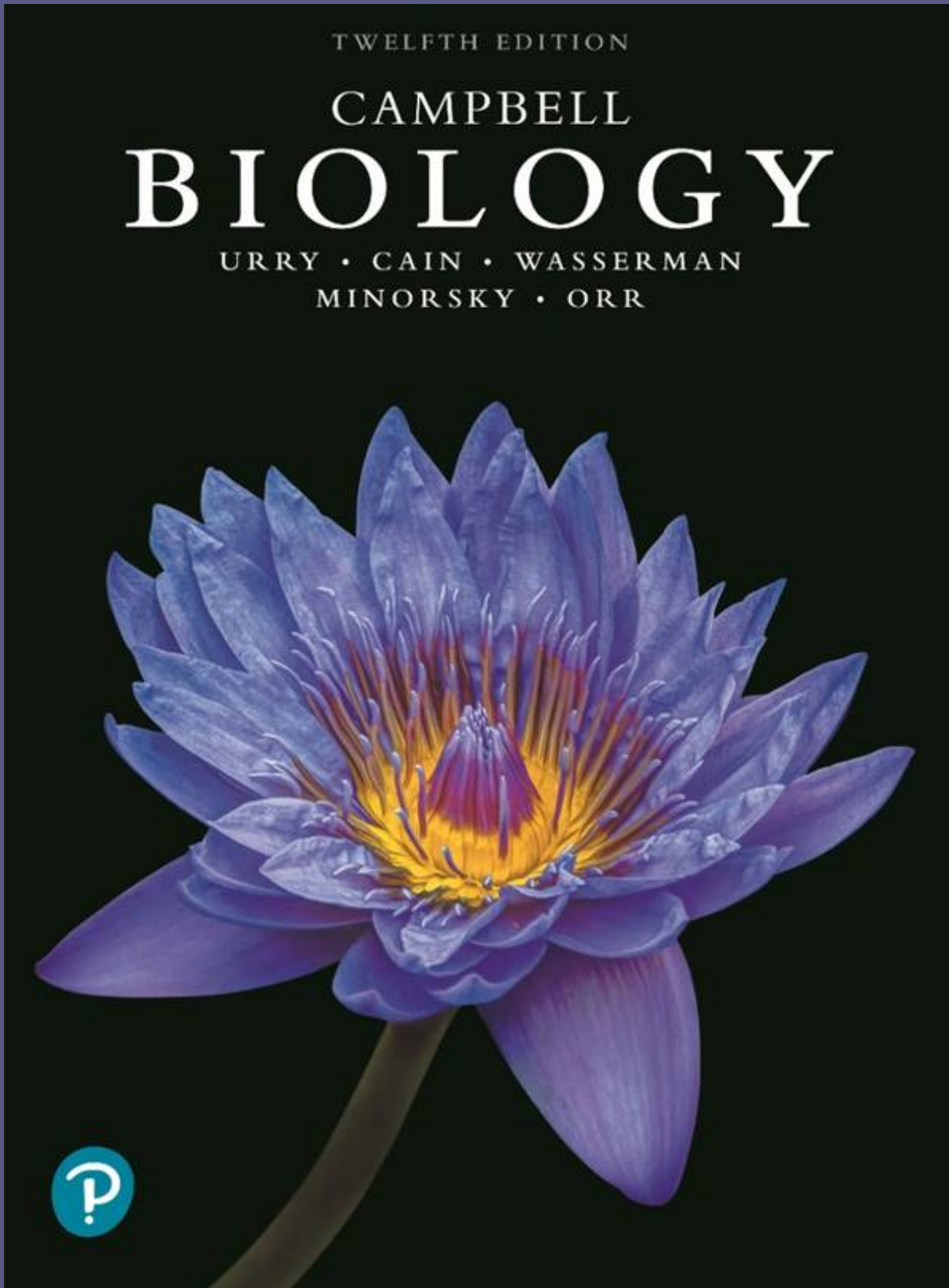


Chapter 42

Circulation and Gas Exchange

Lecture Presentations by
Nicole Tunbridge and
Kathleen Fitzpatrick

Figure 42.1a

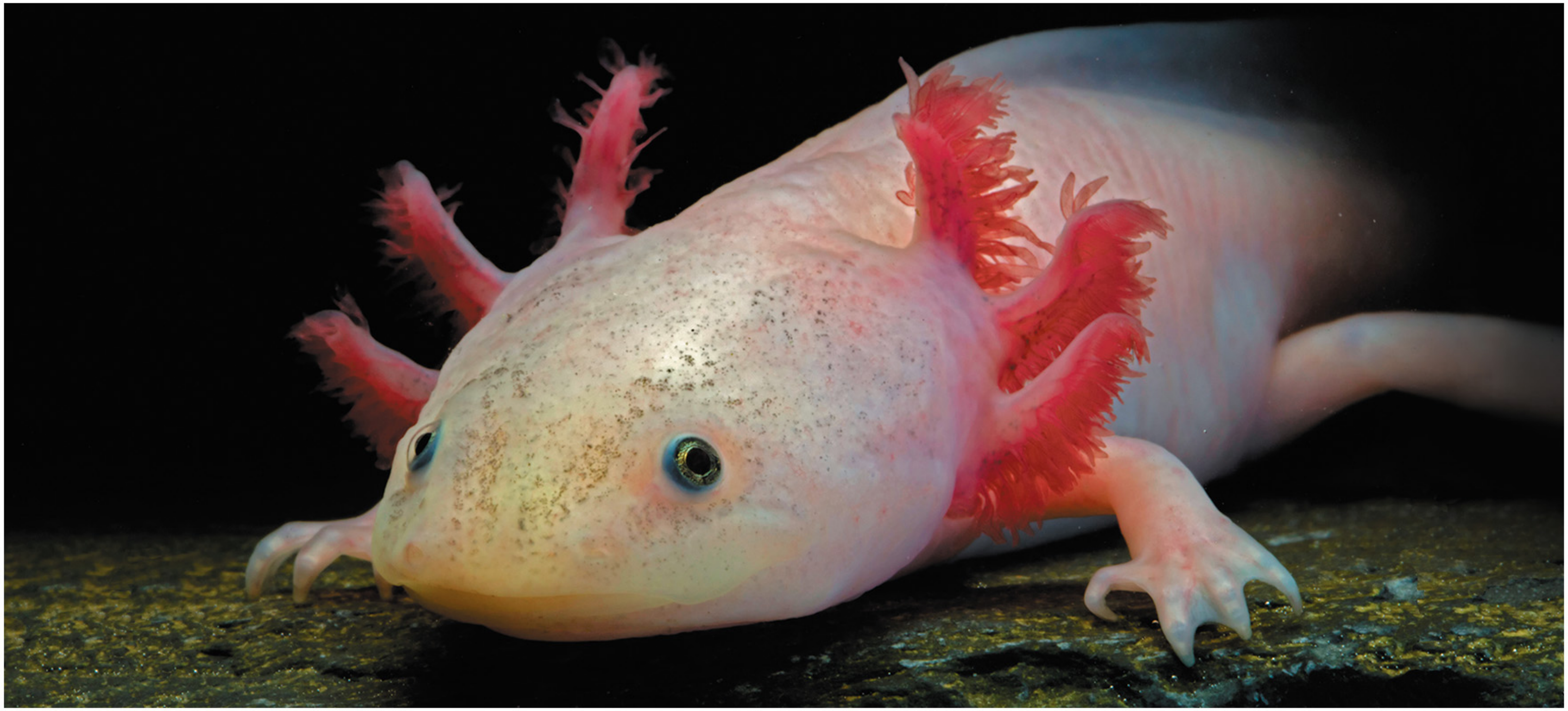
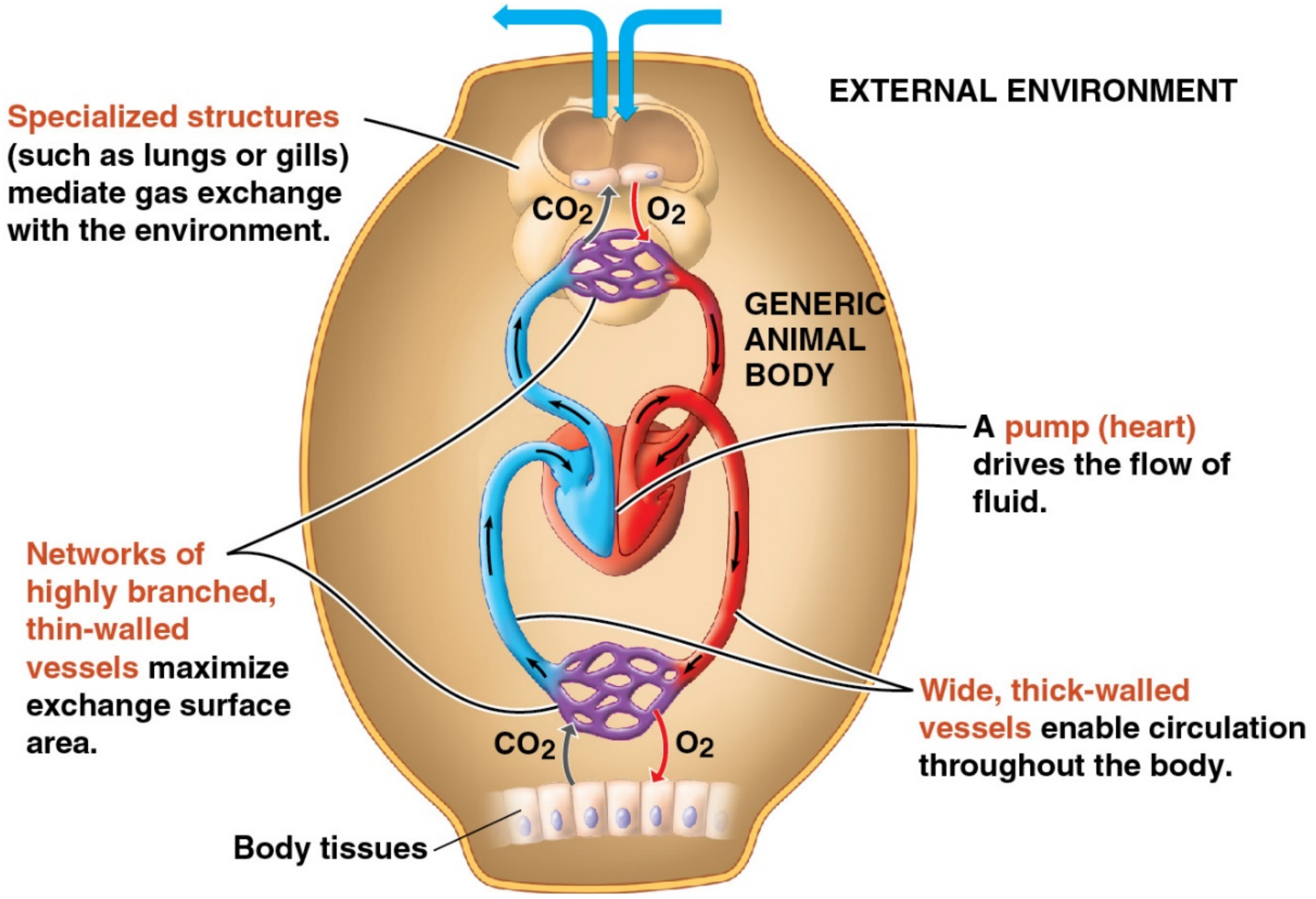


Figure 42.1b

How are structure and function related in the exchange and circulation of oxygen and carbon dioxide?



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

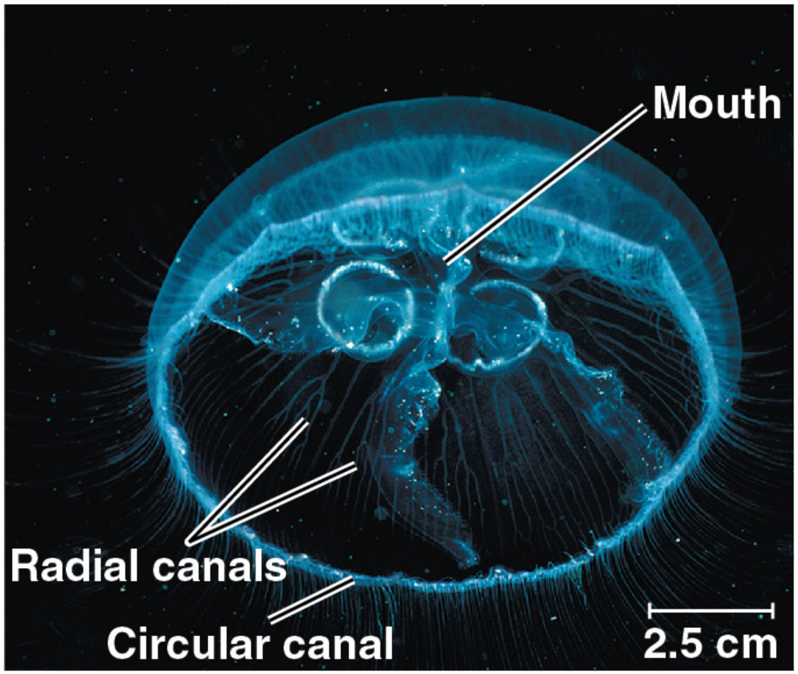
- Small molecules can move between cells and their surroundings by **diffusion**
- Diffusion, random thermal motion, is only efficient over small distances because the time it takes to diffuse is proportional to the square of the distance

- In some animals with a simple body plan, many or all cells are in direct contact with the environment
- In most animals, the circulatory system is functionally linked to the exchange of gases with the environment and with body cells

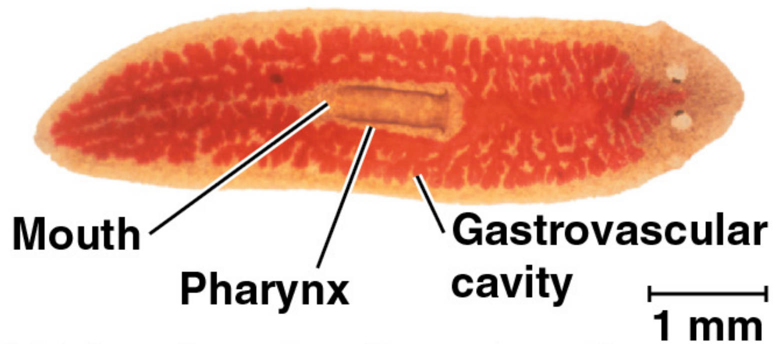
Gastrovascular Cavities

- Some animals lack a circulatory system
- Cnidarians have elaborate **gastrovascular cavities**
- These function in both digestion and distribution of substances throughout the body
- The body wall that encloses the gastrovascular cavity is only two cells thick
- Flatworms have a gastrovascular cavity and a flat body that minimizes diffusion distances

Figure 42.2



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



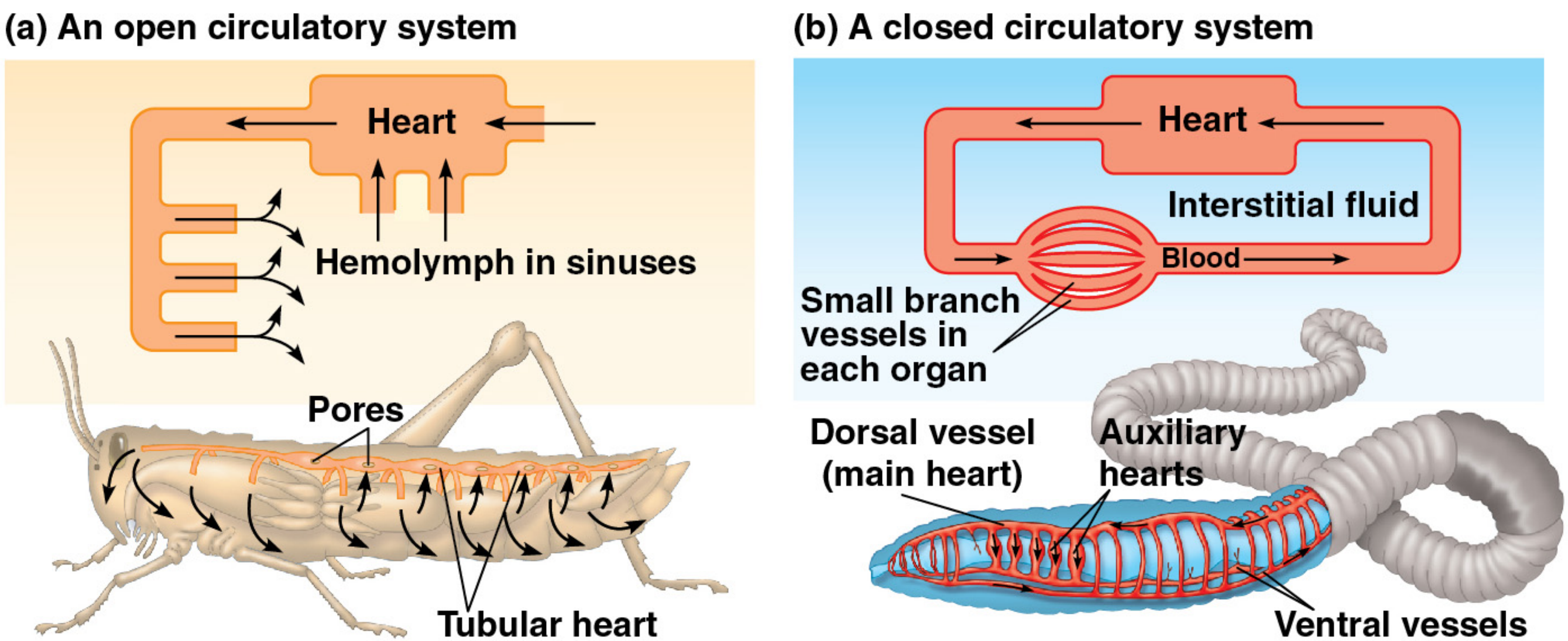
(b) The planarian *Dugesia*, a flatworm

Open and Closed Circulatory Systems

- A circulatory system has
  - A circulatory fluid
  - A set of interconnecting vessels
  - A muscular pump, the **heart**
- The circulatory system connects the fluid that surrounds cells with the organs that exchange gases, absorb nutrients, and dispose of wastes
- Circulatory systems can be open or closed

- In insects, other arthropods, and some molluscs, circulatory fluid called **hemolymph** bathes the organs directly in an **open circulatory system**
- In a **closed circulatory system**, **blood** is confined to vessels and is distinct from the interstitial fluid
- Annelids, cephalopods, and vertebrates have closed circulatory systems

Figure 42.3


(a) An open circulatory system
Heart
Hemolymph in sinuses
Pores
Tubular heart
(b) A closed circulatory system
Heart
Interstitial fluid
Blood
Small branch vessels in each organ
Dorsal vessel (main heart)
Auxiliary hearts
Ventral vessels

- Both open and closed circulatory systems offer evolutionary advantages
- Open systems allow organisms to use less energy than needed in closed systems
- Closed systems allow organisms to grow larger and be more active due to effective delivery of oxygen and nutrients
- Closed systems also regulate the distribution of blood to different organs

Organization of Vertebrate Circulatory Systems

- Humans and other vertebrates have a closed circulatory system called the **cardiovascular system**
- It includes the heart and blood vessels
- The three main types of blood vessels are arteries, veins, and capillaries
- Blood flows only one way in these vessels

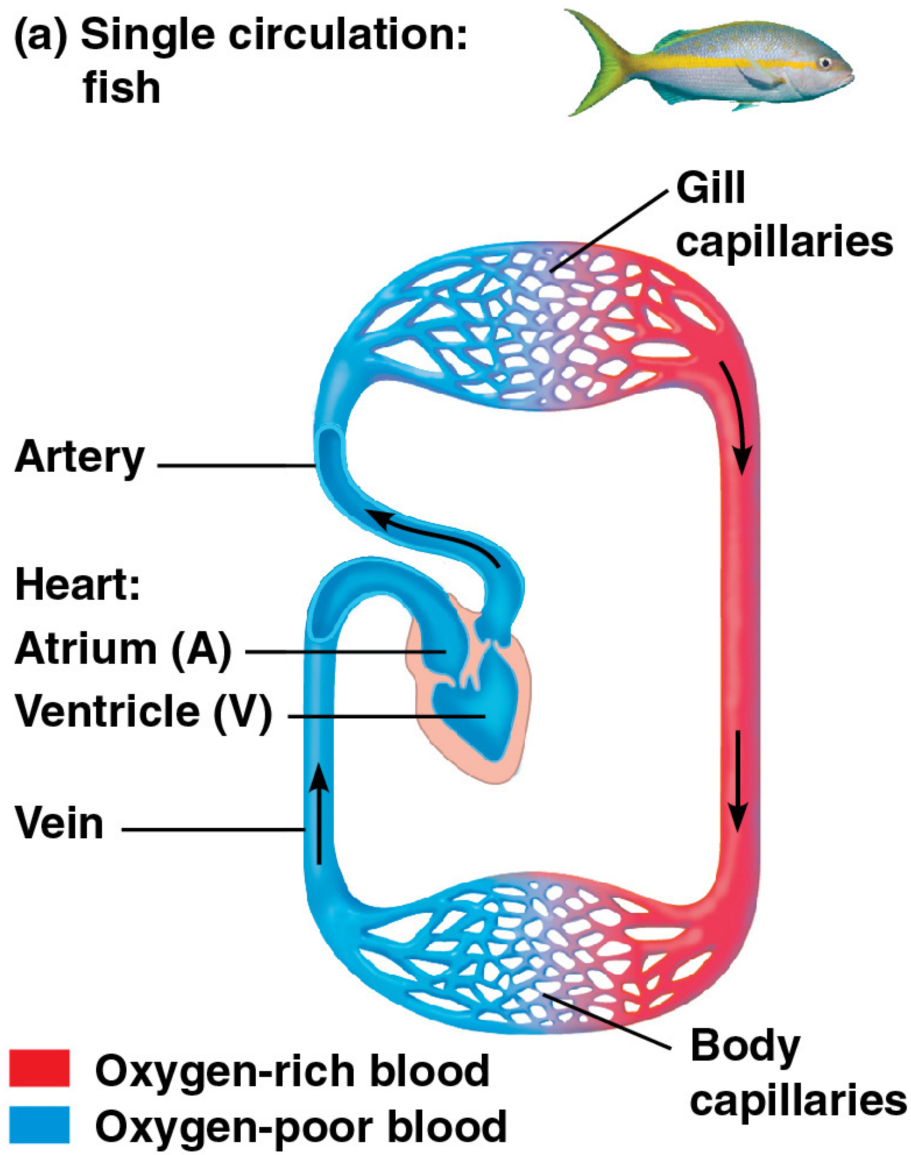
- **Arteries** branch into **arterioles** and carry blood away from the heart to **capillaries**
- Networks of capillaries called **capillary beds** are the sites of chemical exchange between the blood and interstitial fluid
- **Venules** converge into **veins** and return blood from capillaries to the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

- Arteries and veins are distinguished by the direction of blood flow, not by O_2 content
- Vertebrate hearts contain two or more chambers
- Blood enters through **atria** and is pumped out through **ventricles**
- The number of chambers and extent to which they are separated from one another varies greatly among vertebrates

Single Circulation

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

Figure 42.4a


(a) Single circulation: fish
Gill capillaries
Artery
Heart:
Atrium (A)
Ventricle (V)
Vein
Body capillaries
Oxygen-rich blood
Oxygen-poor blood

Double Circulation

- Amphibians, reptiles, and mammals have **double circulation**
- Oxygen-poor blood is pumped from the right side of the heart in one circuit
- Oxygen-rich blood is pumped from the left side of the heart in a separate circuit

- 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

Figure 42.4b

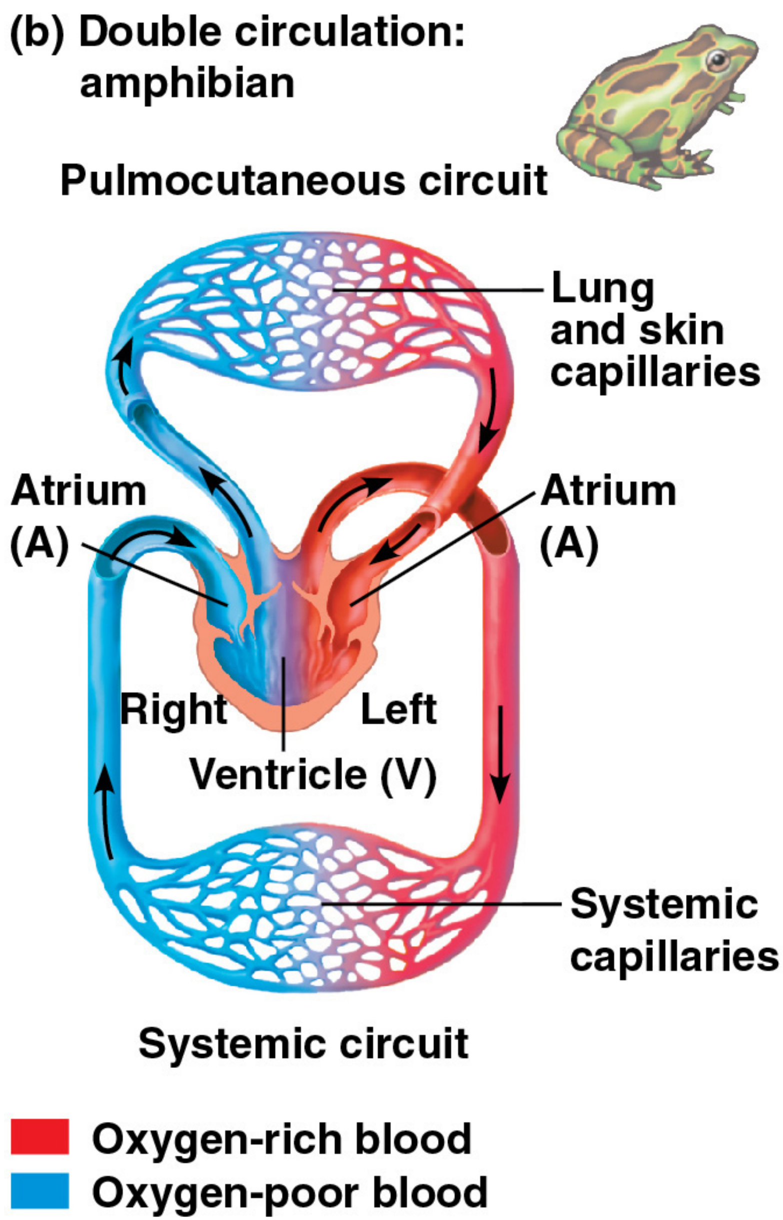
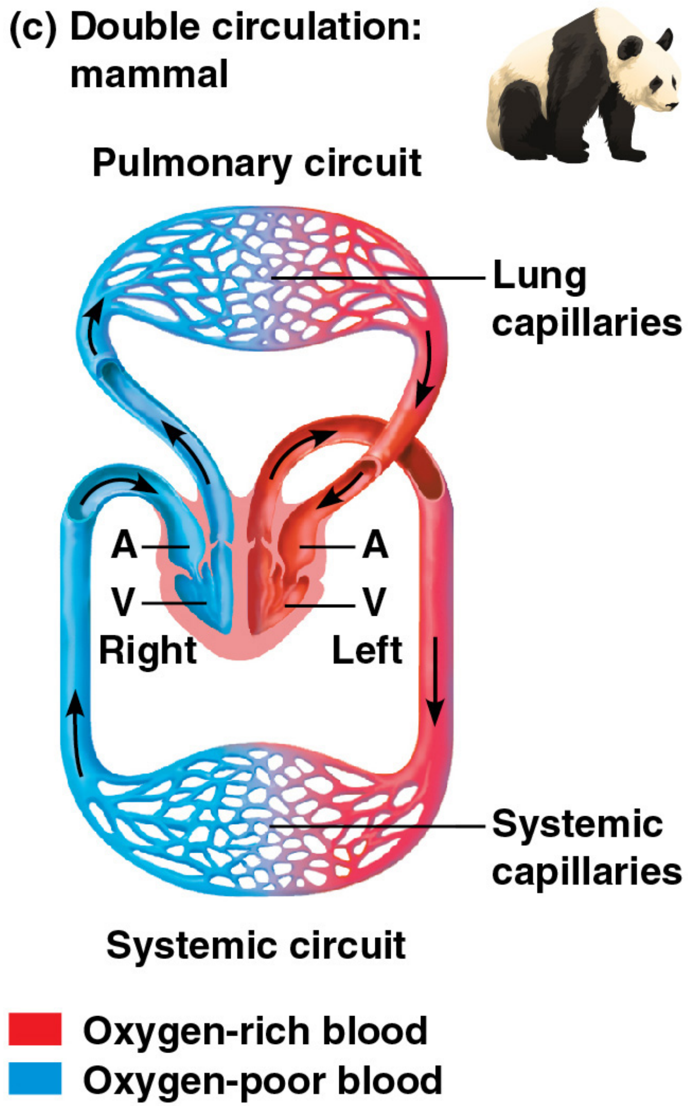

(b) Double circulation:
amphibian
Pulmocutaneous circuit
Lung
and skin
capillaries
Atrium
(A)
Atrium
(A)
Right
Left
Ventricle (V)
Systemic
capillaries
Systemic circuit
Oxygen-rich blood
Oxygen-poor blood

Figure 42.4c


(c) Double circulation: mammal
Pulmonary circuit
Lung capillaries
A
V
Right
A
V
Left
Systemic capillaries
Systemic circuit
Oxygen-rich blood
Oxygen-poor blood

Evolutionary Variation in Double Circulation

- Some vertebrates with double circulation are intermittent breathers
- Amphibians and many reptiles may pass long periods without gas exchange or relying on gas exchange from another tissue, usually the skin

- Frogs and other amphibians have a three-chambered heart: two atria and one ventricle
- A ridge in the ventricle diverts most of the oxygen-rich blood into the systemic circuit and most oxygen-poor blood into the pulmocutaneous circuit
- When the frog is underwater, blood flow to the lungs is nearly shut off

- Turtles, snakes, and lizards have a three-chambered heart: two atria and one ventricle, partially divided by an incomplete septum
- In alligators, caimans, and other crocodilians, a septum divides the ventricles, but pulmonary and systemic circuits connect where arteries exit the heart

- 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

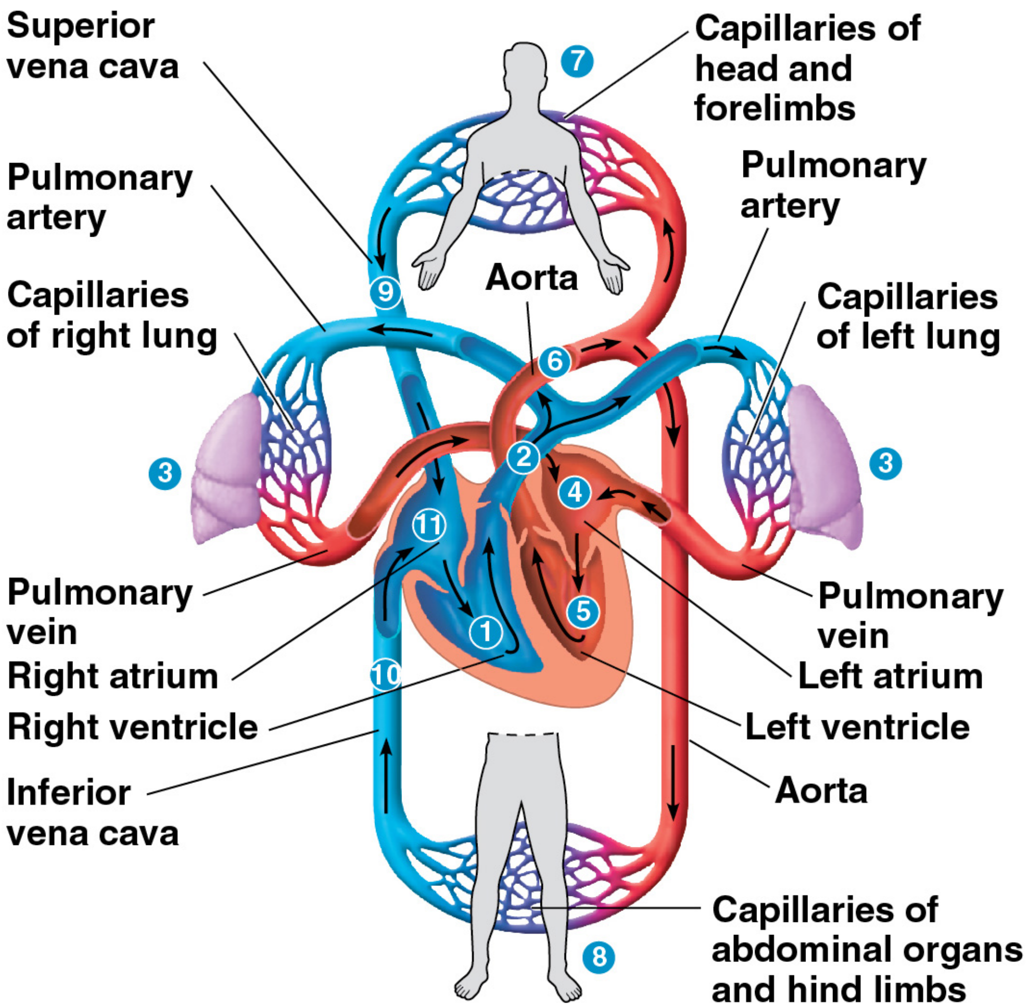
- Contraction of the right ventricle pumps blood to the lungs via the pulmonary arteries
- The blood flows through capillary beds in the left and right lungs and loads O_2 and unloads CO_2
- Oxygen-rich blood returns from the lungs via the pulmonary veins to the left atrium of the heart

- Oxygen-rich blood flows into the left ventricle and is pumped out to body tissues via the systemic circuit
- Blood leaves the left ventricle via the aorta, which conveys blood to arteries leading throughout the body
- The first branches are the coronary arteries, supplying the heart muscle

- Further branches lead to capillary beds in the abdominal organs and hind limbs
- O_2 diffuses from blood to tissues, and CO_2 diffuses from tissues to blood
- Capillaries rejoin, forming venules, conveying blood to veins
- Oxygen-poor blood from the head, neck, and forelimbs is channeled into the superior vena cava

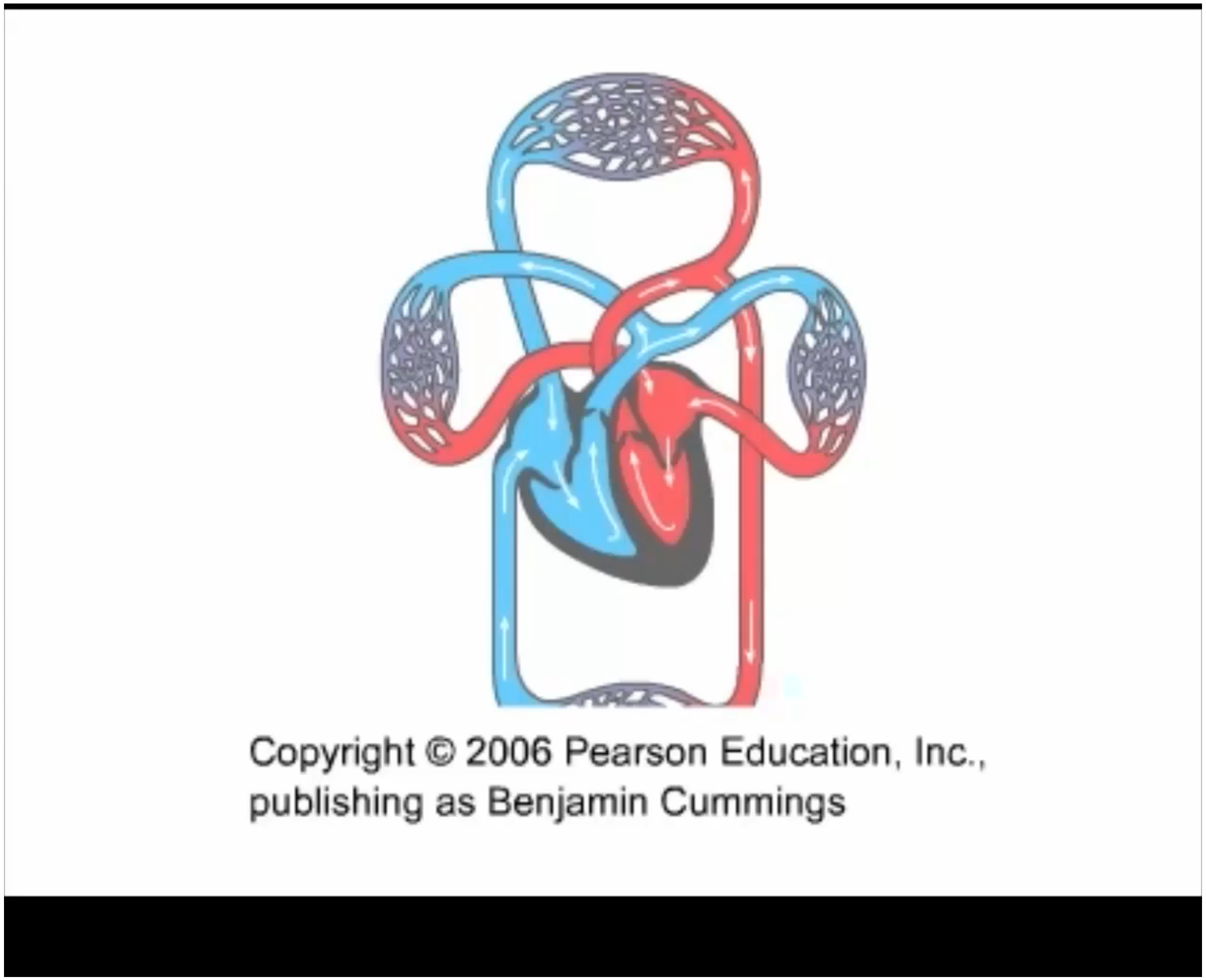
- The inferior vena cava drains blood from the trunk and hind limbs
- The two venae cavae empty their blood into the right atrium from which the oxygen-poor blood flows into the right ventricle

Figure 42.5



Superior vena cava
Pulmonary artery
Capillaries of right lung
Pulmonary vein
Right atrium
Right ventricle
Inferior vena cava
Capillaries of head and forelimbs
Pulmonary artery
Aorta
Capillaries of left lung
Pulmonary vein
Left atrium
Left ventricle
Aorta
Capillaries of abdominal organs and hind limbs
1
2
3
3
4
5
6
7
8
9
10
11

Animation: Path of Blood Flow in Mammals



The Mammalian Heart: *A Closer Look*

- The human heart is about the size of a clenched fist and consists mainly of cardiac muscle
- The two atria have relatively thin walls and serve as collection chambers for blood returning to the heart
- The ventricles have thicker walls and contract much more forcefully

Animation: Structure of the Human Heart

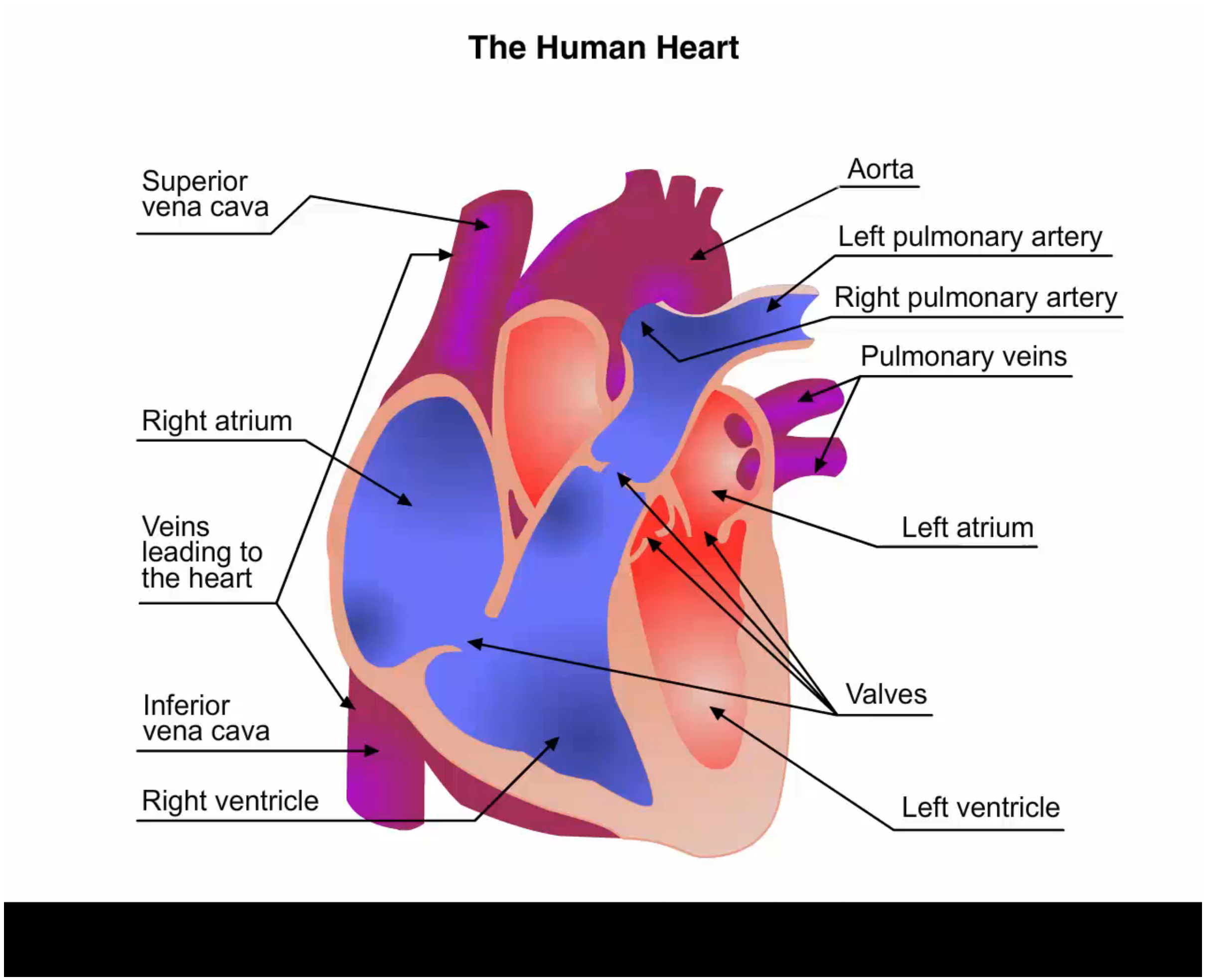
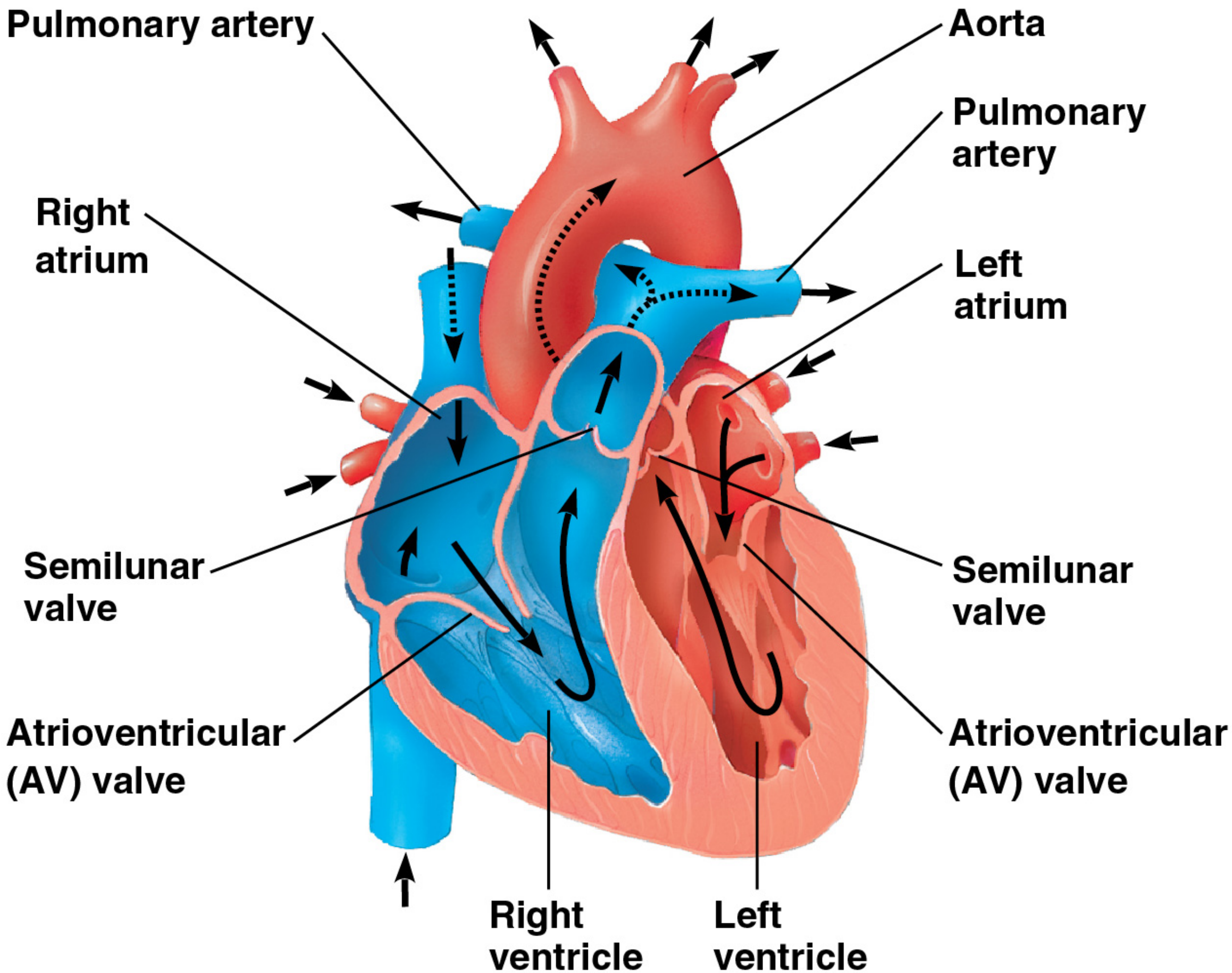


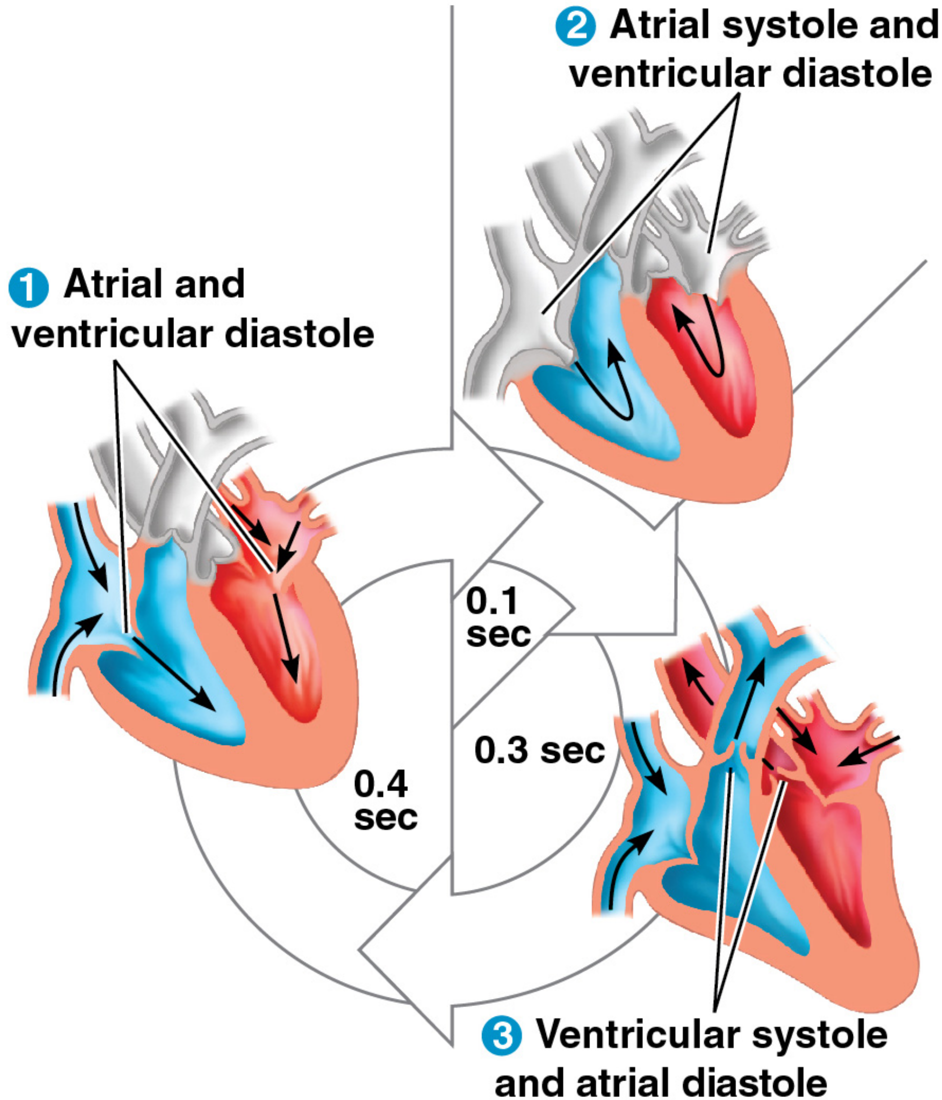
Figure 42.6



Pulmonary artery
Aorta
Pulmonary artery
Right atrium
Left atrium
Semilunar valve
Semilunar valve
Atrioventricular (AV) valve
Atrioventricular (AV) 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 42.7

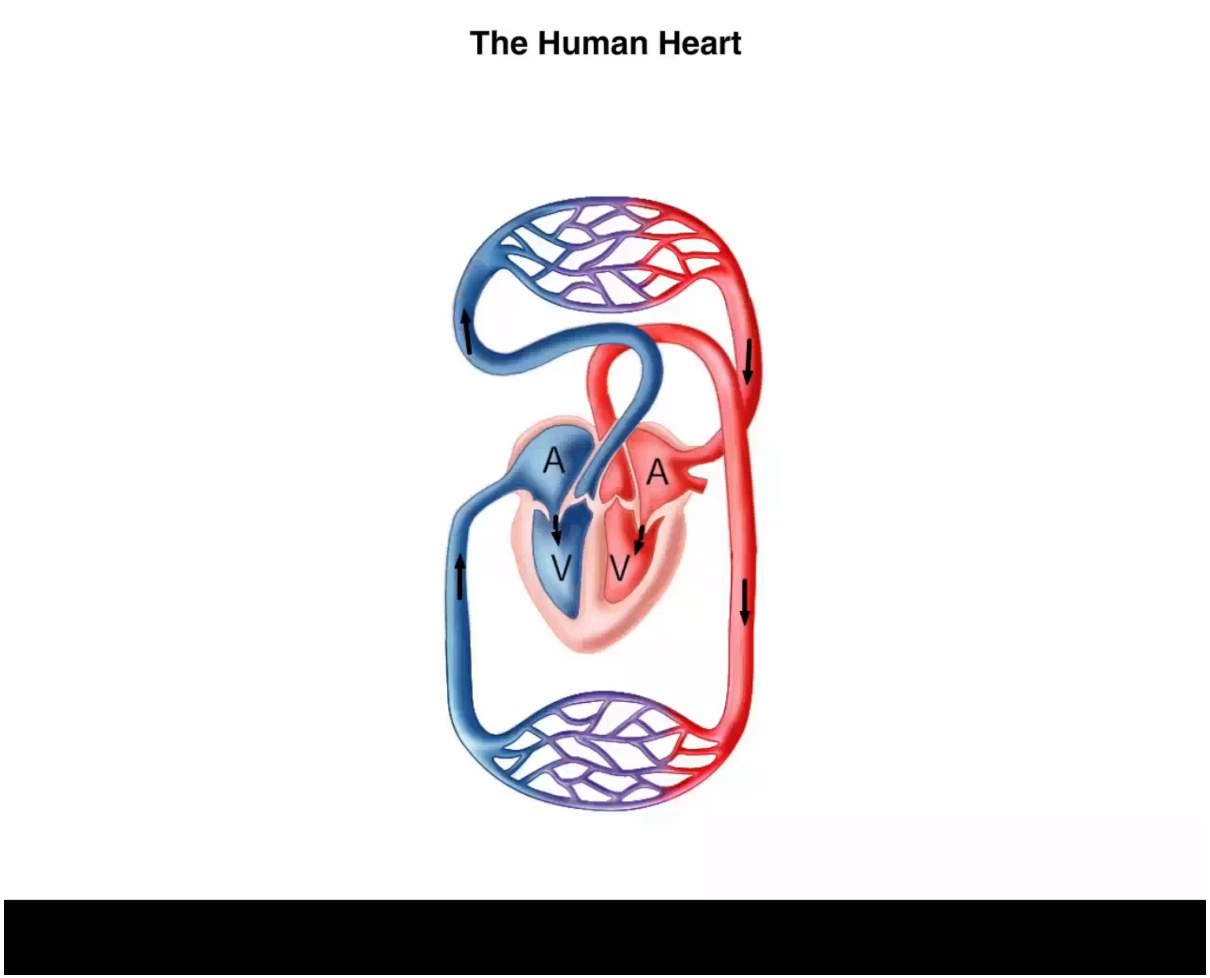

1 Atrial and ventricular diastole
2 Atrial systole and ventricular diastole
3 Ventricular systole and atrial diastole
0.1 sec
0.3 sec
0.4 sec

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

- 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**

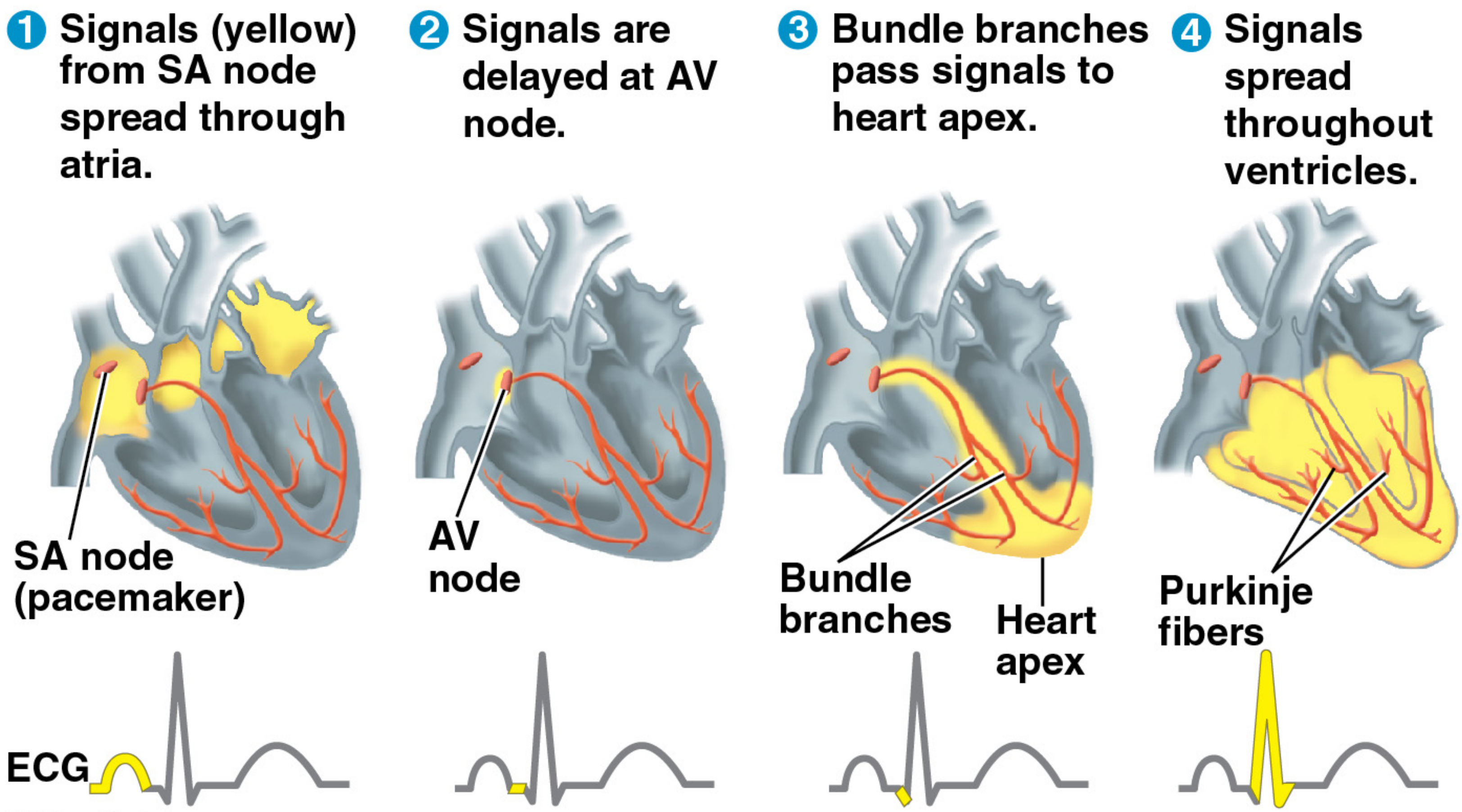
Animation: The Human Heart and Circulation



Maintaining the Heart's Rhythmic Beat

- Some cardiac muscle cells are autorhythmic, 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 42.8



1 Signals (yellow) from SA node spread through atria.
2 Signals are delayed at AV node.
3 Bundle branches pass signals to heart apex.
4 Signals spread throughout ventricles.
SA node (pacemaker)
AV node
Bundle branches
Heart apex
Purkinje fibers
ECG

- Impulses from the SA node travel to the **atrioventricular (AV) node**
- Here, 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

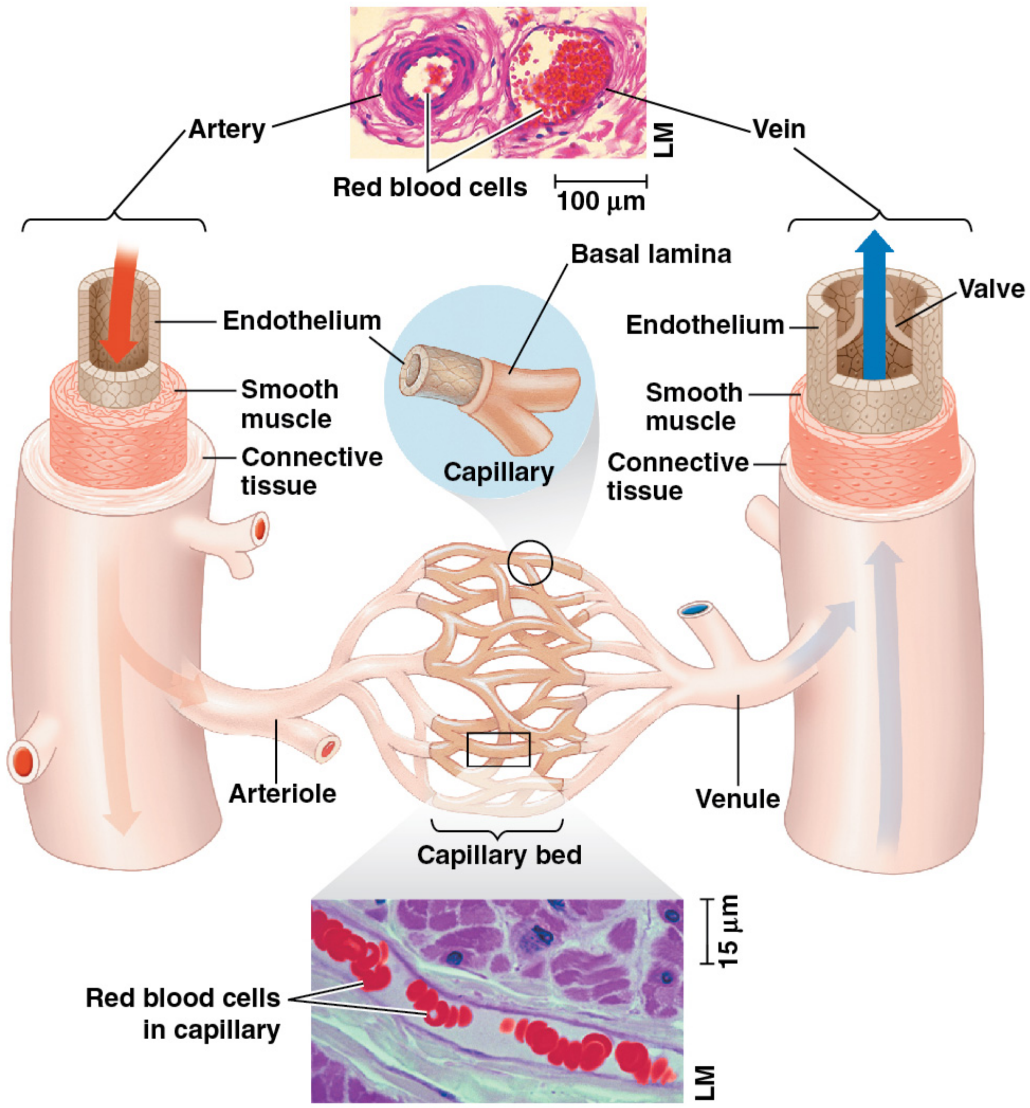
- The vertebrate circulatory system relies on blood vessels that exhibit a close match of structure and function

Blood Vessel Structure and Function

- All blood vessels contain a central lumen lined with an epithelial layer that lines blood vessels
- This **endothelium** is smooth and minimizes resistance
- Capillaries are only slightly wider than a red blood cell
- 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 thick, elastic walls to accommodate the high pressure of blood pumped from the heart
- Because veins convey blood back to the heart at a lower pressure, they do not require thick walls
- Unlike arteries, veins contain valves to maintain unidirectional blood flow

Figure 42.9

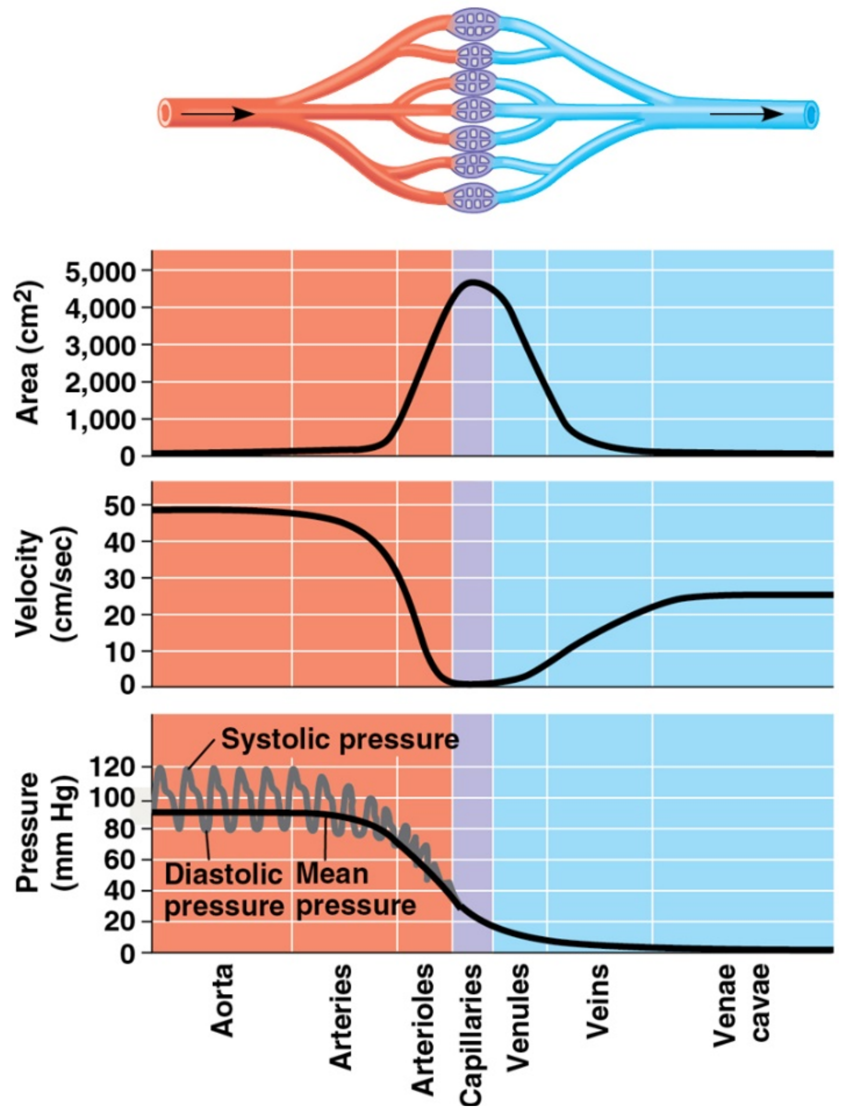


Artery
Red blood cells
LM
100 µm
Vein
Basal lamina
Endothelium
Smooth muscle
Connective tissue
Capillary
Valve
Endothelium
Smooth muscle
Connective tissue
Arteriole
Venule
Capillary bed
Red blood cells in capillary
15 µm
LM

Blood Flow Velocity

- Blood slows as it moves from arteries to arterioles to the narrow capillaries
- This is a result of the high resistance and large total cross-sectional area
- As the blood enters venules and veins, the flow speeds up as the total cross-sectional area decreases

Figure 42.10



Area (cm2)
5,000
4,000
3,000
2,000
1,000
0
Velocity (cm/sec)
50
40
30
20
10
0
Systolic pressure
Pressure (mm Hg)
120
100
80
60
40
20
0
Diastolic pressure
Mean 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 a force exerted in all directions, including against the walls of blood vessels
- The recoil of elastic arterial walls plays a role in maintaining blood pressure
- The resistance to blood flow in the narrow diameters of tiny capillaries and arterioles dissipates much of the pressure

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
- A **pulse** is the rhythmic bulging of artery walls with each heartbeat
- **Diastolic pressure** is the pressure in the arteries during diastole (when the ventricles are relaxed); it is lower than systolic pressure

Regulation of Blood Pressure

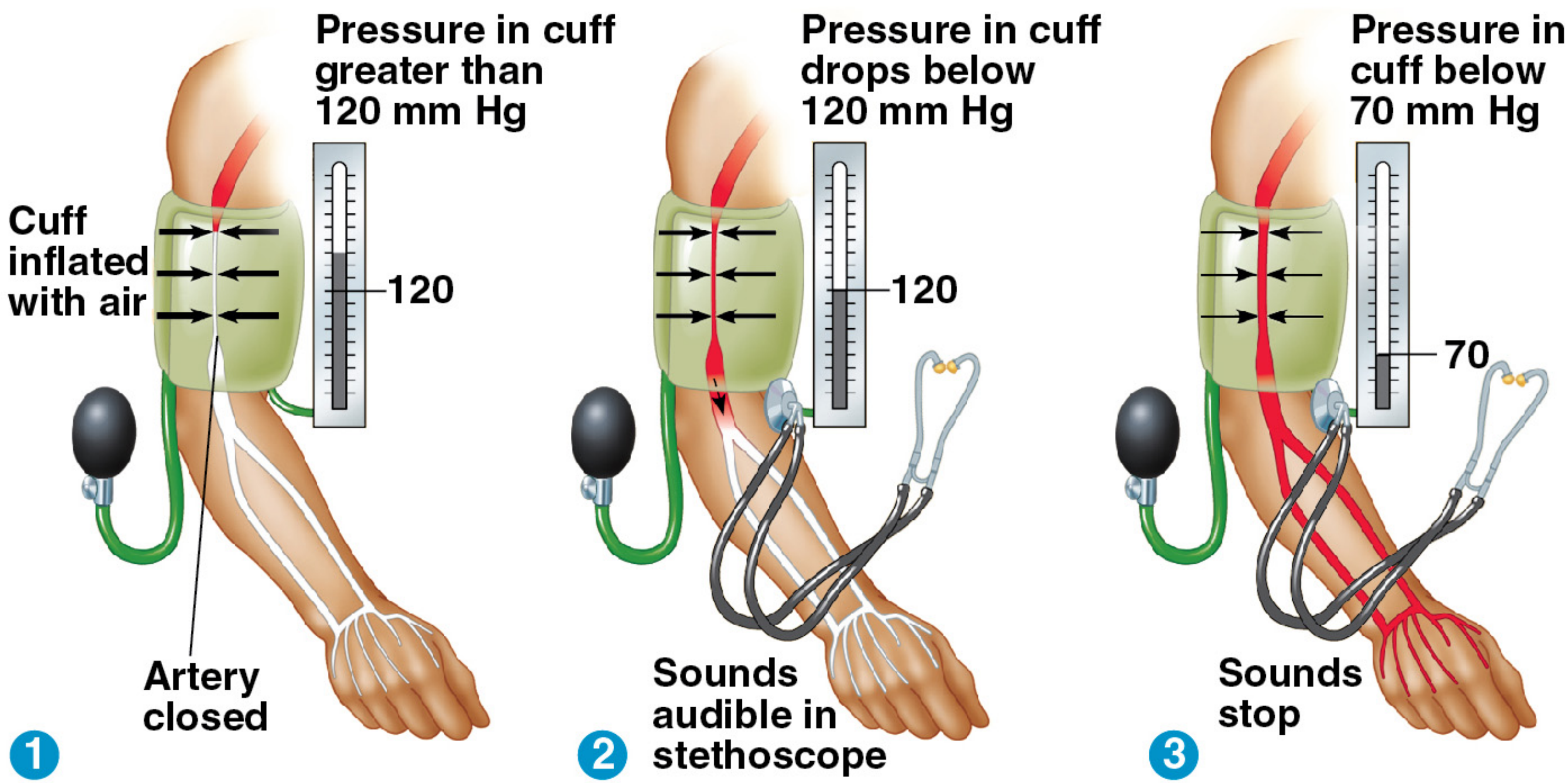
- Homeostatic mechanisms regulate arterial blood pressure by altering the diameter of arterioles
- **Vasoconstriction** is the narrowing of arteriole walls; it increases blood pressure
- **Vasodilation** is the increase in diameter of the arterioles; it causes blood pressure to fall

- Nitric oxide (NO) is a major inducer of vasodilation
- The peptide endothelin is a potent inducer of vasoconstriction
- Vasoconstriction and vasodilation are often coupled to changes in cardiac output that affect blood pressure

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 human at rest is about 120 mm Hg at systole and 70 mm Hg at diastole
- Gravity has a significant effect on blood pressure

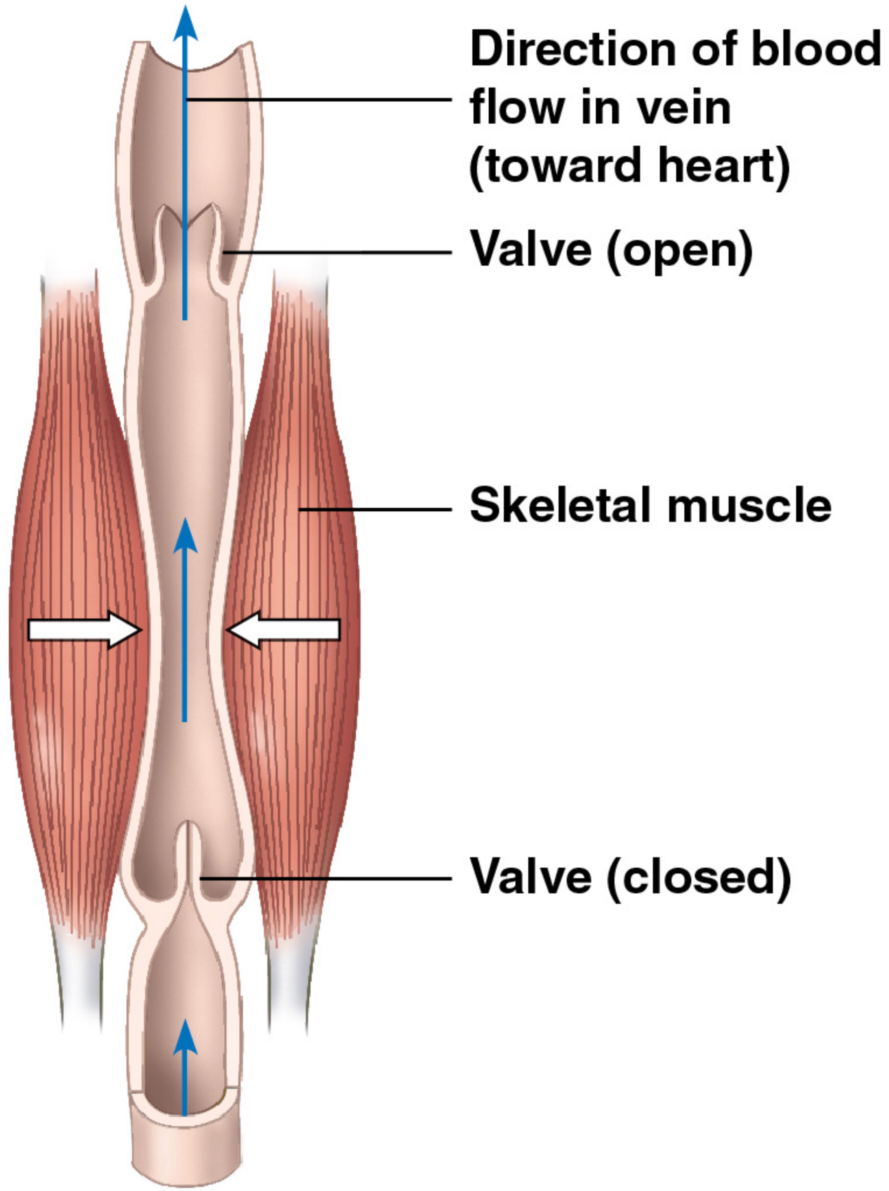
Figure 42.11



Pressure in cuff greater than 120 mm Hg
Cuff inflated with air
120
Artery closed
1
Pressure in cuff drops below 120 mm Hg
120
Sounds audible in stethoscope
2
Pressure in cuff below 70 mm Hg
70
Sounds stop
3

- Fainting is caused by inadequate blood flow to the head
- Animals with long necks require a very high systolic pressure to pump blood a great distance against gravity
- Because blood pressure is low in veins, one-way valves in veins prevent backflow of blood
- Return of blood is also enhanced by contraction of smooth muscle in venule walls and skeletal muscle contraction

Figure 42.12

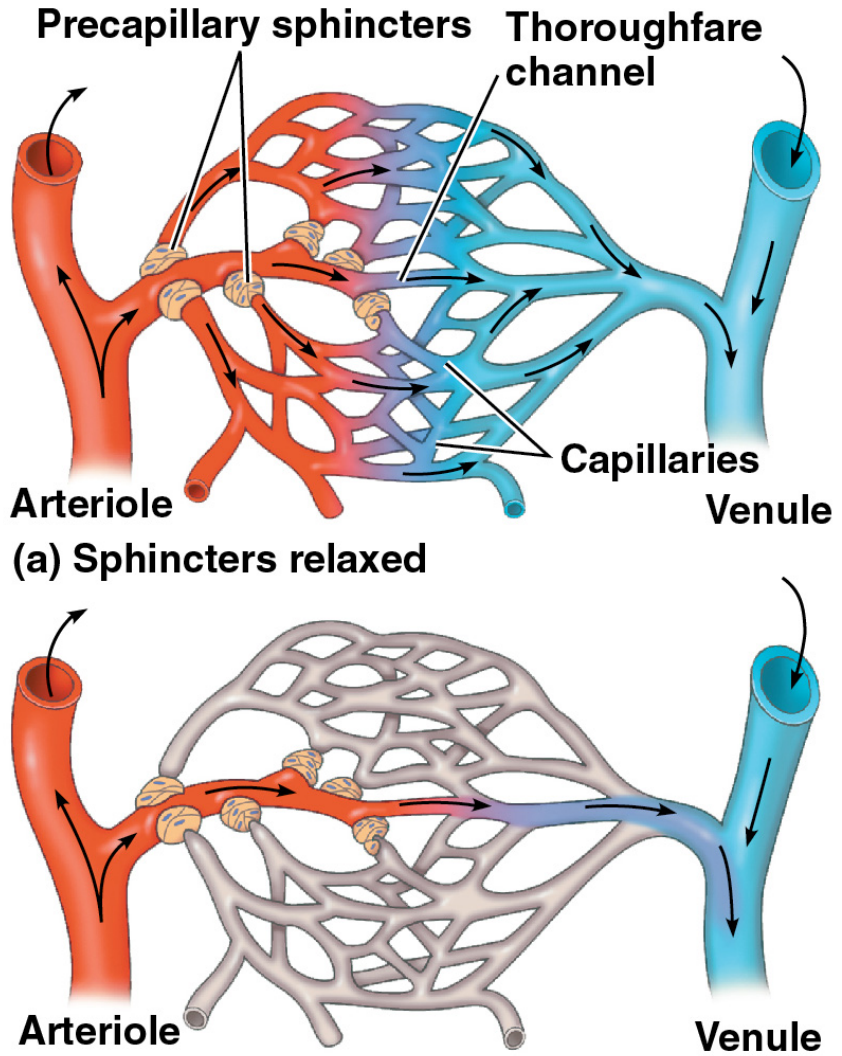

Direction of blood flow in vein (toward heart)
Valve (open)
Skeletal muscle
Valve (closed)

Capillary Function

- Blood flows through only 5–10% of the body's capillaries at any given 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
  - Constriction or dilation of arterioles that supply capillary beds
  - Precapillary sphincters that control flow of blood between arterioles and venules
- Blood flow is regulated by nerve impulses, hormones, and other chemicals

Figure 42.13

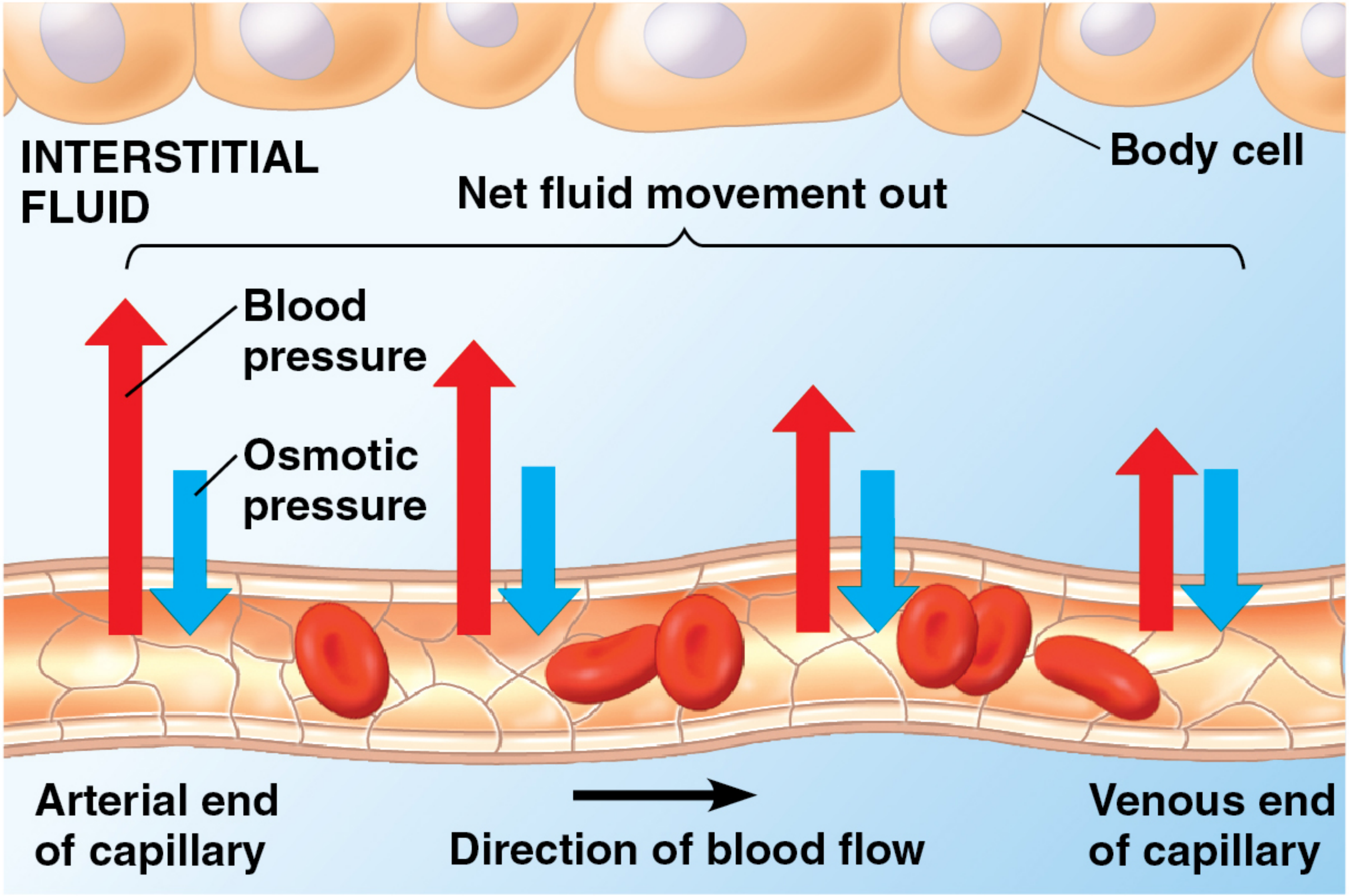


(a) Sphincters relaxed

(b) Sphincters contracted

- The exchange of substances between the blood and interstitial fluid takes place across the thin endothelial walls of the capillaries
- Blood pressure tends to drive fluid out of capillaries, and blood proteins tend to pull fluid back
- These proteins are responsible for much of the blood’s osmotic pressure
- On average, there is a net loss of fluid from capillaries

Figure 42.14



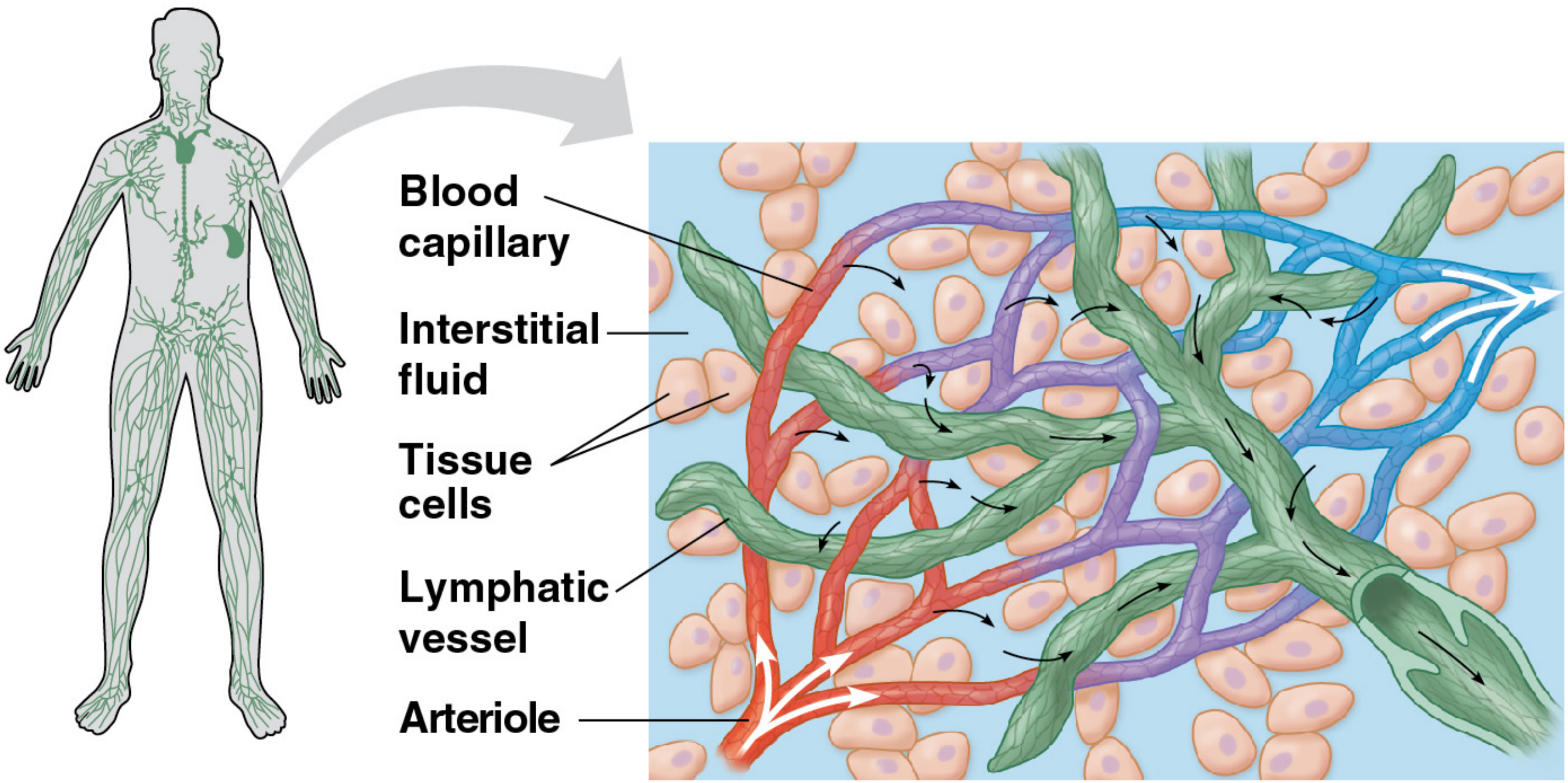
INTERSTITIAL FLUID
Net fluid movement out
Body cell
Blood pressure
Osmotic pressure
Arterial end of capillary
Direction of blood flow
Venous end of capillary

Fluid Return by the Lymphatic System

- The **lymphatic system** returns fluid that leaks out from the capillary beds
- Fluid lost by capillaries is called **lymph**
- The lymphatic system drains into veins in the neck
- Valves in lymph vessels prevent the backflow of fluid

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

Figure 42.15



Blood capillary
Interstitial fluid
Tissue cells
Lymphatic vessel
Arteriole

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

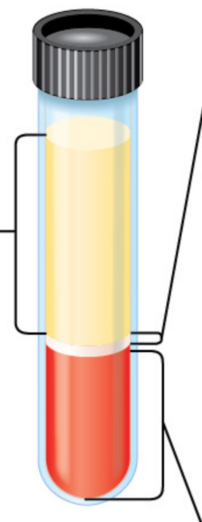
- With open circulation, the fluid is continuous with the fluid surrounding all body cells
- The closed circulatory systems of vertebrates contain a more highly specialized fluid called blood

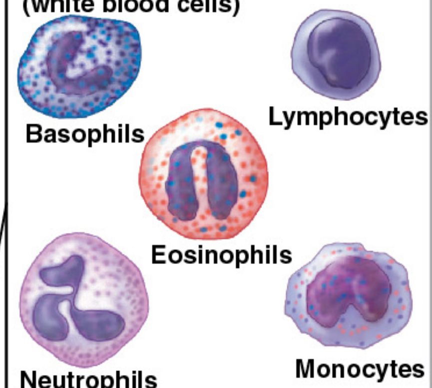
Blood Composition and Function

- Blood in vertebrates is a connective tissue consisting of several kinds of cells suspended in a liquid matrix called **plasma**
- Cells and cell fragments occupy about 45% of the volume of blood

Figure 42.16

Plasma 55%	
Constituent	**Major functions**
Water	Solvent
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
Immunoglobulins (antibodies)	Defense and immunity
Apolipoproteins	Lipid transport
Fibrinogen	Blood clotting
Substances transported by blood Nutrients (such as glucose, fatty acids, vitamins), waste products of metabolism, respiratory gases (O_2 and CO_2), and hormones	



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) 	5,000,000–6,000,000	Transport of O_2 and some CO_2

Plasma

- Plasma contains inorganic salts as dissolved ions, sometimes called electrolytes
- Plasma proteins influence blood pH and help maintain osmotic balance between blood and interstitial fluid
- Certain plasma proteins function in lipid transport, immunity, and blood clotting
- Plasma is similar in composition to interstitial fluid, but plasma has a much higher protein concentration

Cellular Elements

- Suspended in blood plasma are two types of cells:
  - Red blood cells (erythrocytes) transport O_2
  - White blood cells (leukocytes) function in defense
- **Platelets** are fragments of cells that are involved in clotting

Erythrocytes

- Red blood cells, or **erythrocytes**, are 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 can block blood vessels, leading to organ swelling, and severe pain
- It leads to reduced numbers of red blood cells available to transport oxygen

Leukocytes

- There are five major types of white blood cells, or **leukocytes**
- They function in defense either by phagocytizing bacteria and debris or by mounting immune responses against foreign substances
- They are found both in and outside of the circulatory system

Platelets

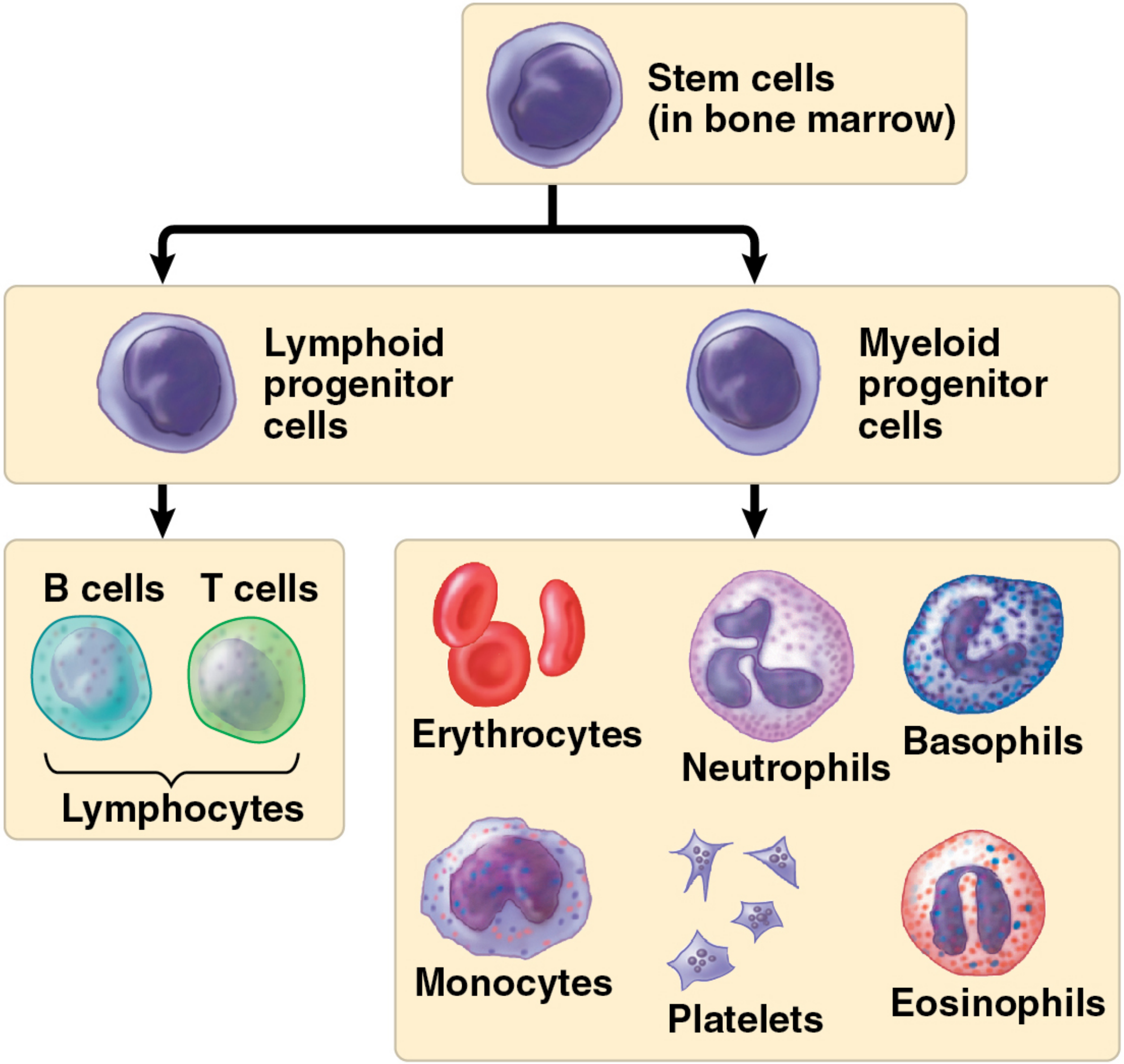
- Platelets are fragments of cells and function in blood clotting

Video: Leukocyte Adhesion and Rolling

Stem Cells and the Replacement of Cellular Elements

- 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
- Physicians can use recombinant EPO to treat people with conditions such as anemia

Figure 42.17

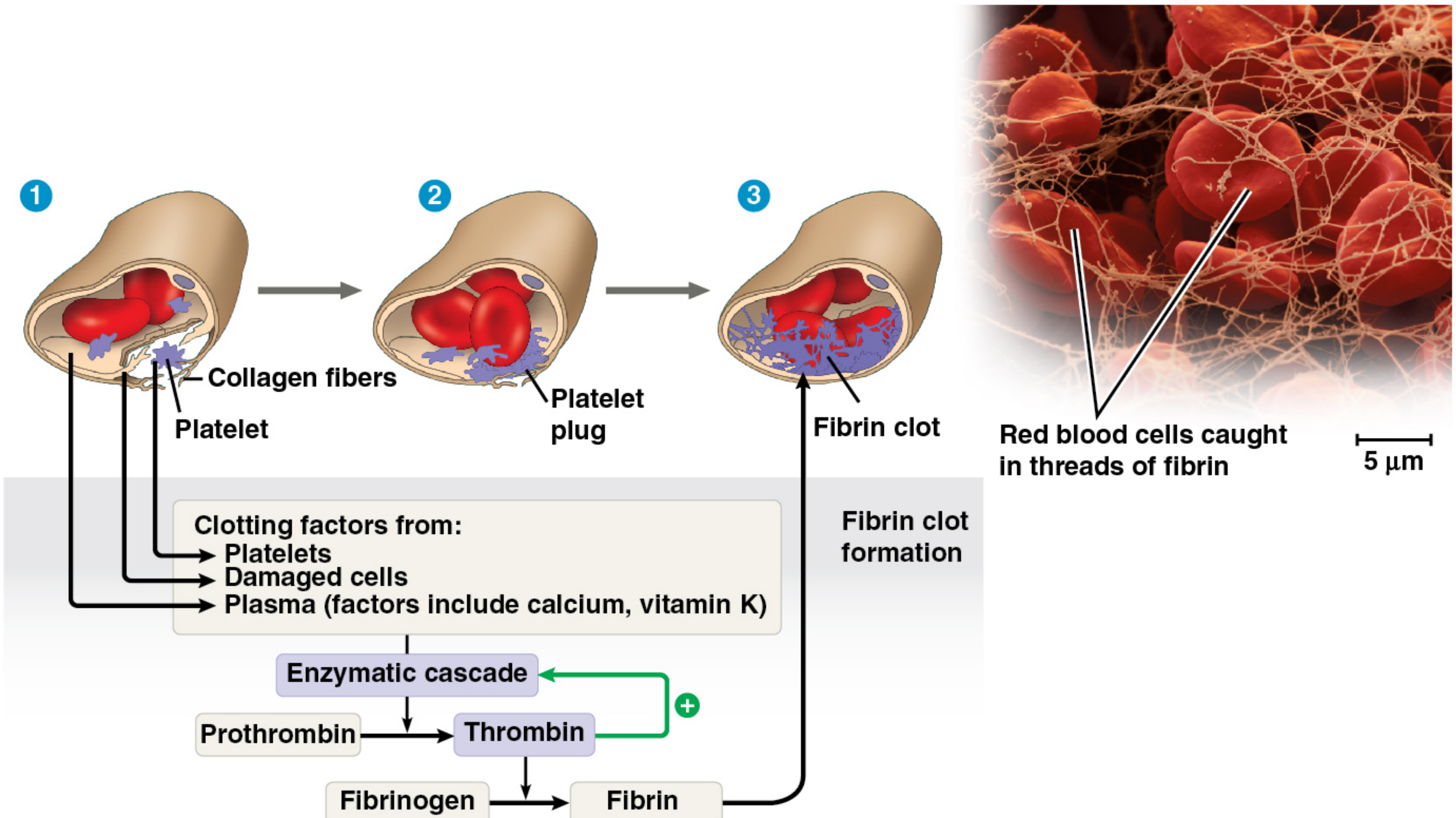


Stem cells
(in bone marrow)
Lymphoid
progenitor
cells
Myeloid
progenitor
cells
B cells
T cells
Lymphocytes
Erythrocytes
Neutrophils
Basophils
Monocytes
Platelets
Eosinophils

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 cells caught in threads of fibrin
5 µm
Fibrin clot formation
Clotting factors from:
Platelets
Damaged cells
Plasma (factors include calcium, vitamin K)
Enzymatic cascade
+
Prothrombin
Thrombin
Fibrinogen
Fibrin

Cardiovascular Disease

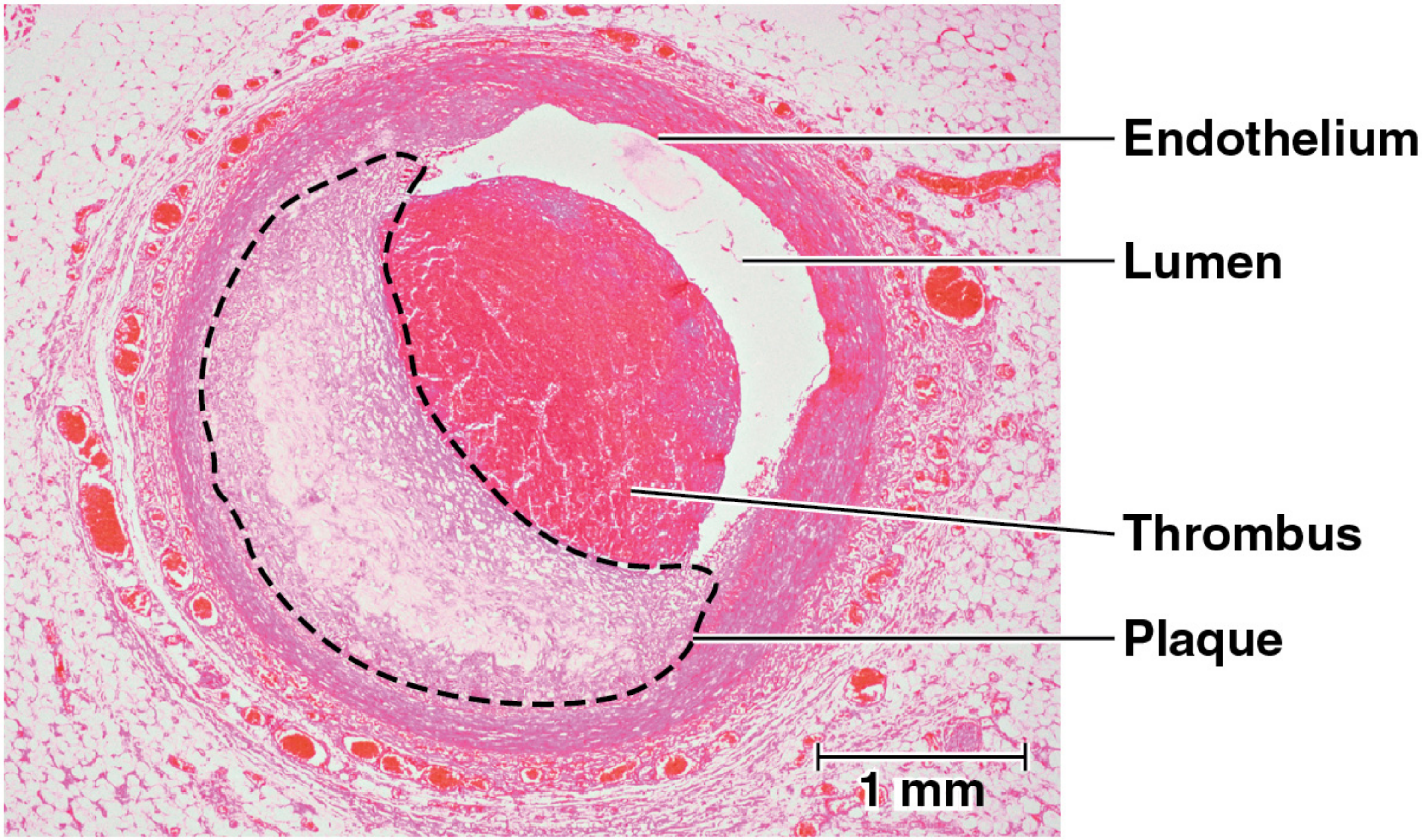
- Cardiovascular diseases are disorders of the heart and the blood vessels
- These diseases range in seriousness from minor disturbances of vein or heart function to life-threatening disruptions of blood flow to the heart or brain

Atherosclerosis, Heart Attacks, and Stroke

- One type of cardiovascular disease, **atherosclerosis**, is hardening of the arteries, caused by the buildup of fatty deposits (plaque) within arteries
- Cholesterol is a steroid that is important for maintaining normal membrane fluidity in animal cells

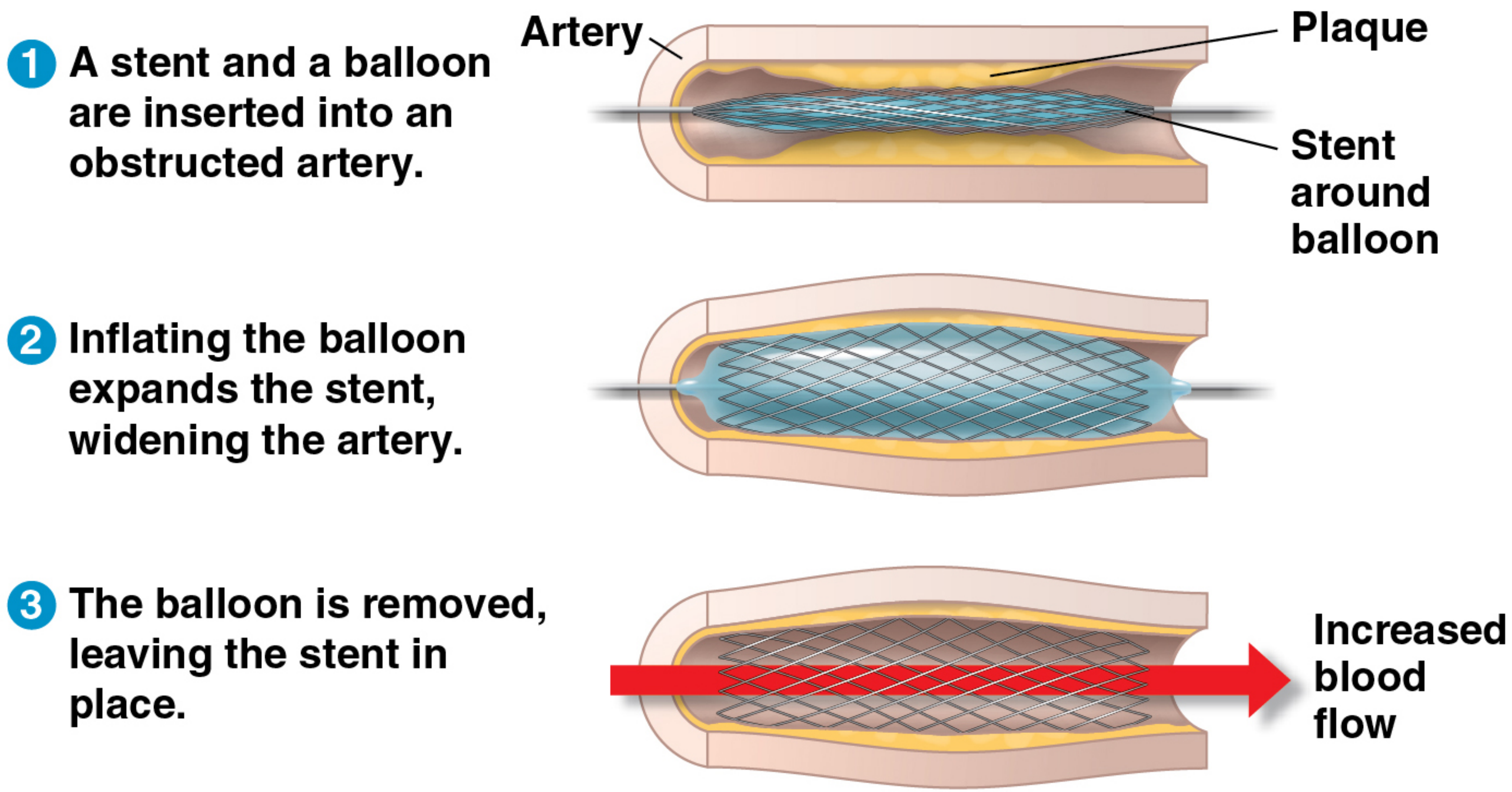
- In atherosclerosis, damage to artery lining results in inflammation
- Leukocytes are attracted to the inflamed area and begin to take up lipids
- A fatty deposit, called a plaque grows, leading to artery walls becoming thick and stiff
- If the plaque ruptures, a thrombus can form, potentially triggering a heart attack or a stroke

Figure 42.19



- A **heart attack**, or myocardial infarction, is the damage or 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
- Angina pectoris is chest pain caused by partial blockage of the coronary arteries
- An obstructed artery can be treated surgically

Figure 42.20



1 A stent and a balloon are inserted into an obstructed artery.
Artery
Plaque
Stent around balloon
2 Inflating the balloon expands the stent, widening the artery.
3 The balloon is removed, leaving the stent in place.
Increased blood flow

Risk Factors and Treatment of Cardiovascular Disease

- **Low-density lipoprotein (LDL)** delivers cholesterol to cells for membrane production
- **High-density lipoprotein (HDL)** scavenges excess 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

- A high LDL/ HDL ratio increases the risk of cardiovascular disease
- The proportion of LDL relative to HDL can be decreased by exercise and by avoiding smoking and foods with trans fats
- Drugs called statins reduce LDL levels and risk of heart attacks

- 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, also contributes to heart attack and stroke, as well as other health problems
- Hypertension can be controlled by dietary changes, exercise, and/or medication

CONCEPT 42.5: Gas exchange occurs across specialized respiratory surfaces

- **Gas exchange** is the uptake of O_2 from the environment and the discharge of CO_2 to the environment

Partial Pressure Gradients in Gas Exchange

- **Partial pressure** is the pressure exerted by a particular gas in a mixture of gases
- Partial pressures also apply to gases dissolved in liquids such as water
- O_2 is much less soluble in water than in air

Table 42.1 Comparing Air and Water as Respiratory Media

	Air (Sea Level)	Water (20°C)	Air-to-Water Ratio
O_2 partial pressure	160 mm	160 mm	1:1
O_2 concentration	210 ml/L	7 ml/L	30:1
Density	0.0013 kg/L	1 kg/L	1:770
Viscosity	0.02 cP	1 cP	1:50

Respiratory Media

- Breathing air is relatively easy and need not be very efficient
- 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

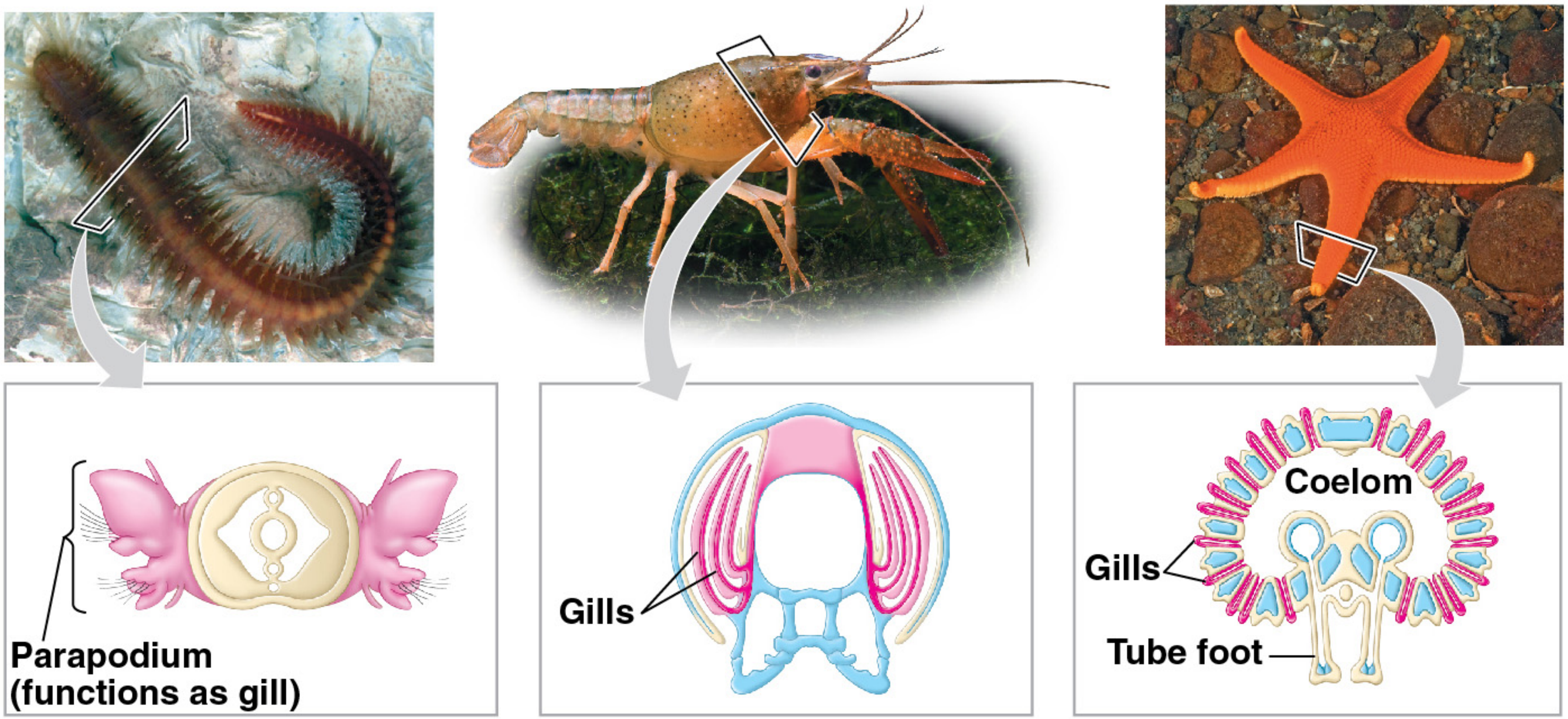
Respiratory Surfaces

- Gas exchange across respiratory surfaces takes place by diffusion
- Respiratory surfaces vary by animal and can include the skin, gills, tracheae, and lungs

Gills in Aquatic Animals

- Gills are outfoldings of the body that create a large surface area for gas exchange
- **Ventilation** moves the respiratory medium over the respiratory surface
- It maintains the partial pressures of O_2 and CO_2 needed for gas exchange
- Aquatic animals move through water or move water over their gills for ventilation

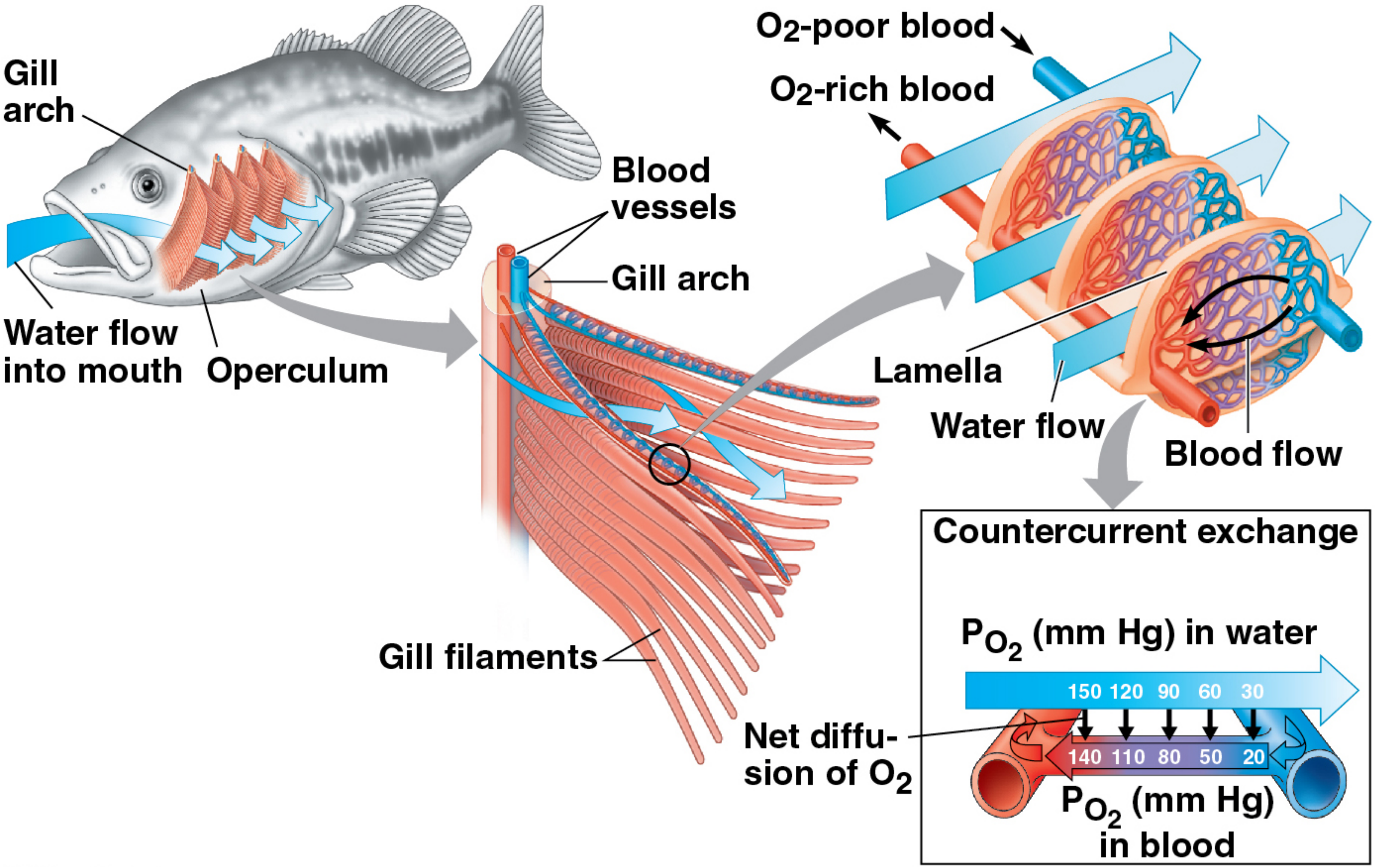
Figure 42.21



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

- 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
- In fish gills, more than 80% of the O_2 dissolved in the water is removed as water passes over the respiratory surface

Figure 42.22

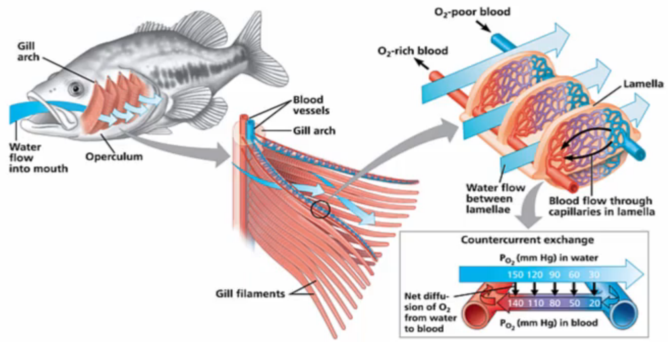


Gill arch
Water flow into mouth
Operculum
Blood vessels
Gill arch
Gill filaments
O2-poor blood
O2-rich blood
Lamella
Water flow
Blood flow
Countercurrent exchange
PO2 (mm Hg) in water
150 120 90 60 30
Net diffusion of O2
140 110 80 50 20
PO2 (mm Hg) in blood

Video: Structure and Function of Fish Gills

CAMPBELL FIGURE WALKTHROUGH

The structure and function of fish gills



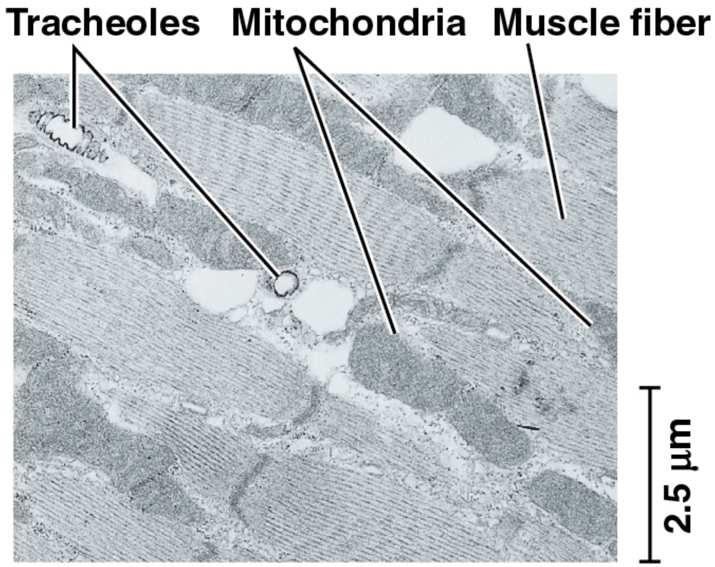
Pearson

Video: Gas Exchange in Fish Gills

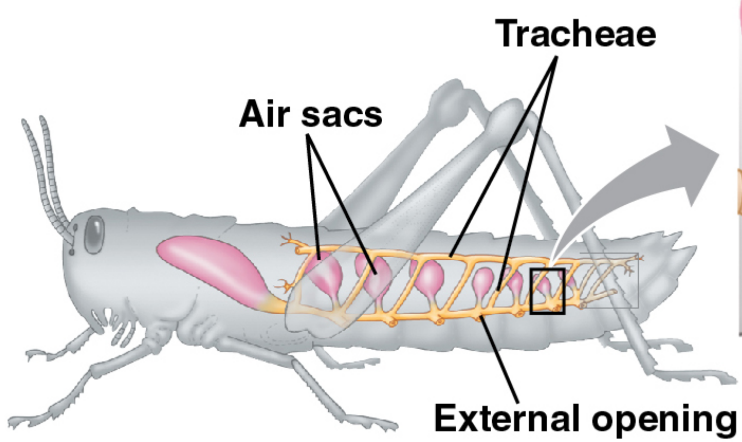
Tracheal Systems in Insects

- The **tracheal system** of insects consists of a network of branching tubes throughout 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

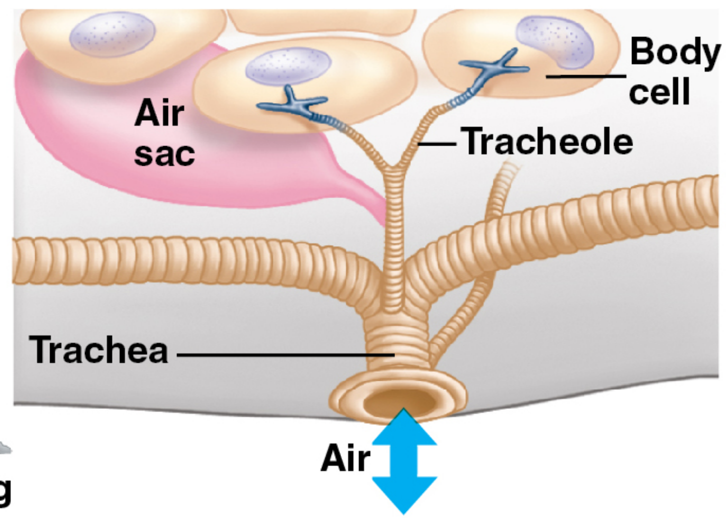
Figure 42.23



Tracheoles
Mitochondria
Muscle fiber
2.5 µm



Tracheae
Air sacs
External opening



Body cell
Air sac
Tracheole
Trachea
Air

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
- Most reptiles and all mammals depend entirely on lungs for gas exchange

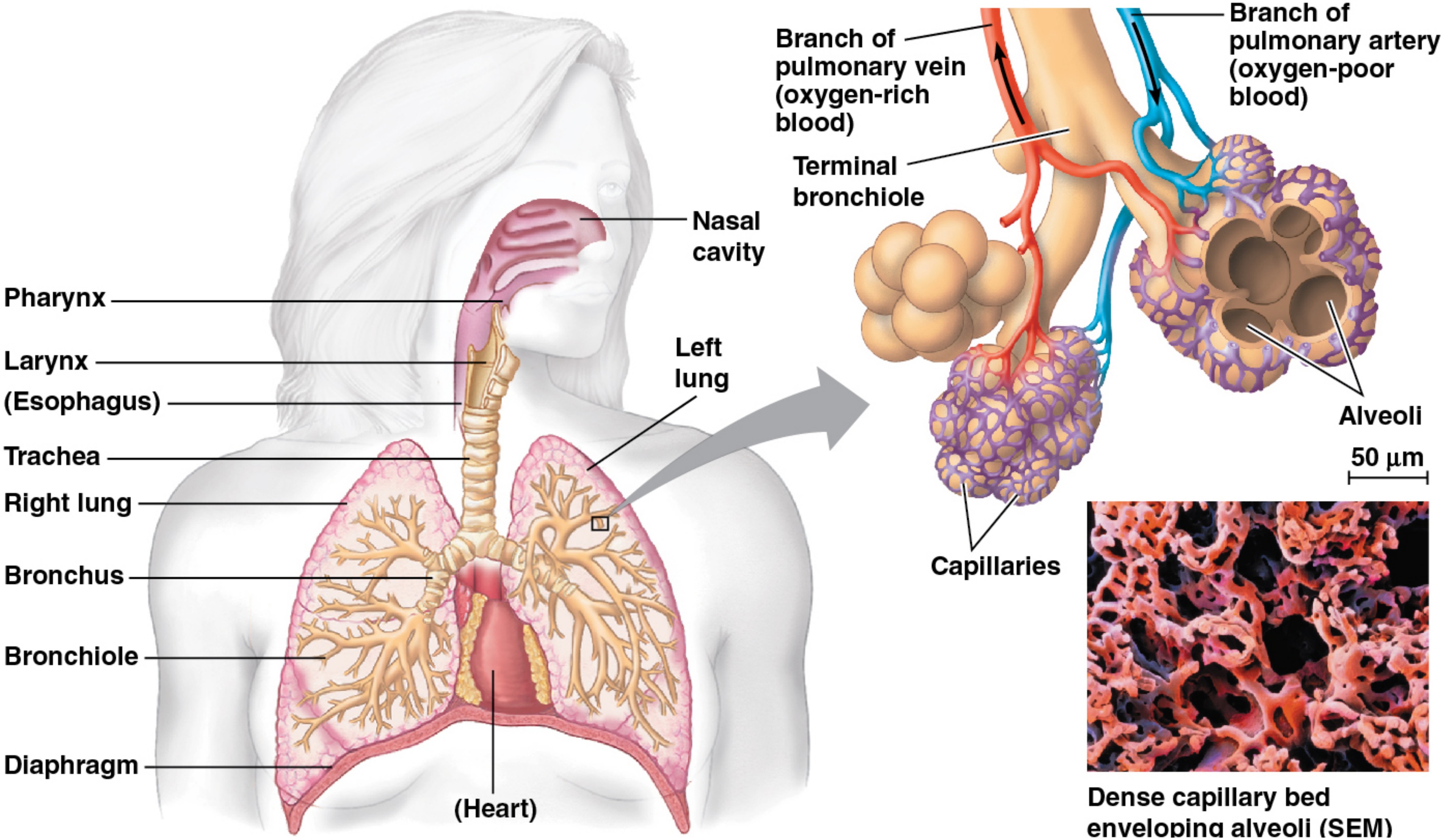
Mammalian Respiratory Systems: A Closer Look

- Branching ducts conveys air to the lungs
- Air inhaled through the nostrils is filtered, warmed, humidified, and sampled for odors
- The pharynx directs air to the lungs and food to the stomach
- Swallowing moves the **larynx** upward and tips the epiglottis over the glottis in the pharynx to prevent food from entering the **trachea**, or windpipe

- Exhaled air passes over the vocal cords in the larynx to create sounds
- Air passes through the pharynx, larynx, trachea, **bronchi**, and **bronchioles** to the alveoli, where gas exchange occurs
- 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

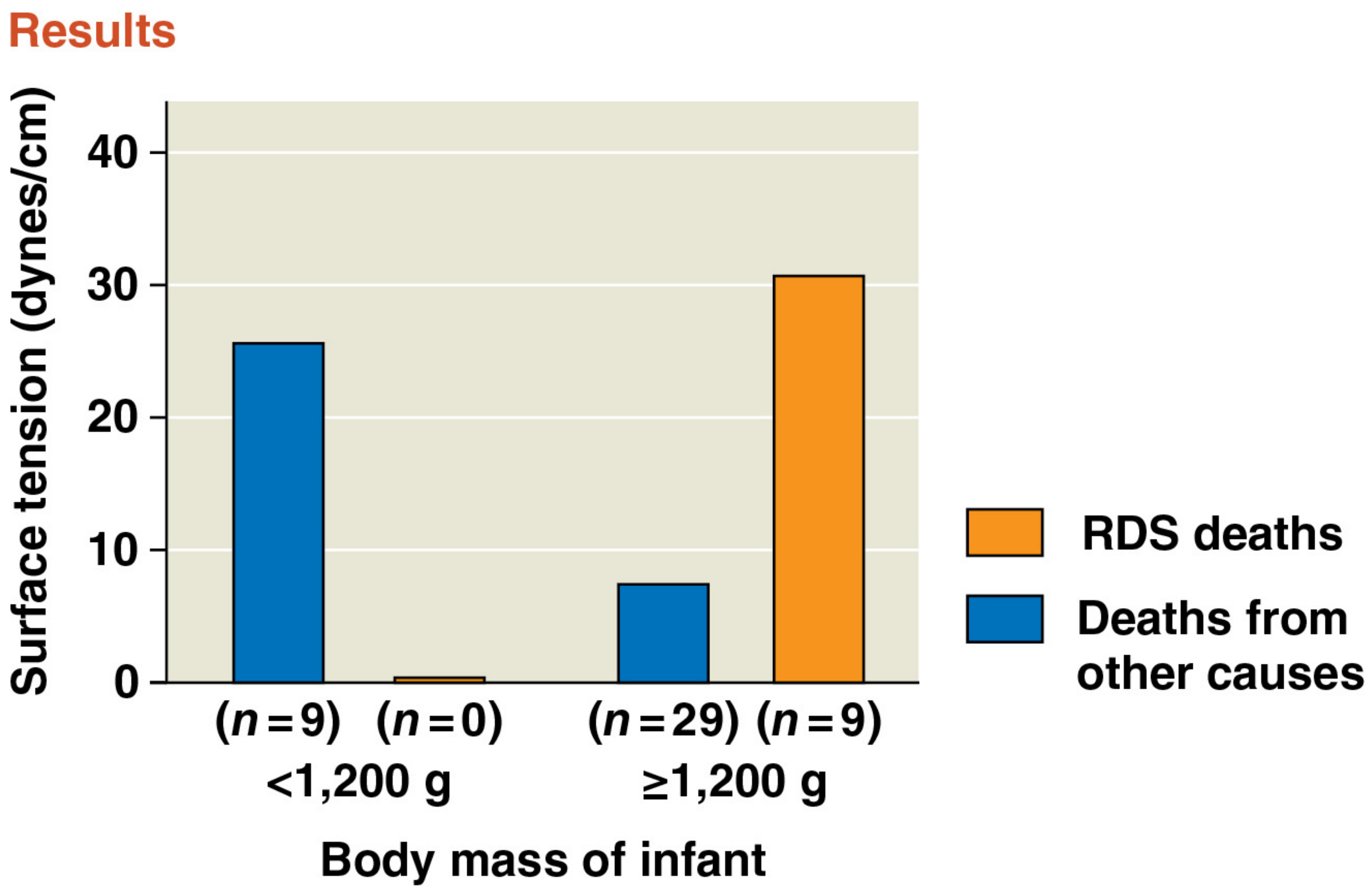
Figure 42.24



Dense capillary bed enveloping alveoli (SEM)

- 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 42.25



Data from M. E. Avery and J. Mead, Surface properties in relation to atelectasis and hyaline membrane disease, *American Journal of Diseases of Children* 97:517–523 (1959).

CONCEPT 42.6: Breathing ventilates the lungs

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

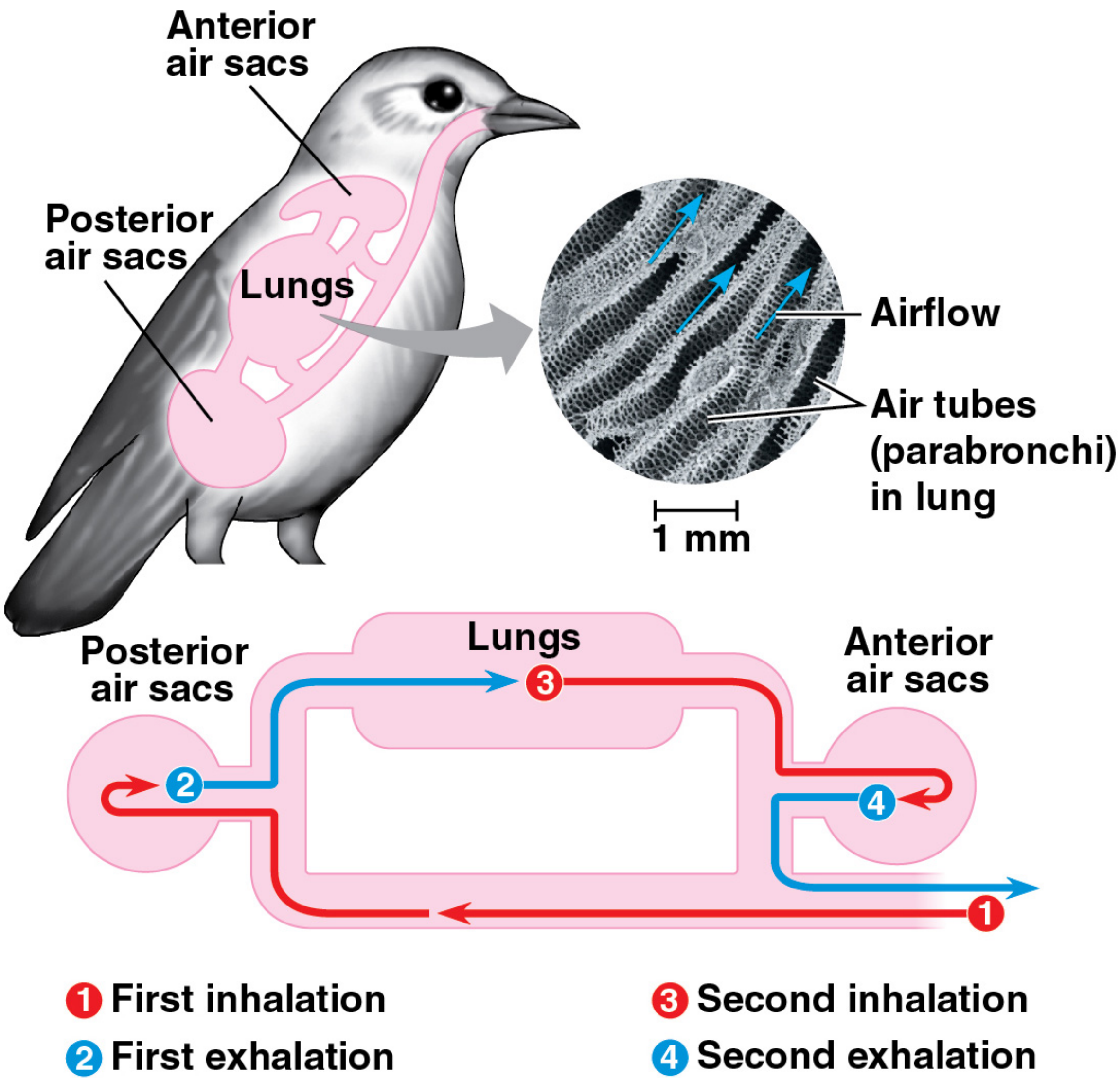
How an Amphibian Breathes

- An amphibian such as a frog ventilates its lungs by **positive pressure breathing**, which forces air down the trachea
- Exhalation follows as air is expelled by the elastic recoil of the lungs and by compression of the body wall

How a Bird Breathes

- Birds have air sacs that function as bellows that keep air flowing through the lungs
- Air passes through the lungs in one direction only
- Passage of air through the entire system of lungs and air sacs requires two cycles of inhalation and exhalation
- Ventilation in birds is highly efficient

Figure 42.26



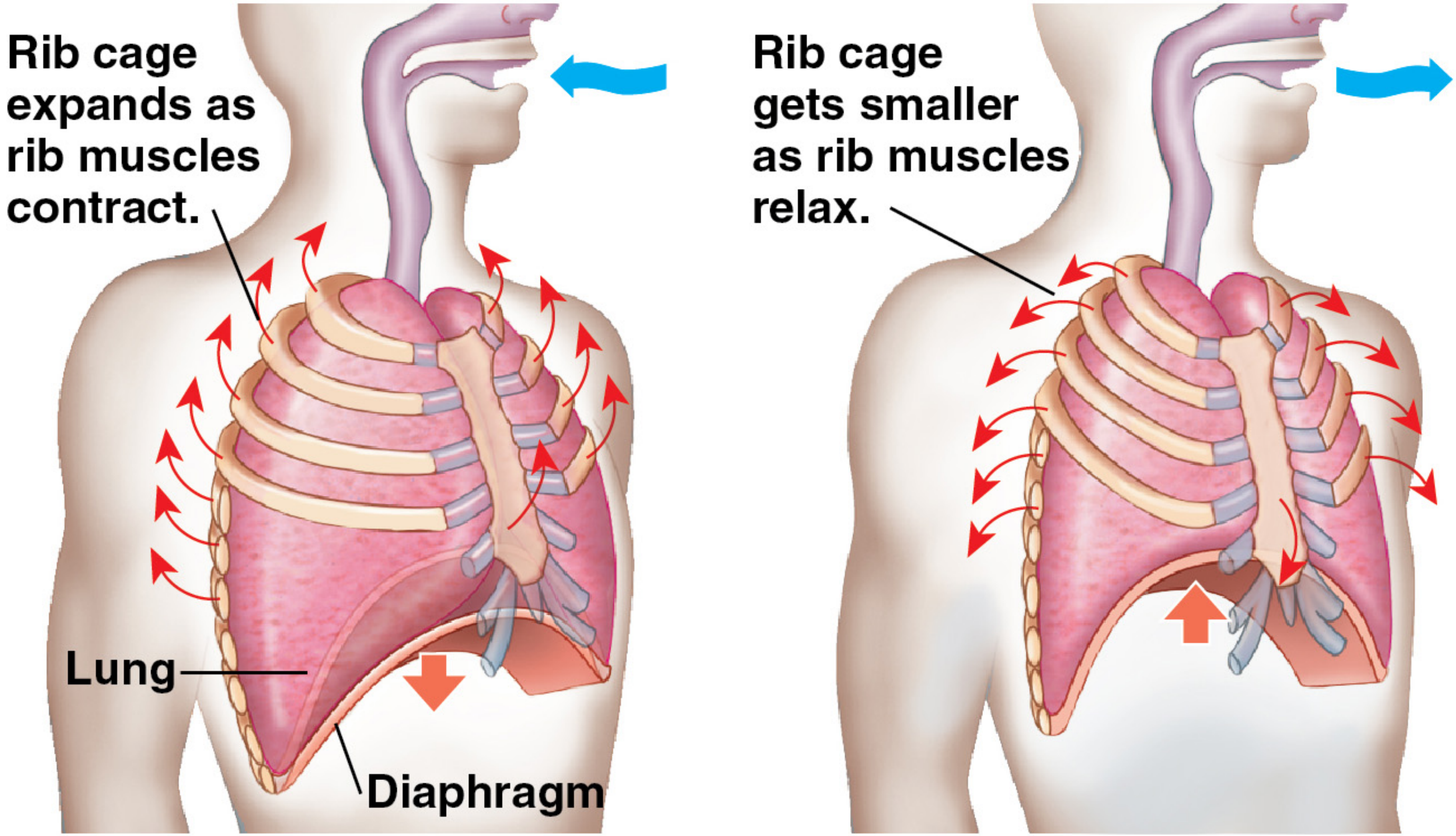
Anterior air sacs
Posterior air sacs
Lungs
Airflow
Air tubes (parabronchi) in lung
1 mm
Posterior air sacs
Lungs
Anterior air sacs
1 First inhalation
2 First exhalation
3 Second inhalation
4 Second exhalation

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
- Inhalation is active, but exhalation is usually passive

- 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
- Thus, each inhalation mixes fresh air with oxygen-depleted residual air

Figure 42.27



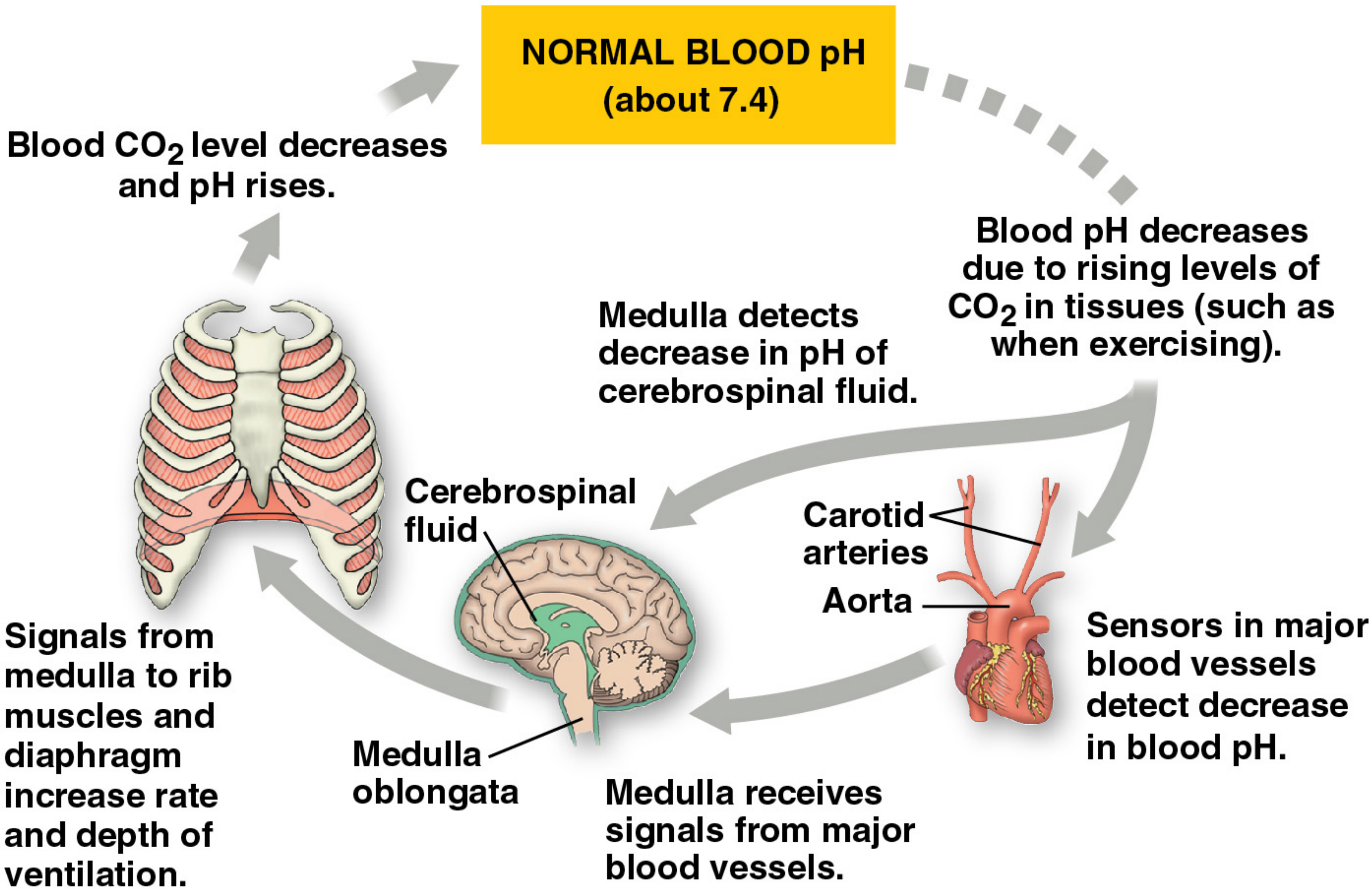
1 INHALATION: Diaphragm contracts (moves down).

2 EXHALATION: Diaphragm relaxes (moves up).

Control of Breathing in Humans

- Breathing is regulated by involuntary mechanisms
- The breathing control centers are found in the medulla oblongata of the brain
- The medulla regulates the rate and depth of breathing in response to pH changes in the cerebrospinal fluid

Figure 42.28

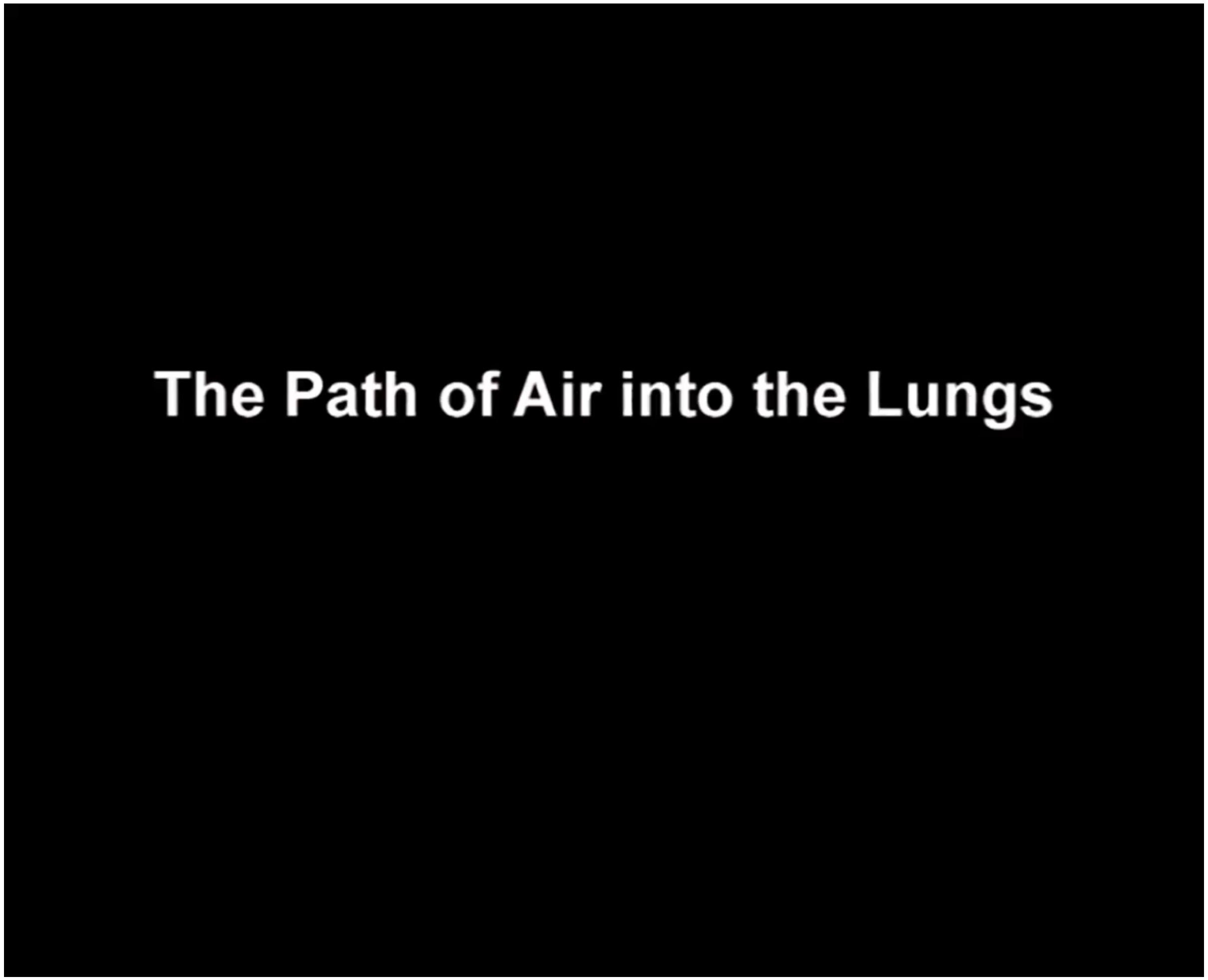


NORMAL BLOOD pH
(about 7.4)
Blood pH decreases due to rising levels of CO_2 in tissues (such as when exercising).
Medulla detects decrease in pH of cerebrospinal fluid.
Cerebrospinal fluid
Carotid arteries
Aorta
Sensors in major blood vessels detect decrease in blood pH.
Medulla oblongata
Medulla receives signals from major blood vessels.
Signals from medulla to rib muscles and diaphragm increase rate and depth of ventilation.
Blood CO_2 level decreases and pH rises.

- Sensors in medulla as well as in major blood vessels monitor O_2 and CO_2 concentrations in the blood
- These signal the breathing control centers, which respond as needed
- Additional modulation of breathing takes place in the pons, next to the medulla

Animation: The Mechanics of Breathing

BioFlix® Animation: Gas Exchange in the Human Body



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

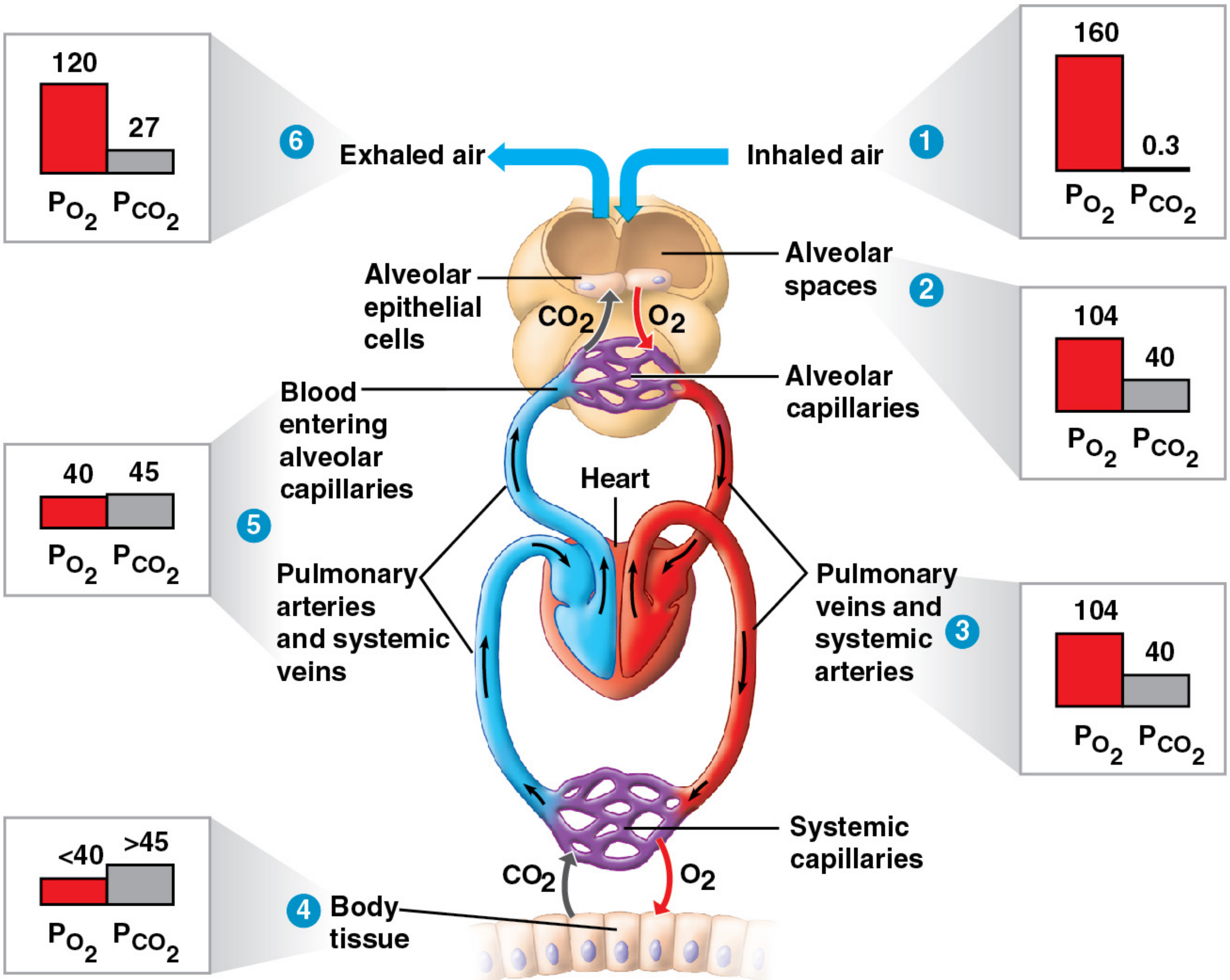
- The metabolic demands of many organisms require that the blood transport large quantities of O_2 and CO_2
- This is facilitated by blood molecules called respiratory pigments

Coordination of Circulation and Gas Exchange

- During inhalation, fresh air mixes with air in the lungs
- The resulting mixture has a higher O_2 pressure than the blood flowing through alveolar capillaries
- In the alveoli, O_2 diffuses into the blood and CO_2 diffuses into the air
- By the time the blood leaves the lungs, the pressures of O_2 and CO_2 match the values for air in the alveoli

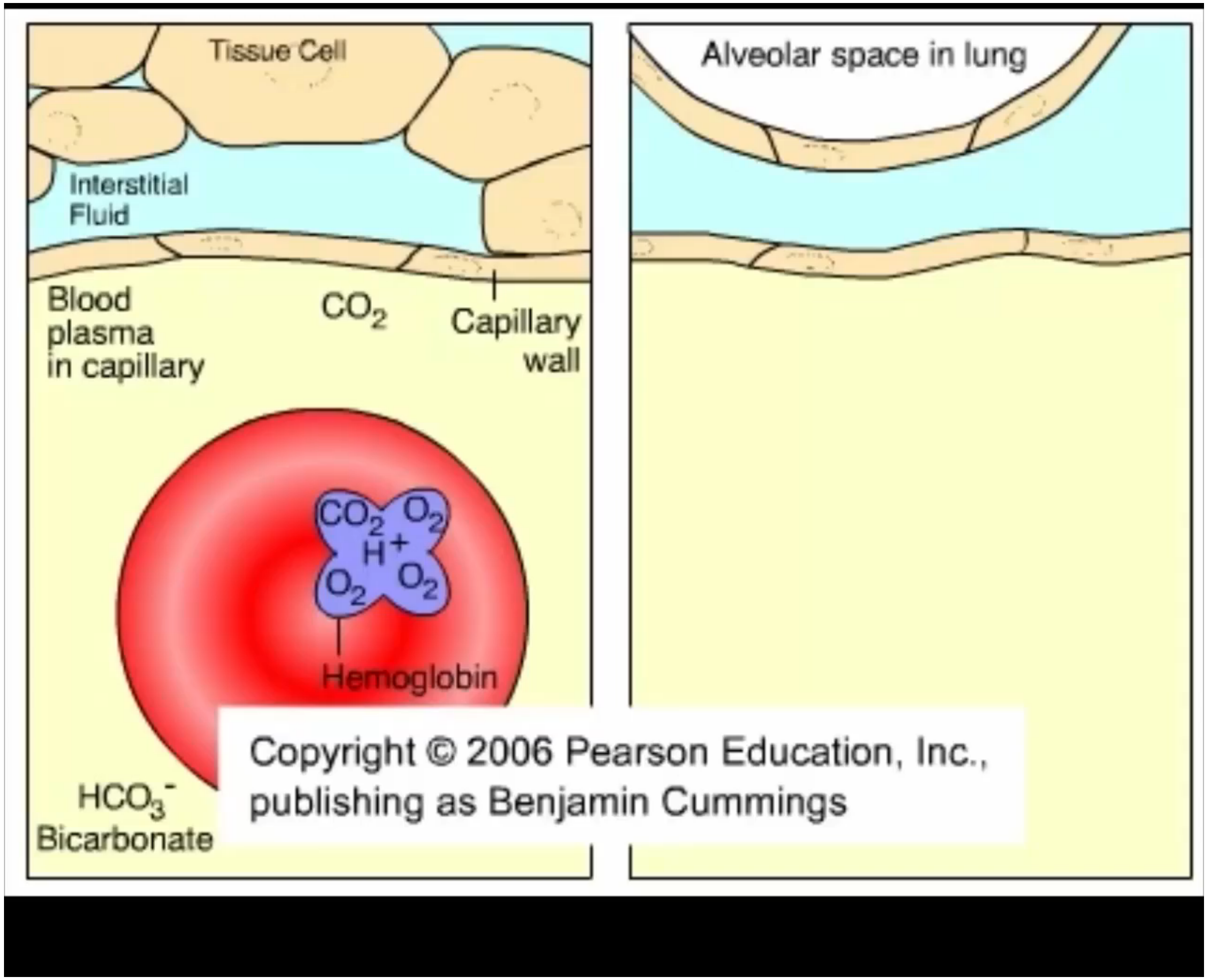
- In the systemic capillaries, gradients of partial pressure favor net diffusion of O_2 out of the blood and CO_2 into the blood
- Having unloaded O_2 and loaded CO_2, the blood is returned to the heart and pumped to the lungs again
- There, exchange occurs across the alveolar capillaries, resulting in exhaled air enriched in CO_2 and partly depleted of O_2

Figure 42.29

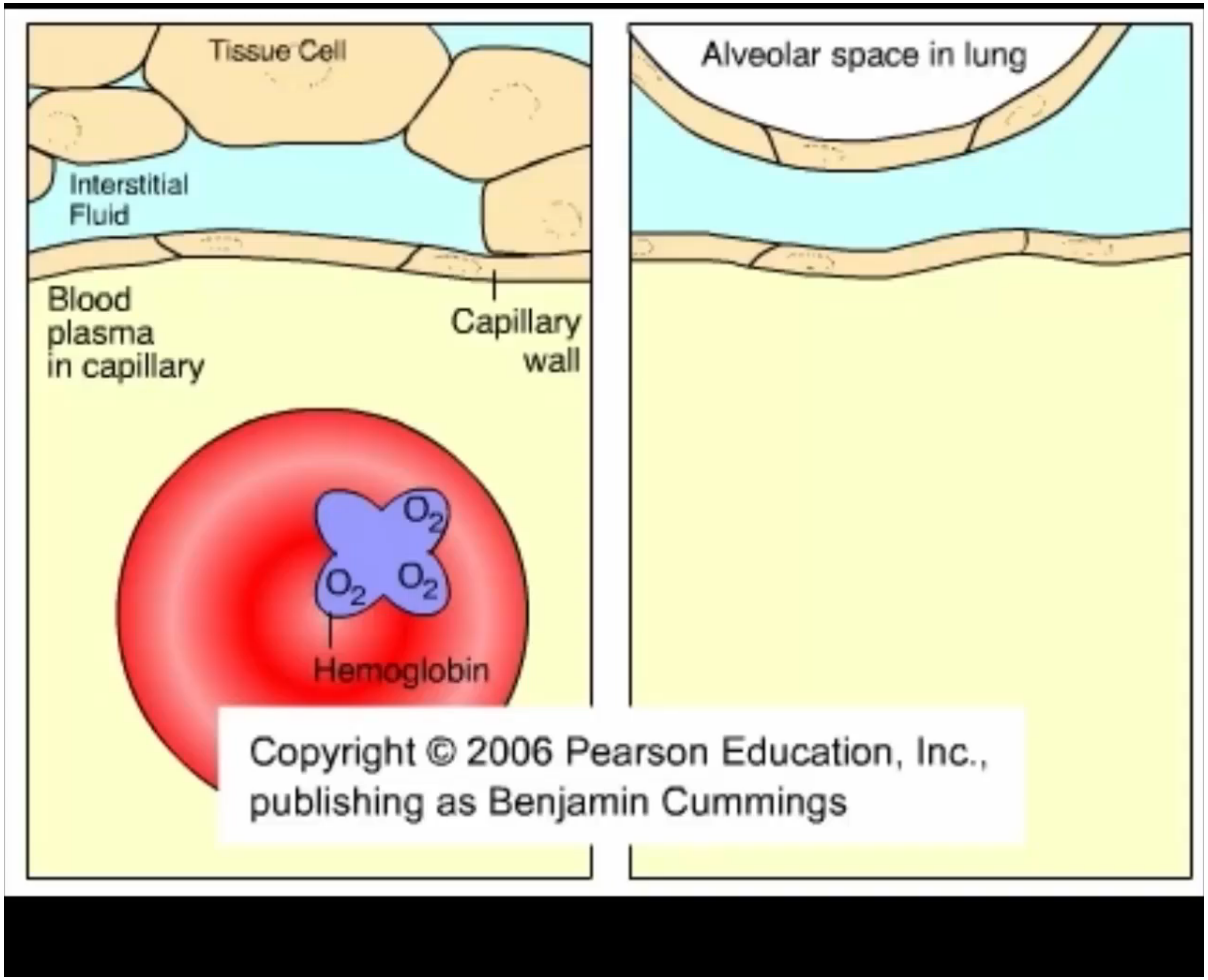


1
Inhaled air
160
0.3
P_{O_2} P_{CO_2}
Alveolar spaces
2
104
40
P_{O_2} P_{CO_2}
Alveolar epithelial cells
CO_2
O_2
Alveolar capillaries
Blood entering alveolar capillaries
Heart
Pulmonary veins and systemic arteries
3
104
40
P_{O_2} P_{CO_2}
Pulmonary arteries and systemic veins
5
40
45
P_{O_2} P_{CO_2}
Systemic capillaries
CO_2
O_2
4
Body tissue
<40
>45
P_{O_2} P_{CO_2}
6
Exhaled air
120
27
P_{O_2} P_{CO_2}

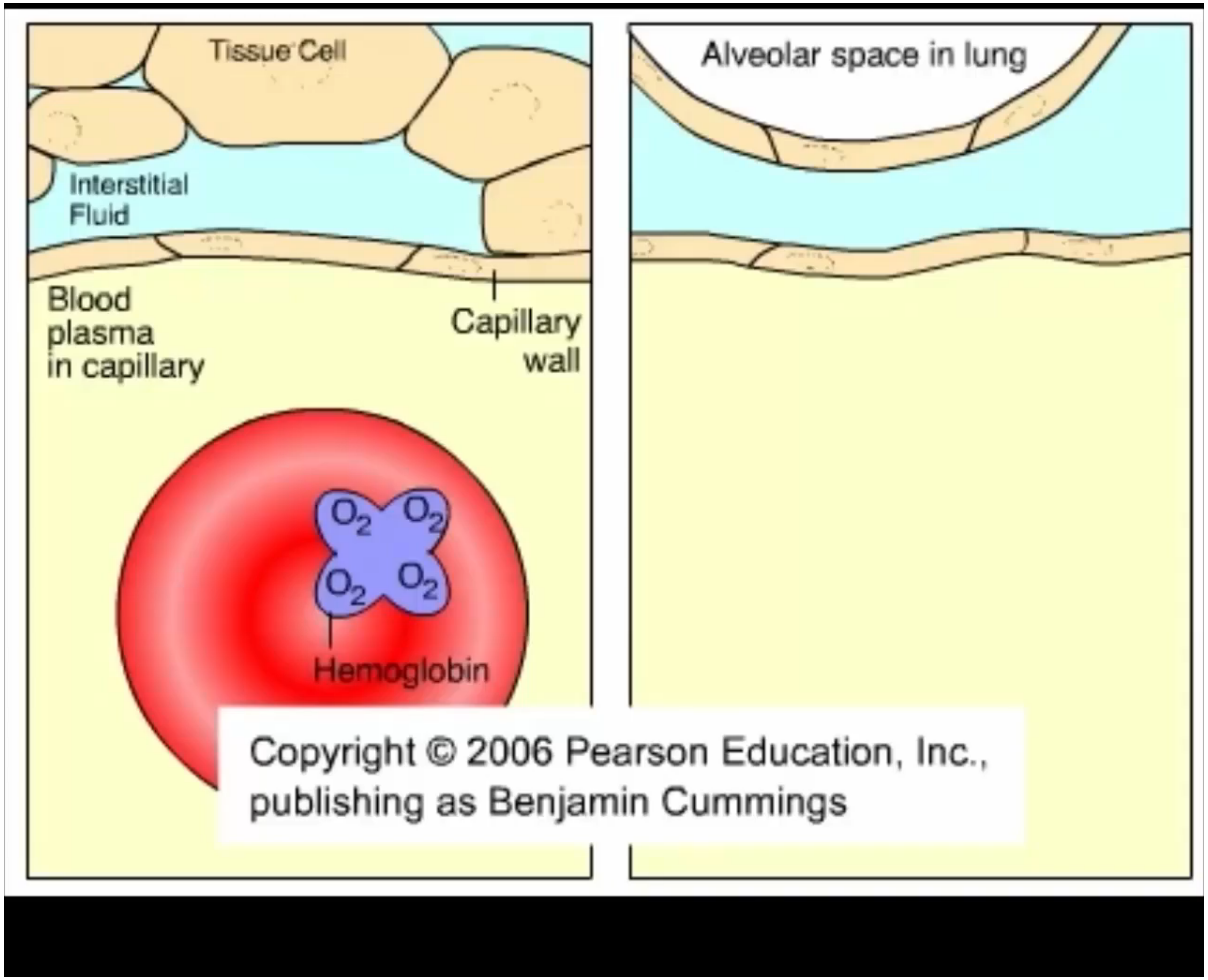
Animation: CO_2 from Blood to Lung



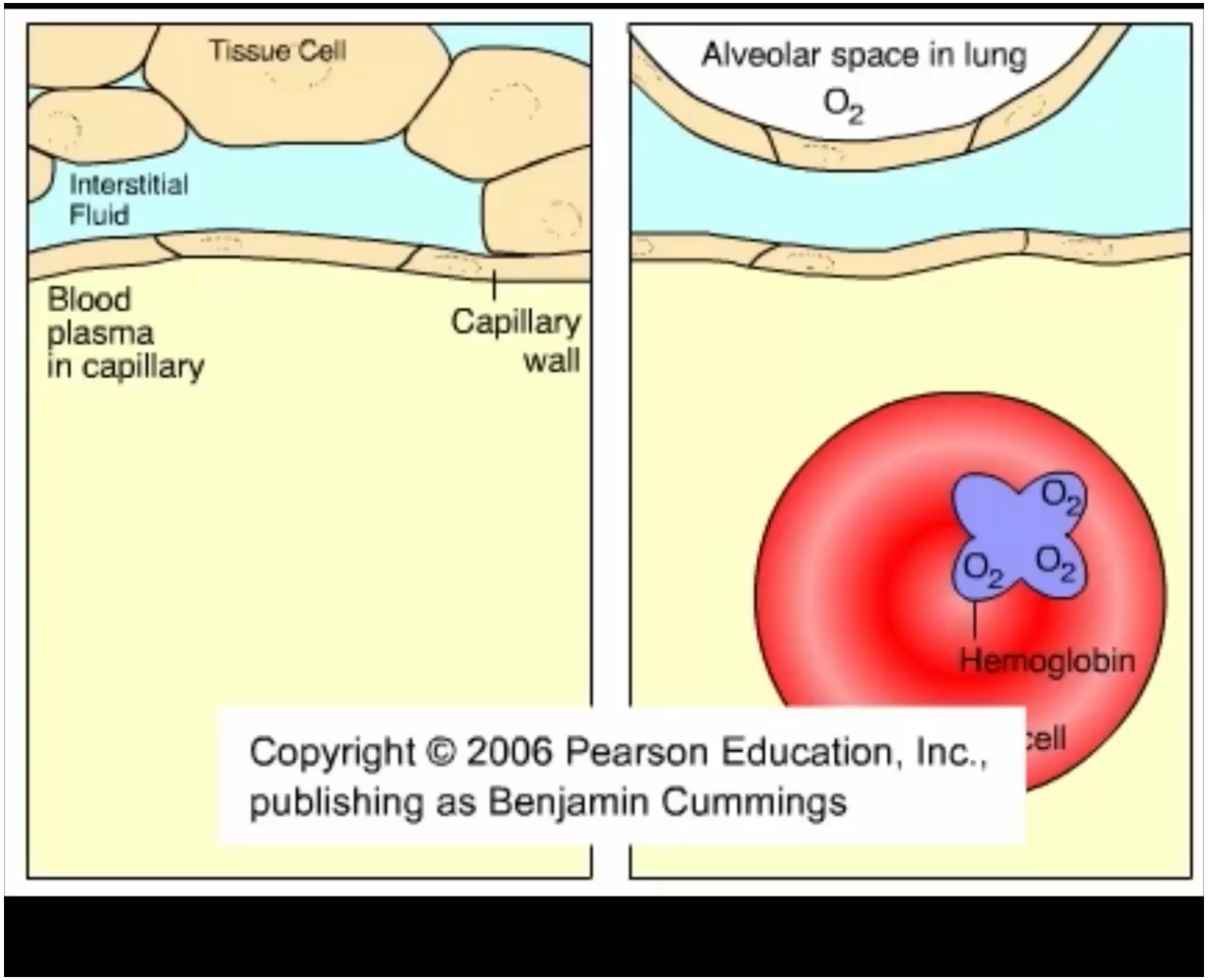
Animation: CO_2 from Tissues to Blood



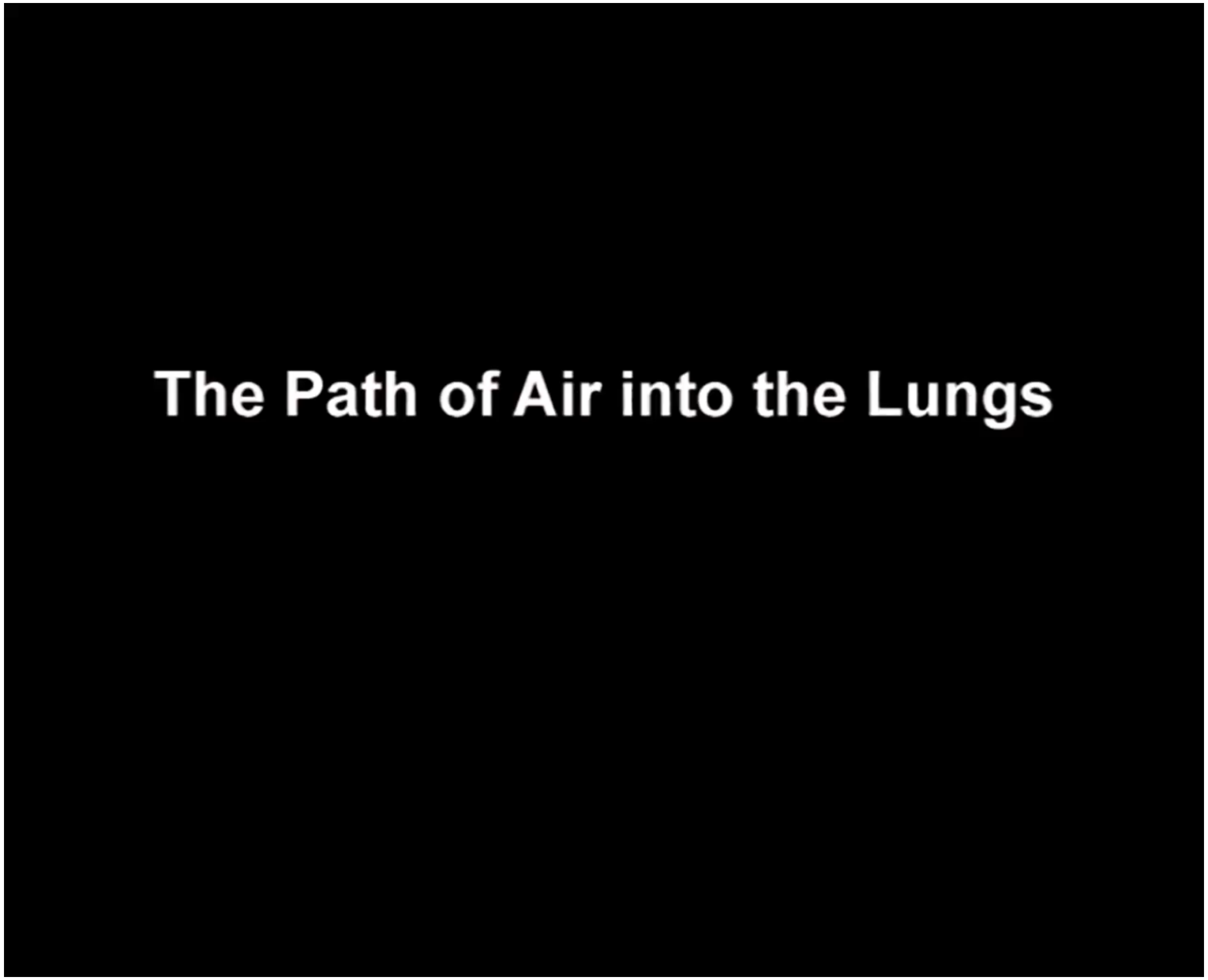
Animation: O_2 from Blood to Tissues



Animation: O_2 from Lungs to Blood



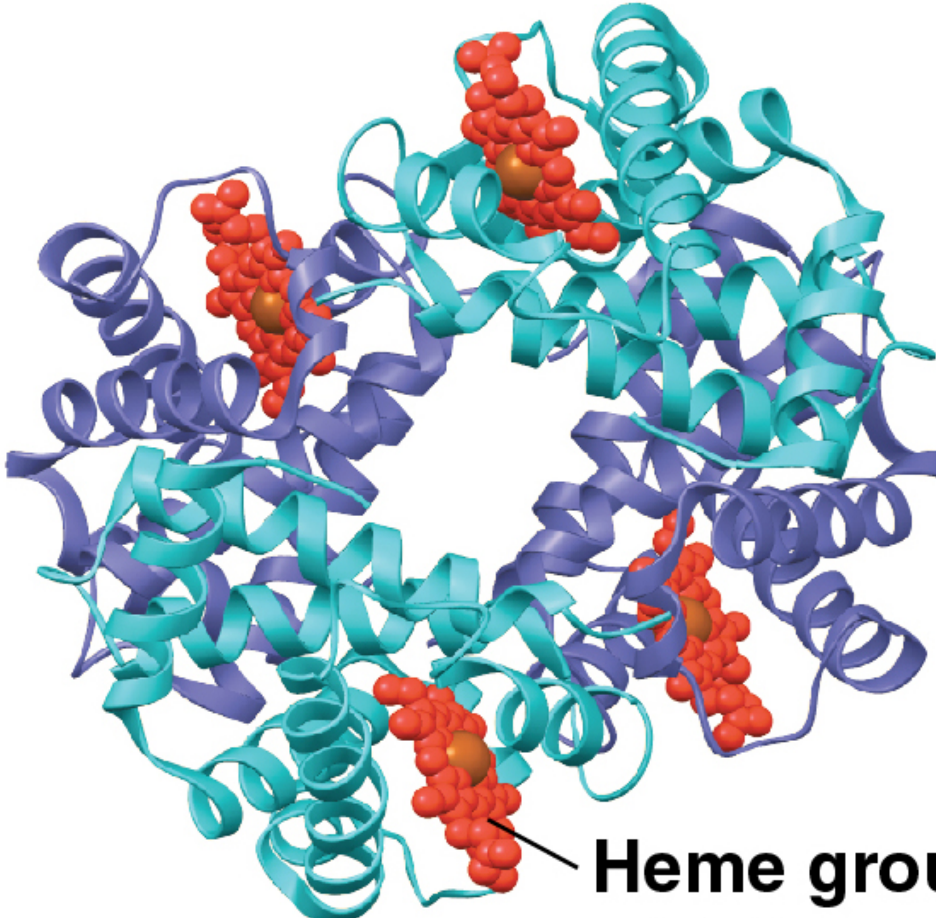
Animation BioFlix®: Gas Exchange



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 has four subunits and is contained within erythrocytes

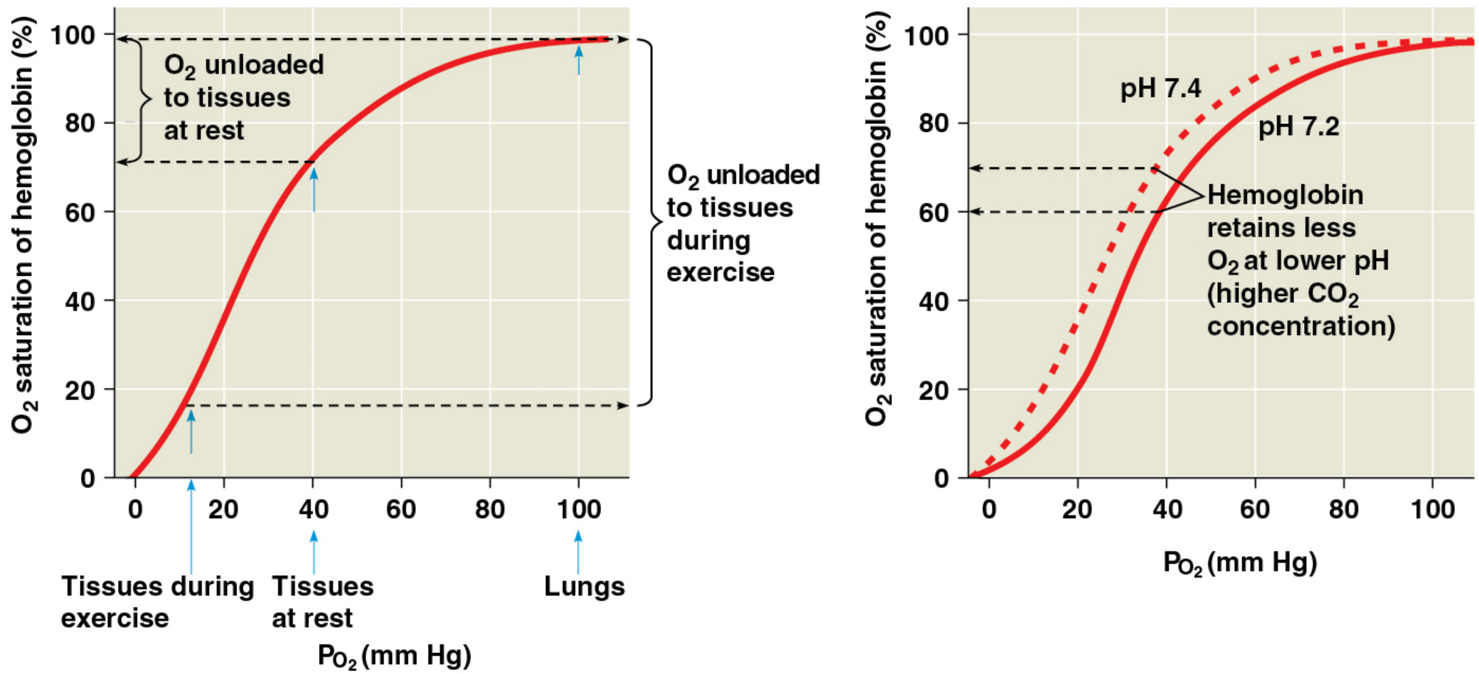
Figure 42.30



- A single hemoglobin molecule can carry four molecules of O_2, one molecule for each iron-containing heme group
- Hemaglobin binds oxygen cooperatively
- When O_2 binds one subunit, the others change shape so that their affinity to O_2 is increased
- Cooperativity in binding is shown in the dissociation curve for hemoglobin

- CO_2 produced during cellular respiration lowers blood pH and decreases the affinity of hemoglobin for O_2; this is called the **Bohr shift**
- Hemoglobin plays a minor role in transport of CO_2 and assists in buffering the blood

Figure 42.31



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

(b) pH and hemoglobin dissociation

Carbon Dioxide Transport

- Only about 7% of CO_2 from respiring cells diffuses into the blood and is transported in blood plasma, bound to hemoglobin
- The remainder diffuses into erythrocytes and reacts with water to form H_2CO_3, which dissociates into H^+ and bicarbonate ions (HCO_3^-)
- In the lungs, the relative partial pressures of CO_2 favor the net diffusion of CO_2 out of the blood

Respiratory Adaptations of Diving Mammals

- Diving mammals have evolutionary adaptations that allow them to perform extraordinary feats
  - Weddell seals in Antarctica can remain underwater for 20 minutes to an hour
  - The Cuvier's beaked whale can dive to 2,900 m and stay submerged for more than 2 hours
- These animals have a high blood-to-body-volume ratio

Figure 42.31

Weddell seal

- Deep-diving air breathers stockpile O_2 and use 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
  - Routing blood to vital tissues
  - Deriving ATP in muscles from fermentation once oxygen is depleted

Figure 42.UN01

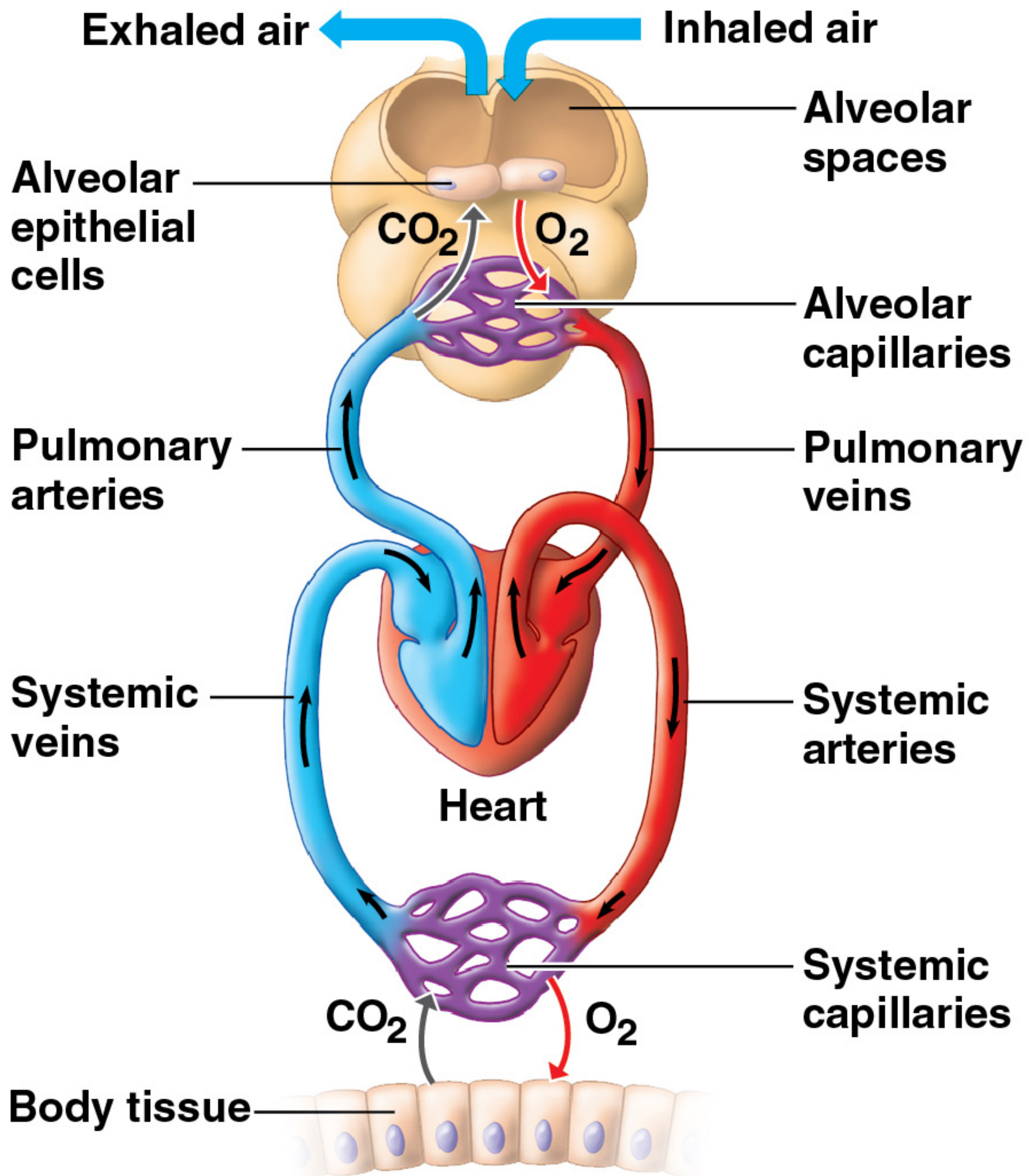


Figure 42.UN02

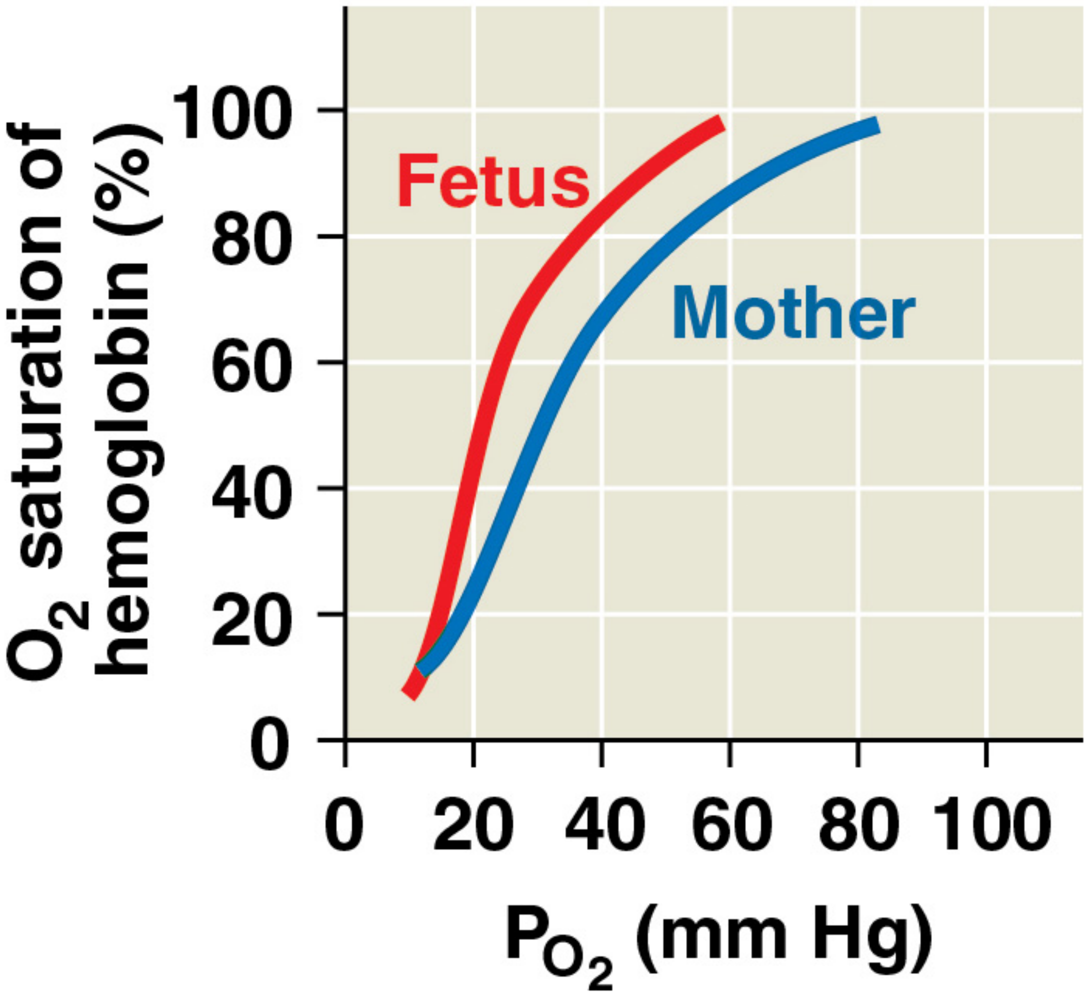


Figure 42.UN03