LECTURE PRESENTATIONS
For CAMPBELL BIOLOGY, NINTH EDITION
Jane B. Reece, Lisa A. Urry, Michael L. Cain, Steven A. Wasserman, Peter V. Minorsky, Robert B. Jackson

Chapter 42

Circulation and Gas Exchange

Lectures by
Erin Barley
Kathleen Fitzpatrick

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

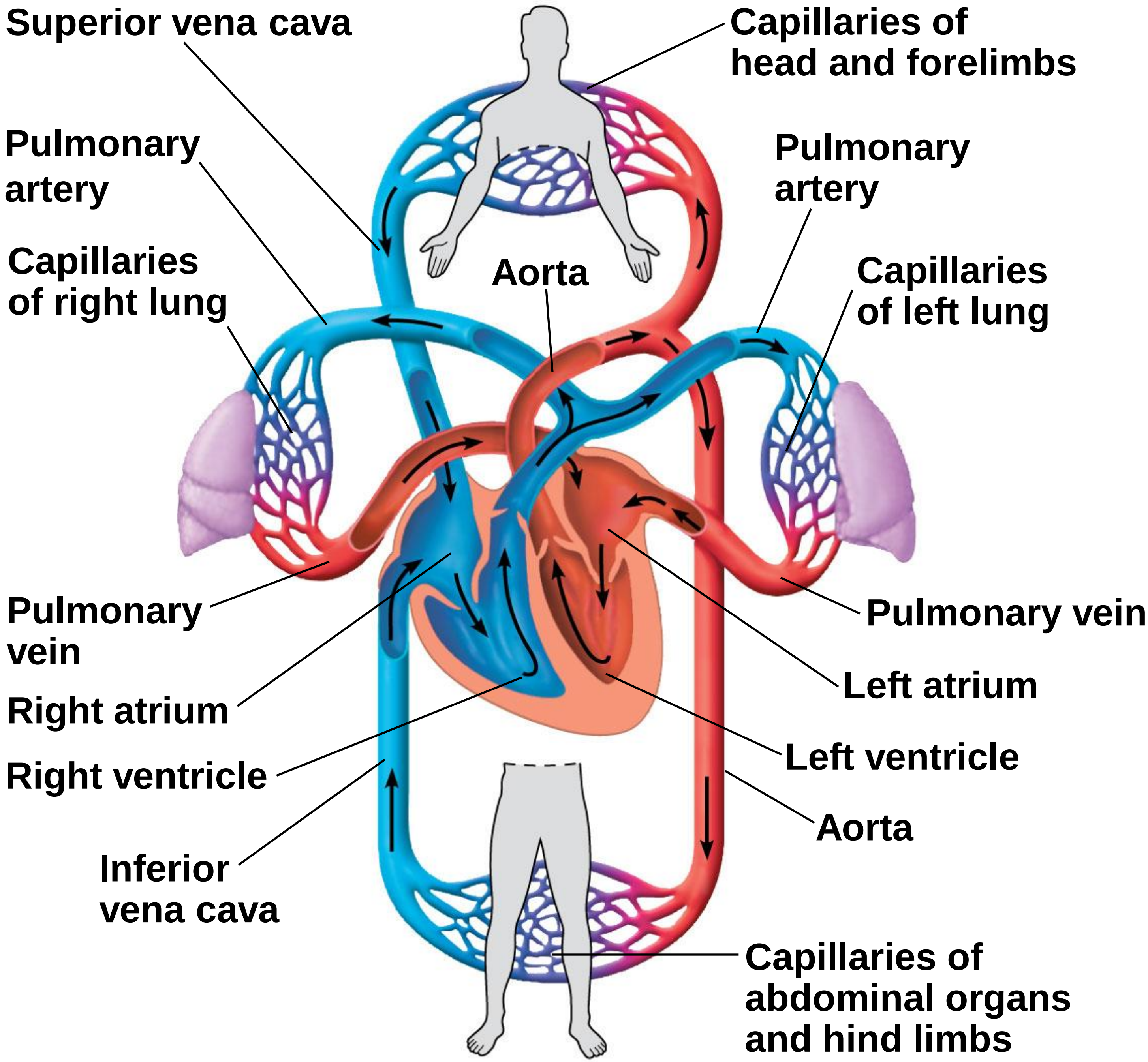
Mammalian Circulation

- 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

Figure 42.6

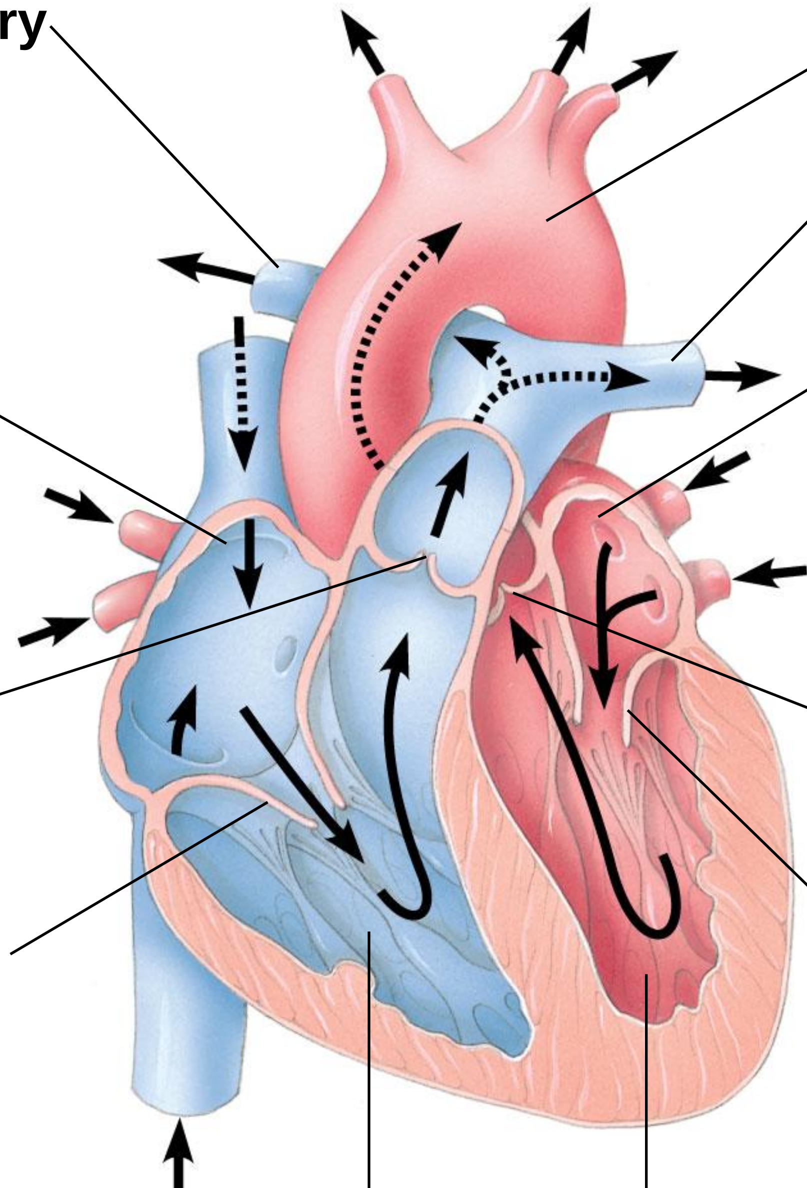


Superior vena cava
Capillaries of head and forelimbs
Pulmonary artery
Pulmonary artery
Capillaries of right lung
Aorta
Capillaries of left lung
Pulmonary vein
Pulmonary vein
Right atrium
Left atrium
Right ventricle
Left ventricle
Aorta
Inferior vena cava
Capillaries of abdominal organs and hind limbs

The Mammalian Heart: *A Closer Look*

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

Figure 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**

Figure 42.8-1

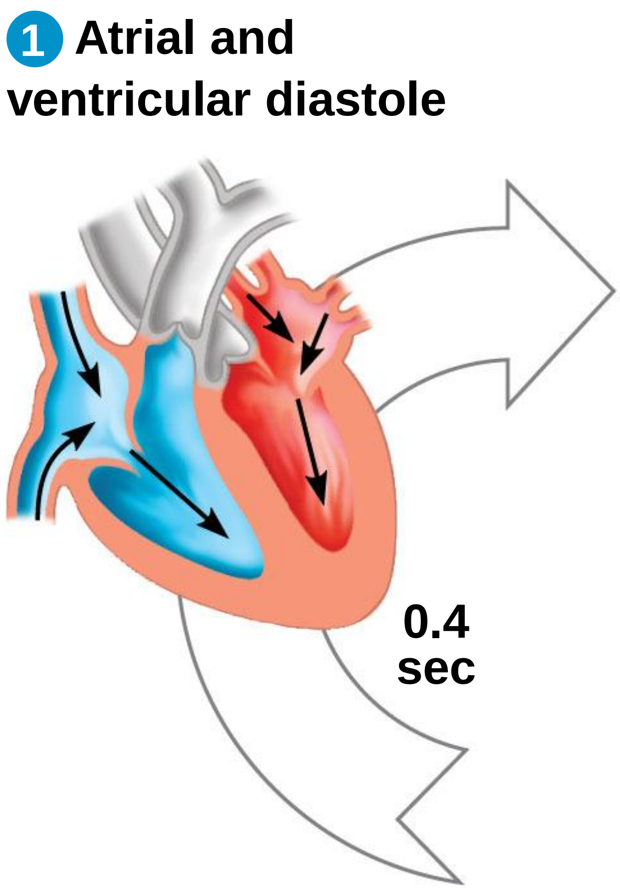
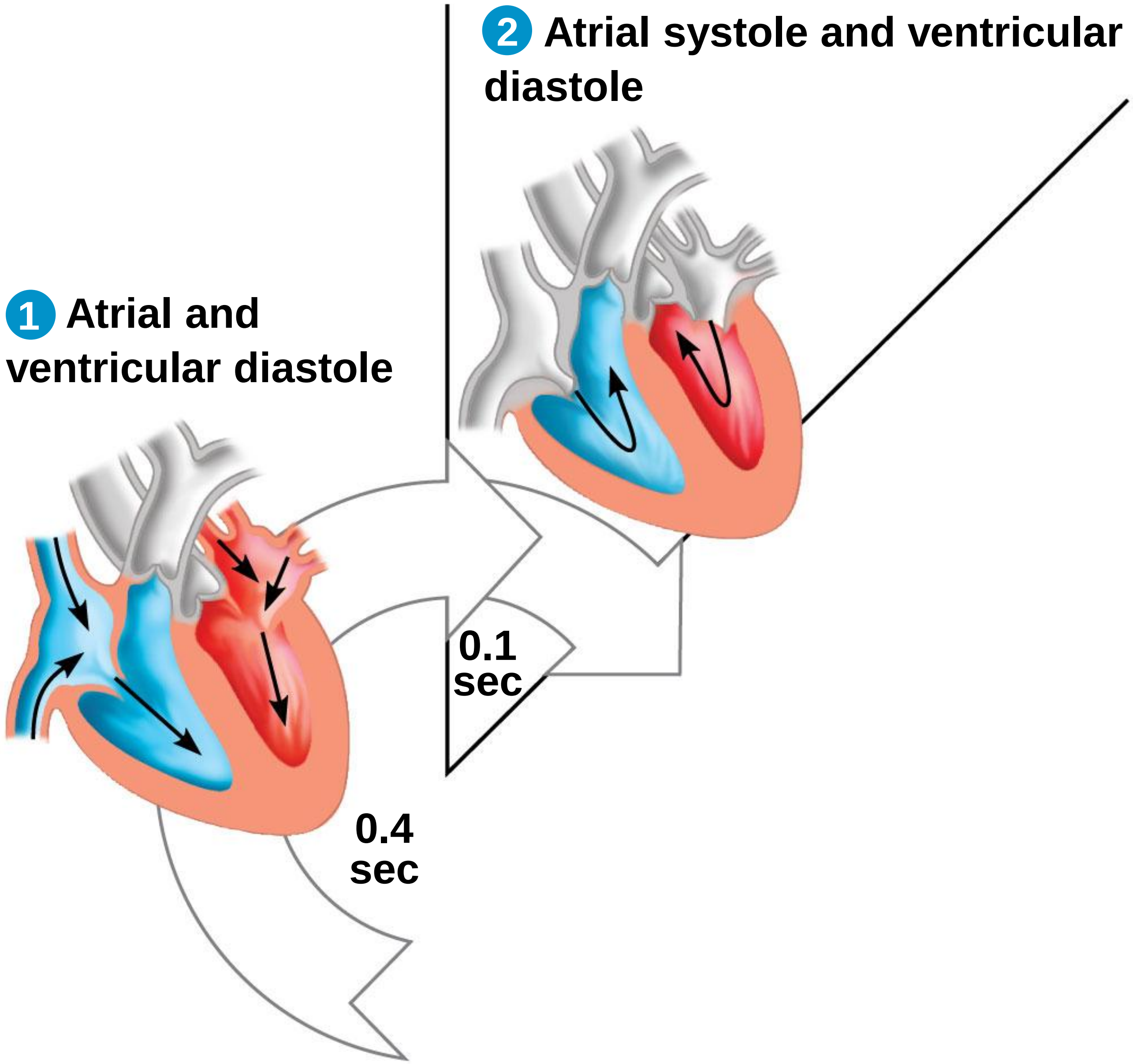
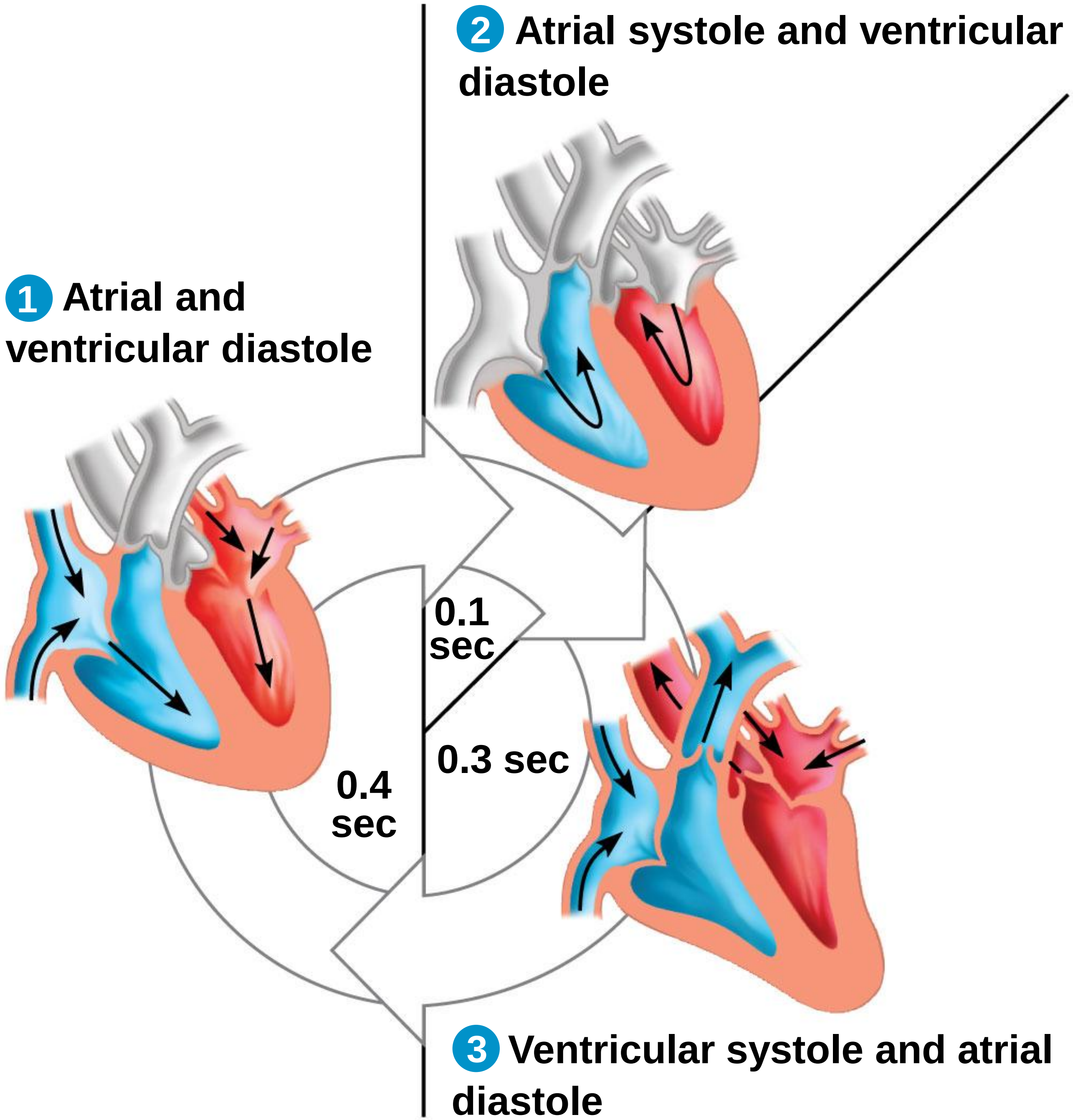


Figure 42.8-2



2 Atrial systole and ventricular diastole
1 Atrial and ventricular diastole
0.1 sec
0.4 sec

Figure 42.8-3



1 Atrial and ventricular diastole
2 Atrial systole and ventricular diastole
3 Ventricular systole and atrial diastole
0.1 sec
0.3 sec
0.4 sec

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

Figure 42.9-1

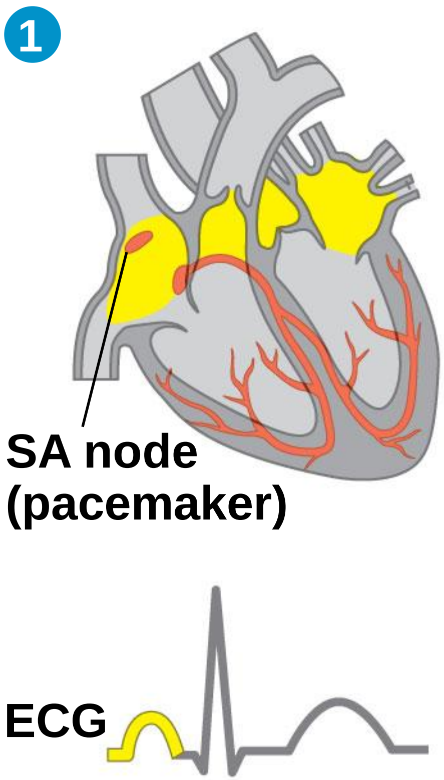


Figure 42.9-2

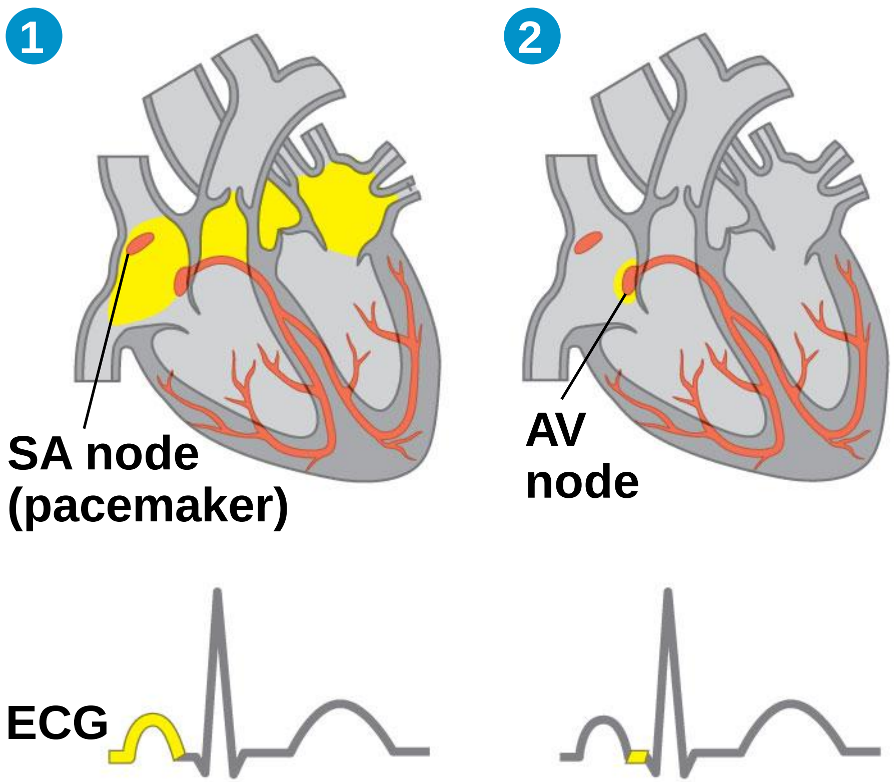


Figure 42.9-3

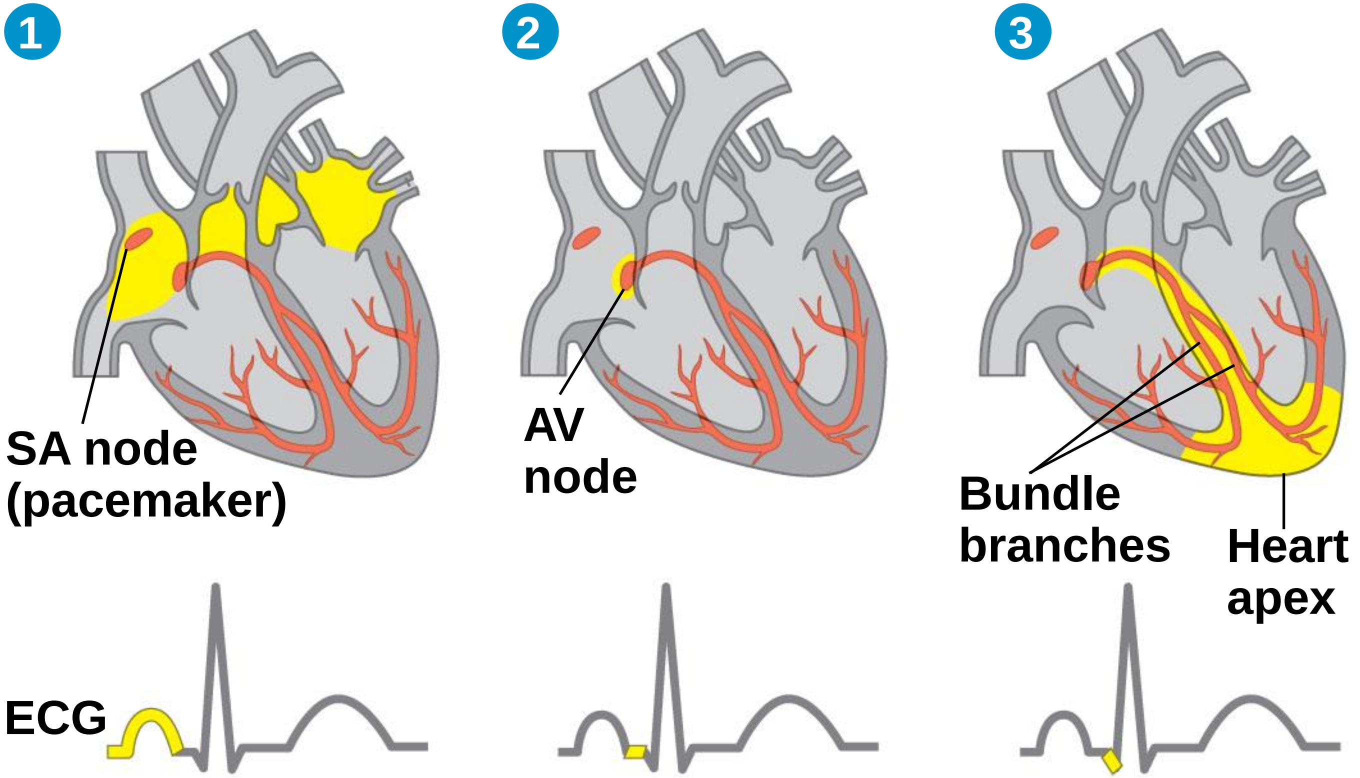
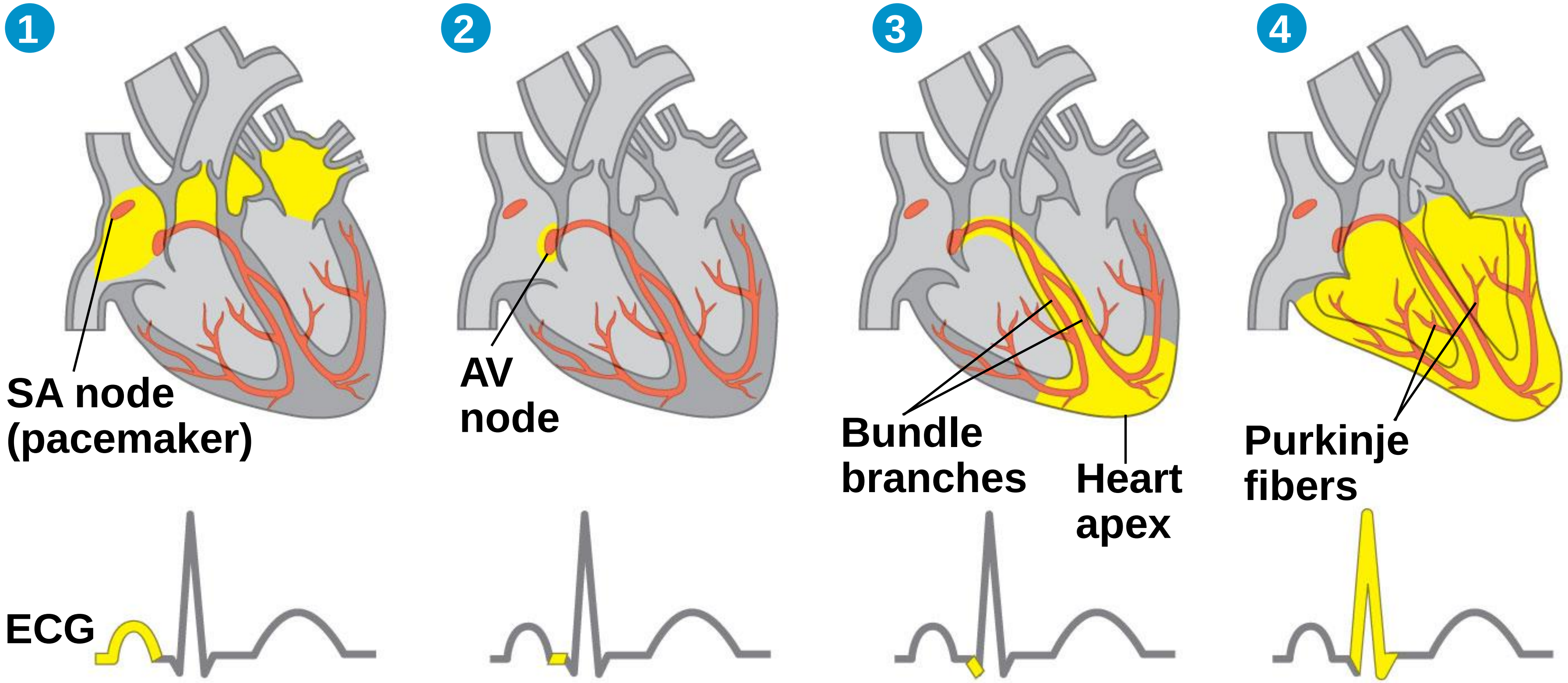

1
2
3
SA node
(pacemaker)
AV
node
Bundle
branches
Heart
apex
ECG

Figure 42.9-4


1
2
3
4
SA node
(pacemaker)
AV
node
Bundle
branches
Heart
apex
Purkinje
fibers
ECG

- 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

- The pacemaker is regulated by two portions of the nervous system: the sympathetic and parasympathetic divisions
- The sympathetic division speeds up the pacemaker
- The parasympathetic division slows down the pacemaker
- The pacemaker is also regulated by hormones and temperature

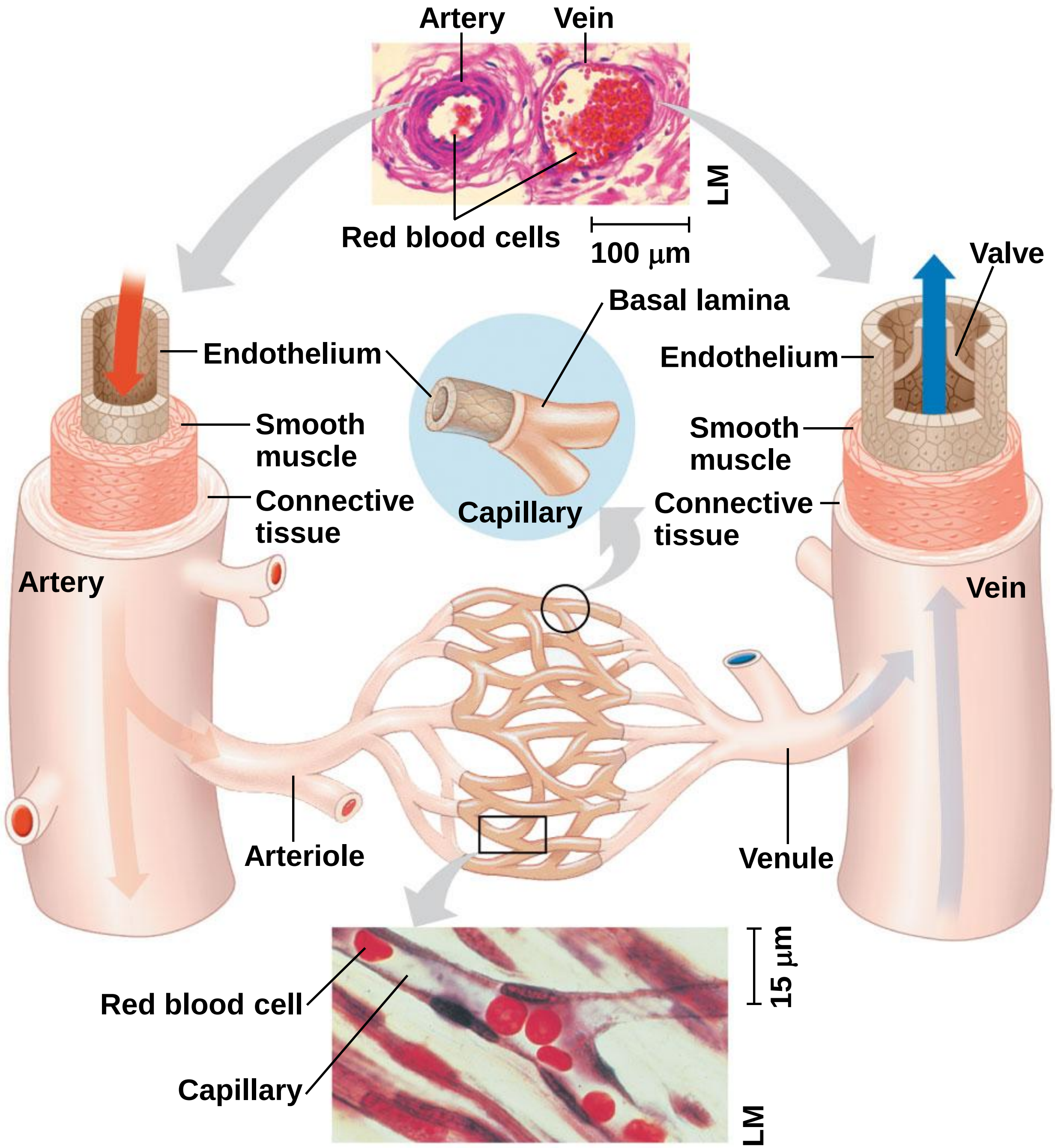
Concept 42.3: Patterns of blood pressure and flow reflect the structure and arrangement of blood vessels

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

Blood Vessel Structure and Function

- A vessel’s cavity is called the central lumen
- The epithelial layer that lines blood vessels is called the **endothelium**
- The endothelium is smooth and minimizes resistance

Figure 42.10



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

Figure 42.10a

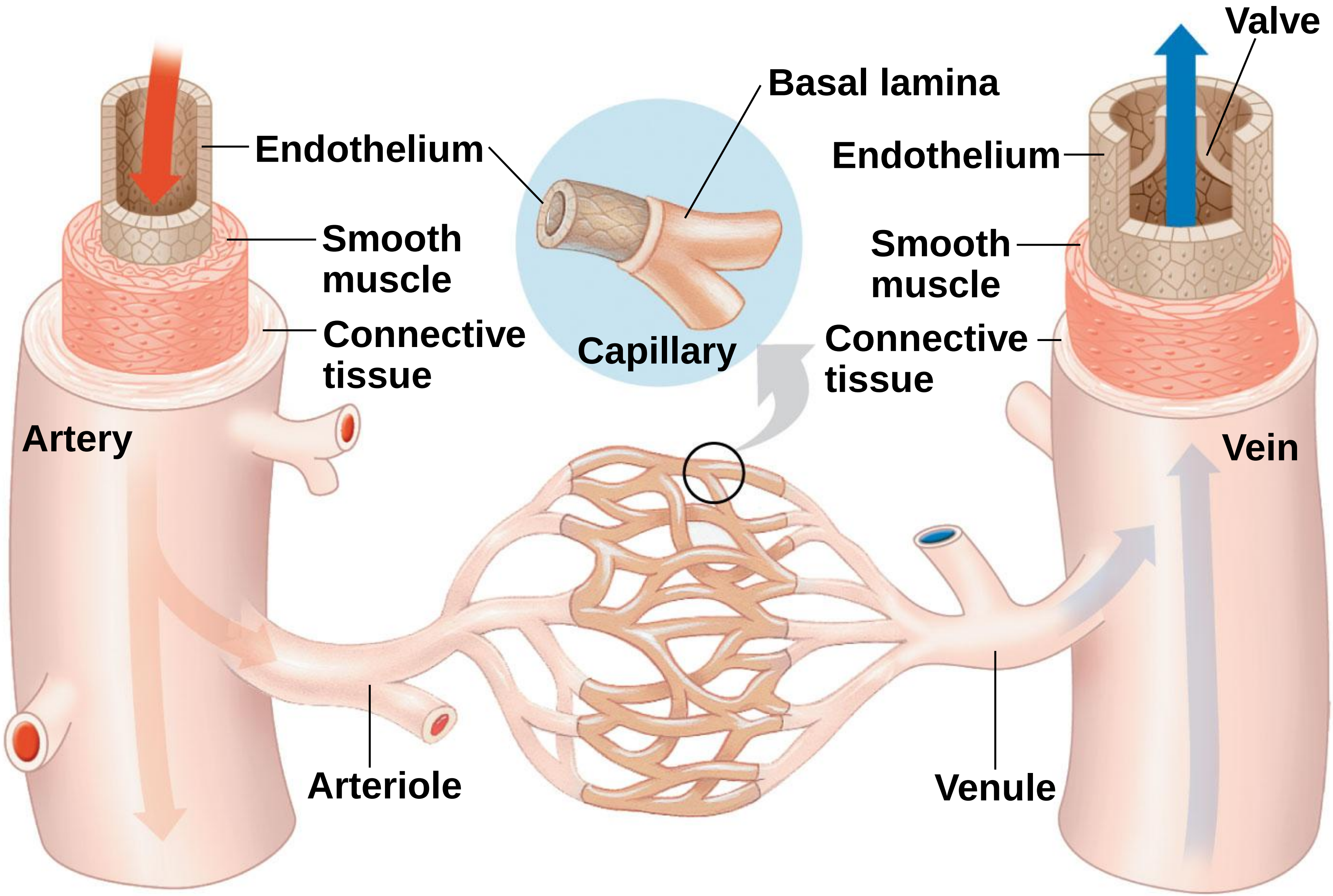


Figure 42.10b

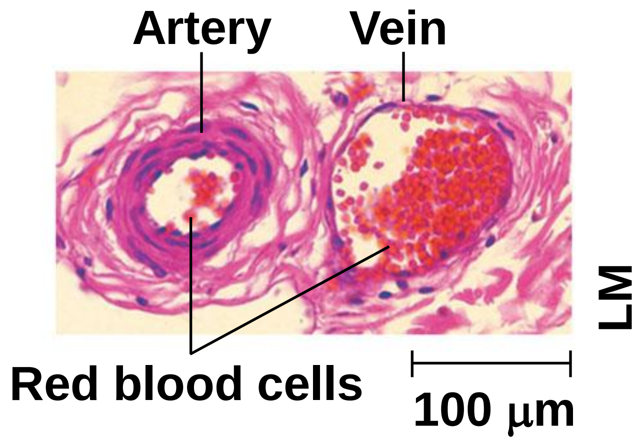
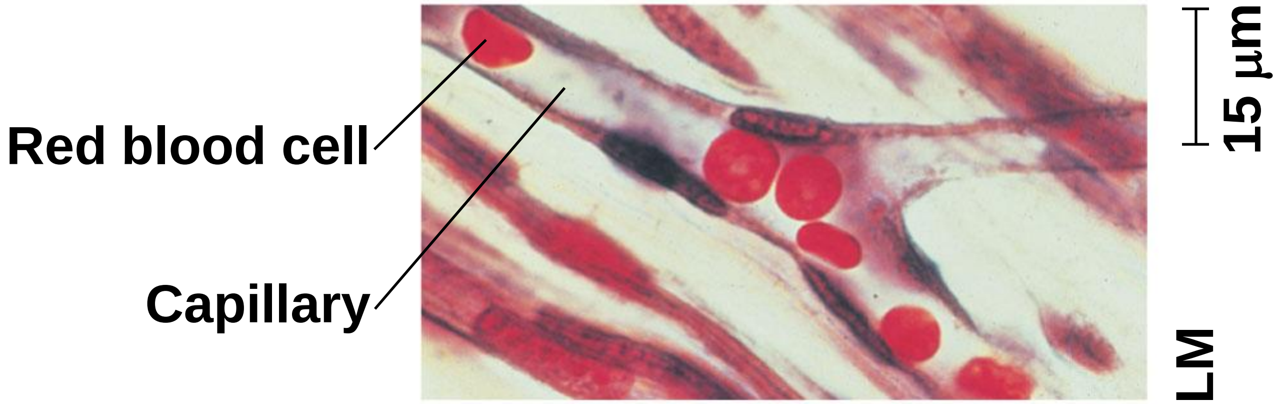


Figure 42.10c

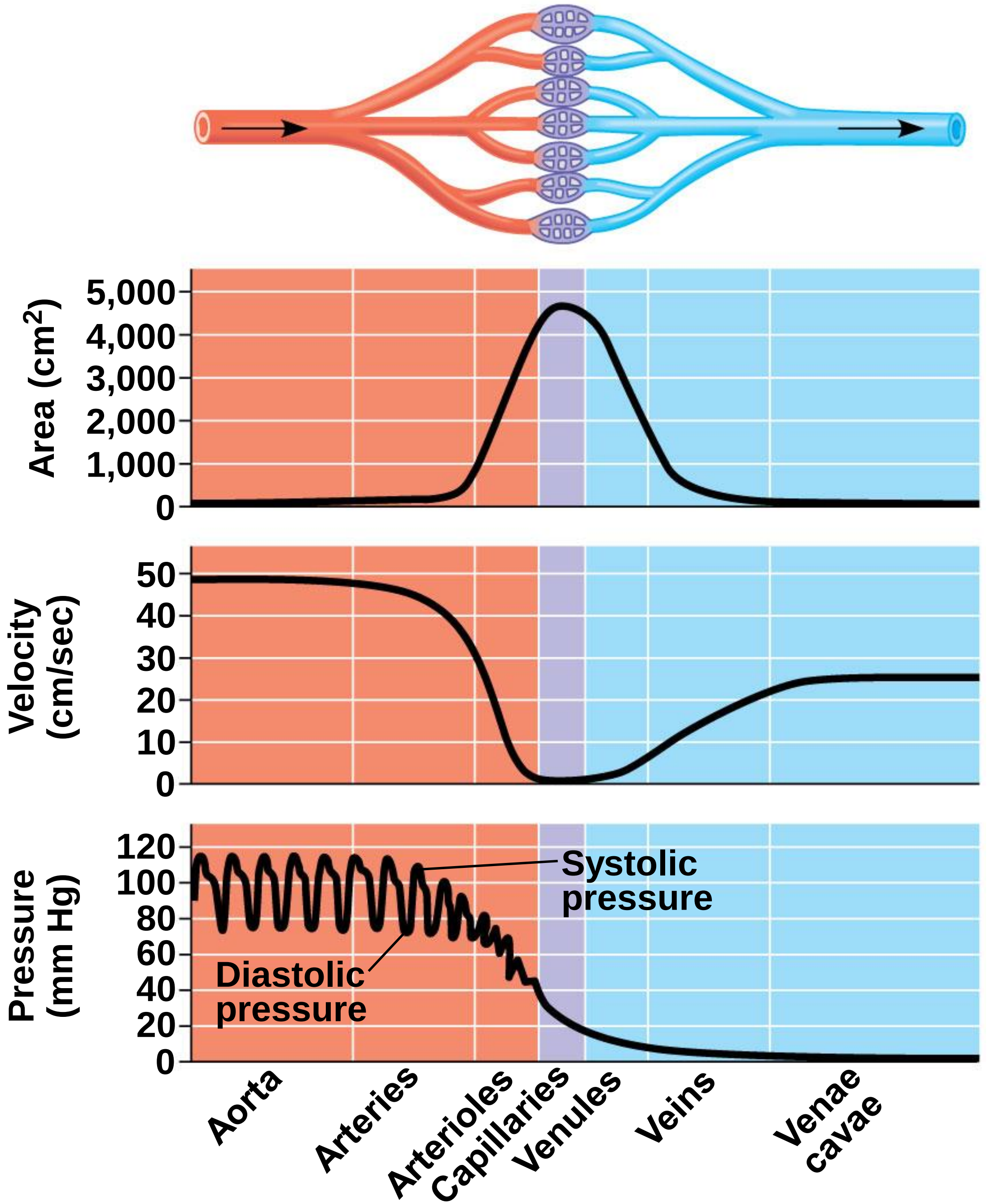


- Capillaries have thin walls, the endothelium plus its basal lamina, to facilitate the exchange of materials
- Arteries and veins have an endothelium, smooth muscle, and connective tissue
- Arteries have thicker walls than veins to accommodate the high pressure of blood pumped from the heart
- In the 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

Figure 42.11



Area (cm^2)
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 flows from areas of higher pressure to areas of lower pressure
- Blood pressure is the 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

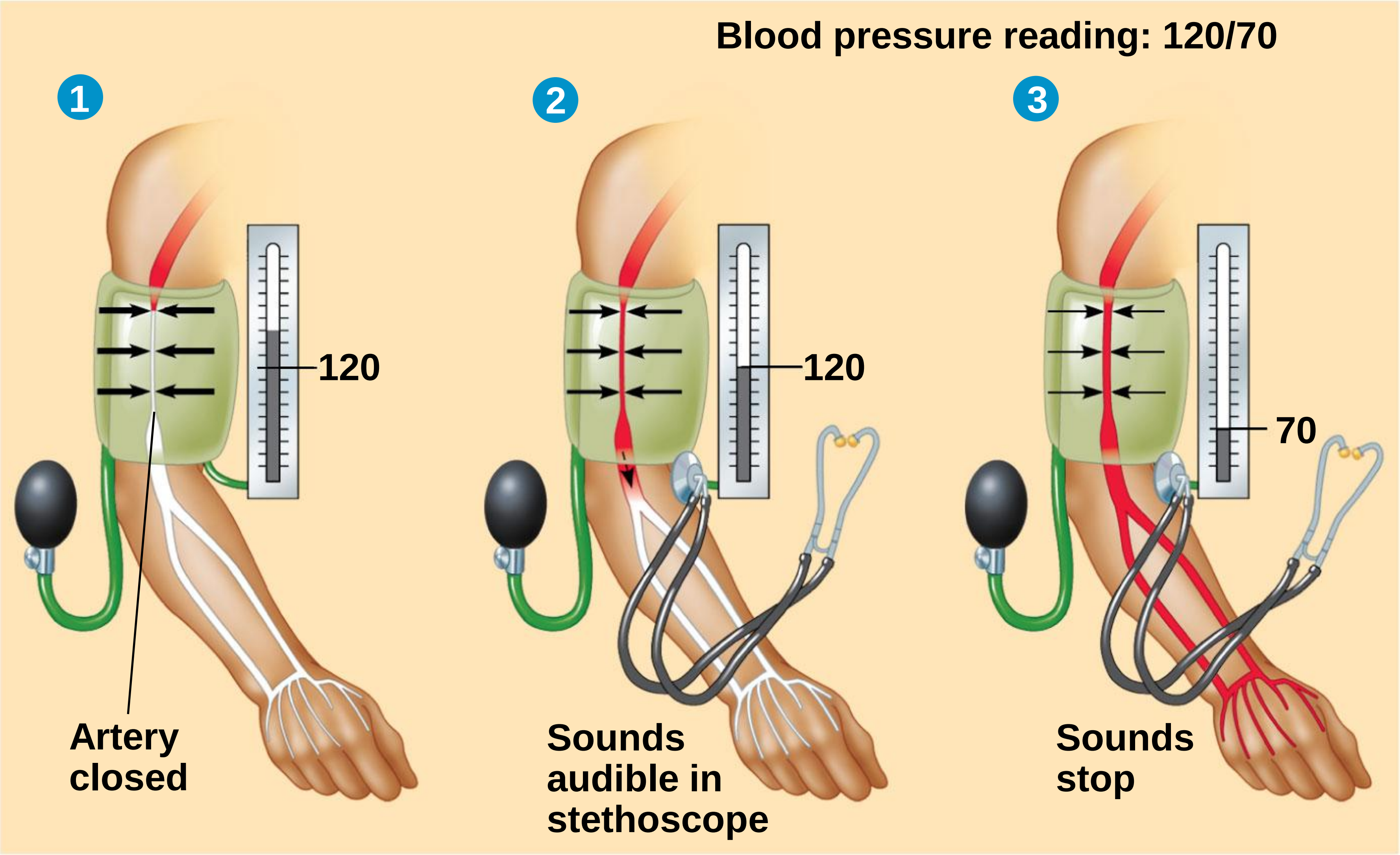
- Blood pressure is determined by cardiac output and peripheral resistance due to constriction of arterioles
- **Vasoconstriction** is the contraction of smooth muscle in arteriole walls; it increases blood pressure
- **Vasodilation** is the relaxation of smooth muscles in the arterioles; it causes blood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

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

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

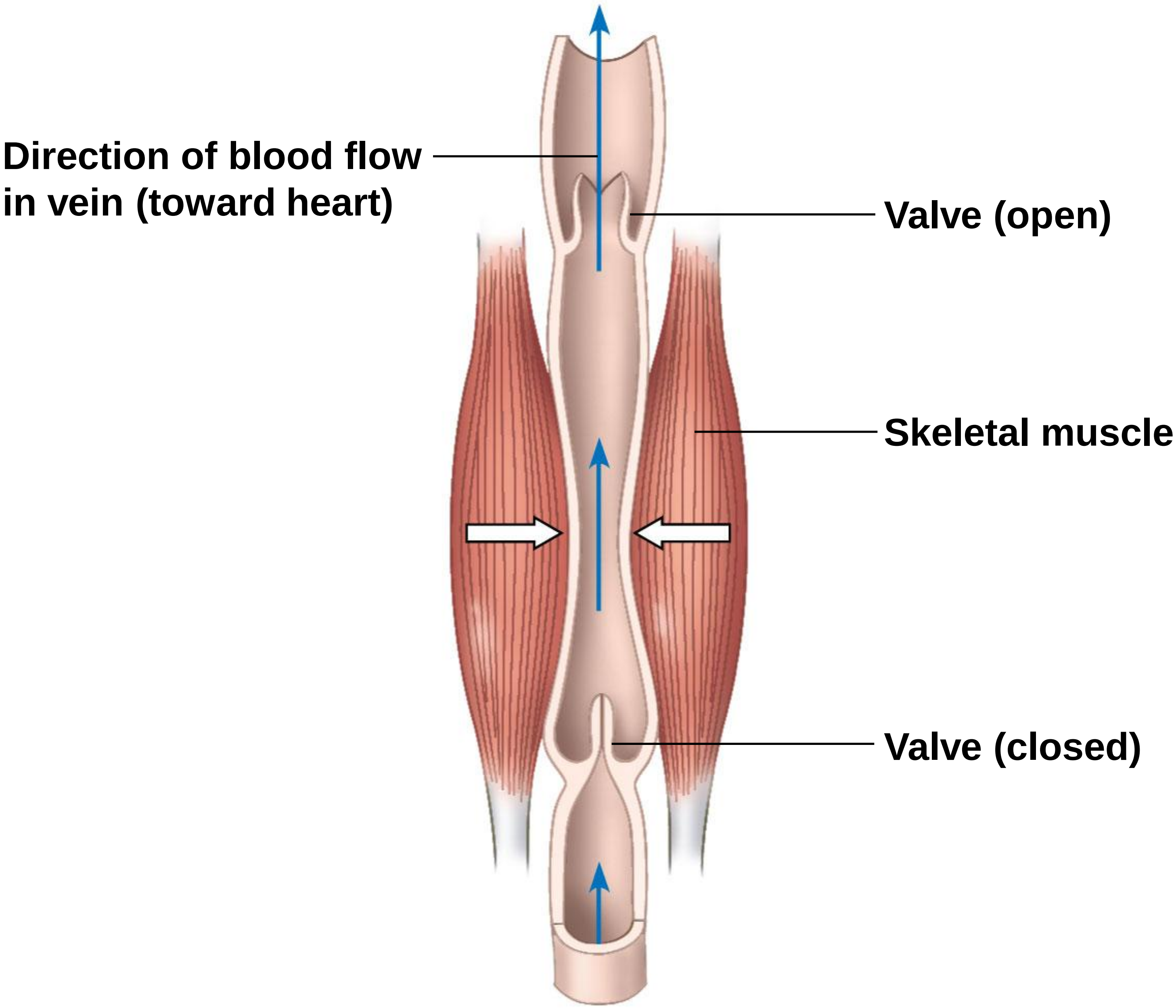
Figure 42.12



Blood pressure reading: 120/70
1
2
3
120
120
70
Artery closed
Sounds audible in stethoscope
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

Figure 42.13

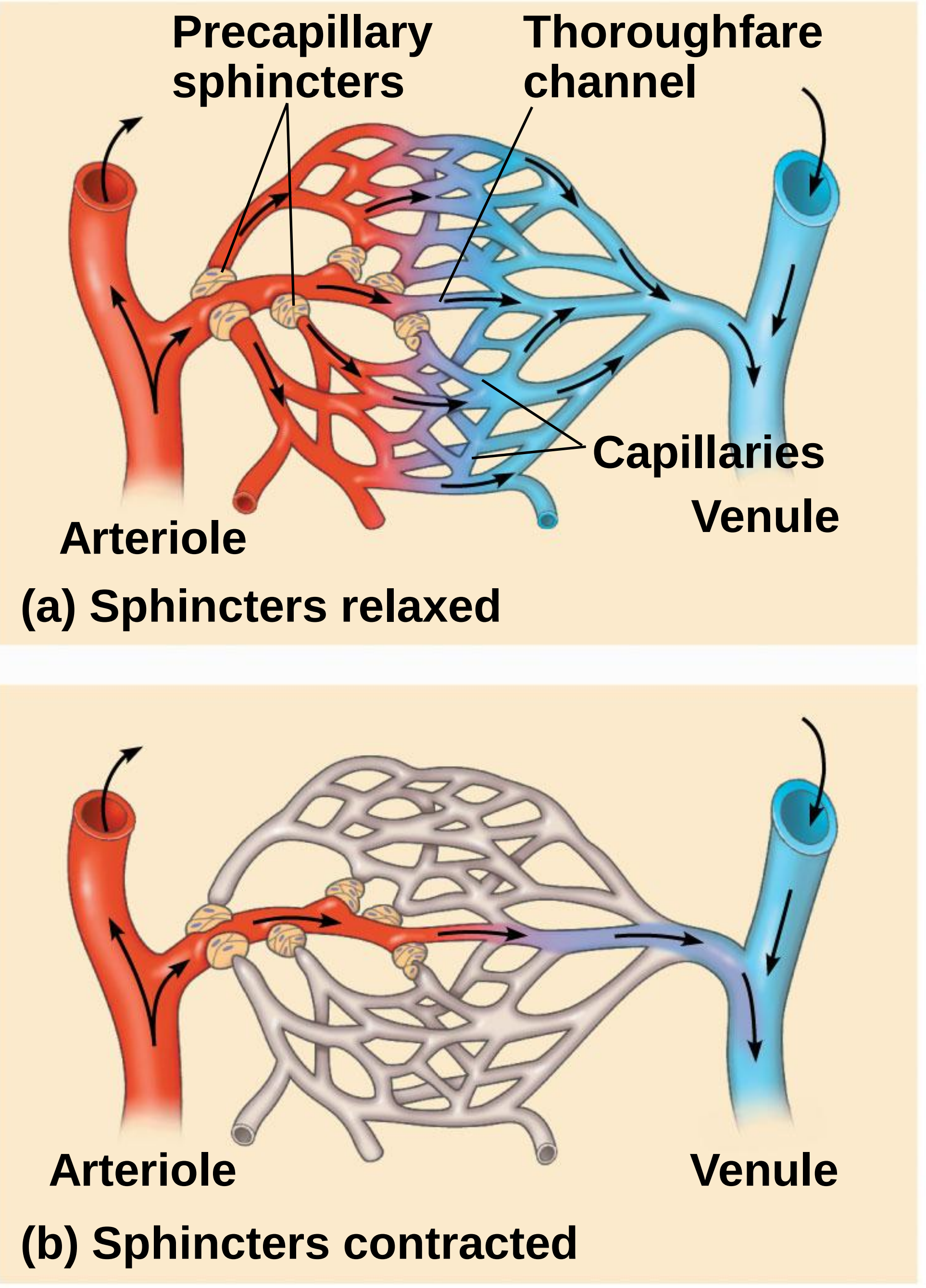

Direction of blood flow
in vein (toward heart)
Valve (open)
Skeletal muscle
Valve (closed)

Capillary Function

- Blood flows through only 5–10% of the body's capillaries at a time
- 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
- Blood flow is regulated by nerve impulses, hormones, and other chemicals

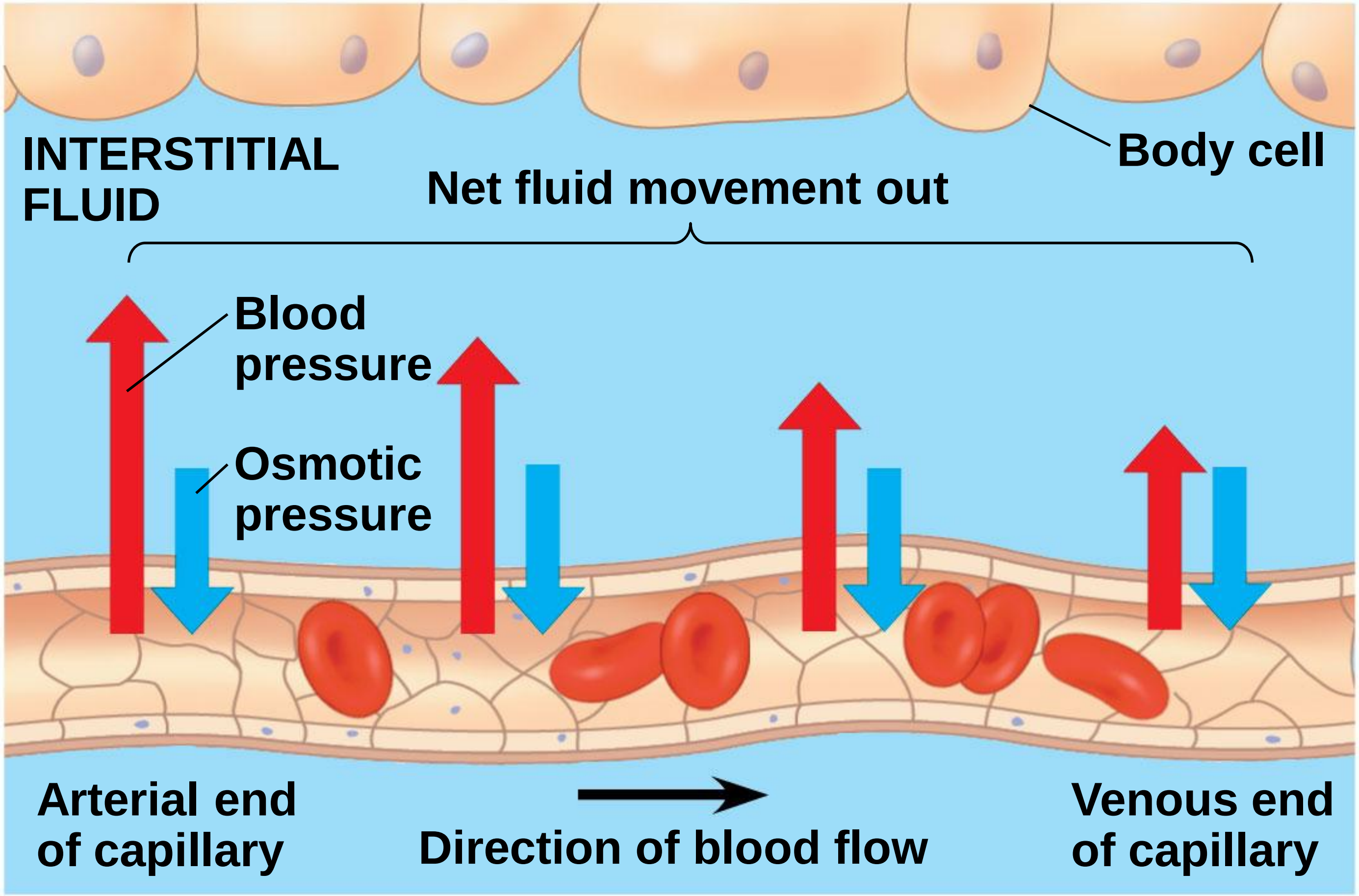
Figure 42.14



Precapillary sphincters
Thoroughfare channel
Capillaries
Venule
Arteriole
(a) Sphincters relaxed
Arteriole
Venule
(b) Sphincters contracted

- The 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
- Most blood proteins and all blood cells are too large to pass through the endothelium

Figure 42.15



INTERSTITIAL FLUID
Net fluid movement out
Body cell
Blood pressure
Osmotic pressure
Arterial end of capillary
Direction of blood flow
Venous end of capillary

Fluid Return by the Lymphatic System

- The **lymphatic system** returns fluid that leaks out from the capillary beds
- 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
- Valves in lymph vessels prevent the backflow of fluid

- **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

Figure 42.16

Concept 42.4: Blood components contribute to exchange, transport, and defense

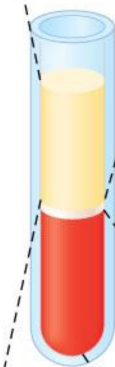
- With open circulation, the fluid that is pumped comes into direct contact with all cells
- The closed circulatory systems of vertebrates contain blood, a specialized connective tissue

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

Figure 42.17

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 permeablity
Plasma proteins	
Albumin	Osmotic balance, pH buffering
Fibrinogen	Clotting
Immunoglobulins (antibodies)	Defense
Substances transported by blood Nutrients Waste products Respiratory gases Hormones	



Cellular elements 45%		
Cell type	**Number per μL (mm^3) of blood**	**Functions**
Leukocytes (white blood cells) Basophils Lymphocytes Eosinophils Neutrophils Monocytes	5,000–10,000	Defense and immunity
Platelets	250,000–400,000	Blood clotting
Erythrocytes (red blood cells)	5–6 million	Transport of O_2 and some CO_2

Figure 42.17a

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 permeablity
Plasma proteins Albumin Fibrinogen Immunoglobulins (antibodies)	 Osmotic balance, pH buffering Clotting Defense
Substances transported by blood Nutrients · Respiratory gases Waste products · Hormones	

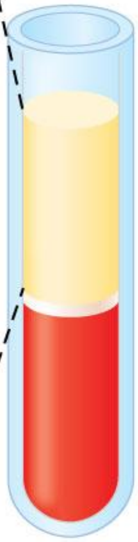
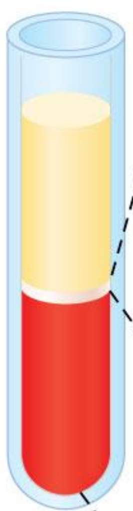
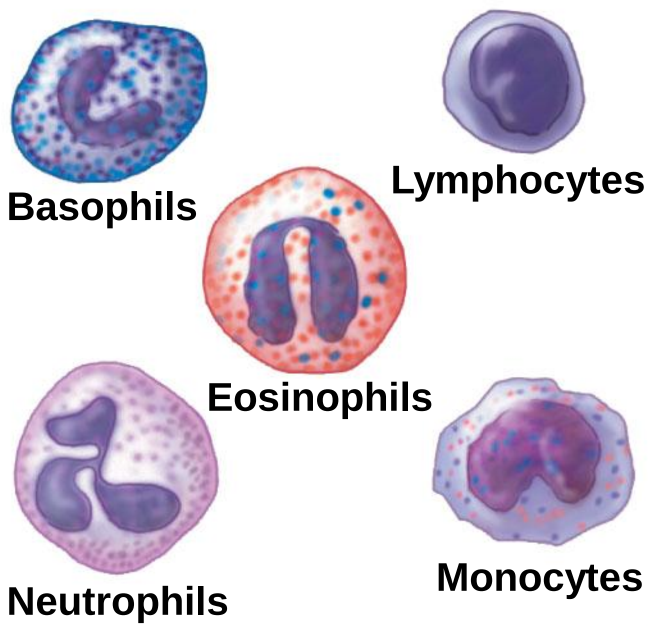


Figure 42.17b

Separated blood elements



Cellular elements 45%		
Cell type	Number per µL (mm^3) of blood	Functions
Leukocytes (white blood cells) 	5,000–10,000	Defense and immunity
Platelets 	250,000–400,000	Blood clotting
Erythrocytes (red blood cells) 	5–6 million	Transport of O_2 and some CO_2

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 O_2
  - 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 contain **hemoglobin**, the iron-containing protein that transports O_2
- Each molecule of hemoglobin binds up to four molecules of O_2
- In mammals, mature erythrocytes lack nuclei and mitochondria

- **Sickle-cell disease** is caused by abnormal hemoglobin proteins that form aggregates
- The aggregates can deform an erythrocyte into a sickle shape
- Sickled cells can rupture, or block blood vessels

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

- Coagulation is the formation of a solid clot from liquid blood
- A cascade of complex reactions converts inactive fibrinogen to fibrin, forming a clot
- A blood clot formed within a blood vessel is called a **thrombus** and can block blood flow

Figure 42.18

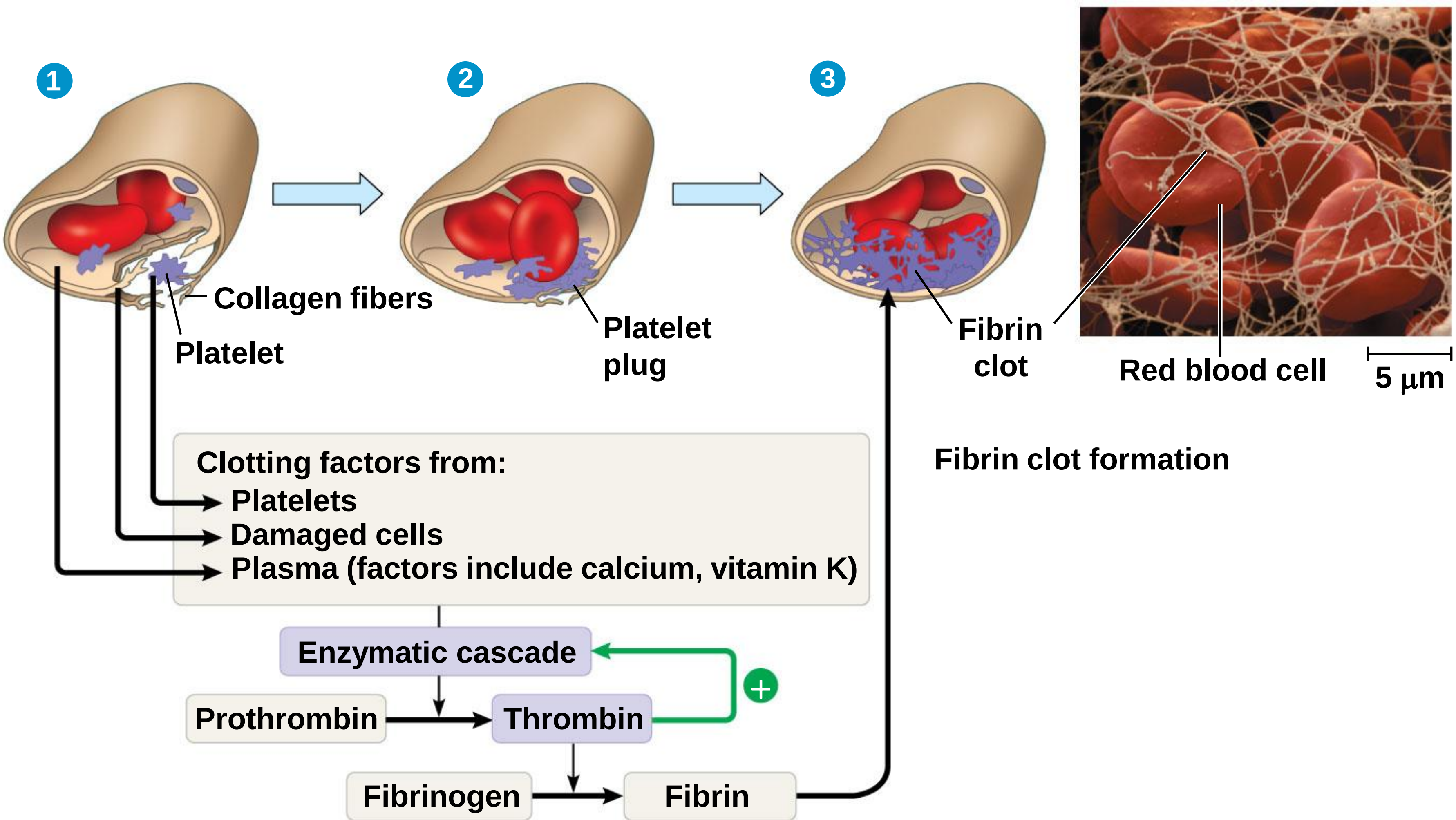

1
2
3
Collagen fibers
Platelet
Platelet plug
Fibrin clot
Red blood cell
5 μm
Fibrin clot formation
Clotting factors from:
Platelets
Damaged cells
Plasma (factors include calcium, vitamin K)
Enzymatic cascade
+
Prothrombin
Thrombin
Fibrinogen
Fibrin

Figure 42.18a

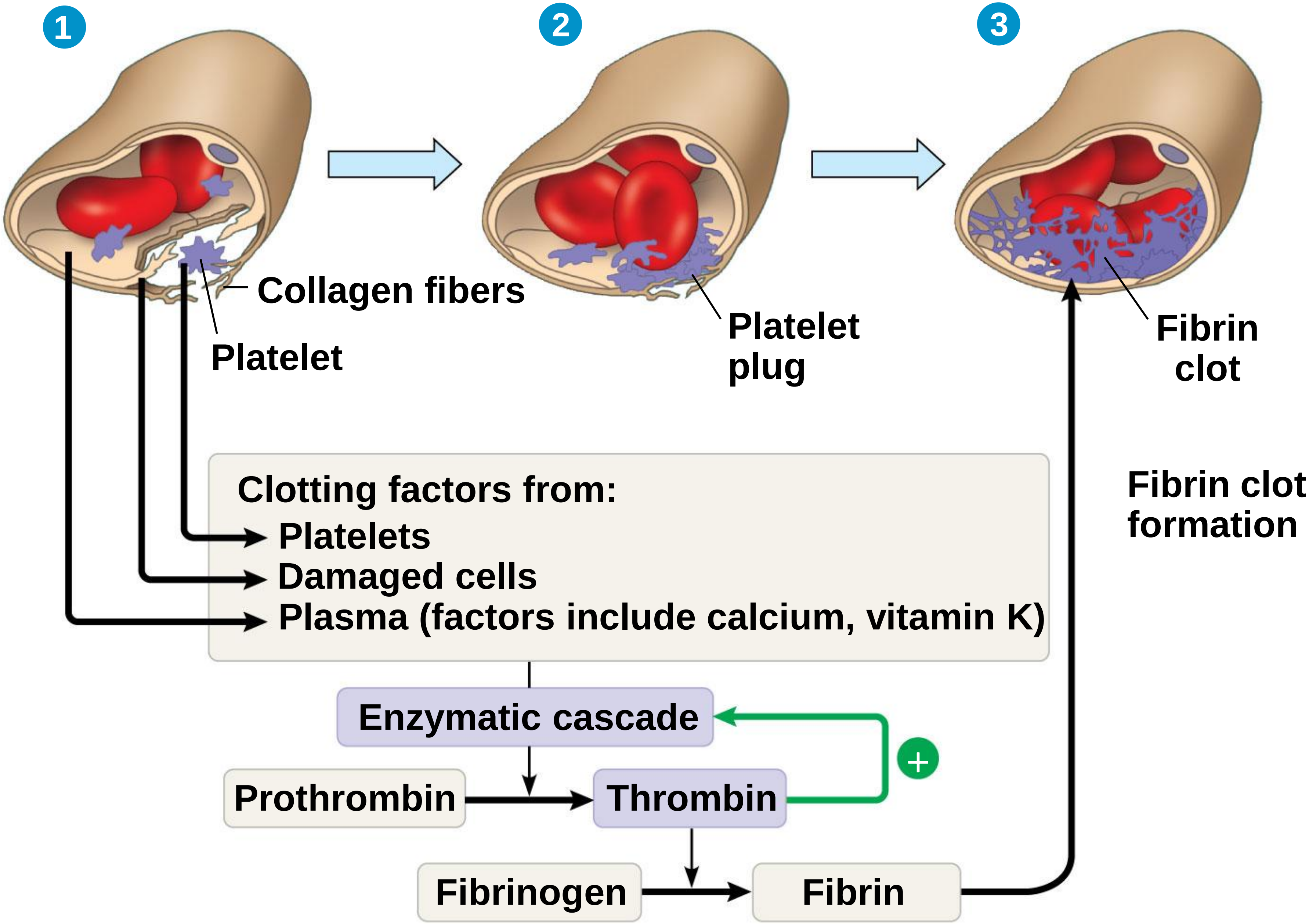
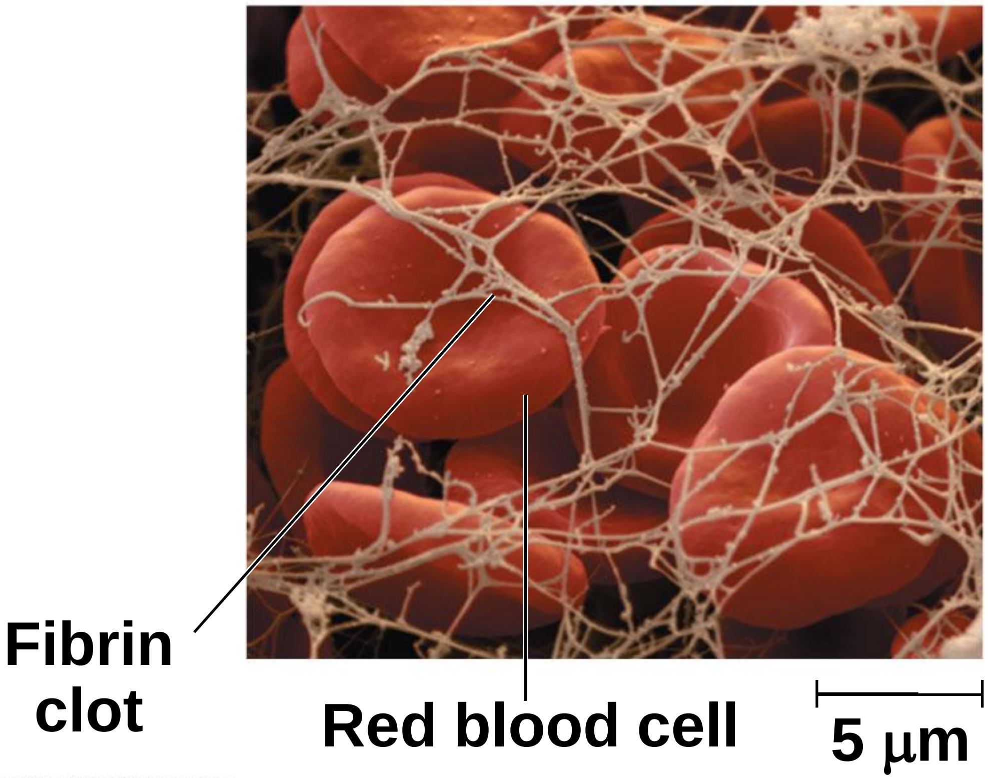


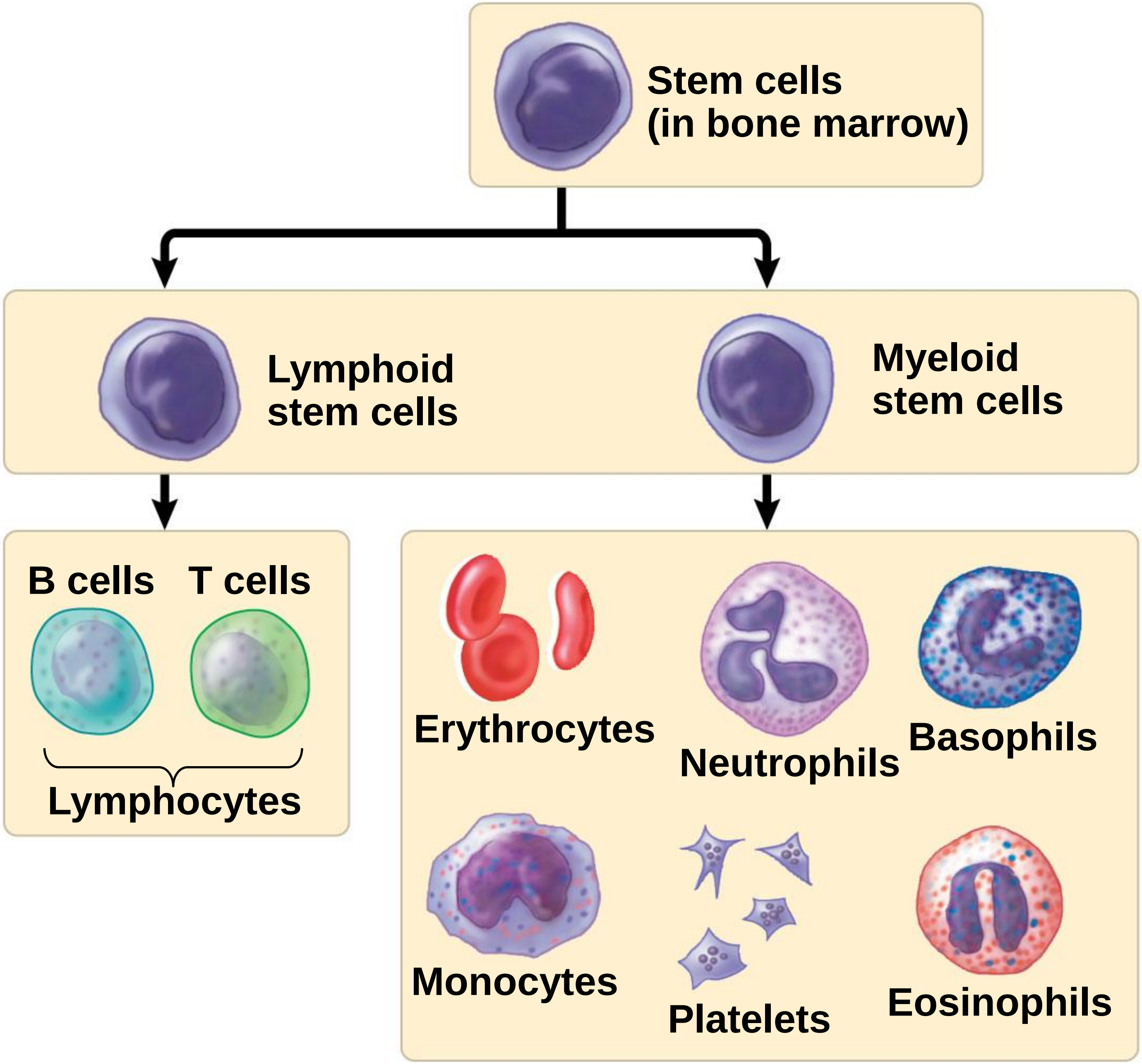
Figure 42.18b



Stem Cells and the Replacement of Cellular Elements

- The cellular elements of blood wear out and are being replaced constantly
- Erythrocytes, leukocytes, and platelets all develop from a common source of **stem cells** in the red marrow of bones, especially ribs, vertebrae, sternum, and pelvis
- The hormone **erythropoietin (EPO)** stimulates erythrocyte production when O_2 delivery is low

Figure 42.19



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

Cardiovascular Disease

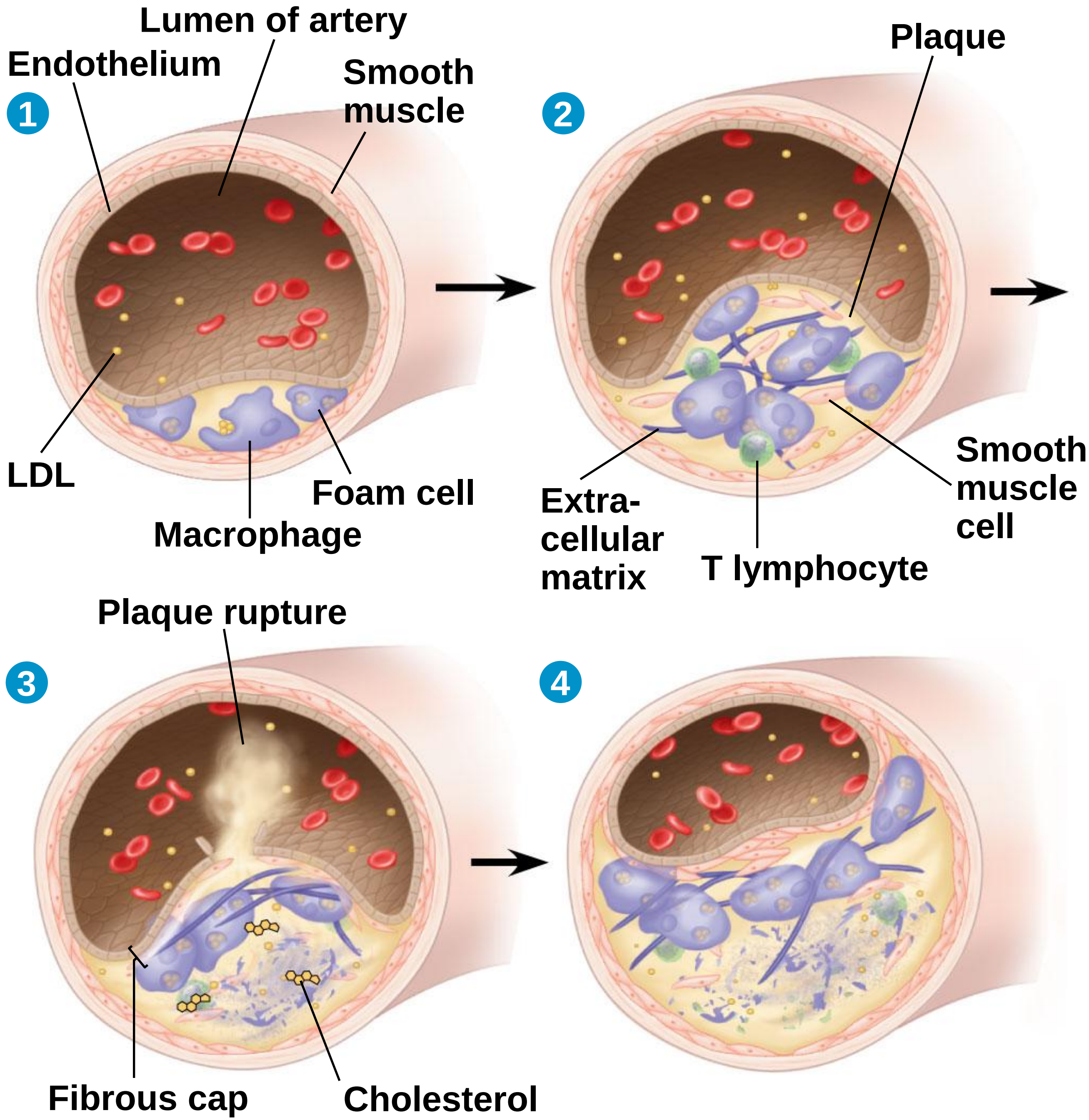
- Cardiovascular diseases are disorders of the heart and the blood vessels
- Cardiovascular diseases account for more than half the deaths in the United States
- Cholesterol, a steroid, helps maintain membrane fluidity

- **Low-density lipoprotein (LDL)** delivers cholesterol to cells for membrane production
- **High-density lipoprotein (HDL)** scavenges cholesterol for return to the liver
- Risk for heart disease increases with a high LDL to HDL ratio
- Inflammation is also a factor in cardiovascular disease

Atherosclerosis, Heart Attacks, and Stroke

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

Figure 42.20



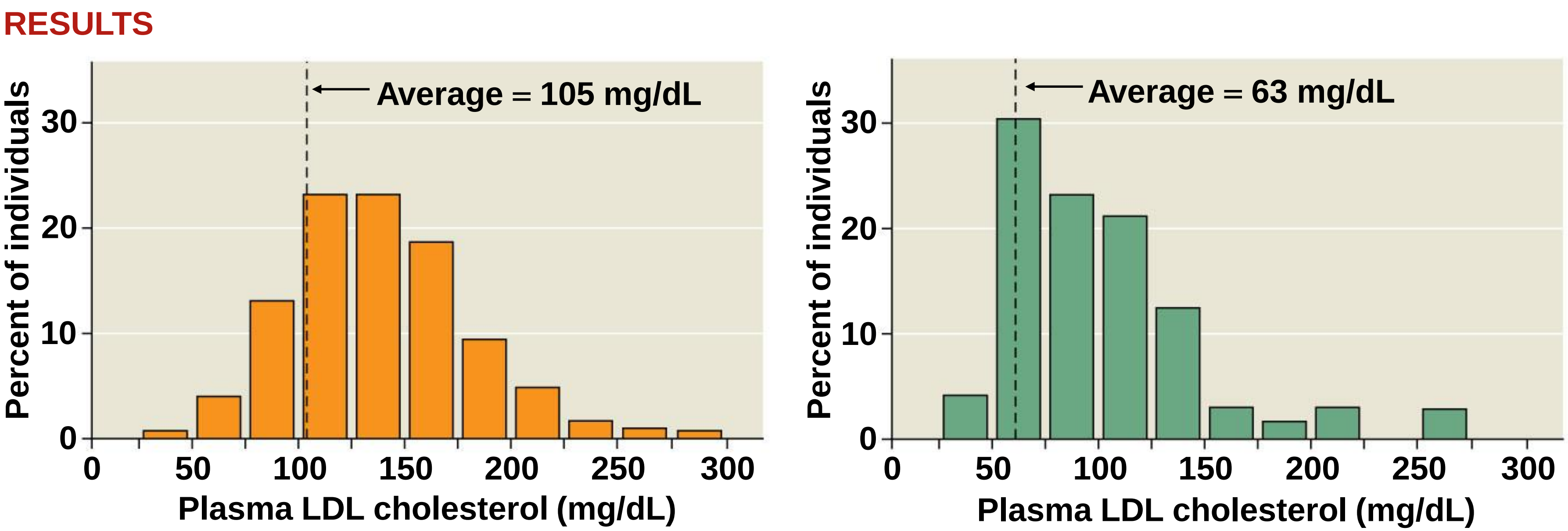
Lumen of artery
Endothelium
Smooth muscle
1
LDL
Foam cell
Macrophage
2
Plaque
Smooth muscle cell
Extra-cellular matrix
T lymphocyte
Plaque rupture
3
4
Fibrous cap
Cholesterol

- A **heart attack,** or myocardial infarction, is the death of cardiac muscle tissue resulting from blockage of one or more coronary arteries
- Coronary arteries supply oxygen-rich blood to the heart muscle
- A **stroke** is the death of nervous tissue in the brain, usually resulting from rupture or blockage of arteries in the head
- Angina pectoris is caused by partial blockage of the coronary arteries and results in chest pains

Risk Factors and Treatment of Cardiovascular Disease

- A high LDL to HDL ratio increases the risk of cardiovascular disease
- The proportion of LDL relative to HDL can be decreased by exercise, not smoking, and avoiding foods with trans fats
- Drugs called statins reduce LDL levels and risk of heart attacks

Figure 42.21



Individuals with two functional copies of *PCSK9* gene (control group)

Individuals with an inactivating mutation in one copy of *PCSK9* gene

- Inflammation plays a role in atherosclerosis and thrombus formation
- Aspirin inhibits inflammation and reduces the risk of heart attacks and stroke
- **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 O_2 for cellular respiration and disposes of CO_2

Partial Pressure Gradients in Gas Exchange

- A gas diffuses from a region of higher partial pressure to a region of lower partial pressure
- **Partial pressure** is the pressure exerted by a particular gas in a mixture of gases
- Gases diffuse down pressure gradients in the lungs and other organs as a result of differences in partial pressure

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

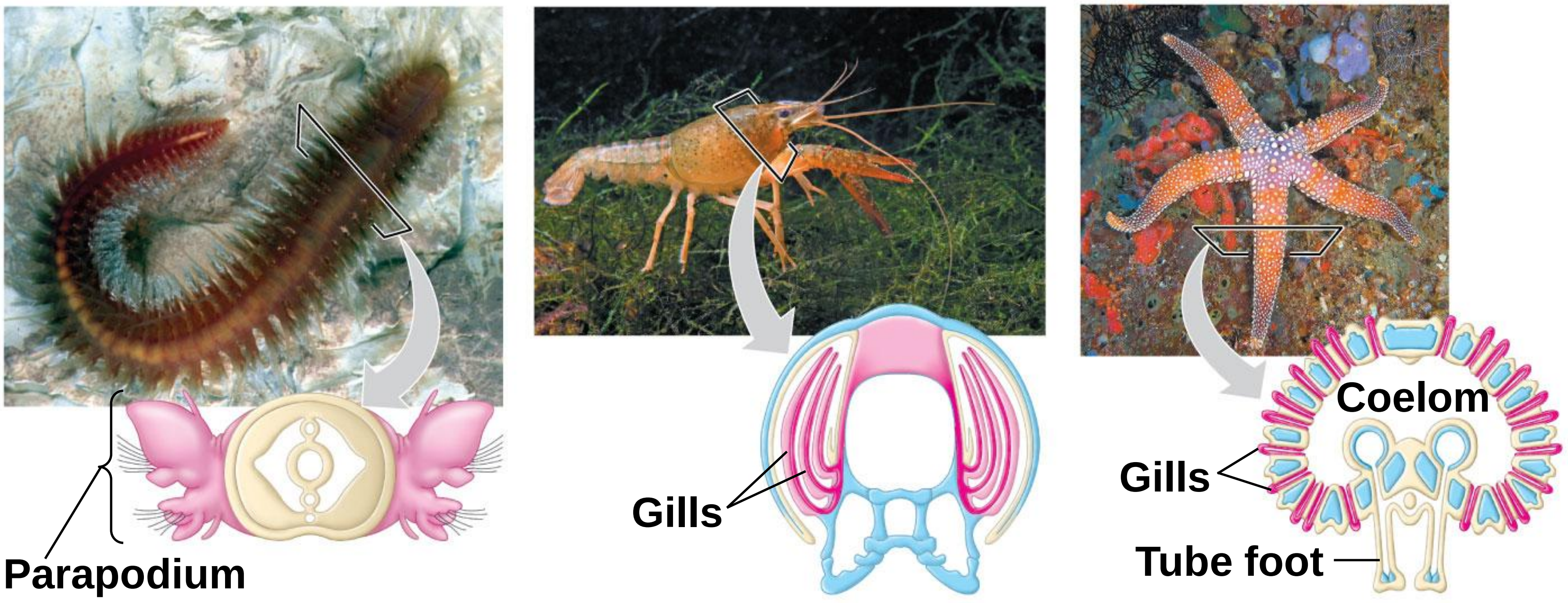
Respiratory Surfaces

- 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

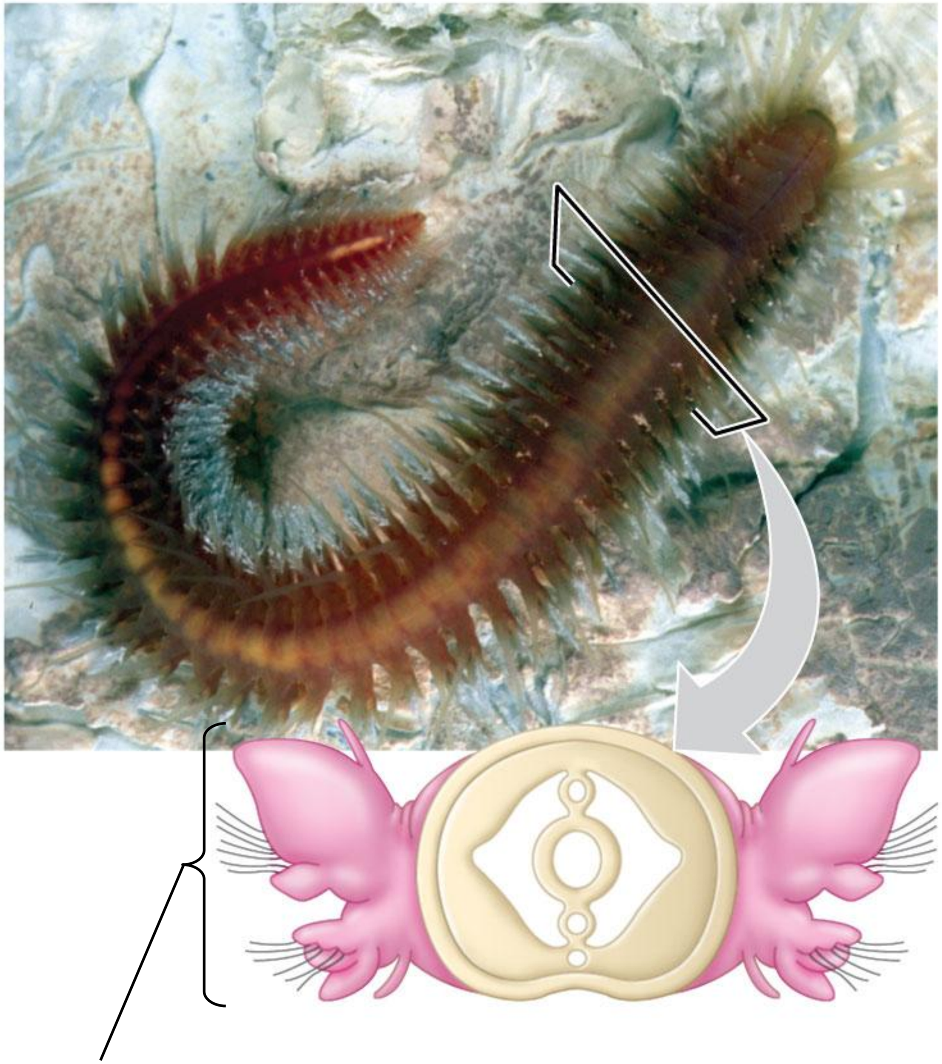
- Gills are outfoldings of the body that create a large surface area for gas exchange

Figure 42.22



(a) Marine worm (b) Crayfish (c) Sea star

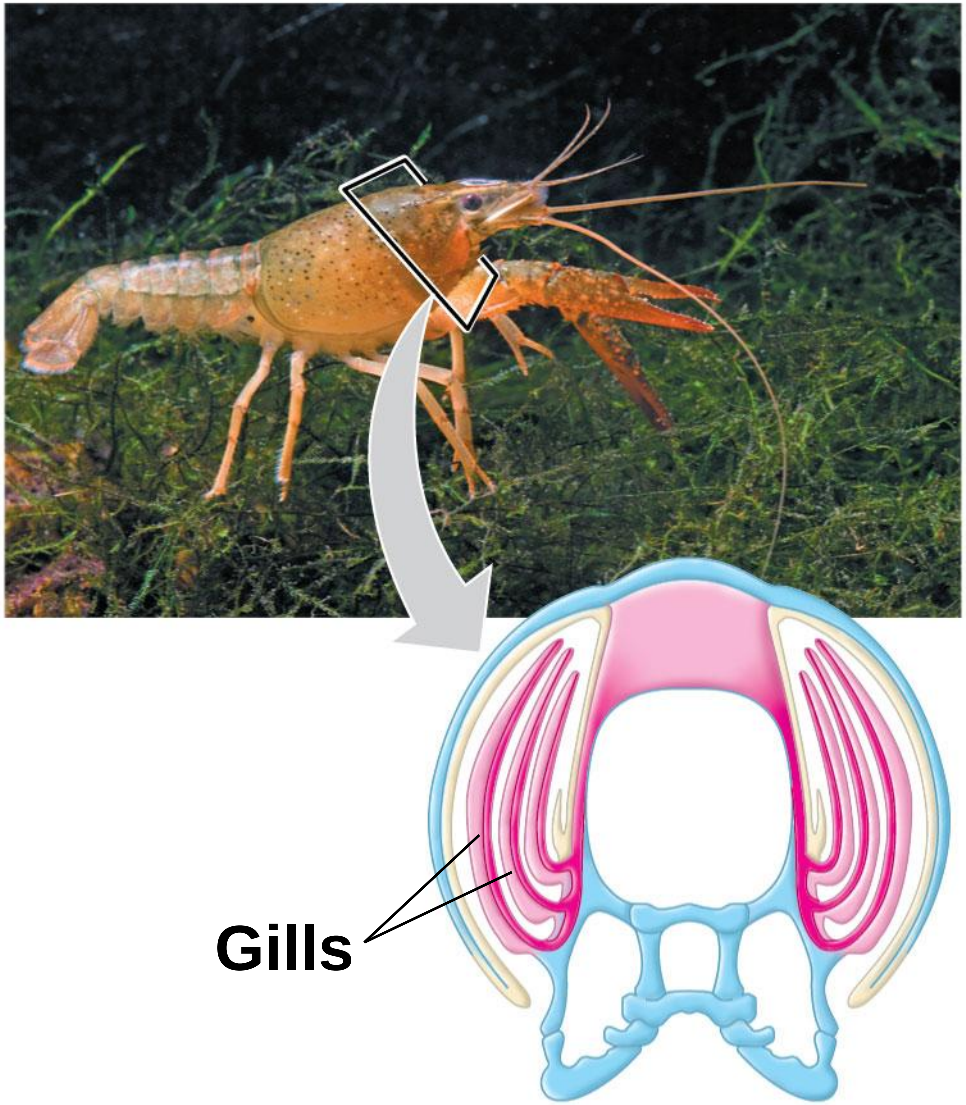
Figure 42.22a



Parapodium (functions as gill)

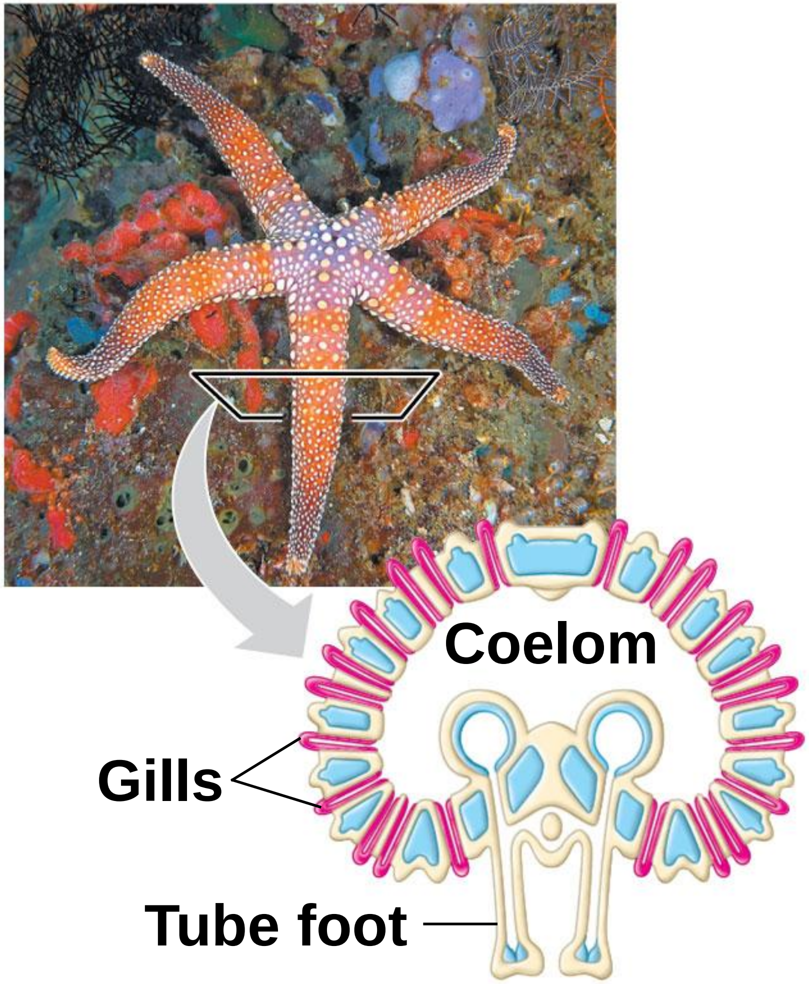
(a) Marine worm

Figure 42.22b



(b) Crayfish

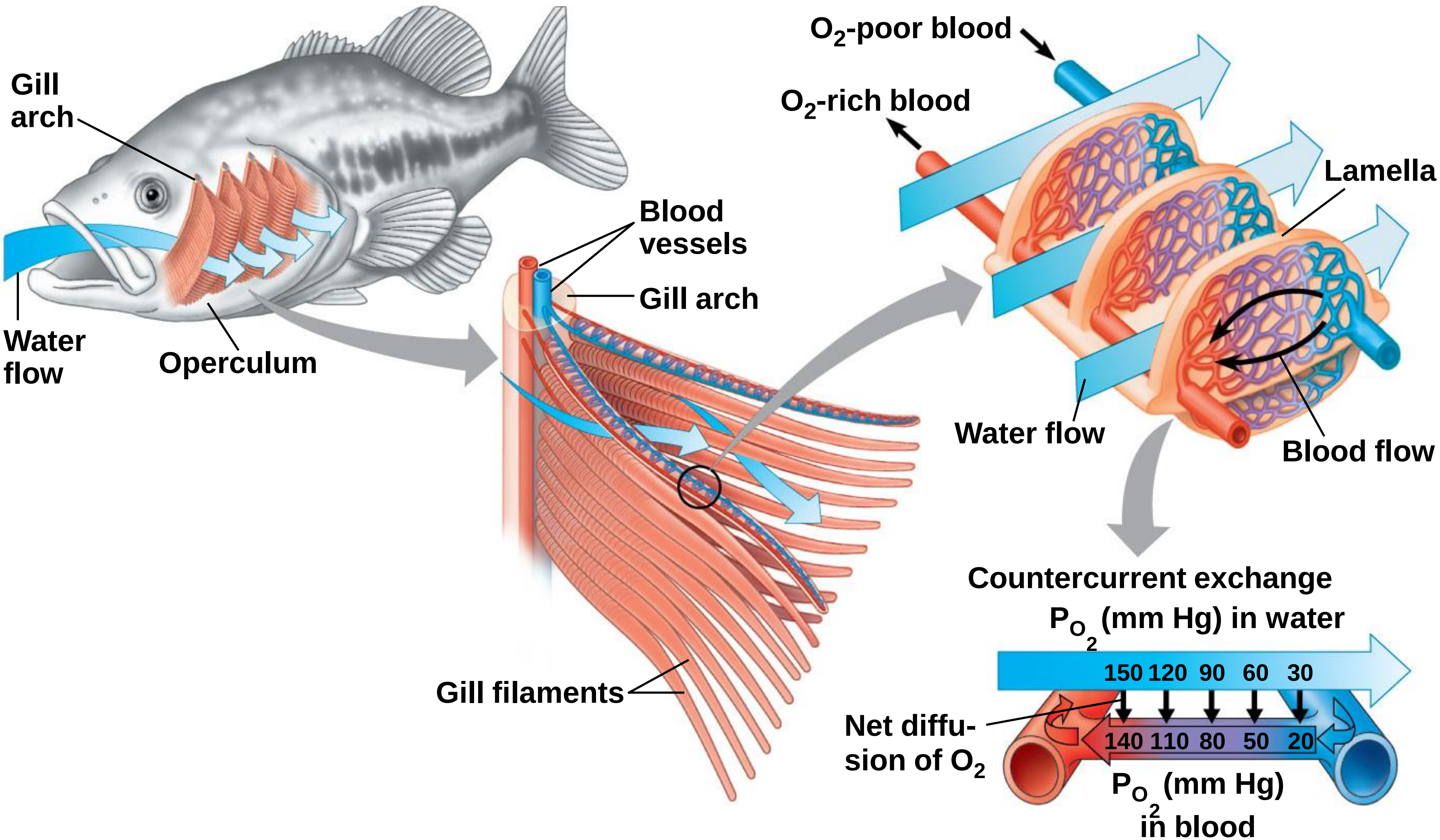
Figure 42.22c



(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

Figure 42.23



Gill arch
Water flow
Operculum
Blood vessels
Gill arch
Gill filaments
O_2-poor blood
O_2-rich blood
Lamella
Water flow
Blood flow
Countercurrent exchange
P_{O_2} (mm Hg) in water
150 120 90 60 30
Net diffusion of O_2
140 110 80 50 20
P_{O_2} (mm Hg) in blood

Figure 42.23a

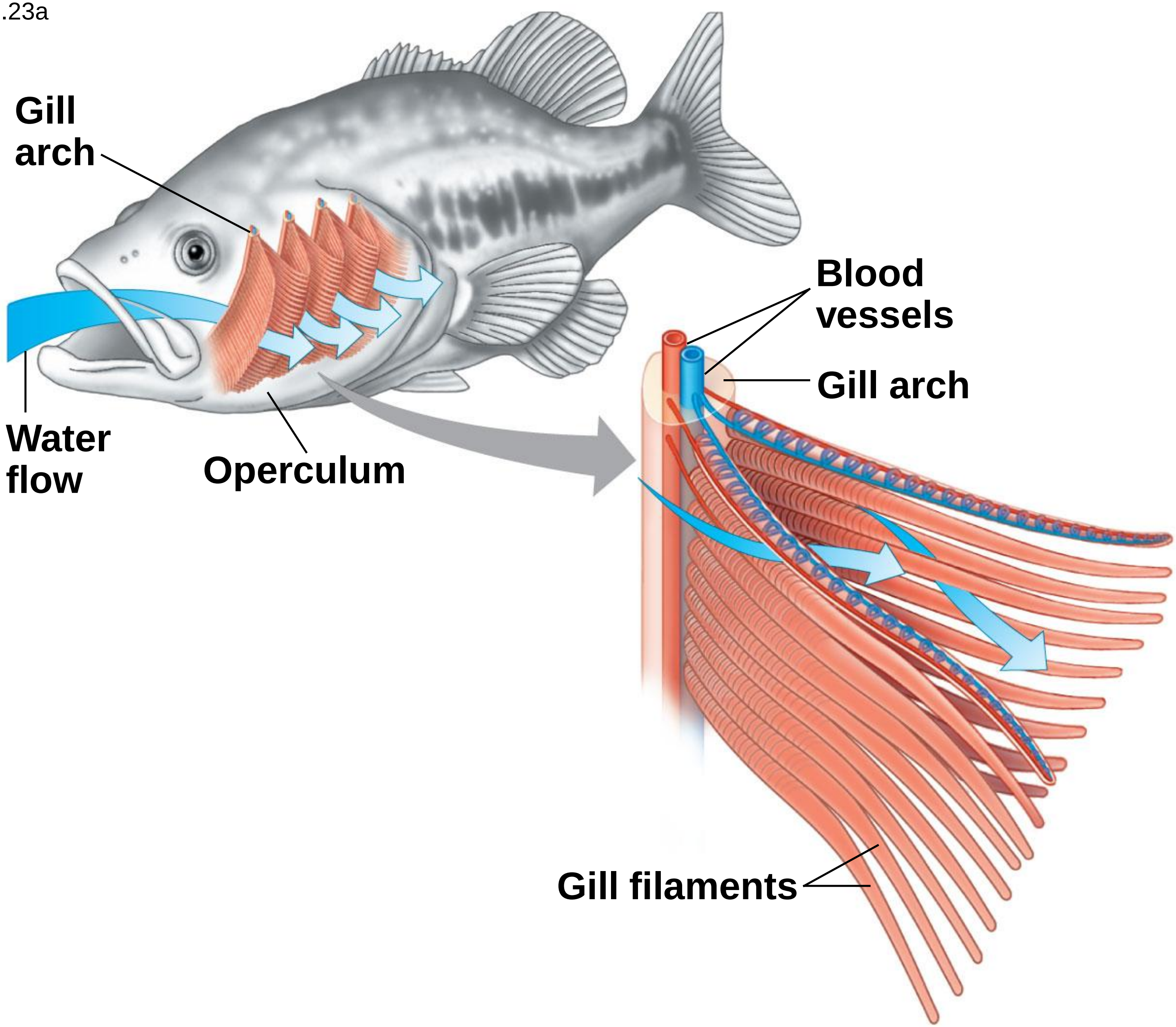
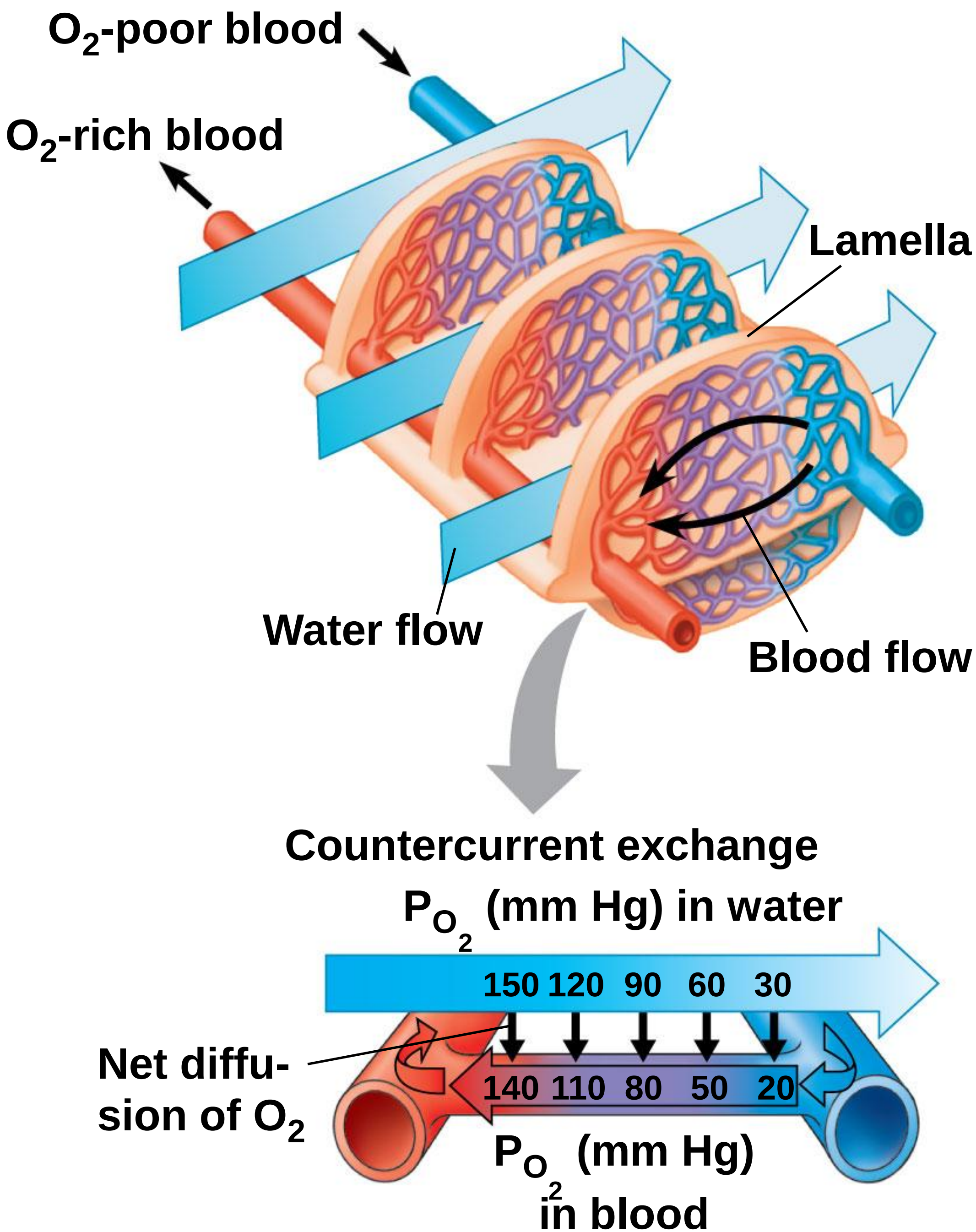


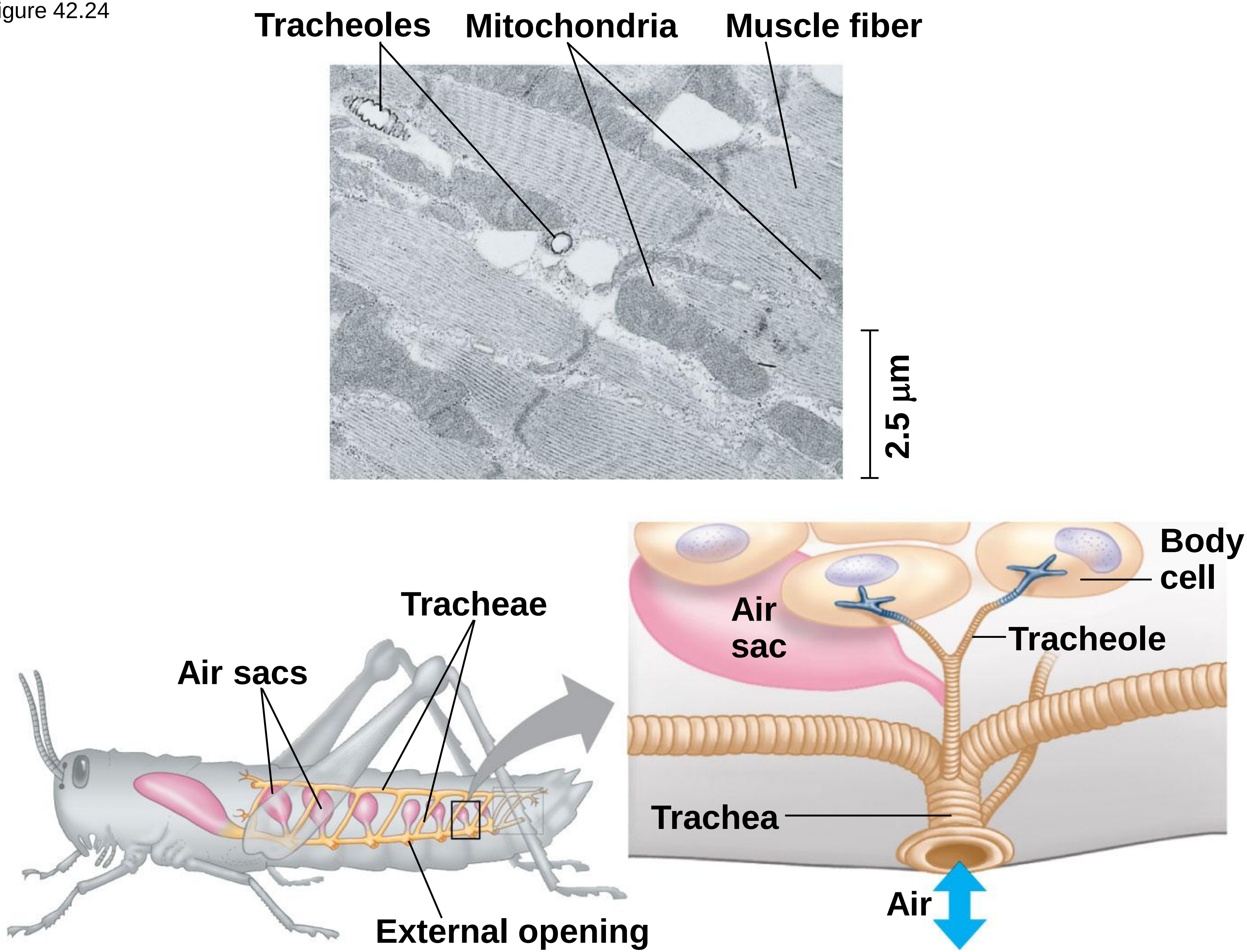
Figure 42.23b



Tracheal Systems in Insects

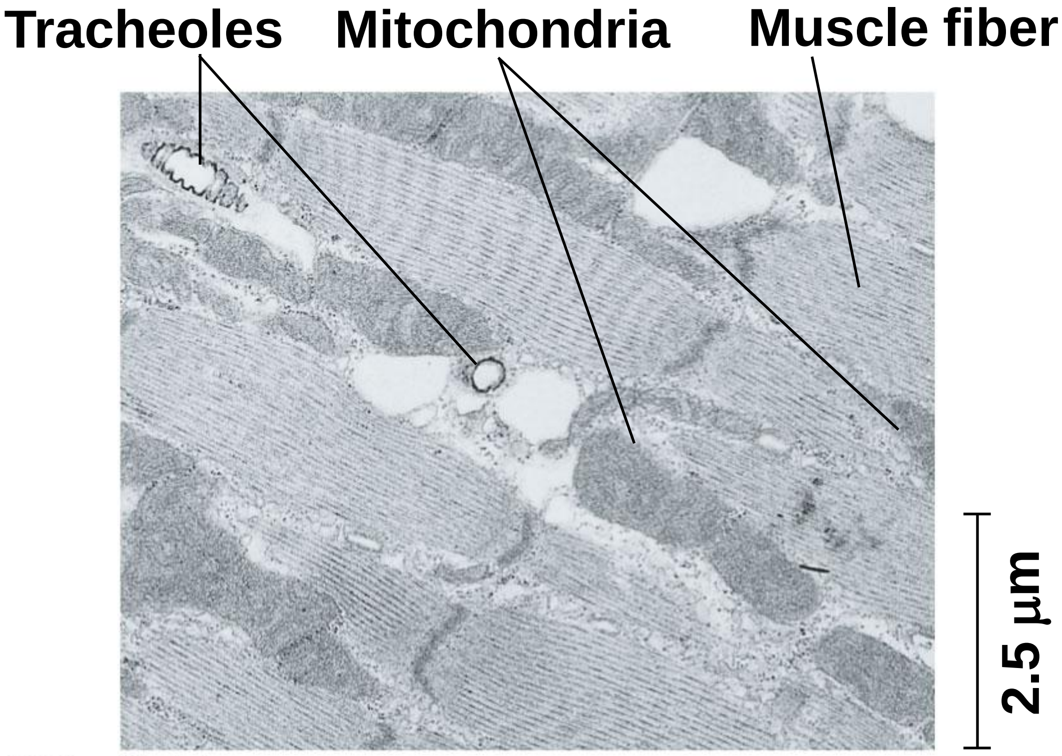
- The **tracheal system** of insects consists of tiny branching tubes that penetrate the body
- The tracheal tubes supply O_2 directly to body cells
- The respiratory and circulatory systems are separate
- Larger insects must ventilate their tracheal system to meet O_2 demands

Figure 42.24



Tracheoles
Mitochondria
Muscle fiber
2.5 µm
Tracheae
Air sacs
External opening
Body cell
Air sac
Tracheole
Trachea
Air

Figure 42.24a



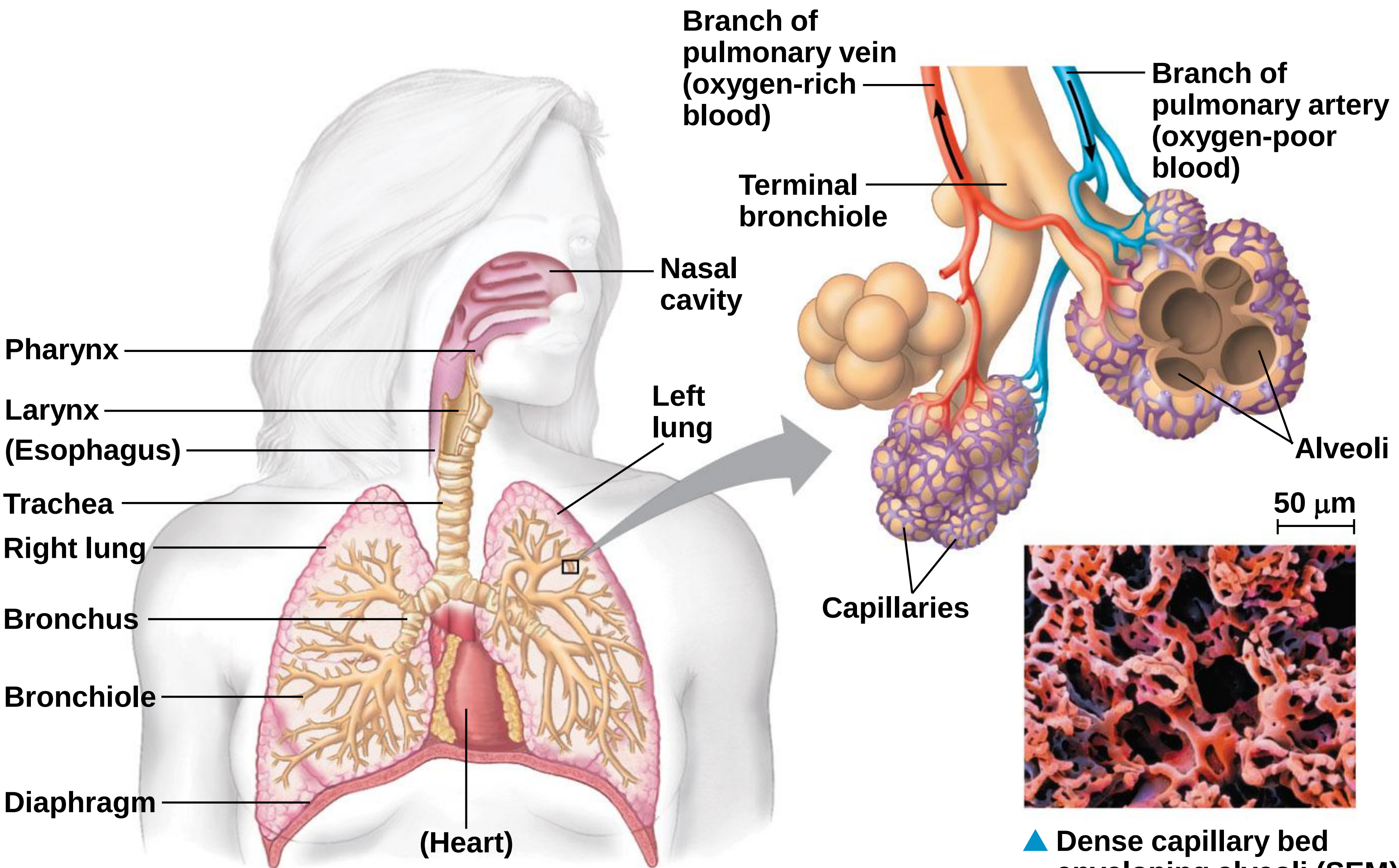
Lungs

- **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 is warmed, humidified, and sampled for odors
- The pharynx directs air to the lungs and food to the stomach
- Swallowing tips the epiglottis over the glottis in the pharynx to prevent food from entering the **trachea**

Figure 42.25



Dense capillary bed enveloping alveoli (SEM)

Figure 42.25a

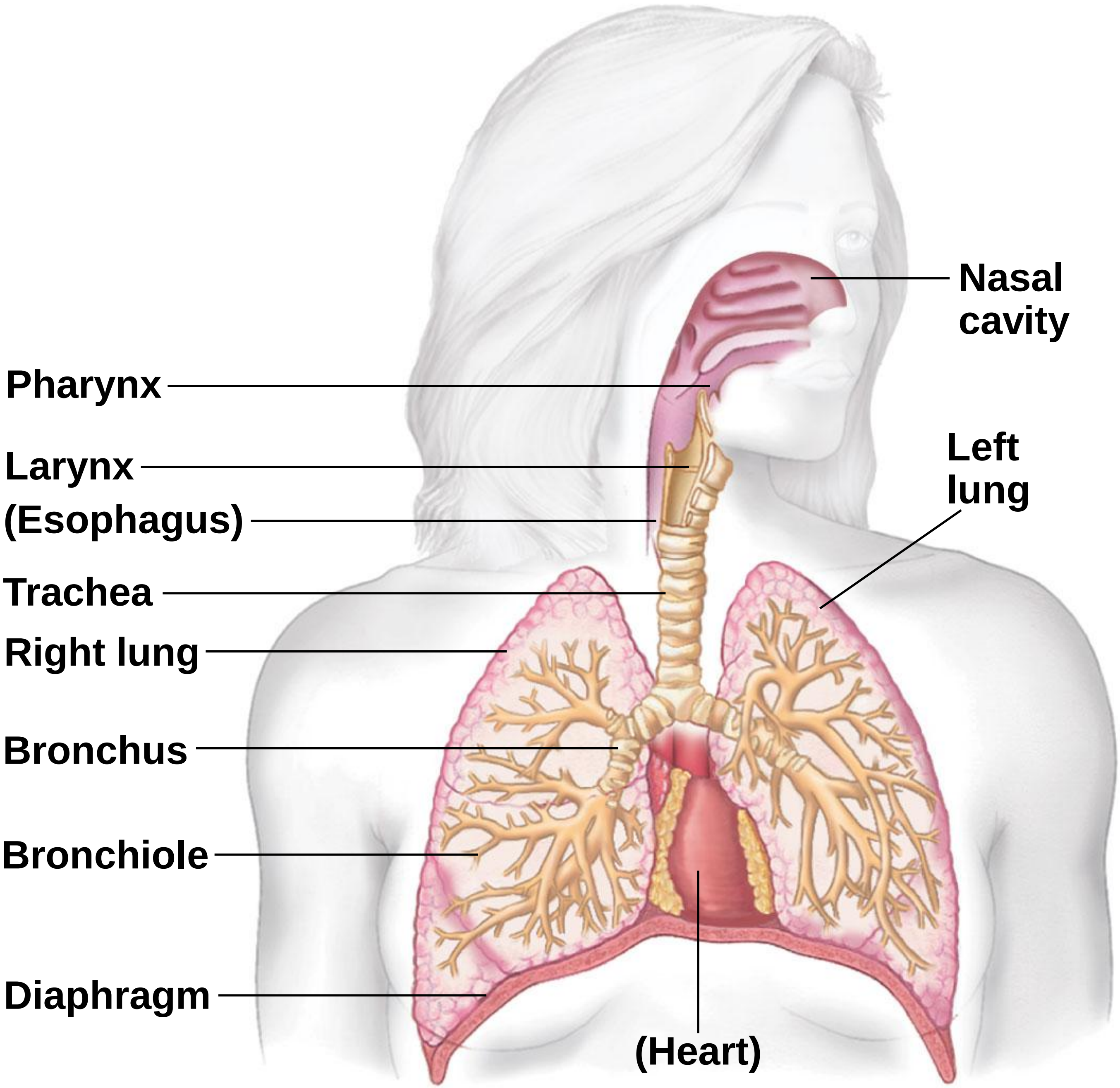


Figure 42.25b

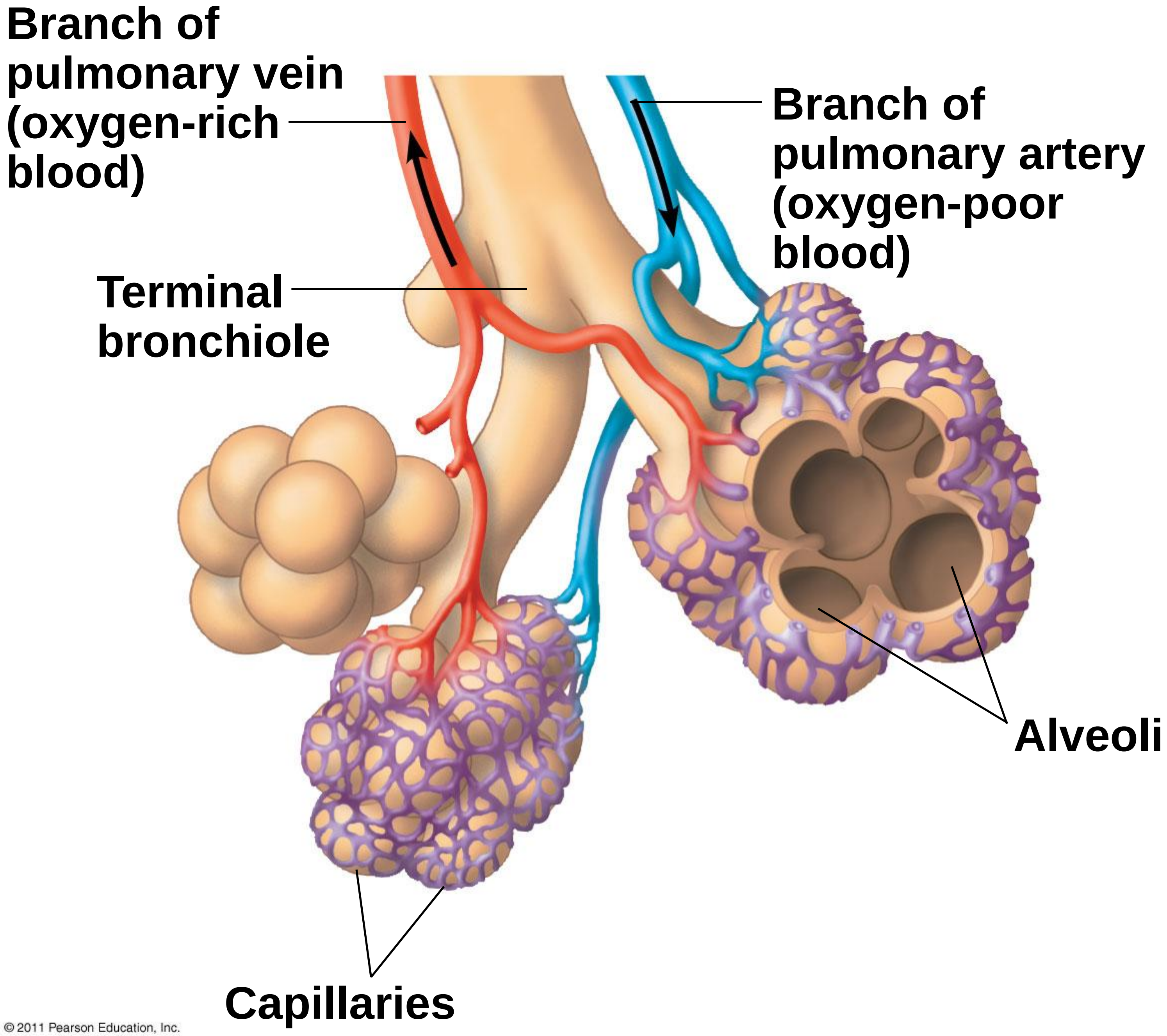
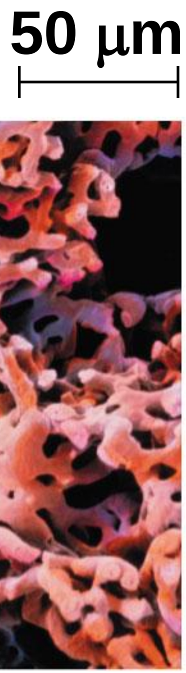


Figure 42.25c



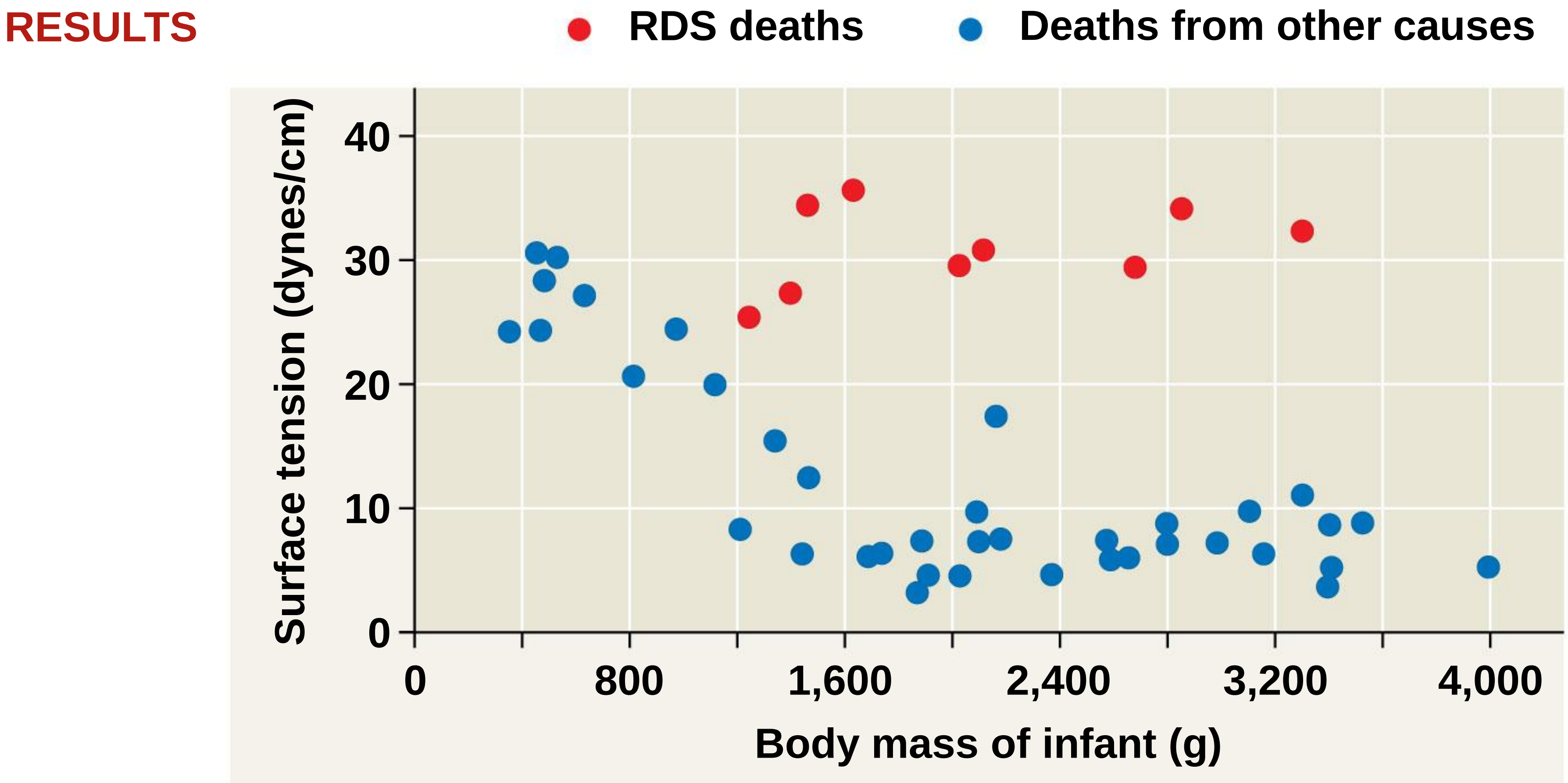
Dense capillary bed enveloping alveoli (SEM)

- Air passes through the pharynx, **larynx**, trachea, **bronchi**, and **bronchioles** to the alveoli, where gas exchange occurs
- Exhaled air passes over the vocal cords in the larynx to create sounds
- Cilia and mucus line the epithelium of the air ducts and move particles up to the pharynx
- This “mucus escalator” cleans the respiratory system and allows particles to be swallowed into the esophagus

- Gas exchange takes place in **alveoli**, air sacs at the tips of bronchioles
- Oxygen diffuses through the moist film of the epithelium and into capillaries
- Carbon dioxide diffuses from the capillaries across the epithelium and into the air space

- Alveoli lack cilia and are susceptible to contamination
- Secretions called **surfactants** coat the surface of the alveoli
- Preterm babies lack surfactant and are vulnerable to respiratory distress syndrome; treatment is provided by artificial surfactants

Figure 42.26


RESULTS
RDS deaths
Deaths from other causes
Surface tension (dynes/cm)
40
30
20
10
0
0
800
1,600
2,400
3,200
4,000
Body mass of infant (g)

Concept 42.6: Breathing ventilates the lungs

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

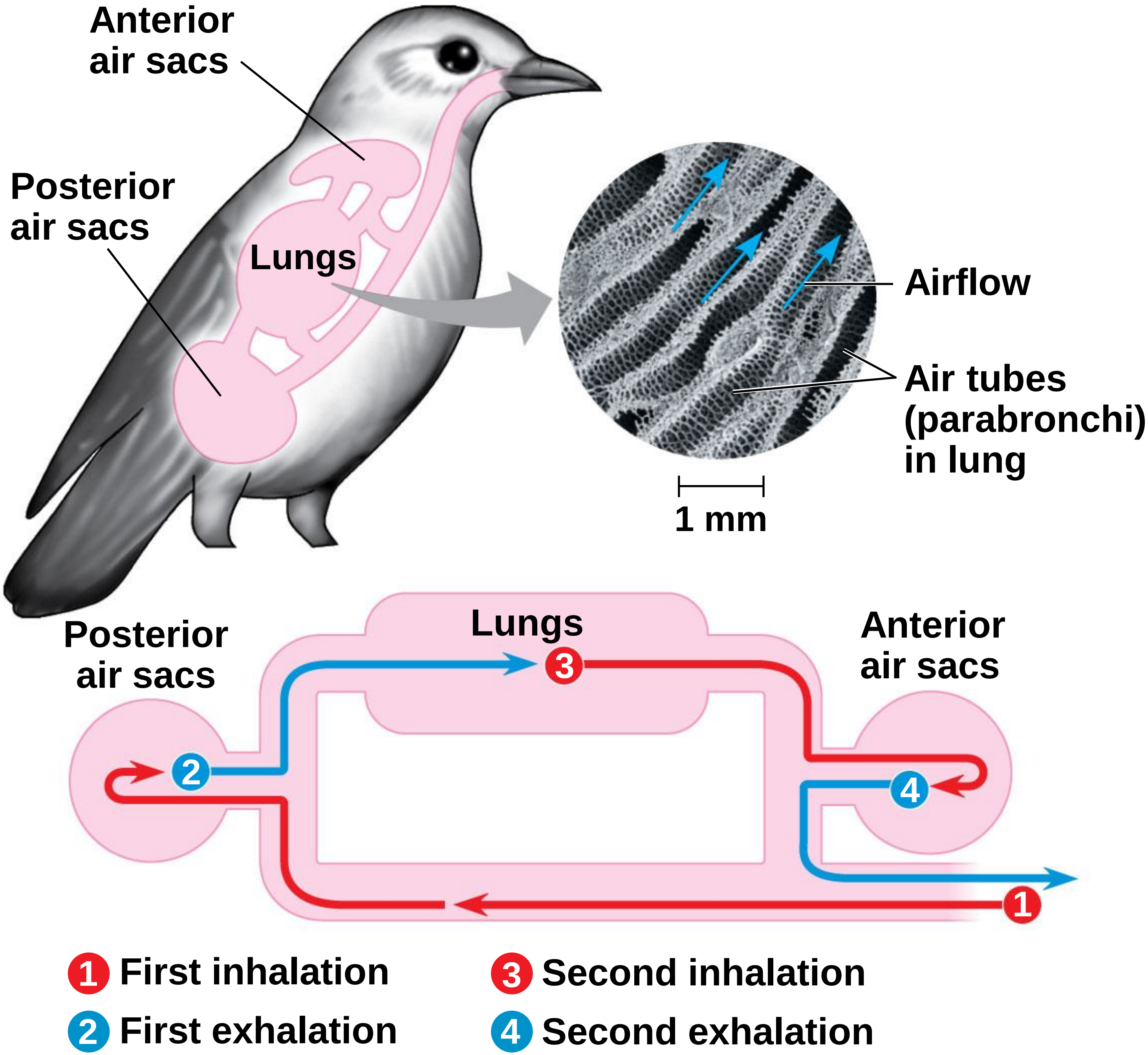
How an Amphibian Breathes

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

How a Bird Breathes

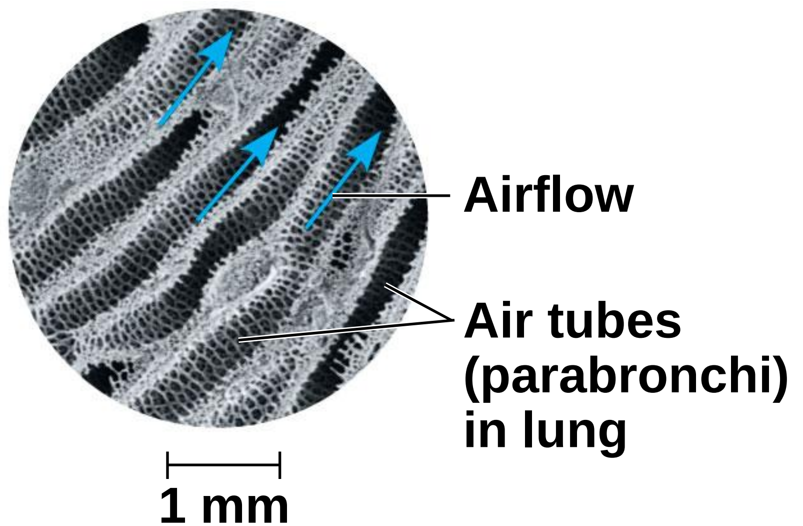
- Birds have eight or nine air sacs that function as bellows that keep air flowing through the lungs
- Air passes through the lungs in one direction only
- Every exhalation completely renews the air in the lungs

Figure 42.27



Anterior air sacs
Posterior air sacs
Lungs
Airflow
Air tubes (parabronchi) in lung
1 mm
Posterior air sacs
Lungs
Anterior air sacs
1 First inhalation
2 First exhalation
3 Second inhalation
4 Second exhalation

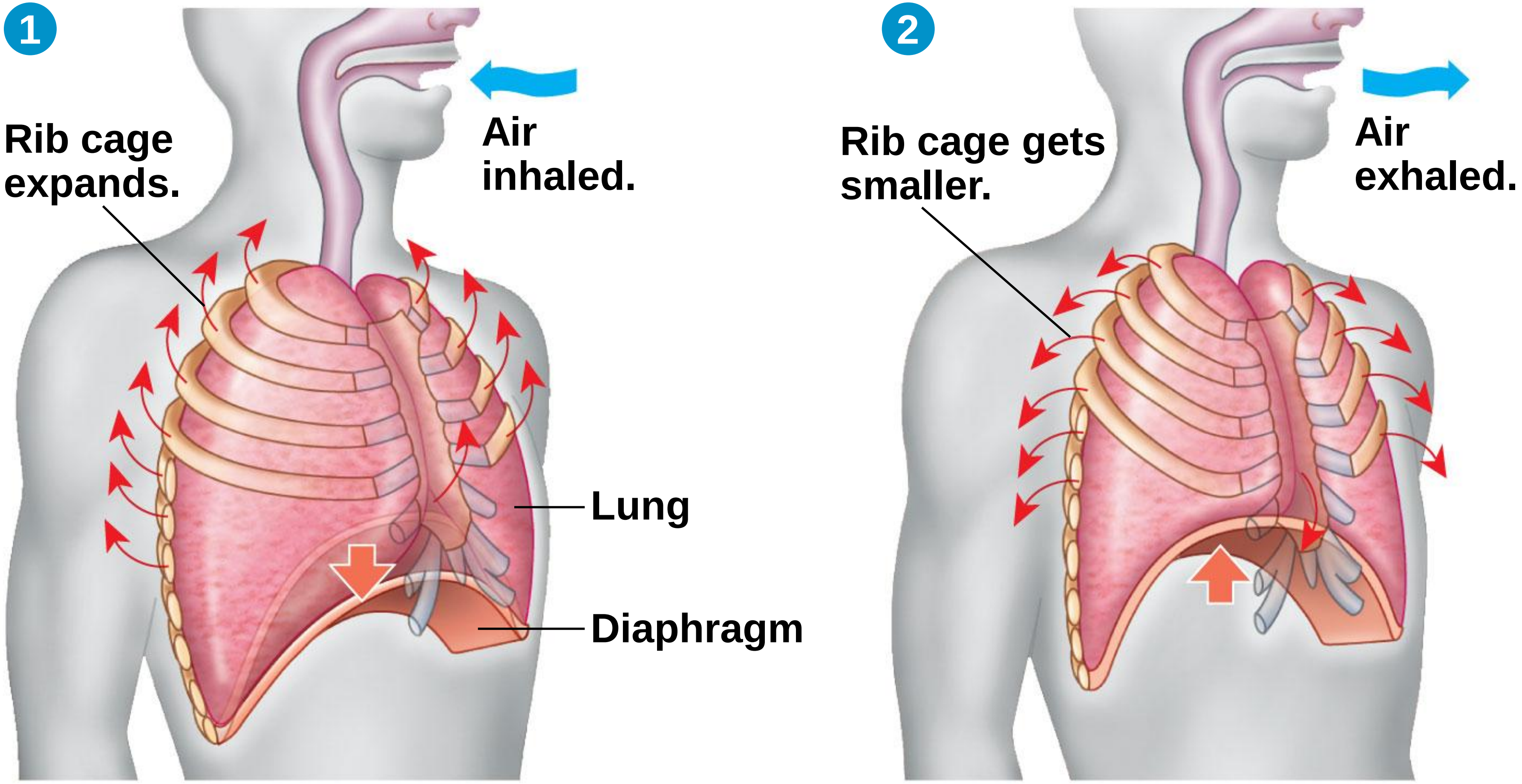
Figure 42.27a



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

Figure 42.28


1
Rib cage expands.
Air inhaled.
Lung
Diaphragm
2
Rib cage gets smaller.
Air exhaled.

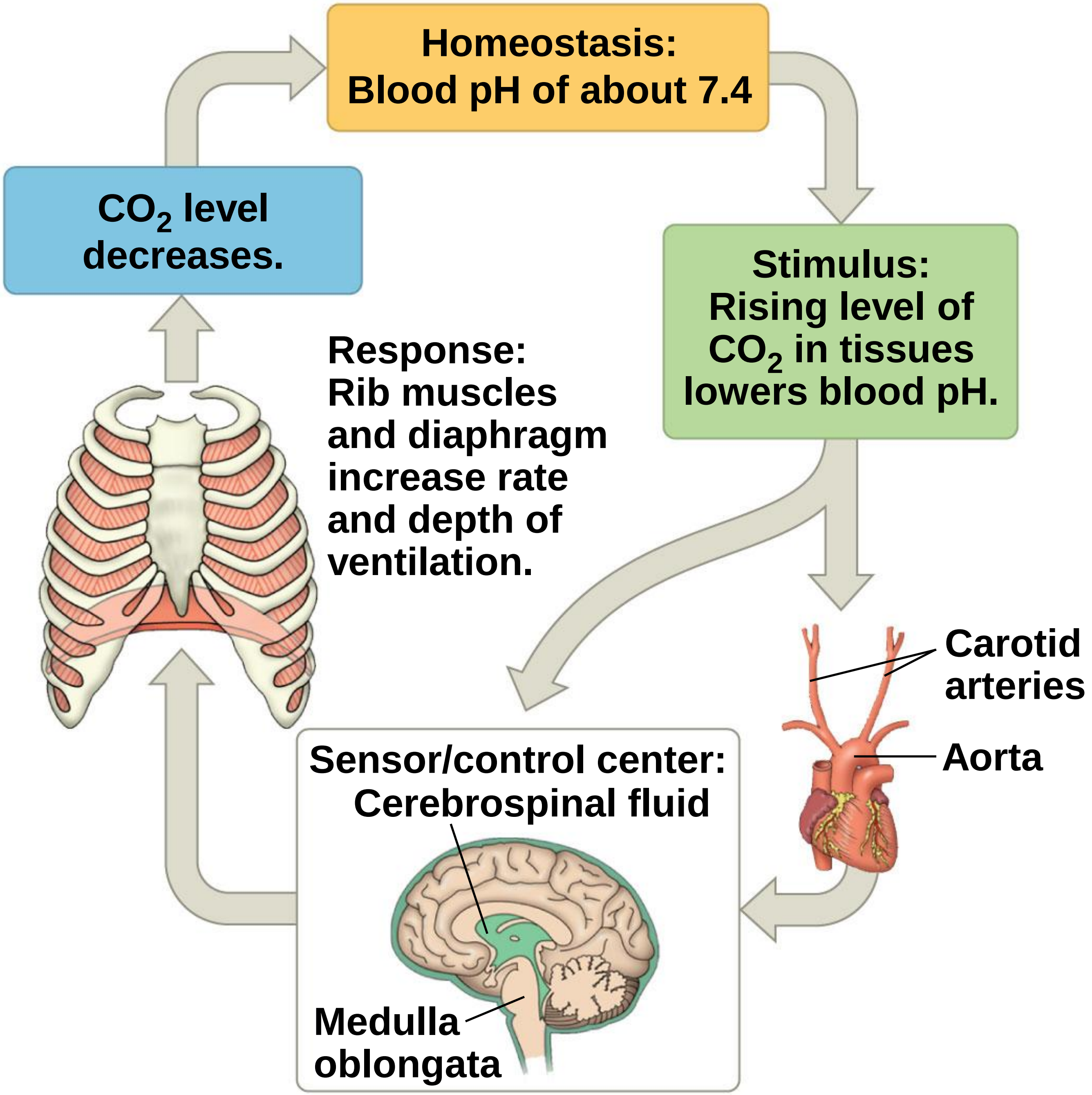
- The maximum tidal volume is the **vital capacity**
- After exhalation, a **residual volume** of air remains in the lungs

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

Figure 42.29


Homeostasis:
Blood pH of about 7.4
Stimulus:
Rising level of CO_2 in tissues lowers blood pH.
Carotid arteries
Aorta
Sensor/control center:
Cerebrospinal fluid
Medulla oblongata
Response:
Rib muscles and diaphragm increase rate and depth of ventilation.
CO_2 level decreases.

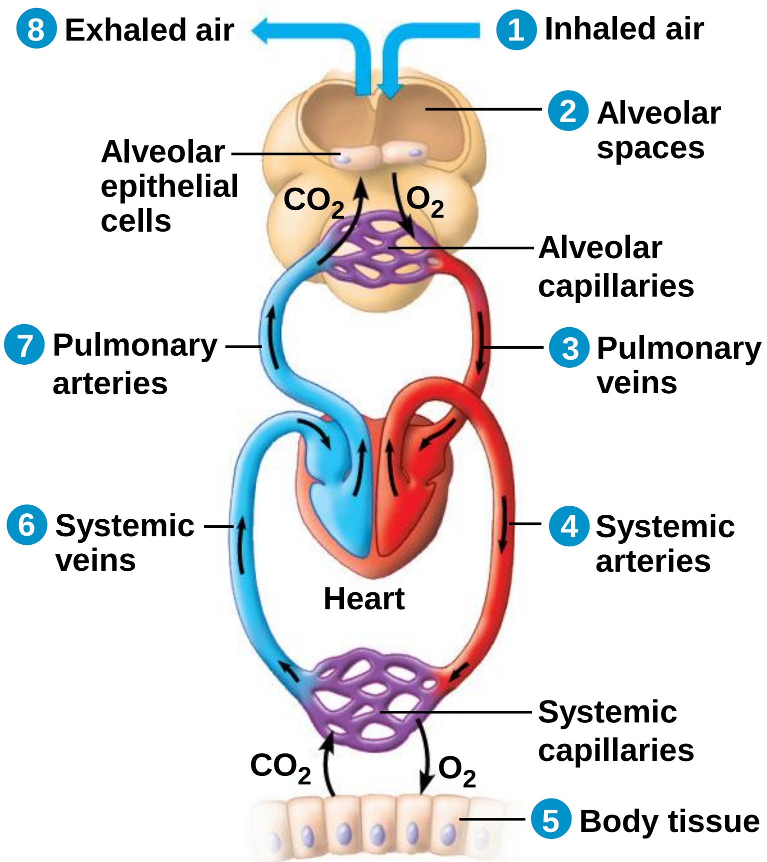
Concept 42.7: Adaptations for gas exchange include pigments that bind and transport gases

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

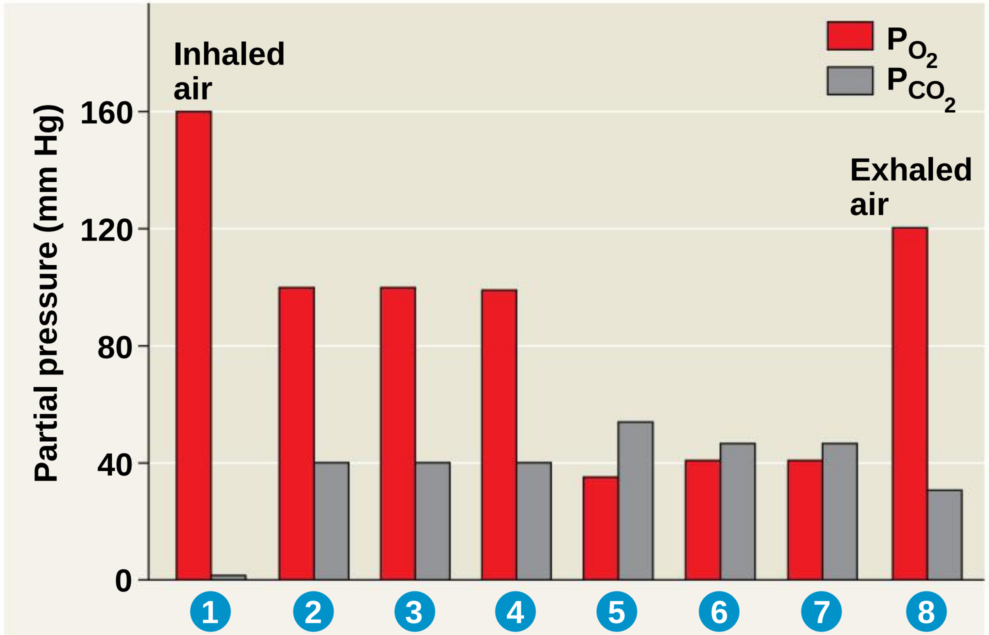
Coordination of Circulation and Gas Exchange

- 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

Figure 42.30

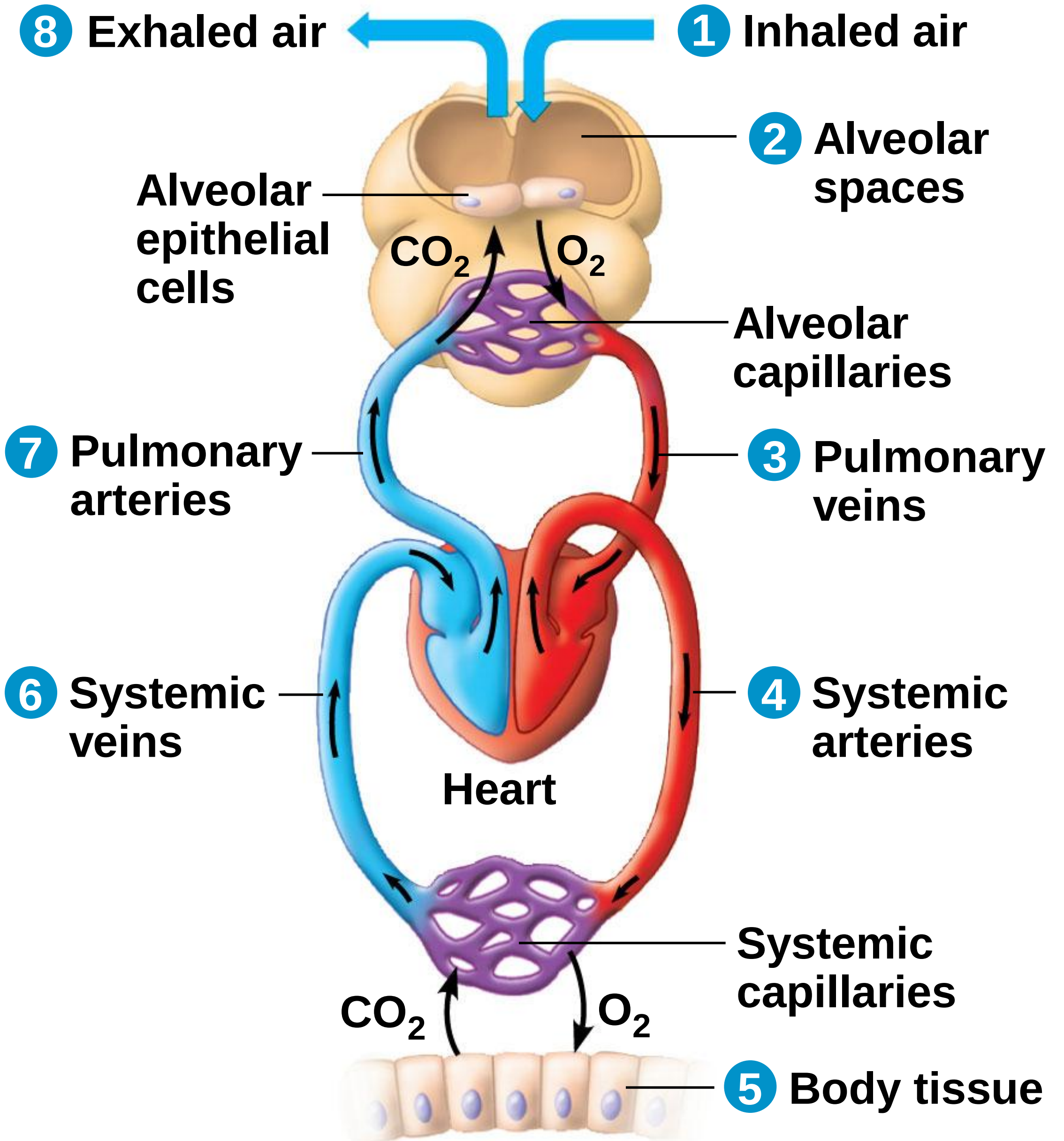


(a) The path of respiratory gases in the circulatory system



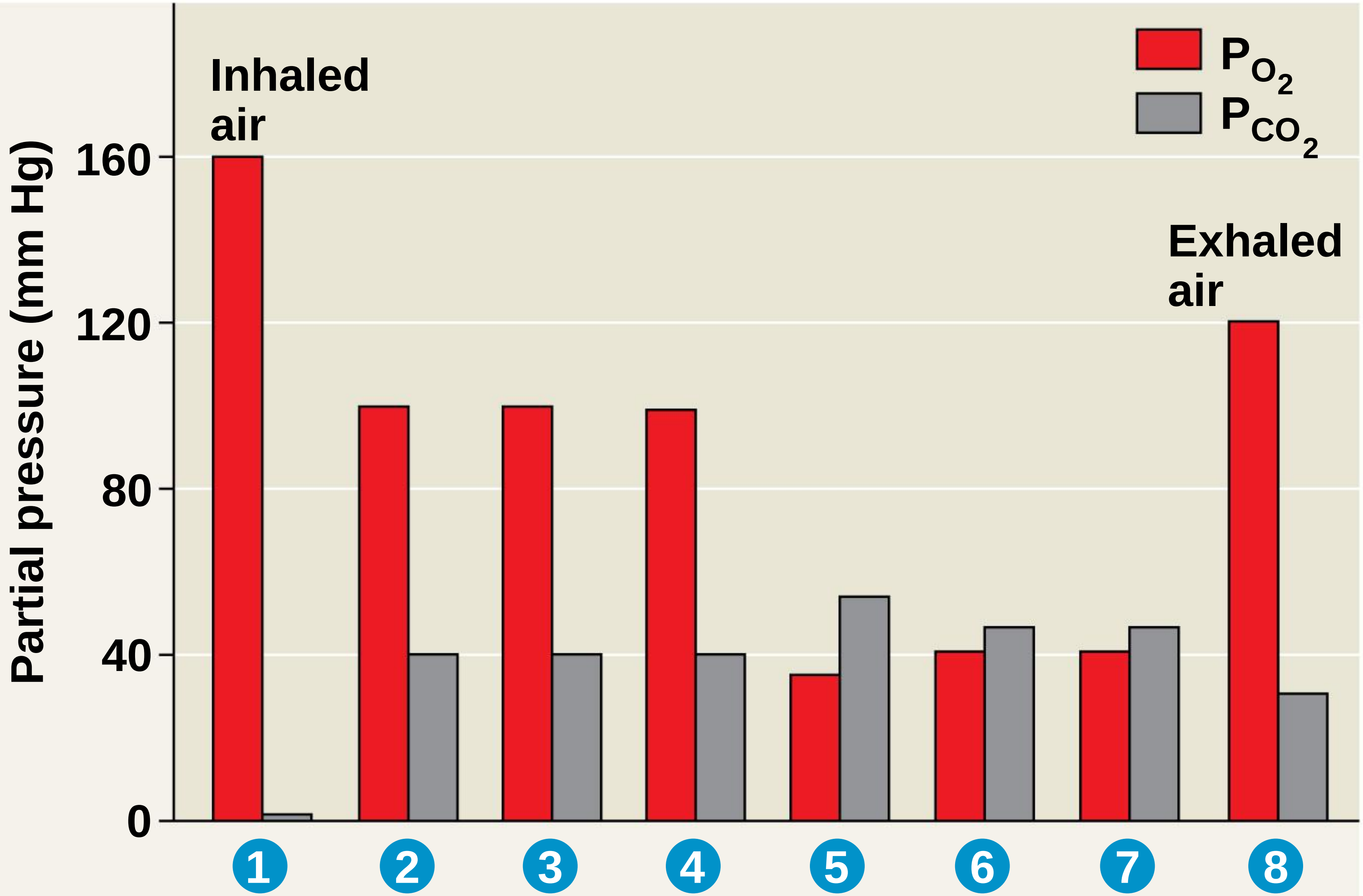
(b) Partial pressure of O_2 and CO_2 at different points in the circulatory system numbered in (a)

Figure 42.30a



(a) The path of respiratory gases in the circulatory system

Figure 42.30b



(b) Partial pressure of O_2 and CO_2 at different points in the circulatory system numbered in (a)

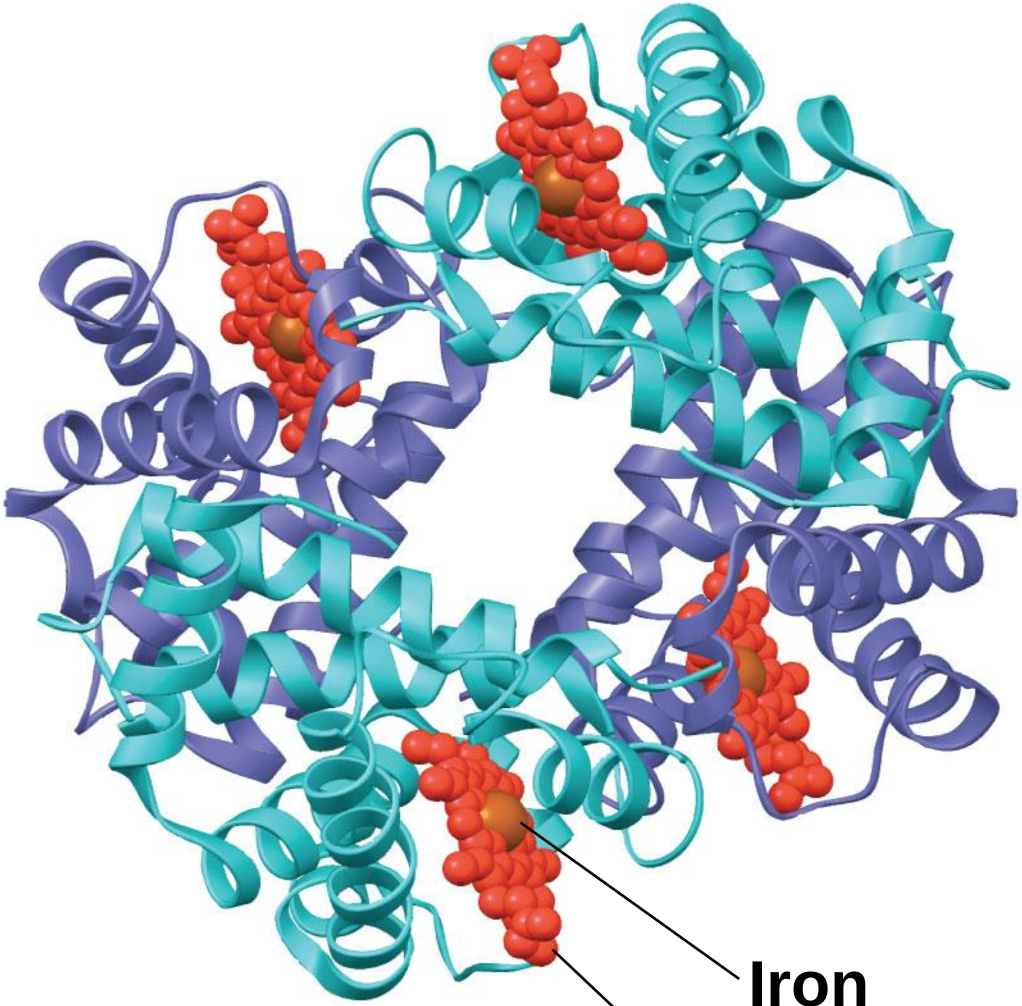
Respiratory Pigments

- **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
- In vertebrates, hemoglobin is contained within erythrocytes

Hemoglobin

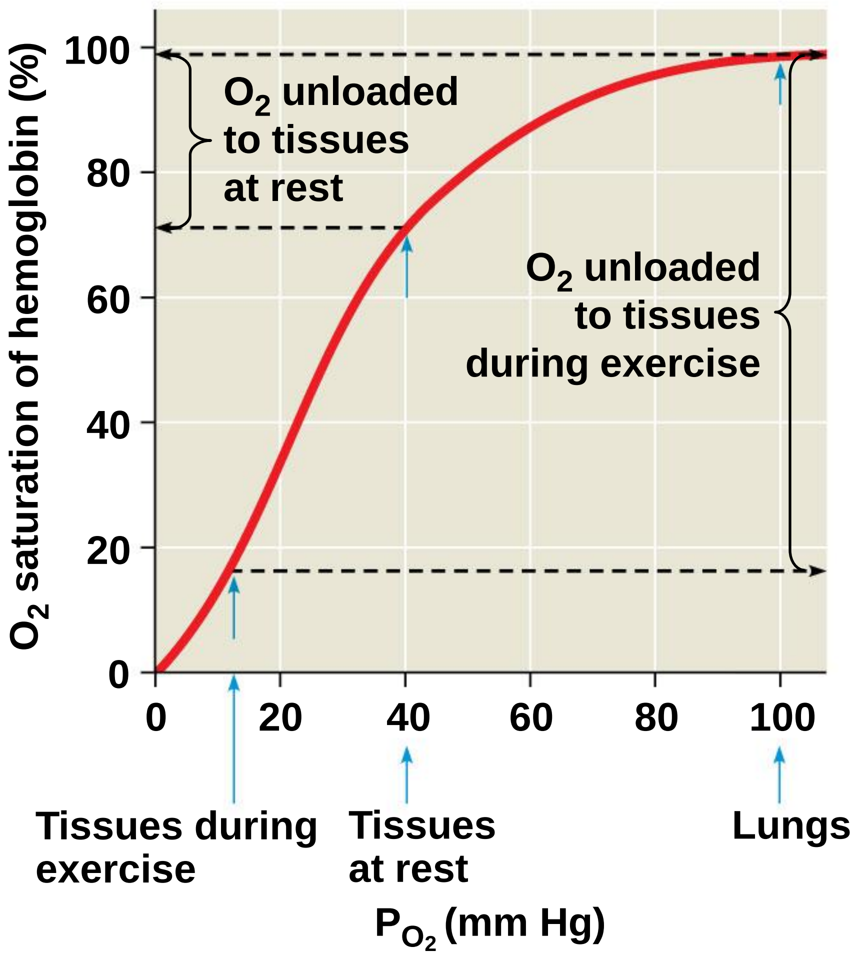
- A single hemoglobin molecule can carry four molecules of O_2, one molecule for each iron containing heme group
- The hemoglobin dissociation curve shows that a small change in the partial pressure of oxygen can result in a large change in delivery of O_2
- CO_2 produced during cellular respiration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

Figure 42.UN01

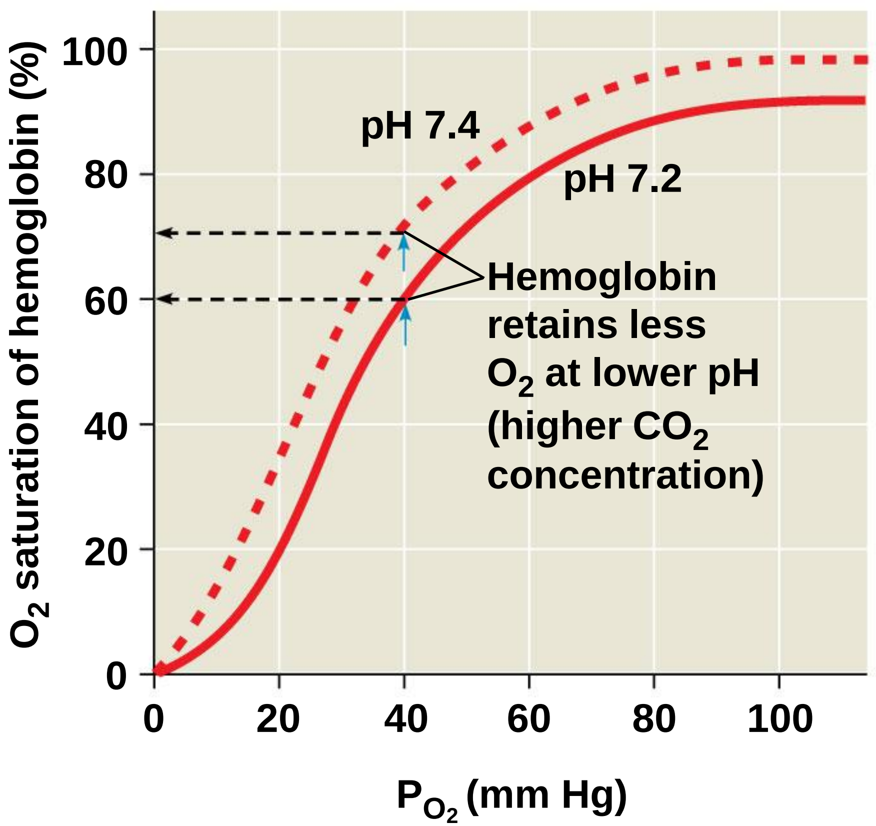


Hemoglobin

Figure 42.31

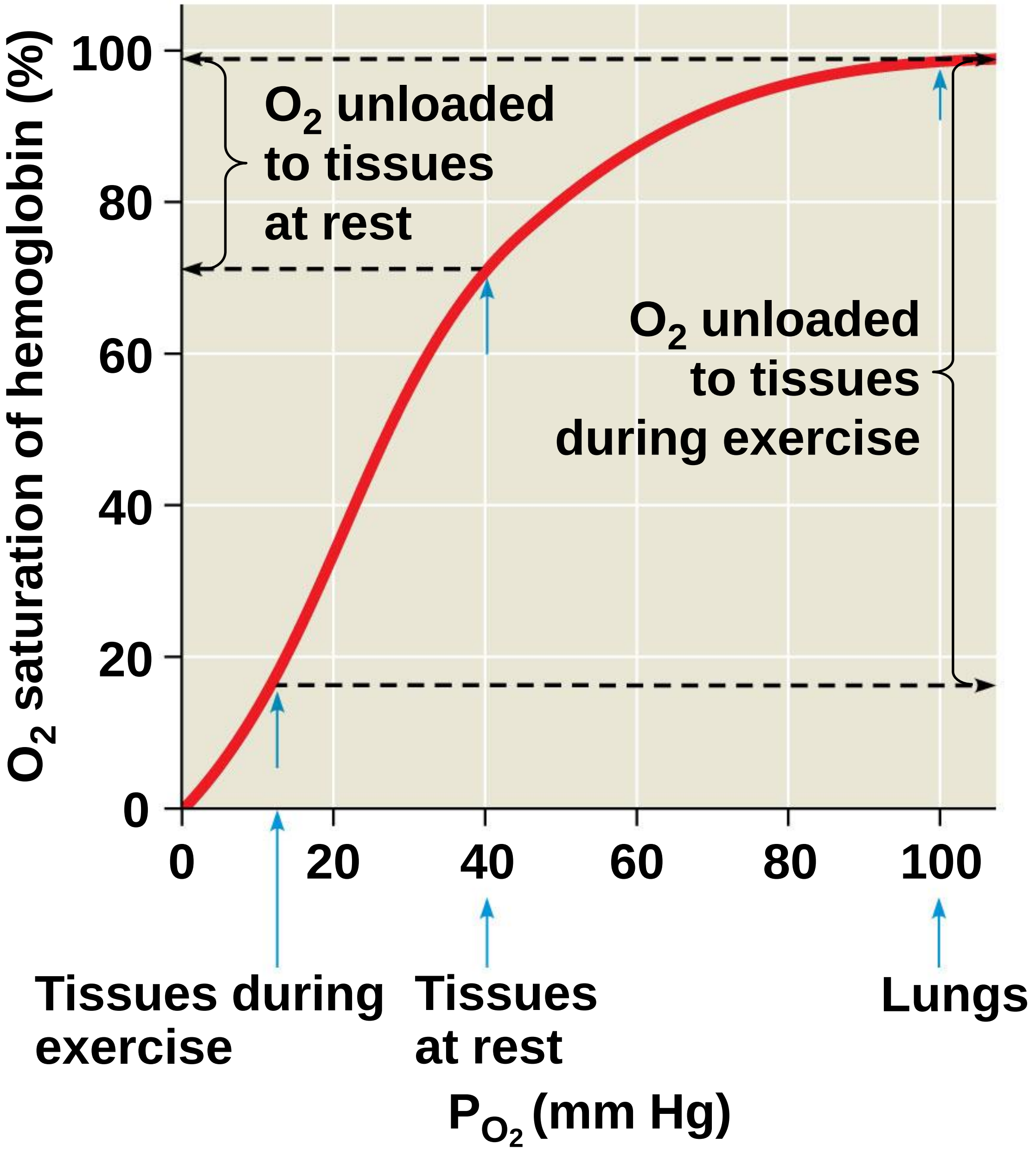


(a) P_{O_2} and hemoglobin dissociation at pH 7.4



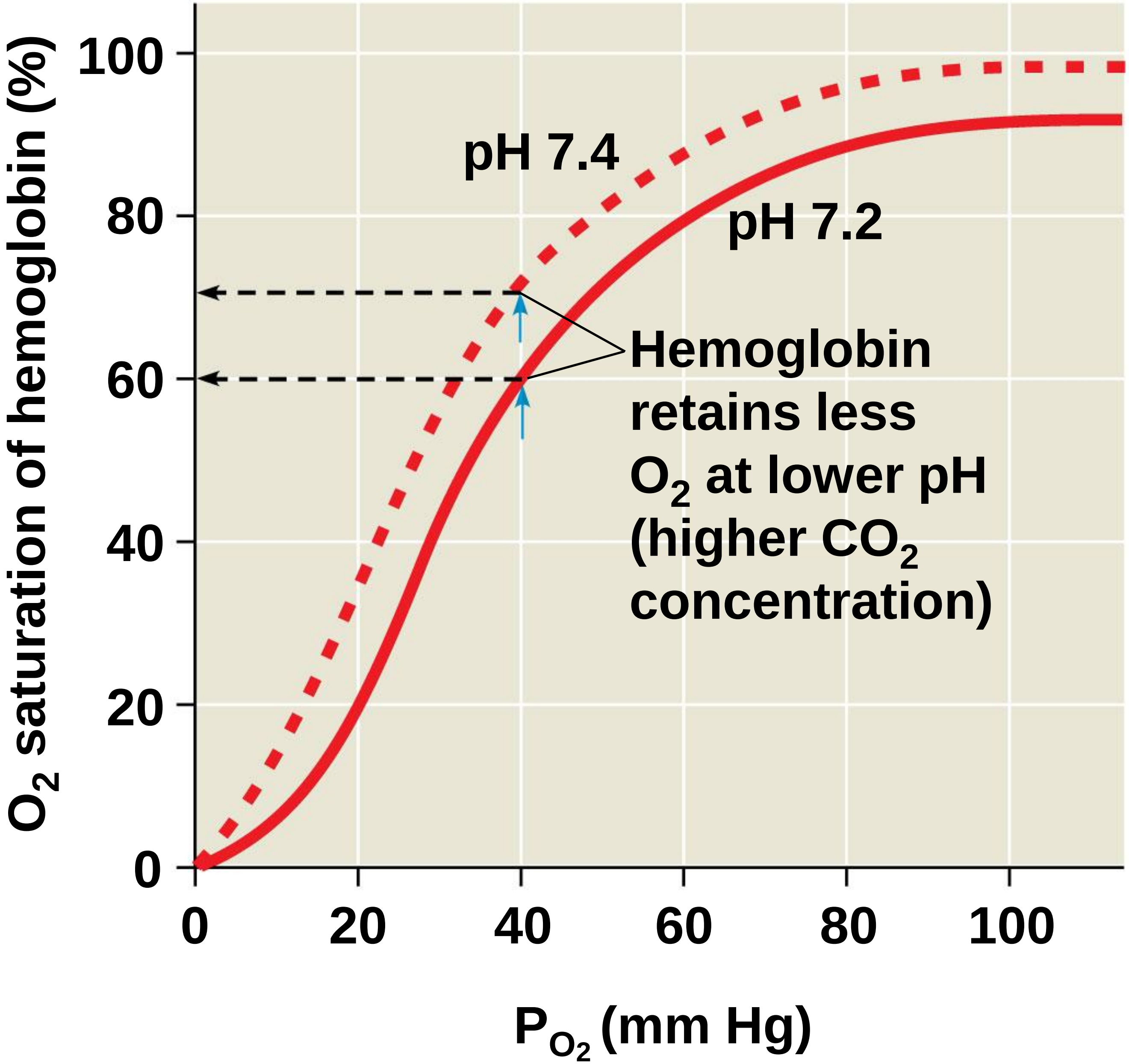
(b) pH and hemoglobin dissociation

Figure 42.31a



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

Figure 42.31b



(b) pH and hemoglobin dissociation

Carbon Dioxide Transport

- Hemoglobin also helps transport CO_2 and assists in buffering the blood
- 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^-)

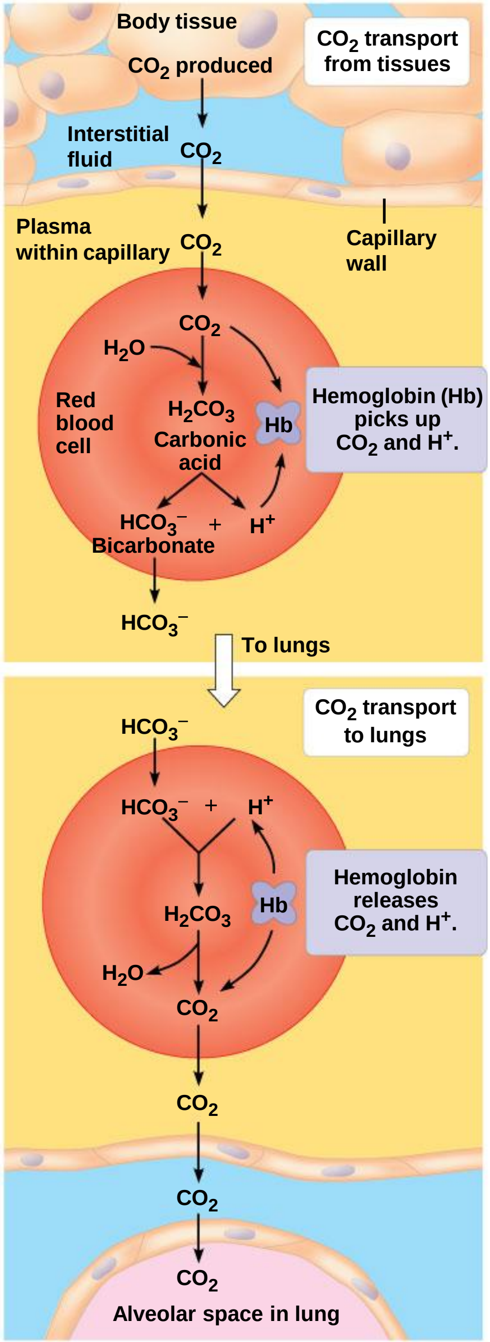
PLAY Animation: O_2 from Blood to Tissues

PLAY Animation: CO_2 from Tissues to Blood

PLAY Animation: CO_2 from Blood to Lungs

PLAY Animation: O_2 from Lungs to Blood

Figure 42.32



Body tissue
CO_2 produced
CO_2 transport from tissues
Interstitial fluid
CO_2
Plasma within capillary
CO_2
Capillary wall
CO_2
H_2O
Red blood cell
H_2CO_3
Carbonic acid
Hb
Hemoglobin (Hb) 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

Figure 42.32a

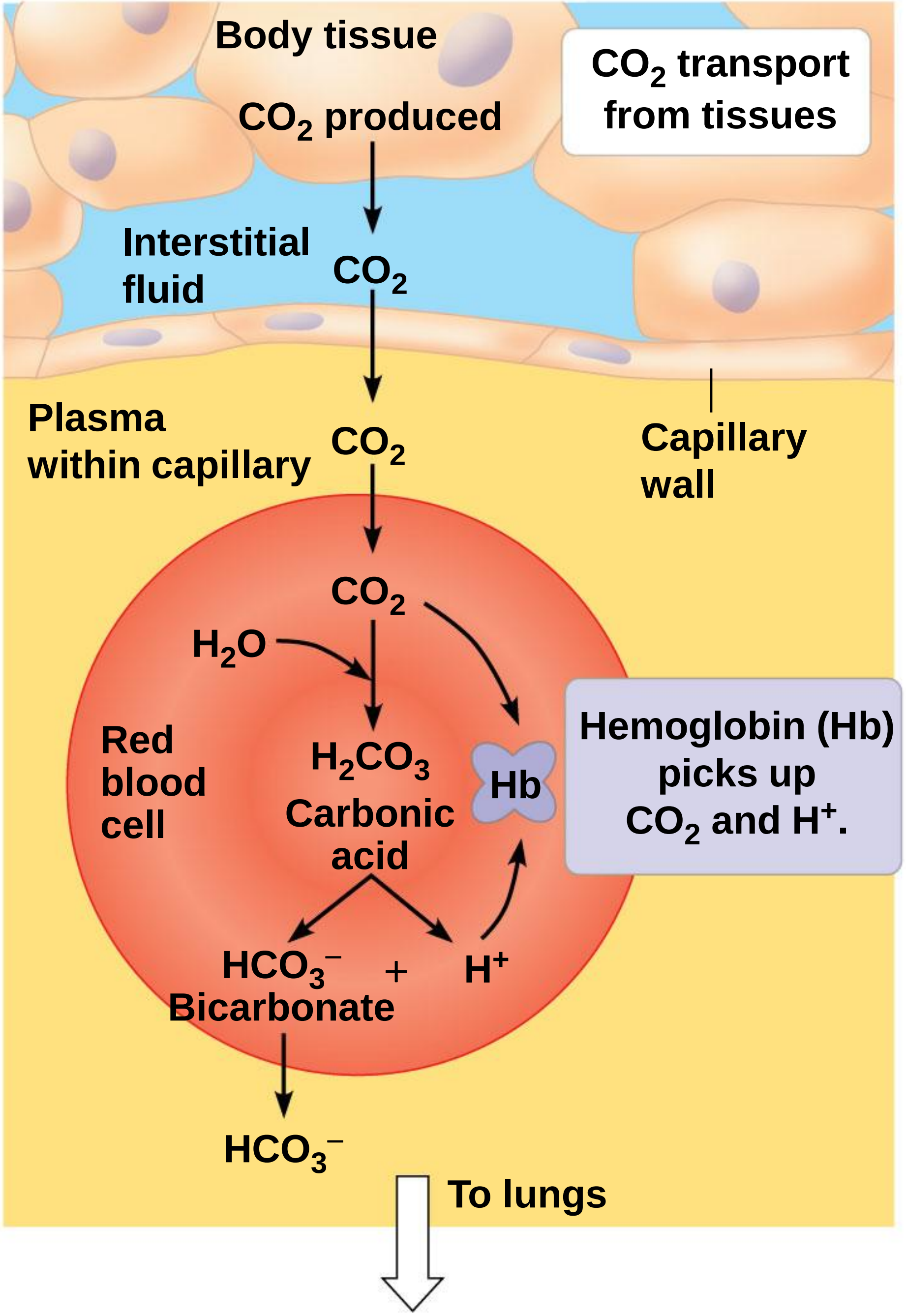
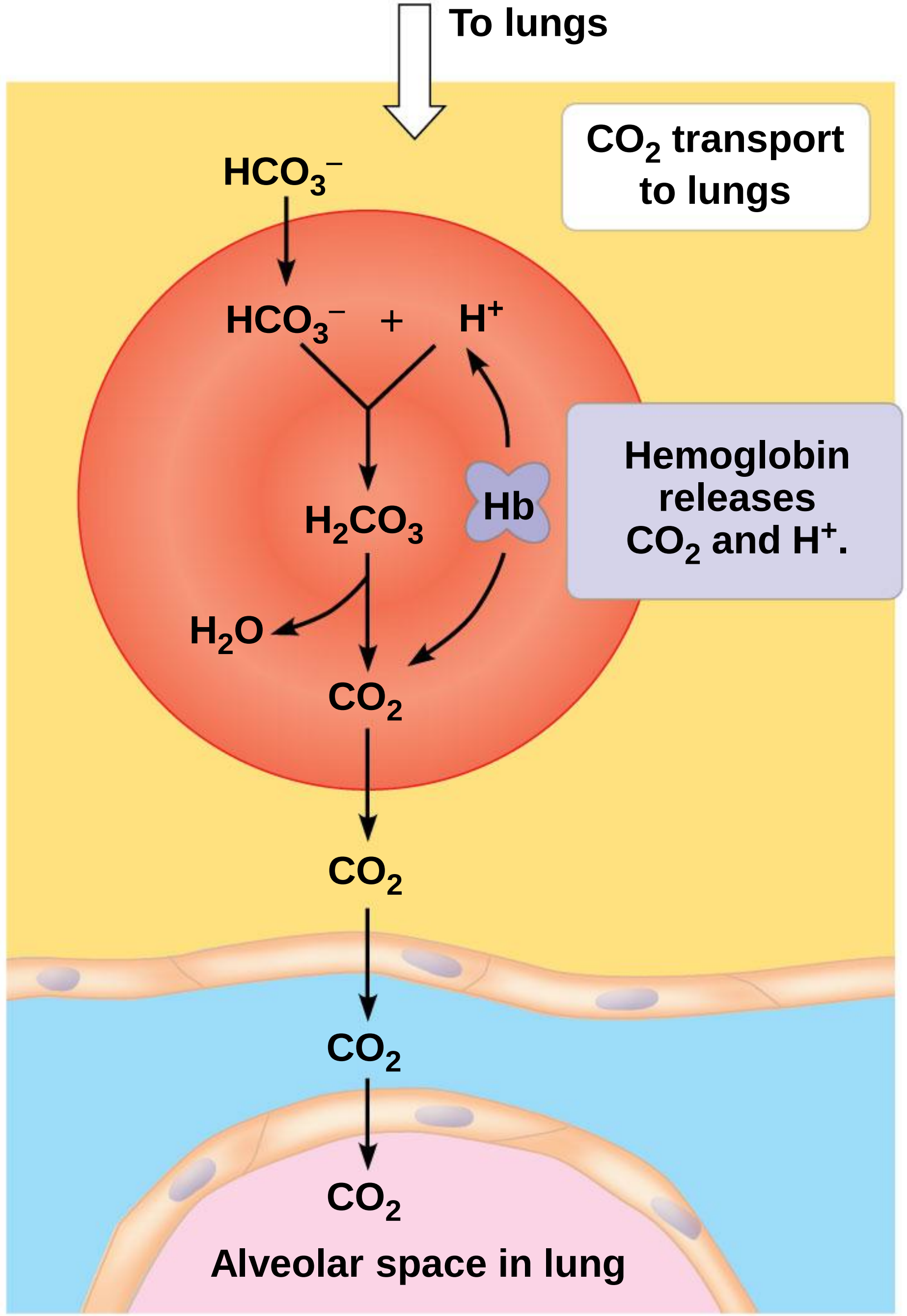


Figure 42.32b



Respiratory Adaptations of Diving Mammals

- Diving mammals have evolutionary adaptations that allow them to perform extraordinary feats
  – For example, Weddell seals in Antarctica can remain underwater for 20 minutes to an hour
  – For example, elephant seals can dive to 1,500 m and remain underwater for 2 hours
- These animals have a high blood to body volume ratio

- Deep-diving air breathers stockpile O_2 and deplete it slowly
- Diving mammals can store oxygen in their muscles in **myoglobin** proteins
- Diving mammals also conserve oxygen by
  - Changing their buoyancy to glide passively
  - Decreasing blood supply to muscles
  - Deriving ATP in muscles from fermentation once oxygen is depleted

Figure 42.UN02

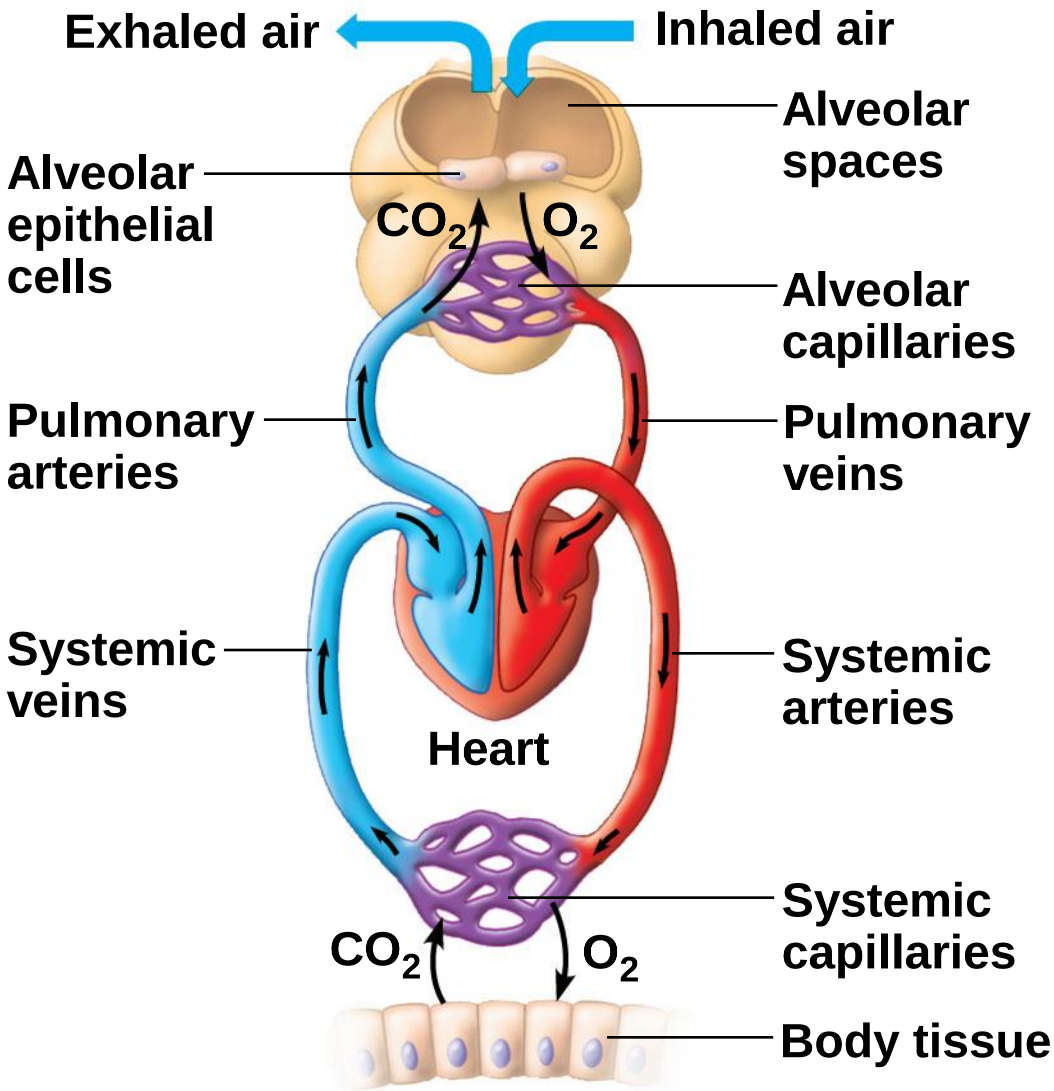


Figure 42.UN03

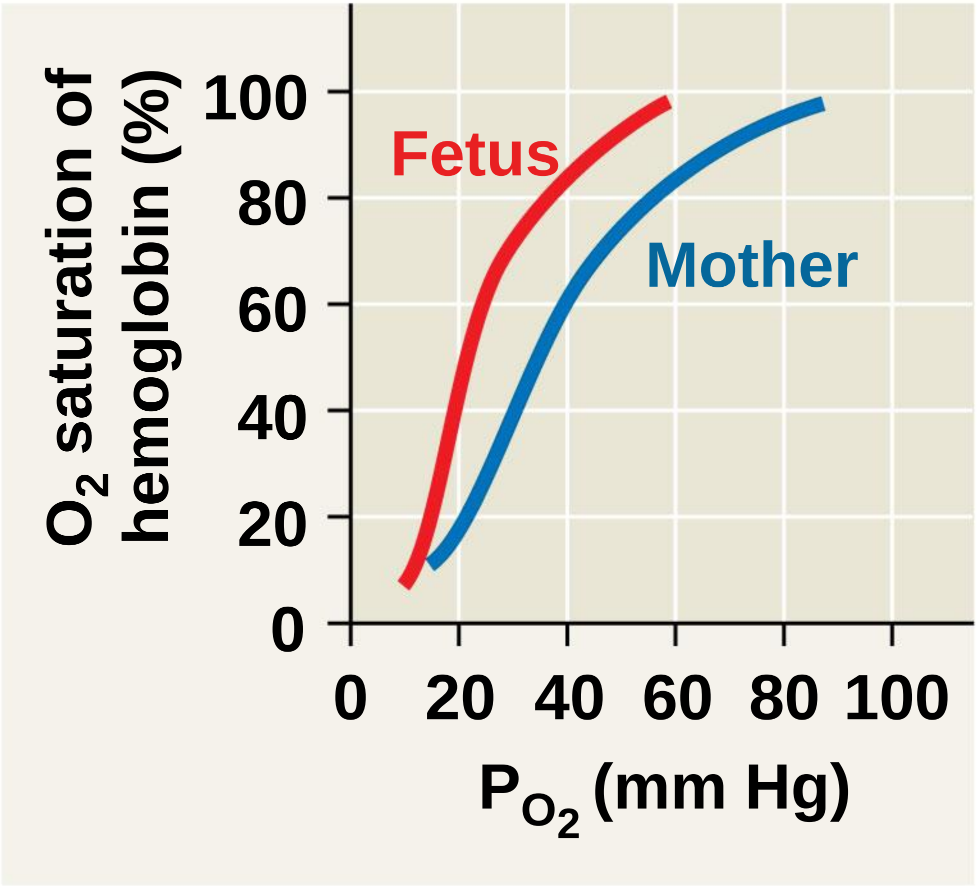


Figure 42.UN04