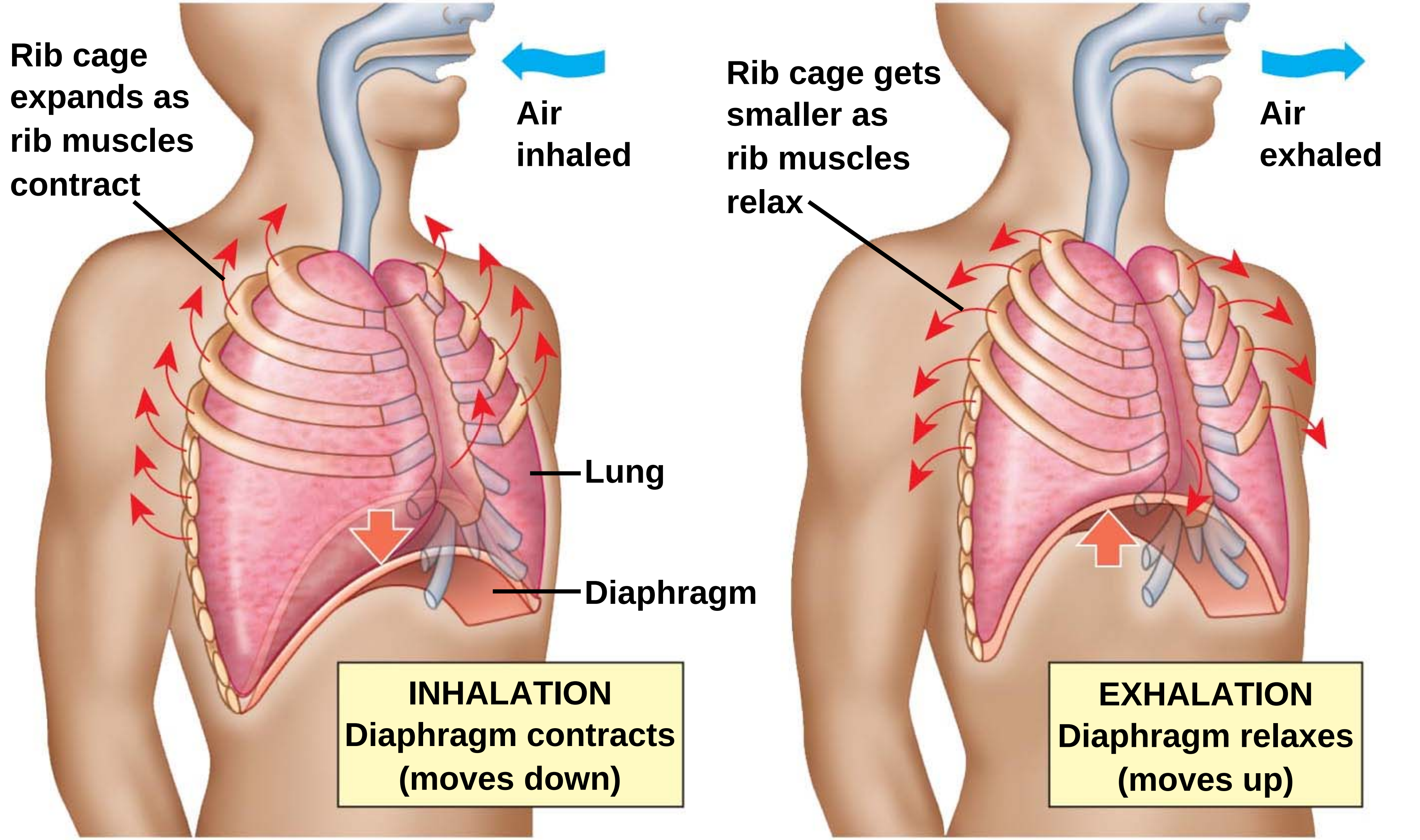
- An amphibian such as a frog ventilates its lungs by **positive pressure breathing**, which forces air down the trachea

How a Mammal Breathes

- Mammals ventilate their lungs by **negative pressure breathing**, which pulls air into the lungs
- Lung volume increases as the rib muscles and **diaphragm** contract
- The **tidal volume** is the volume of air inhaled with each breath

- The maximum tidal volume is the **vital capacity**
- After exhalation, a **residual volume** of air remains in the lungs

Fig. 42-25

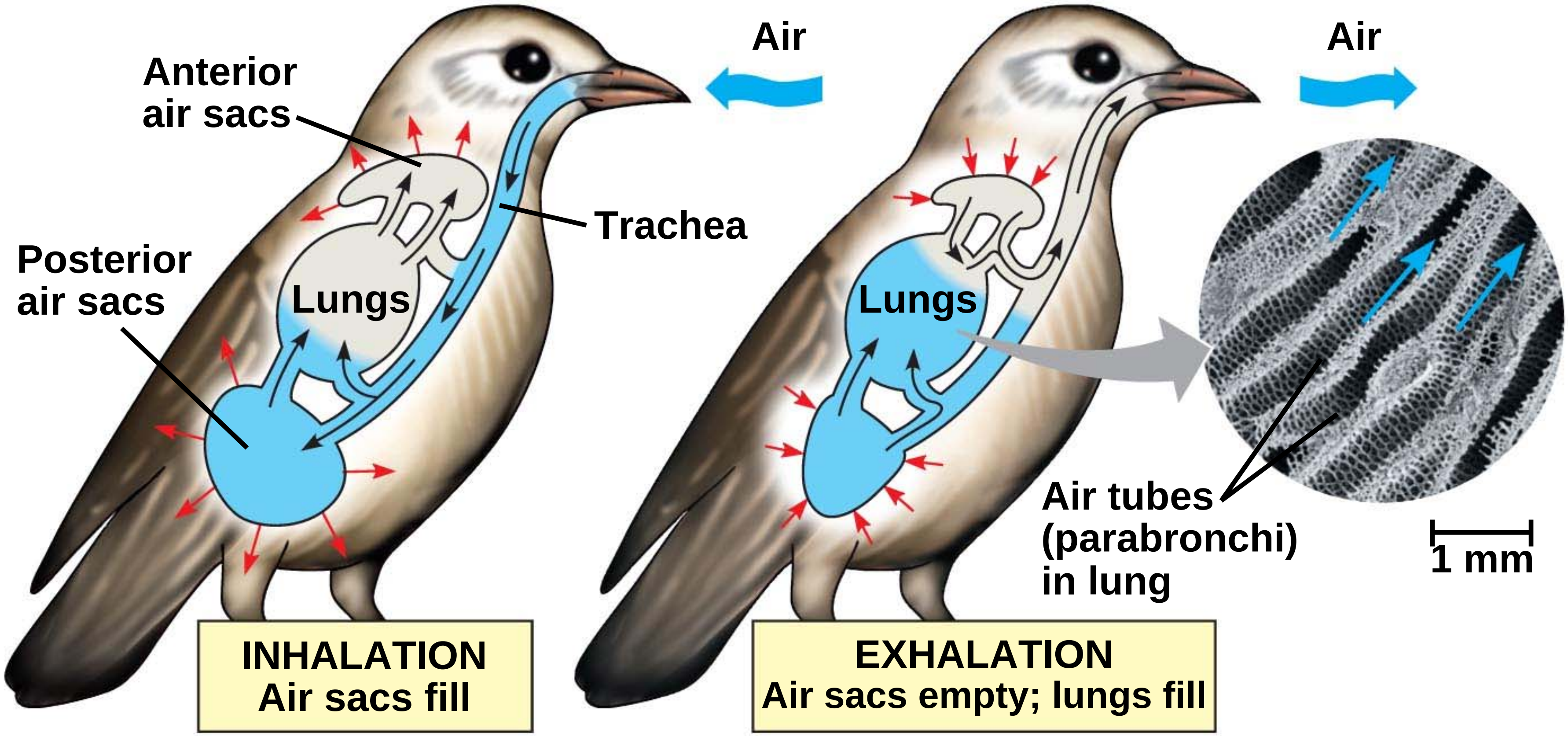


Rib cage expands as rib muscles contract
Air inhaled
Lung
Diaphragm
INHALATION
Diaphragm contracts
(moves down)
Rib cage gets smaller as rib muscles relax
Air exhaled
EXHALATION
Diaphragm relaxes
(moves up)

How a Bird Breathes

- Birds have eight or nine air sacs that function as bellows that keep air flowing through the lungs
- Air passes through the lungs in one direction only
- Every exhalation completely renews the air in the lungs

Fig. 42-26



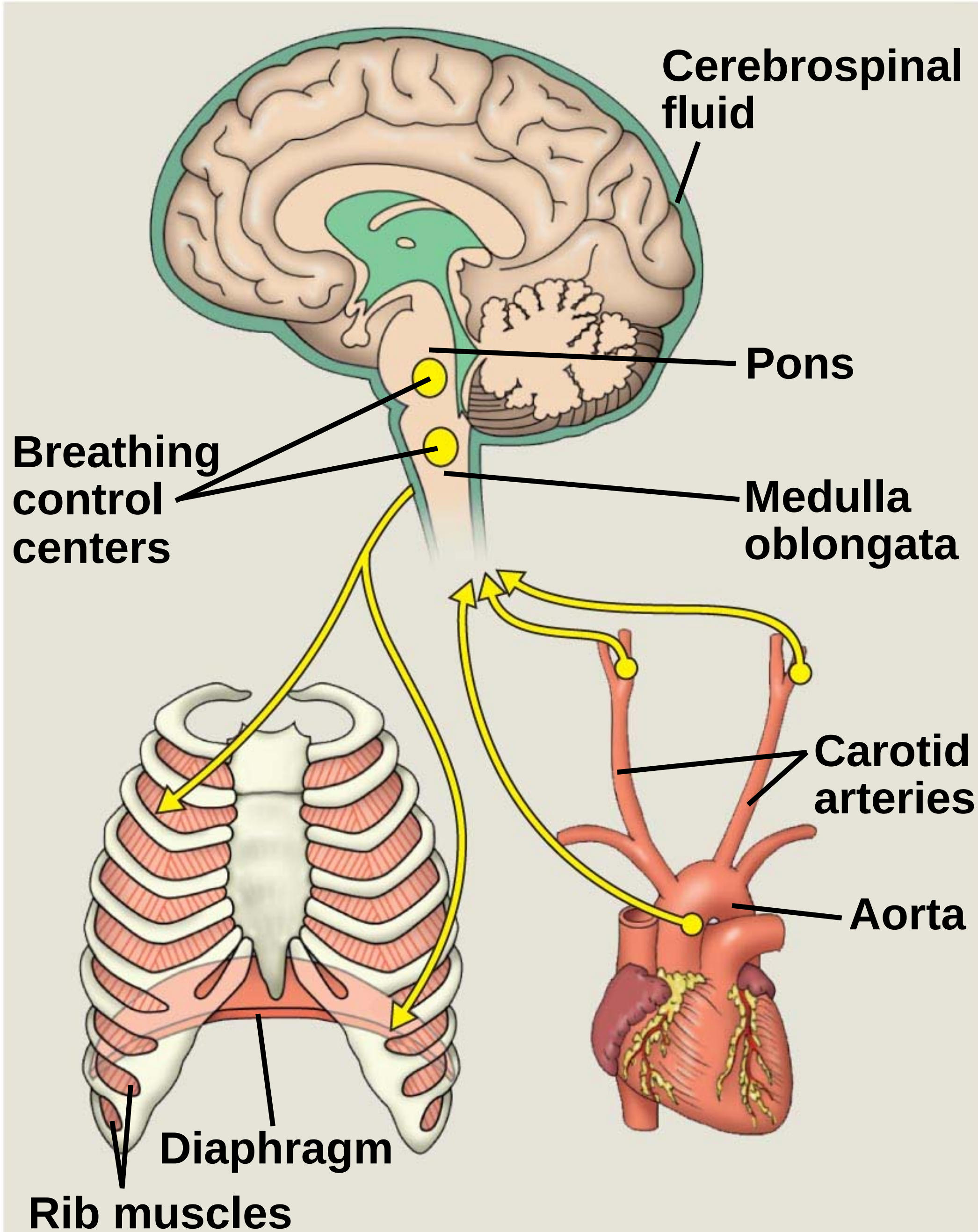
Anterior air sacs
Posterior air sacs
Lungs
Trachea
Air
INHALATION
Air sacs fill
Lungs
Air
EXHALATION
Air sacs empty; lungs fill
Air tubes (parabronchi) in lung
1 mm

Control of Breathing in Humans

- In humans, the main **breathing control centers** are in two regions of the brain, the medulla oblongata and the pons
- The medulla regulates the rate and depth of breathing in response to pH changes in the cerebrospinal fluid
- The medulla adjusts breathing rate and depth to match metabolic demands
- The pons regulates the tempo

- Sensors in the aorta and carotid arteries monitor O_2 and CO_2 concentrations in the blood
- These sensors exert secondary control over breathing

Fig. 42-27


Cerebrospinal fluid
Pons
Breathing control centers
Medulla oblongata
Carotid arteries
Aorta
Diaphragm
Rib muscles

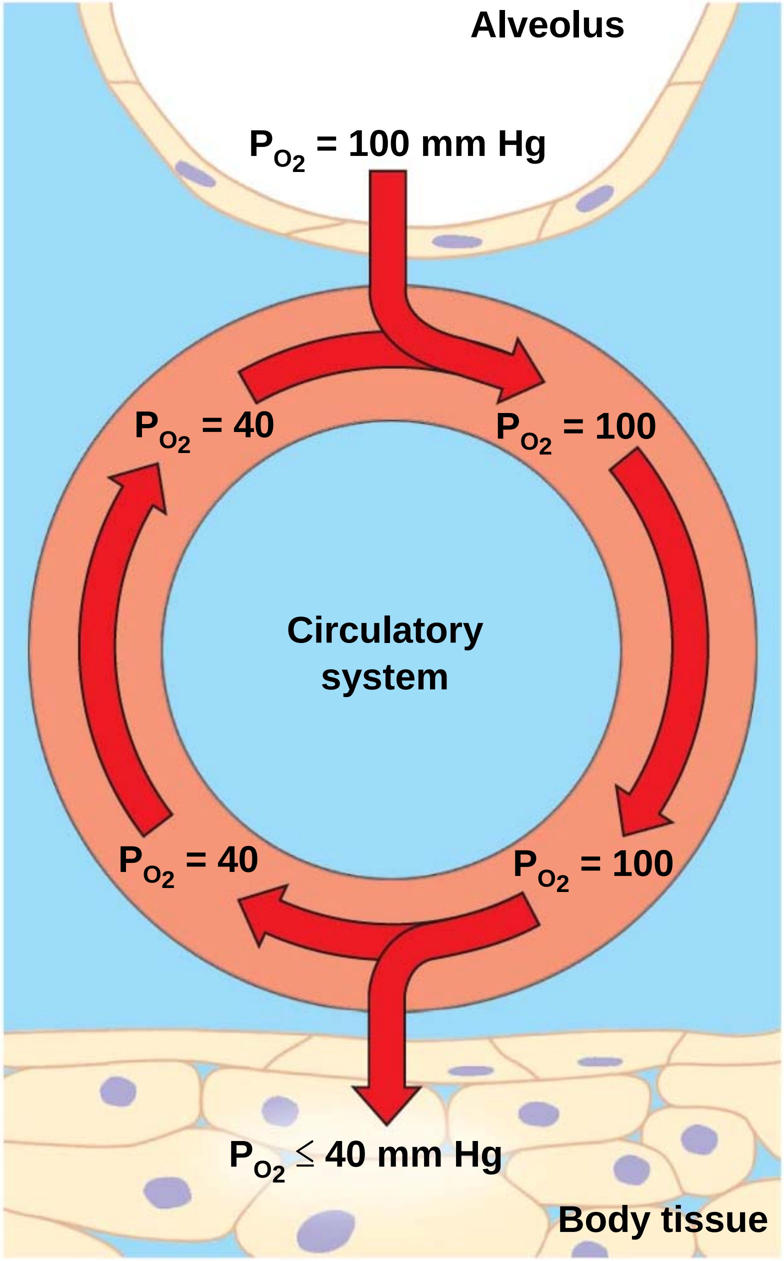
Concept 42.7: Adaptations for gas exchange include pigments that bind and transport gases

- The metabolic demands of many organisms require that the blood transport large quantities of O_2 and CO_2

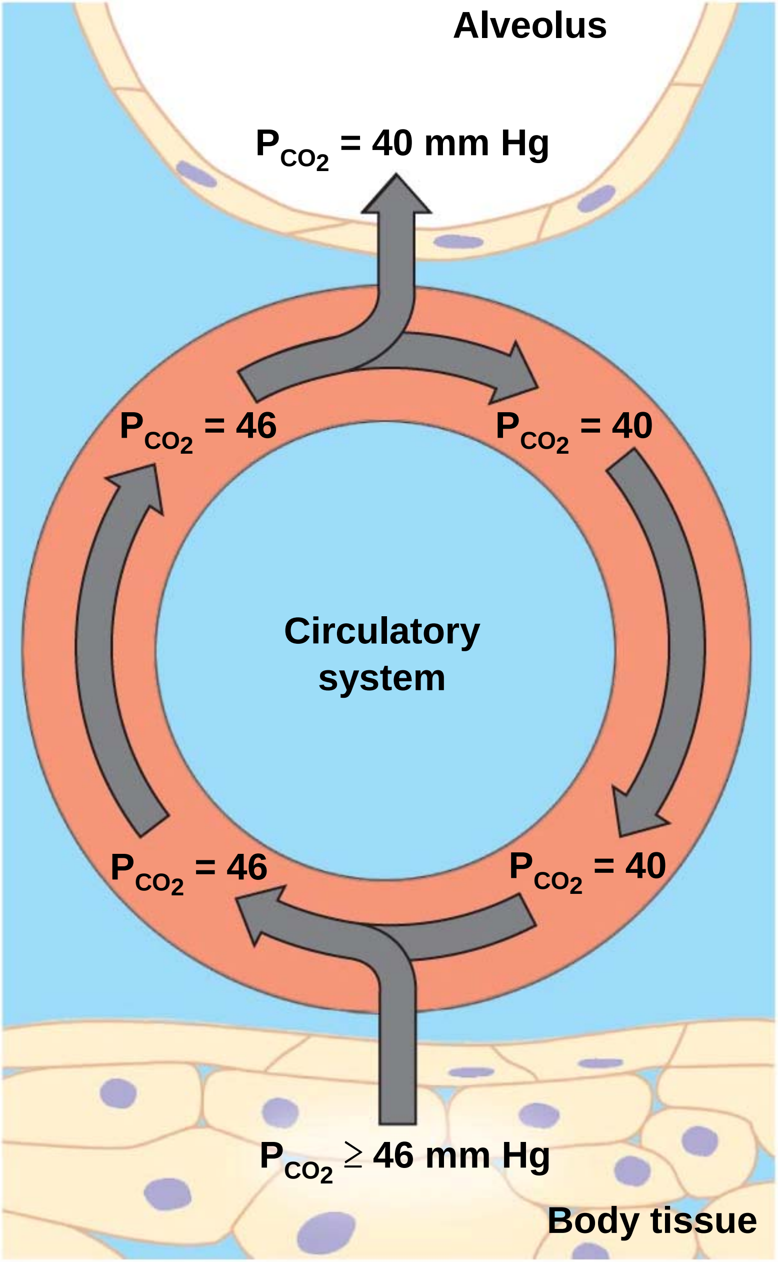
Coordination of Circulation and Gas Exchange

- Blood arriving in the lungs has a low partial pressure of O_2 and a high partial pressure of CO_2 relative to air in the alveoli
- In the alveoli, O_2 diffuses into the blood and CO_2 diffuses into the air
- In tissue capillaries, partial pressure gradients favor diffusion of O_2 into the interstitial fluids and CO_2 into the blood

Fig. 42-28



(a) Oxygen



(b) Carbon dioxide

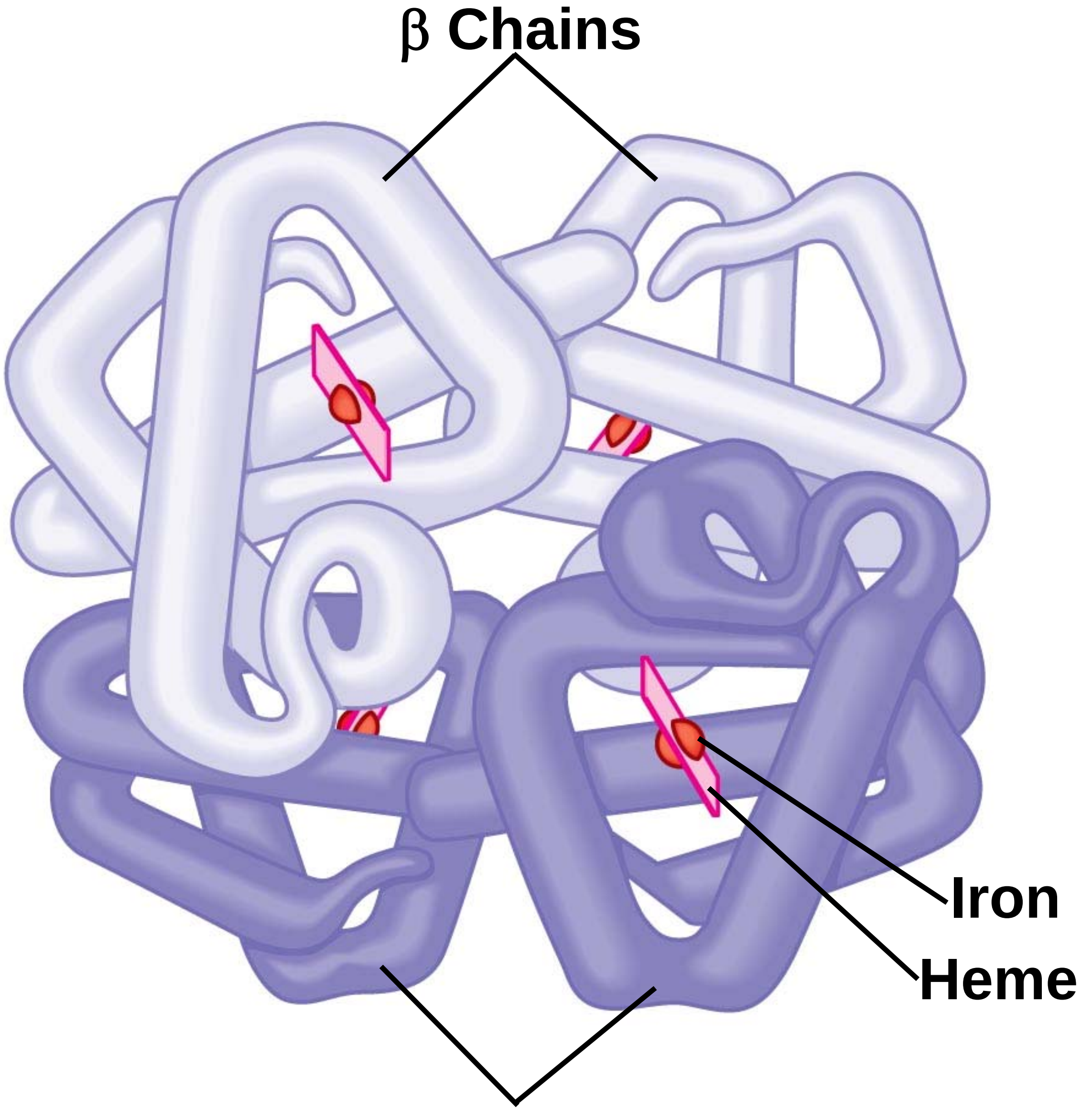
Respiratory Pigments

- **Respiratory pigments**, proteins that transport oxygen, greatly increase the amount of oxygen that blood can carry
- Arthropods and many molluscs have hemocyanin with copper as the oxygen-binding component
- Most vertebrates and some invertebrates use hemoglobin contained within erythrocytes

Hemoglobin

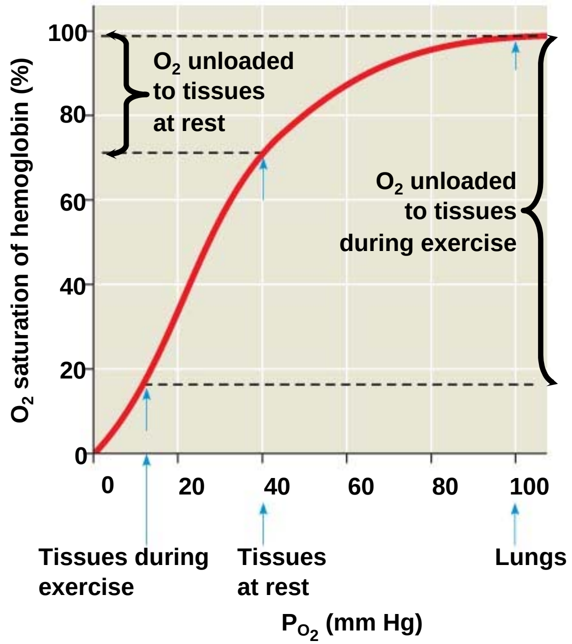
- A single hemoglobin molecule can carry four molecules of O_2
- The hemoglobin dissociation curve shows that a small change in the partial pressure of oxygen can result in a large change in delivery of O_2
- CO_2 produced during cellular respiration lowers blood pH and decreases the affinity of hemoglobin for O_2; this is called the **Bohr shift**

Fig. 42-UN1

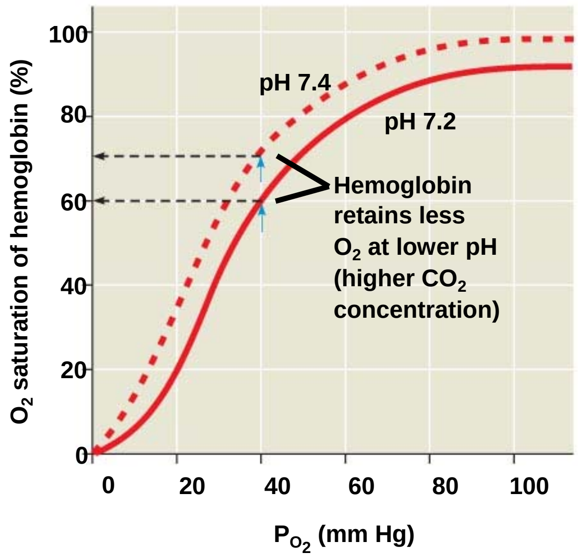


Hemoglobin

Fig. 42-29

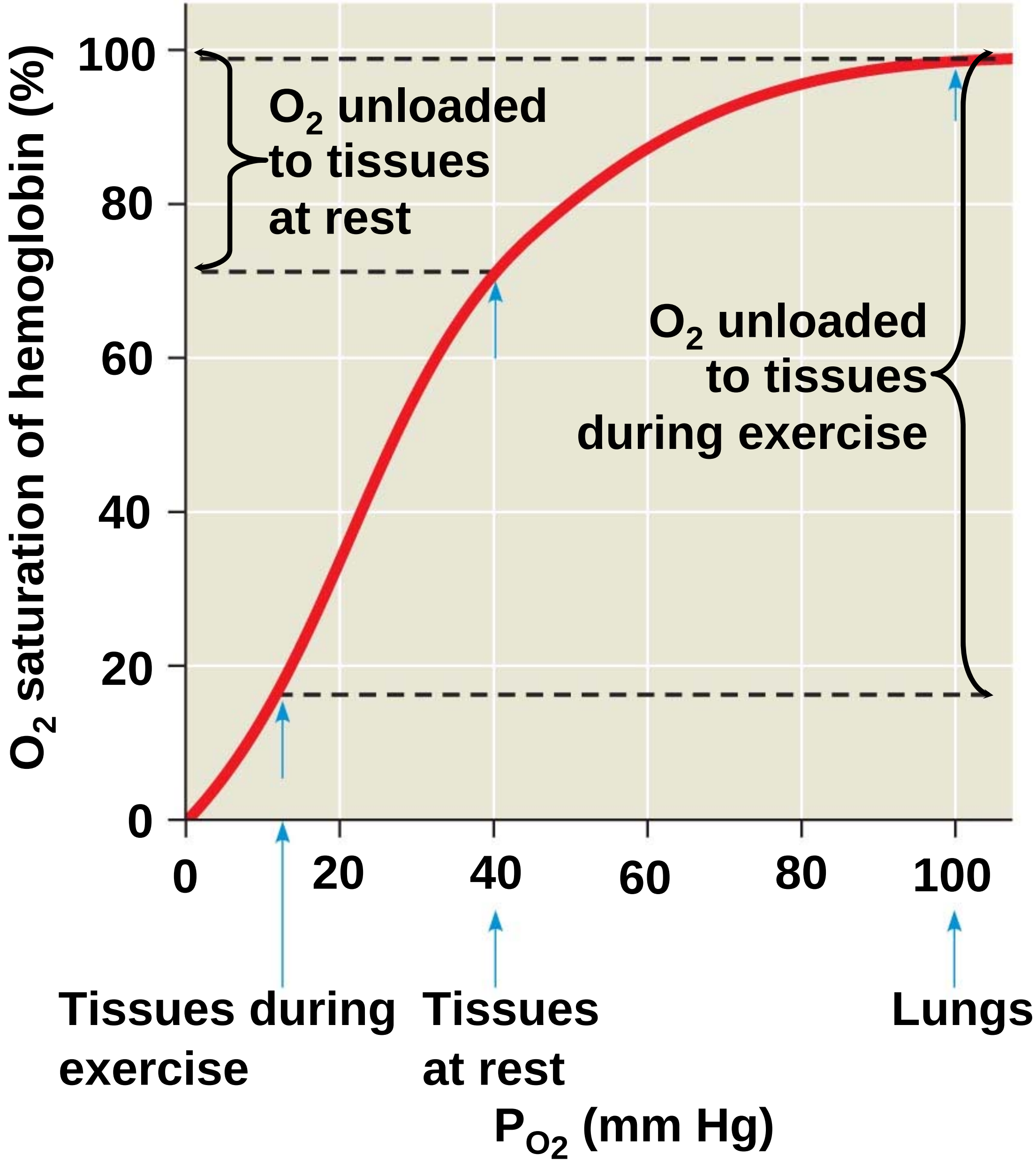


(a) P_{O_2} and hemoglobin dissociation at pH 7.4



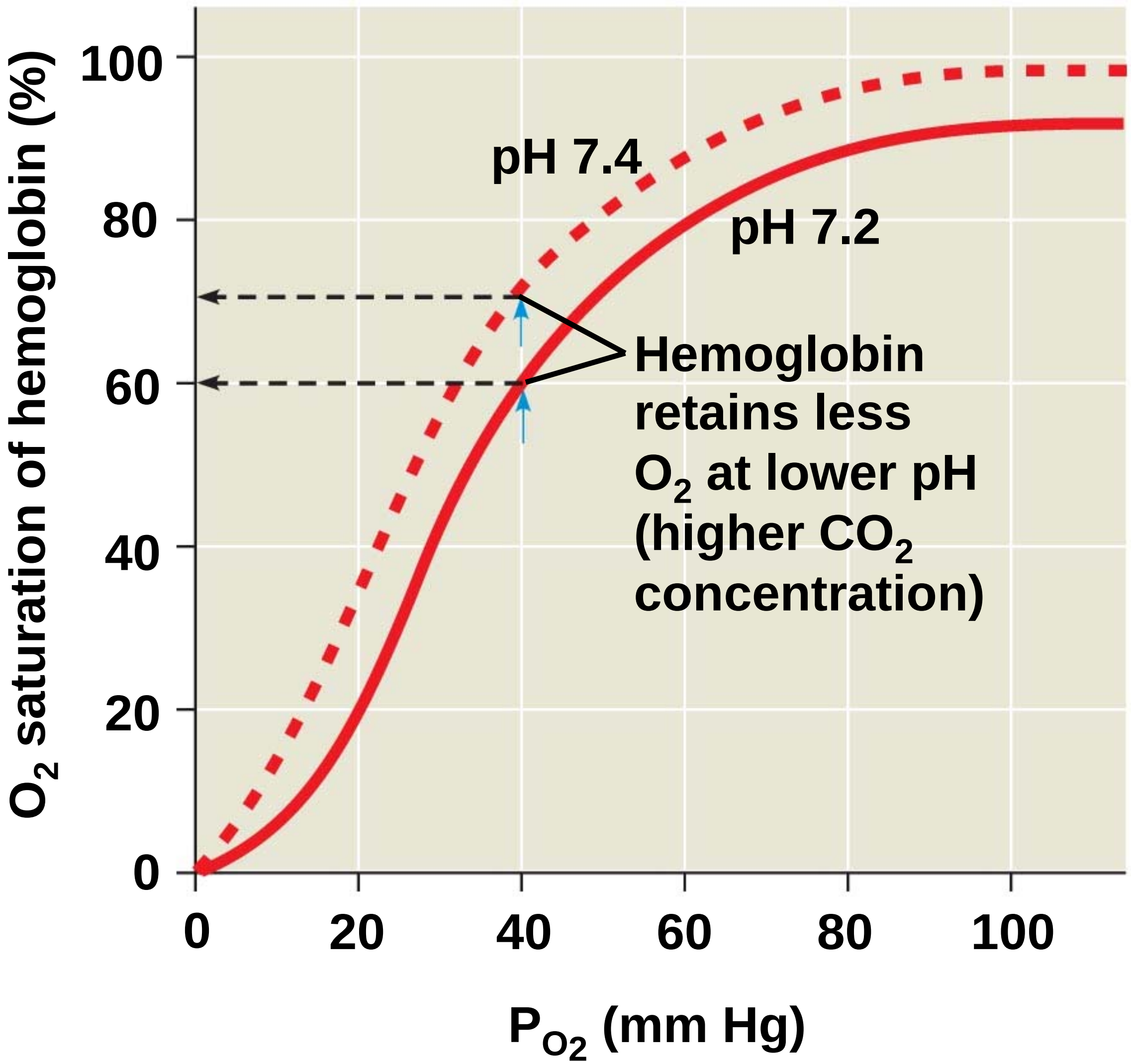
(b) pH and hemoglobin dissociation

Fig. 42-29a



(a) P_{O_2} and hemoglobin dissociation at pH 7.4

Fig. 42-29b



(b) pH and hemoglobin dissociation

Carbon Dioxide Transport

- Hemoglobin also helps transport CO_2 and assists in buffering
- CO_2 from respiring cells diffuses into the blood and is transported either in blood plasma, bound to hemoglobin, or as bicarbonate ions (HCO_3^-)

PLAY Animation: O_2 from Blood to Tissues

PLAY Animation: CO_2 from Tissues to Blood

PLAY Animation: CO_2 from Blood to Lungs

PLAY Animation: O_2 from Lungs to Blood

Fig. 42-30

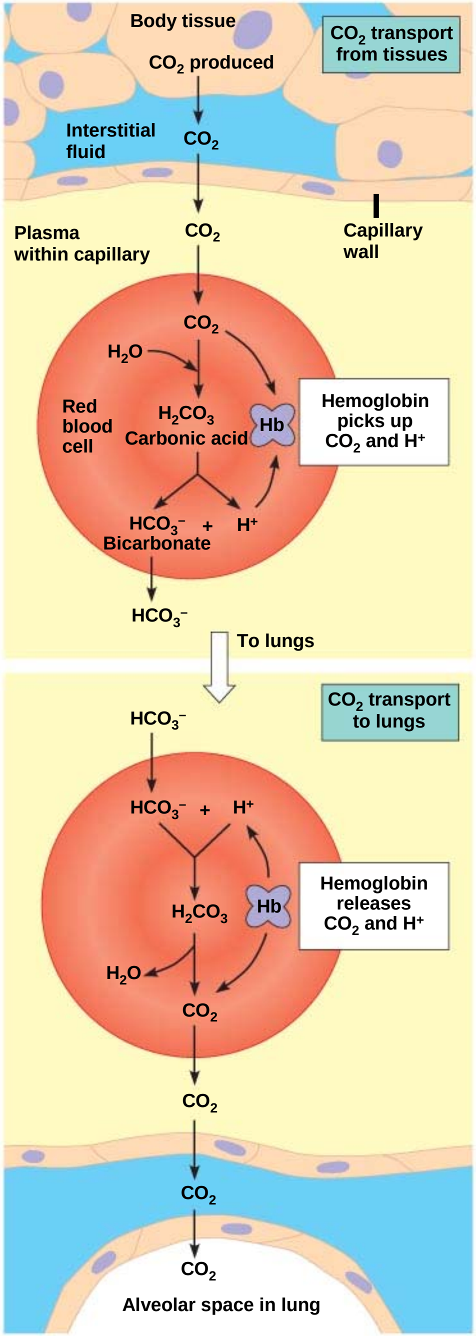
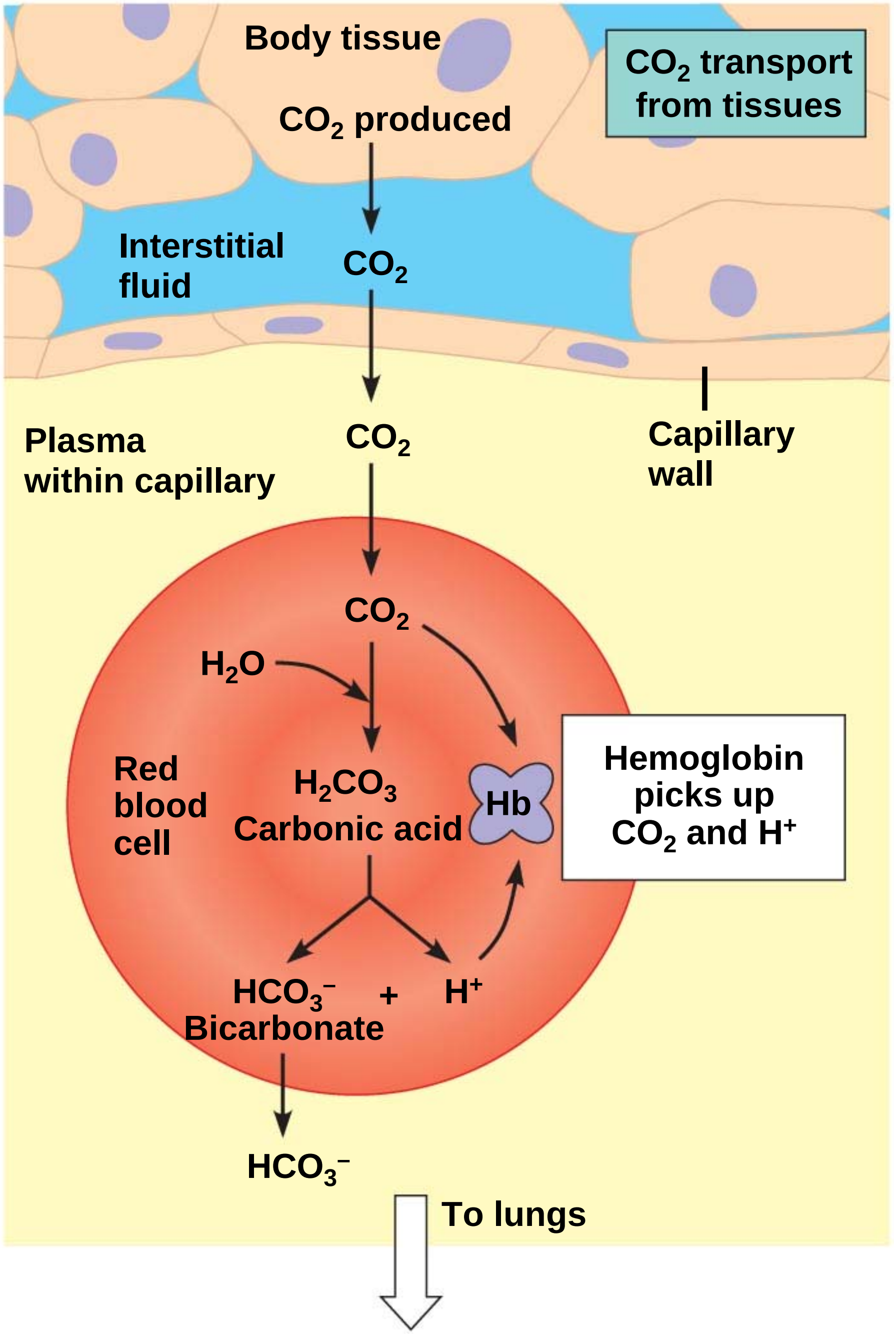
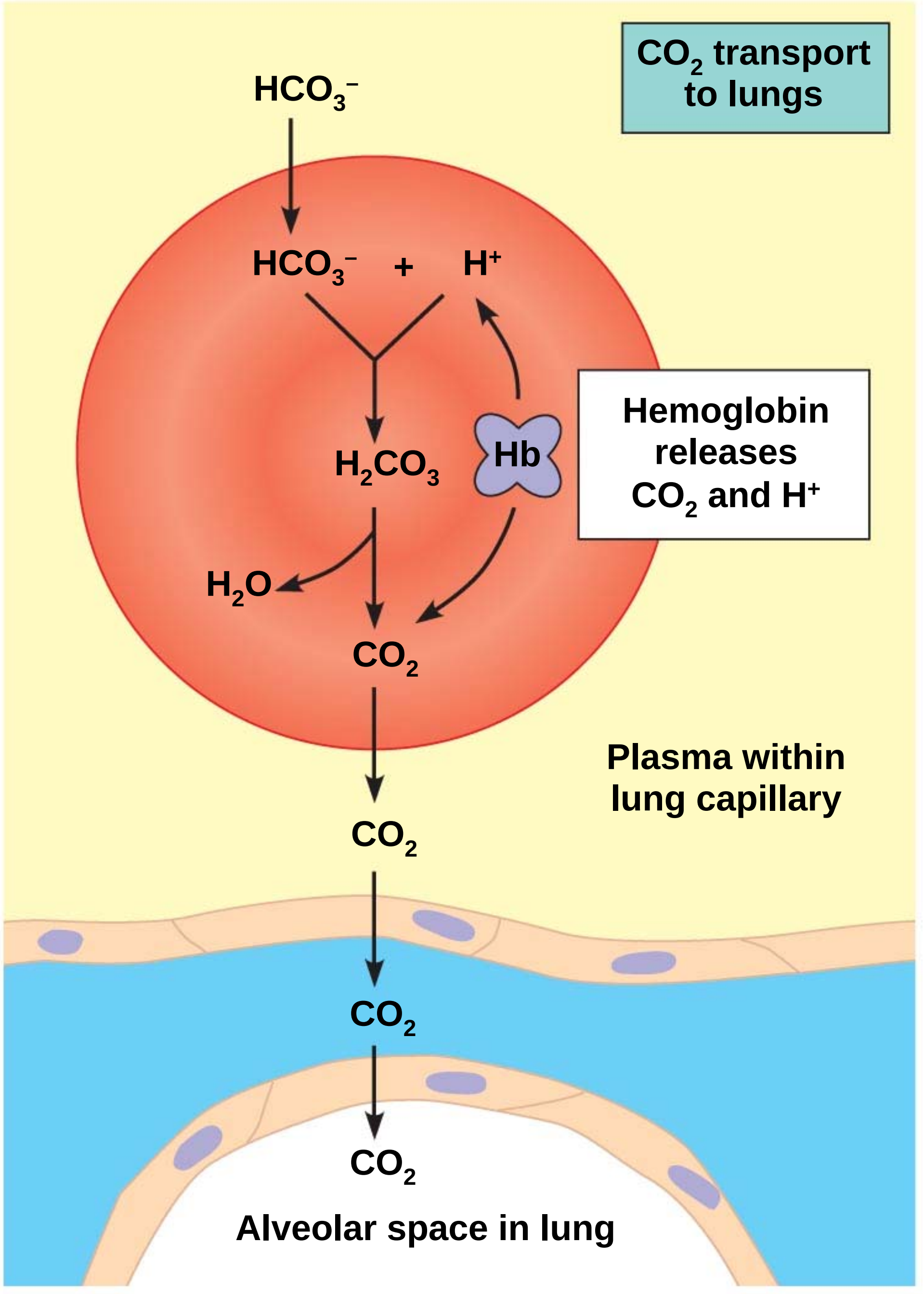

Body tissue
CO_2 transport from tissues
CO_2 produced
Interstitial fluid
CO_2
CO_2
Plasma within capillary
Capillary wall
CO_2
H_2O
Red blood cell
H_2CO_3
Carbonic acid
Hb
Hemoglobin picks up CO_2 and H^+
HCO_3^- + H^+
Bicarbonate
HCO_3^-
To lungs
CO_2 transport to lungs
HCO_3^-
HCO_3^- + H^+
H_2CO_3
Hb
Hemoglobin releases CO_2 and H^+
H_2O
CO_2
CO_2
CO_2
CO_2
Alveolar space in lung

Fig. 42-30a



Body tissue
CO_2 transport from tissues
CO_2 produced
Interstitial fluid
CO_2
CO_2
Plasma within capillary
Capillary wall
CO_2
H_2O
Red blood cell
H_2CO_3 Carbonic acid
Hb
Hemoglobin picks up CO_2 and H^+
HCO_3^- + H^+
Bicarbonate
HCO_3^-
To lungs

Fig. 42-30b



CO_2 transport to lungs
HCO_3^-
HCO_3^- + H^+
H_2CO_3
Hb
Hemoglobin releases CO_2 and H^+
H_2O
CO_2
Plasma within lung capillary
CO_2
CO_2
CO_2
Alveolar space in lung

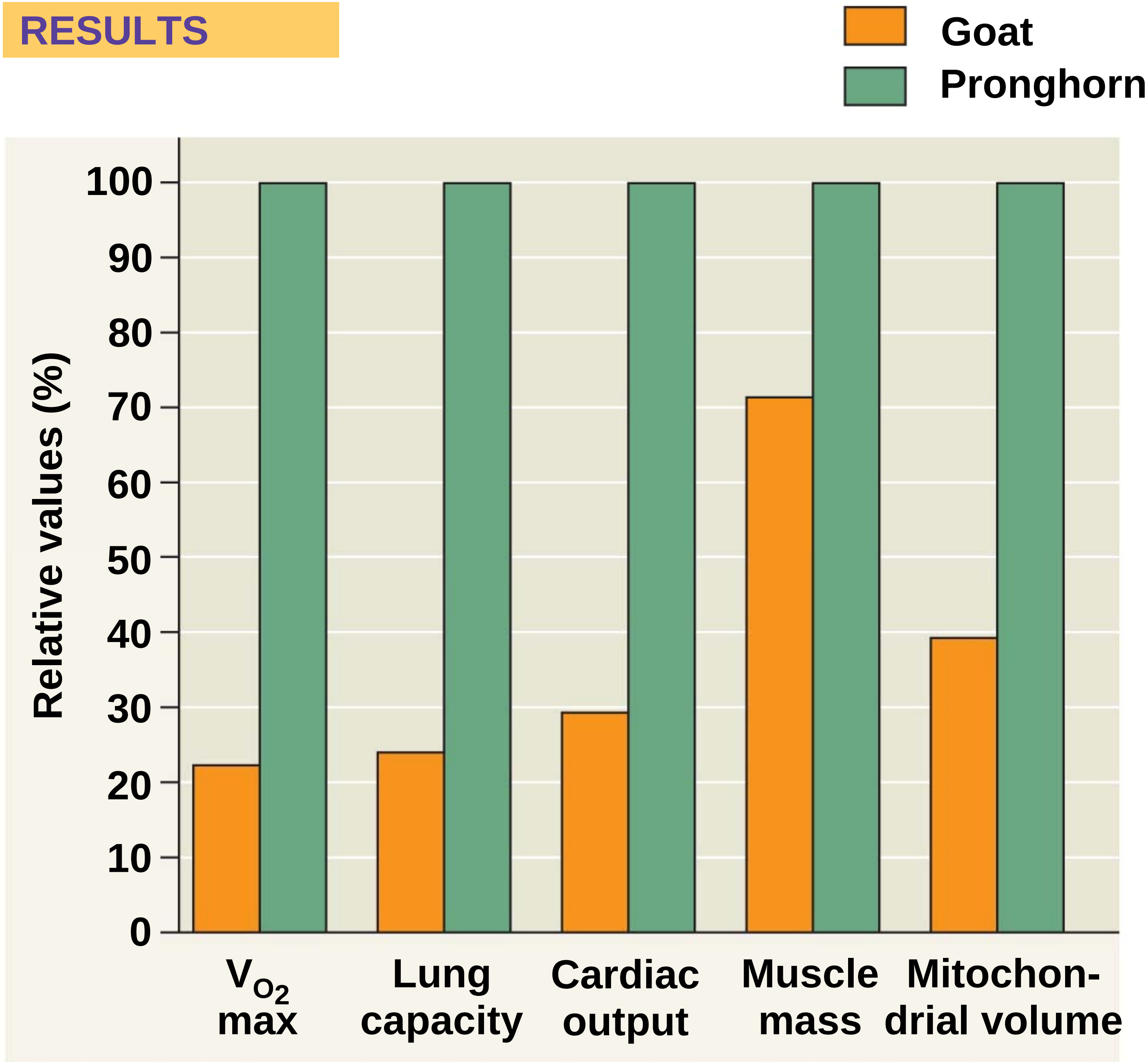
Elite Animal Athletes

- Migratory and diving mammals have evolutionary adaptations that allow them to perform extraordinary feats

The Ultimate Endurance Runner

- The extreme O_2 consumption of the antelope-like pronghorn underlies its ability to run at high speed over long distances

Fig. 42-31

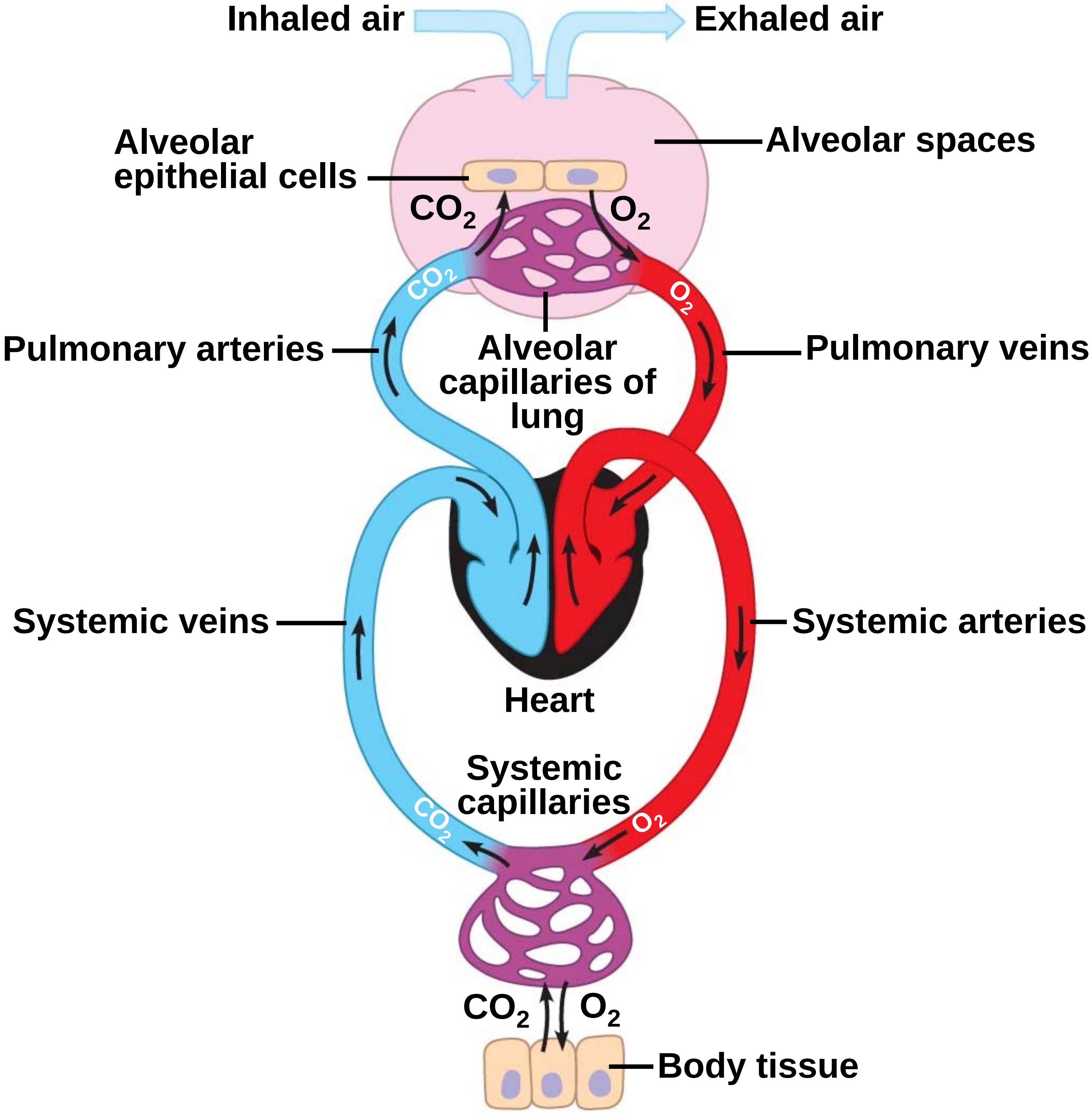


RESULTS
Goat
Pronghorn
Relative values (%)
100
90
80
70
60
50
40
30
20
10
0
V_{O_2} max
Lung capacity
Cardiac output
Muscle mass
Mitochondrial volume

Diving Mammals

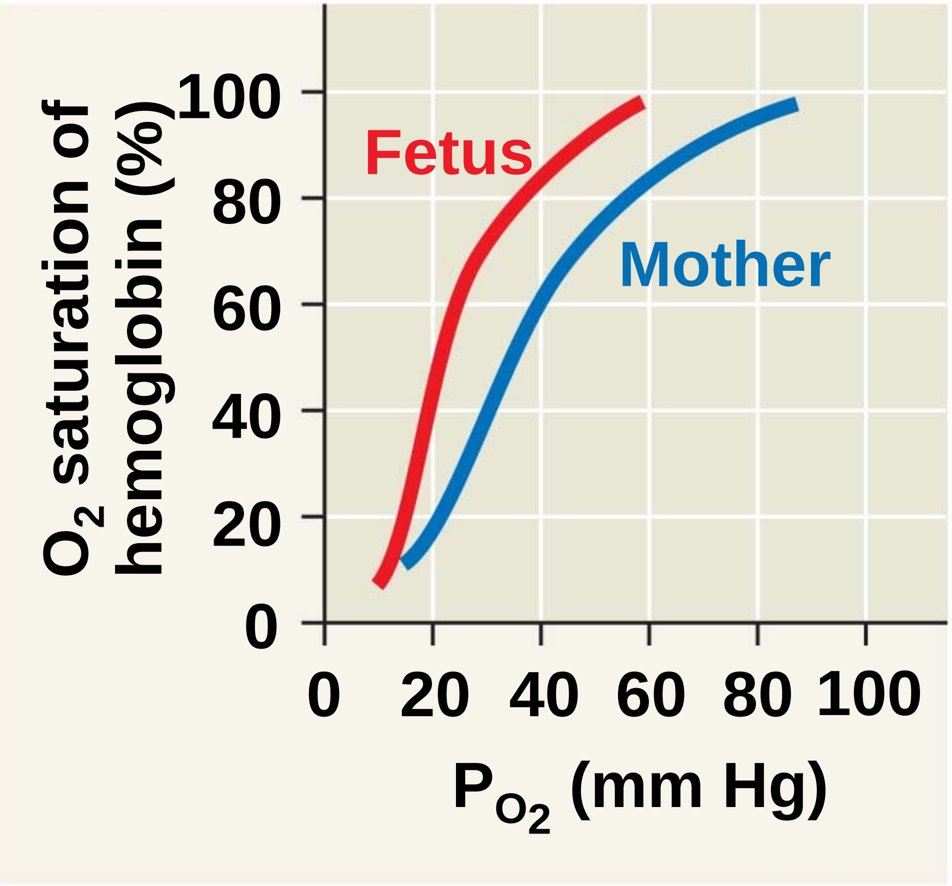
- Deep-diving air breathers stockpile O_2 and deplete it slowly
- Weddell seals have a high blood to body volume ratio and can store oxygen in their muscles in **myoglobin** proteins

Fig. 42-UN2



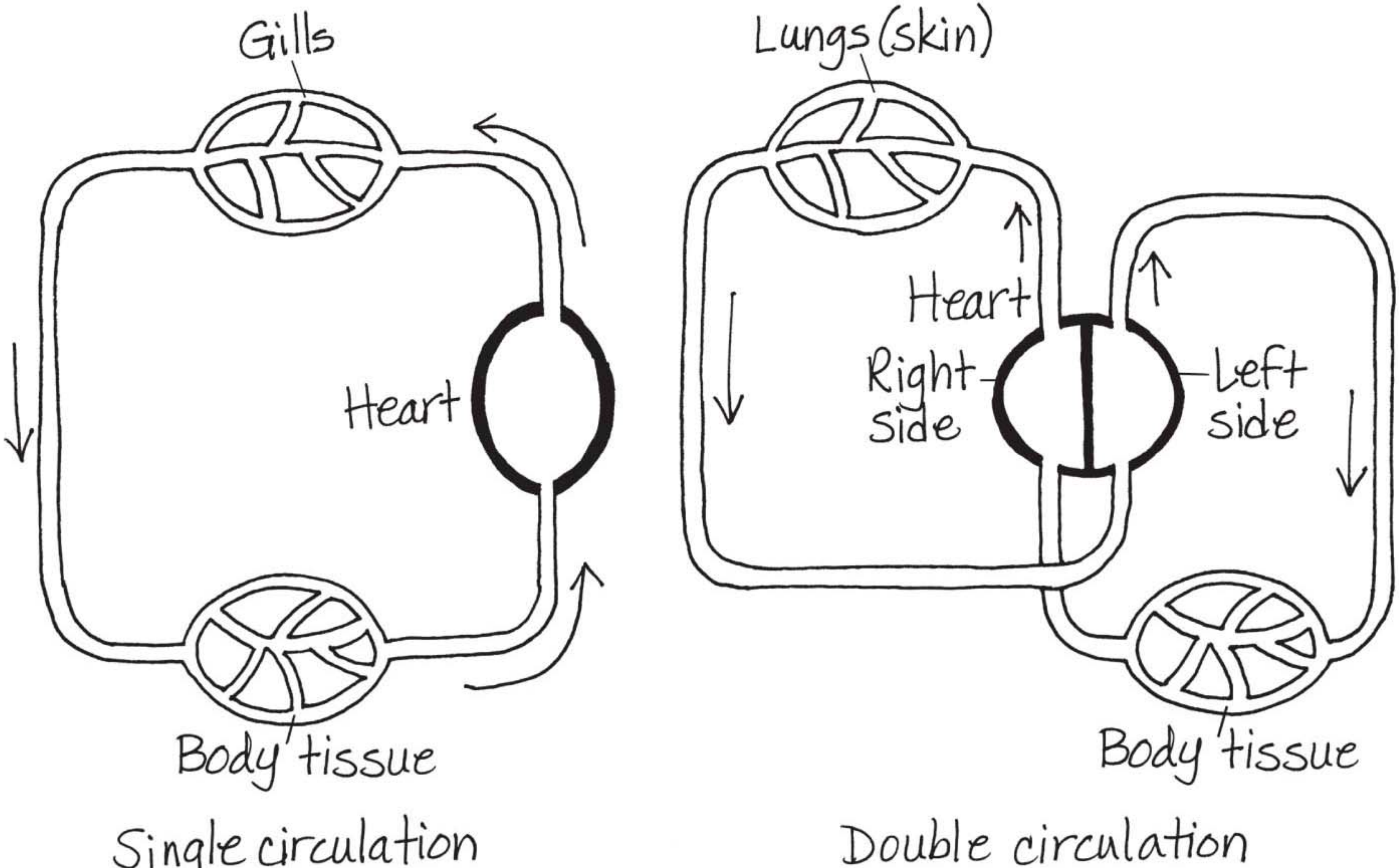
Inhaled air
Exhaled air
Alveolar epithelial cells
Alveolar spaces
CO_2
O_2
CO_2
O_2
Pulmonary arteries
Alveolar capillaries of lung
Pulmonary veins
Systemic veins
Systemic arteries
Heart
Systemic capillaries
CO_2
O_2
CO_2
O_2
Body tissue

Fig. 42-UN3



Fetus
Mother
O2 saturation of hemoglobin (%)
100
80
60
40
20
0
0
20
40
60
80
100
PO2 (mm Hg)

Fig. 42-UN4


Gills
Heart
Body tissue
Single circulation
Lungs (skin)
Heart
Right side
Left side
Body tissue
Double circulation

You should now be able to:

1. Compare and contrast open and closed circulatory systems
2. Compare and contrast the circulatory systems of fish, amphibians, non-bird reptiles, and mammals or birds
3. Distinguish between pulmonary and systemic circuits and explain the function of each
4. Trace the path of a red blood cell through the human heart, pulmonary circuit, and systemic circuit

5. Define cardiac cycle and explain the role of the sinoatrial node
6. Relate the structures of capillaries, arteries, and veins to their function
7. Define blood pressure and cardiac output and describe two factors that influence each
8. Explain how osmotic pressure and hydrostatic pressure regulate the exchange of fluid and solutes across the capillary walls

9. Describe the role played by the lymphatic system in relation to the circulatory system

10. Describe the function of erythrocytes, leukocytes, platelets, fibrin

11. Distinguish between a heart attack and stroke

12. Discuss the advantages and disadvantages of water and of air as respiratory media

13. For humans, describe the exchange of gases in the lungs and in tissues

14. Draw and explain the hemoglobin-oxygen dissociation curve