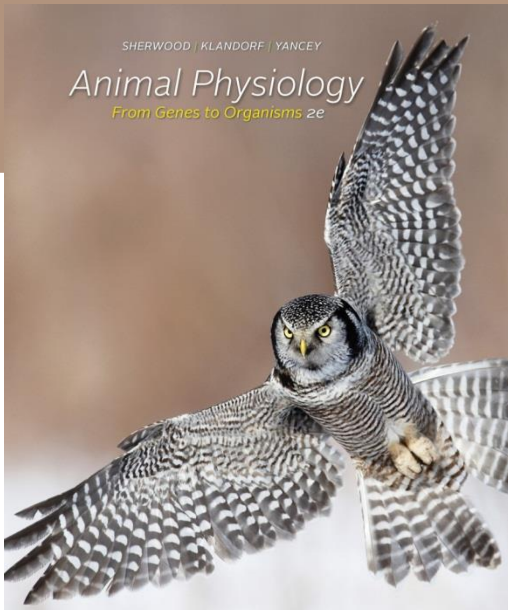


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*Lauralee Sherwood*
*Hillar Klandorf*
*Paul Yancey*

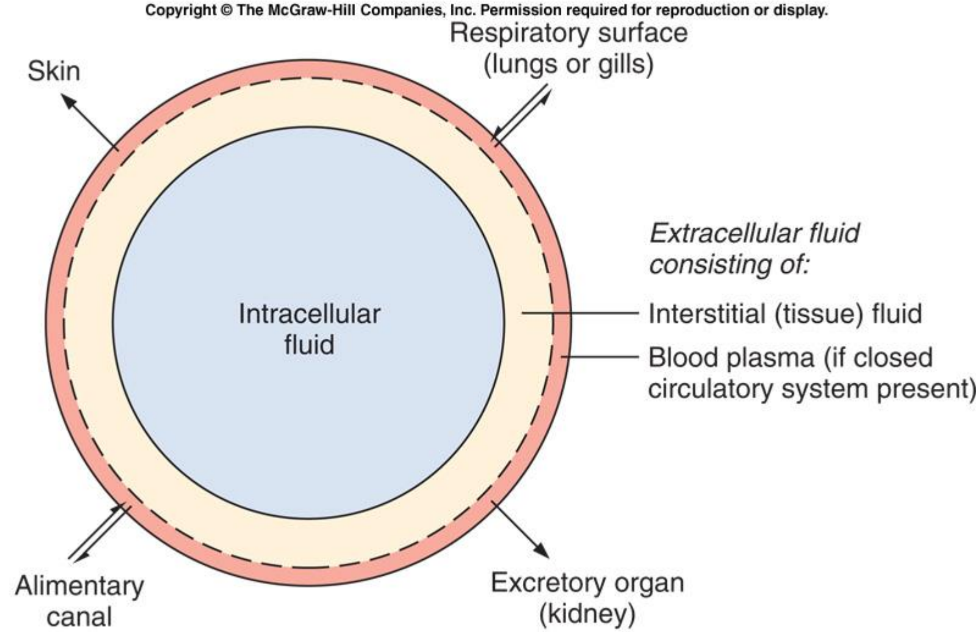
# Chapter 11
# Respiratory Systems

*Kip McGilliard • Eastern Illinois University*

# Exchanging Materials

- Every organism must exchange materials with its environment.
  - This exchange ultimately occurs at the cellular level.



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# Exchanging Materials

- In unicellular organisms, these exchanges occur directly with the environment.
- For most of the cells making up multicellular organisms, direct exchange with the environment is not possible.

# Circulatory Systems Reflect Phylogeny

- Transport systems functionally connect the organs of exchange with the body cells.

Solubility of Gases in Distilled Water

| °C | Oxygen | Carbon Dioxide | Nitrogen | Helium |
|---|---|---|---|---|
| 0 | 21.7 | 767.5 | — | — |
| 10 | 16.9 | 531.2 | — | — |
| 20 | 13.7 | 386.8 | 6.82 | — |
| 30 | 11.6 | 294.9 | — | — |
| 37 | 10.6 | 250.5 | 5.61 | 3.75 |
| 40 | 10.2 | 234.8 | — | — |

## Effect of Salinity on Oxygen Solubility

| °C | Salinity | 0‰ | 10‰ | 20‰ | 30‰ | 40‰ |
|---|---|---|---|---|---|---|
| 0 | | 21.7 | 20.2 | 18.9 | 17.7 | 16.6 |
| 10 | | 16.9 | 15.8 | 14.8 | 13.9 | 13.1 |
| 20 | | 13.7 | 12.9 | 12.2 | 11.5 | 10.8 |
| 30 | | 11.6 | 11.0 | 10.4 | 9.86 | 9.33 |
| 40 | | 10.2 | 9.71 | 9.26 | 8.73 | 8.35 |

Effects of high altitude on atmospheric pressure ($P_b$; kPa), ambient $pO_2$ (kPa), and alveolar $pO_2$ and $pCO_2$ ($p_A O_2$, and $p_A CO_2$; kPa) for a human.

| Altitude | $P_b$ | Ambient $pO_2$ | $p_A O_2$ | $p_A CO_2$ |
|---|---|---|---|---|
| 0 | 101 | 21.1 | 13.8 | 5.3 |
| 3100 | 70.6 | 14.6 | 8.9 | 4.8 |
| 4340 | 61.9 | 12.8 | 6.0 | — |
| 6200 | 46 | 9.7 | 5.3 | 3.2 |
| 7100 | ——— | normal "ceiling" | | ——— |
| 8848 | 33 | 6.9 | 4.0 | 1.5 |
| 9200 | 30 | 6.3 | 2.8 | — |
| 12300 | 19 | 3.9 | 1.1 | — |
| 14460 | ——— | "ceiling" with pure $O_2$ | | ——— |
| 15400 | 12 | 2.4 | 0.1 | — |
| 20000 | 6 | 1.3 | 0 | 0 |

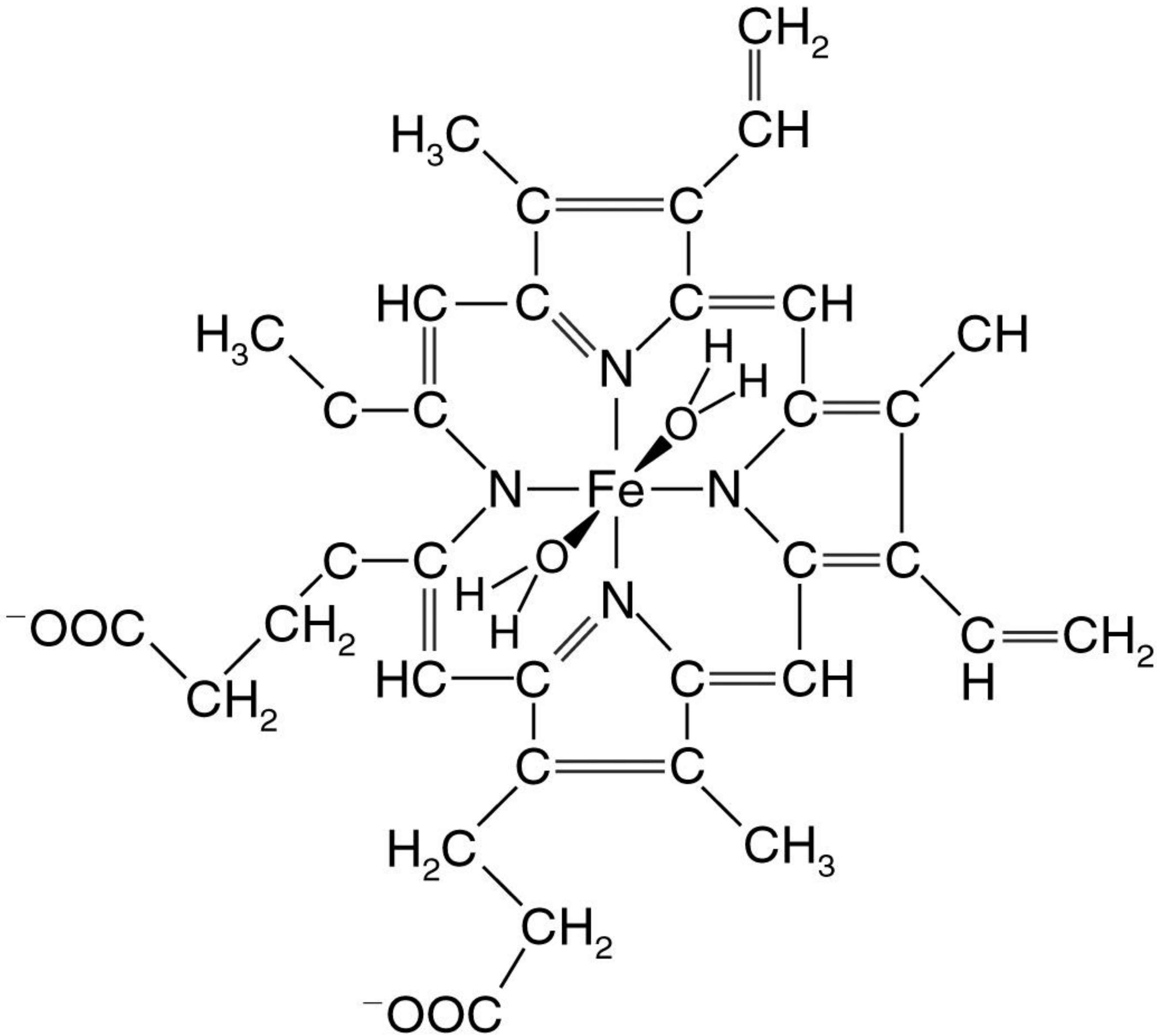
Sea level

$P_{O2}$ =760*0.2094 = 159 mmHg

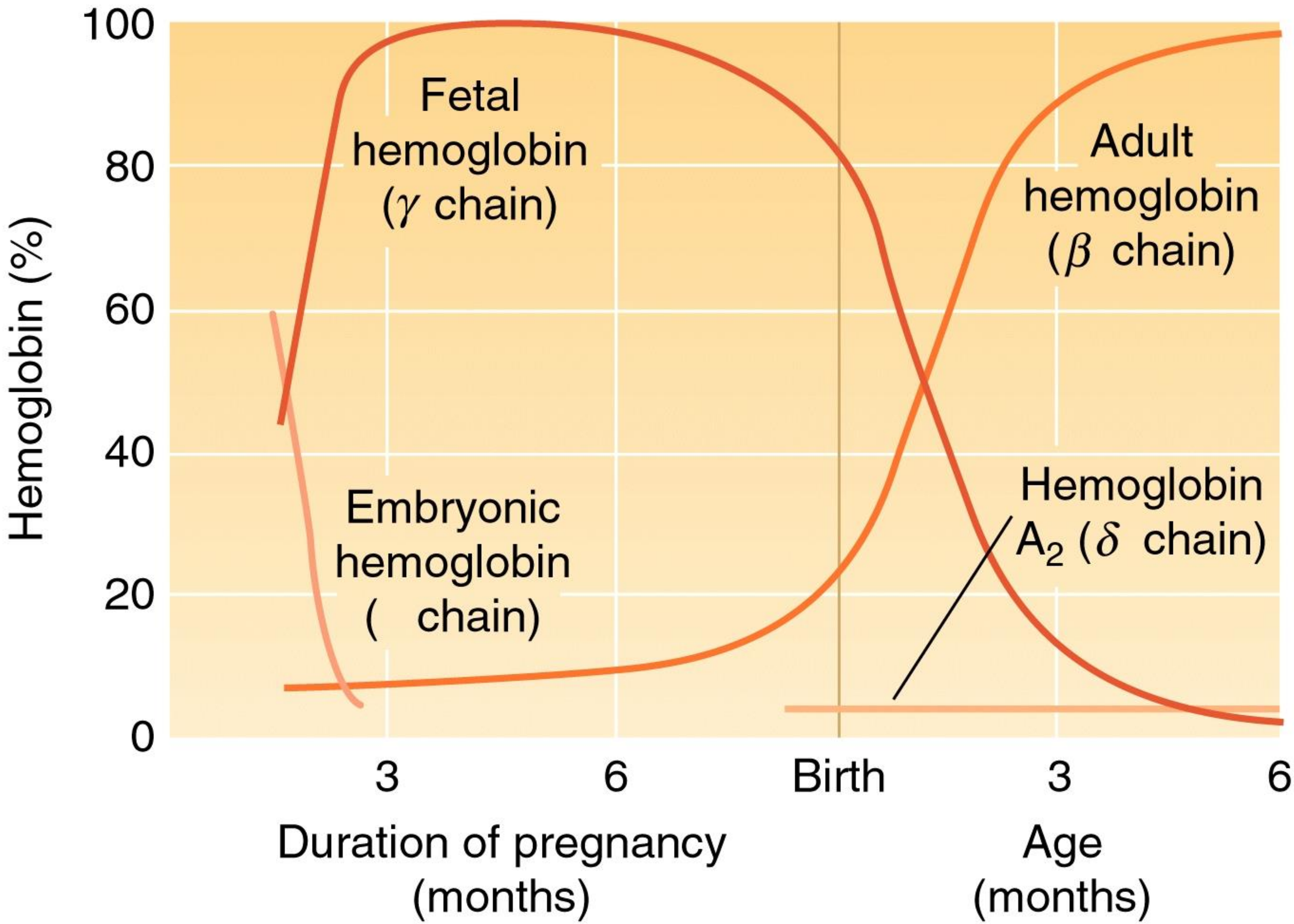
$P_{O2}$ =(760-18)*0.2094 = 155 mmHg

Partial pressures (kPa) for oxygen and nitrogen (dry, $CO_2$-free values for ambient air), alveolar carbon dioxide, and plasma-dissolved $O_2$ (ml $O_2$ per liter plasma; assuming plasma solubility of $O_2$ is 0.209 ml liter$^{-1}$ kPa$^{-1}$) and fat $N_2$ content (ml $N_2$ per liter body fat; assuming fat solubility of $N_2$ is 0.67 ml liter$^{-1}$ kPa$^{-1}$ dissolved $N_2$) for a human scuba diver in equilibrium with the ambient hydrostatic pressure as a function of depth of diving.

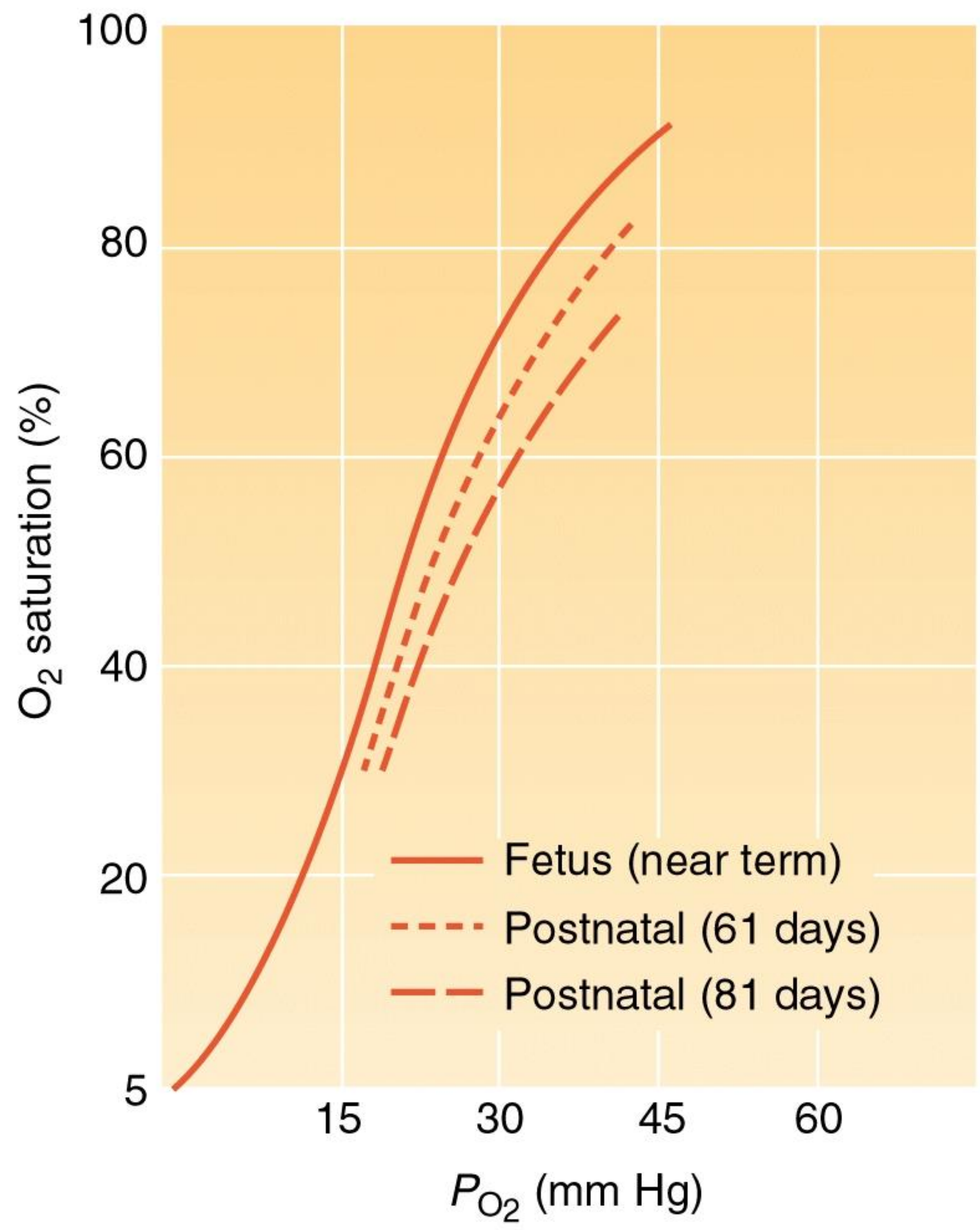
| **Depth (m)** | **0** | **50** | **100** | **500** |
|---|---|---|---|---|
| Ambient Pressure | 101 | 202 | 1111 | 5151 |
| $pO_2$ | 21.1 | 42.4 | 233.5 | 1082.6 |
| $pN_2$ | 79.8 | 159.7 | 878.3 | 4072.5 |
| Alveolar $pCO_2$ | 5.32 | 5.32 | 5.32 | 5.32 |
| Plasma $O_2$ | 4.4 | 8.8 | 48.3 | 223.9 |
| Fat $N_2$ | 53 | 106 | 582 | 2700 |

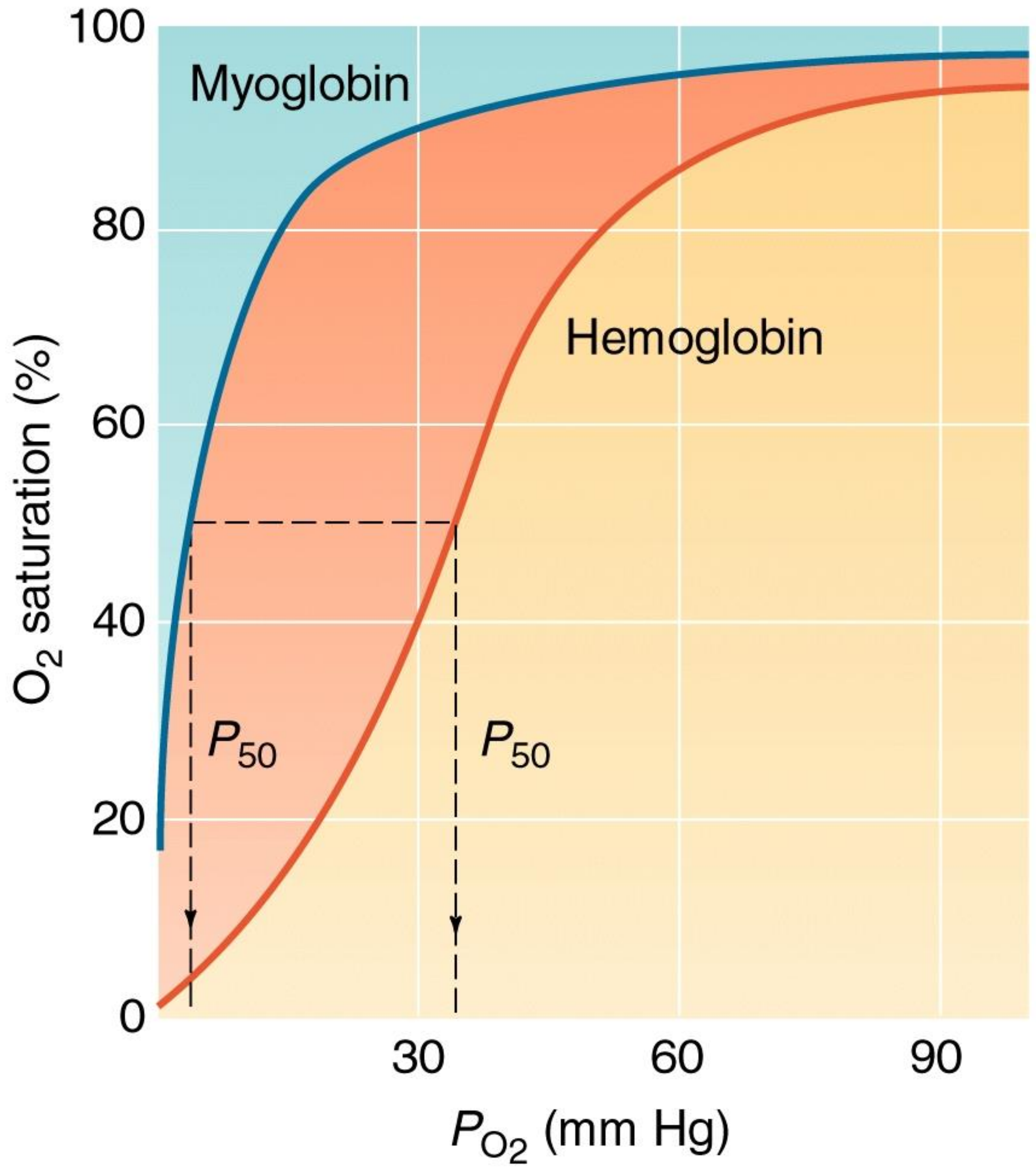


**Heme**

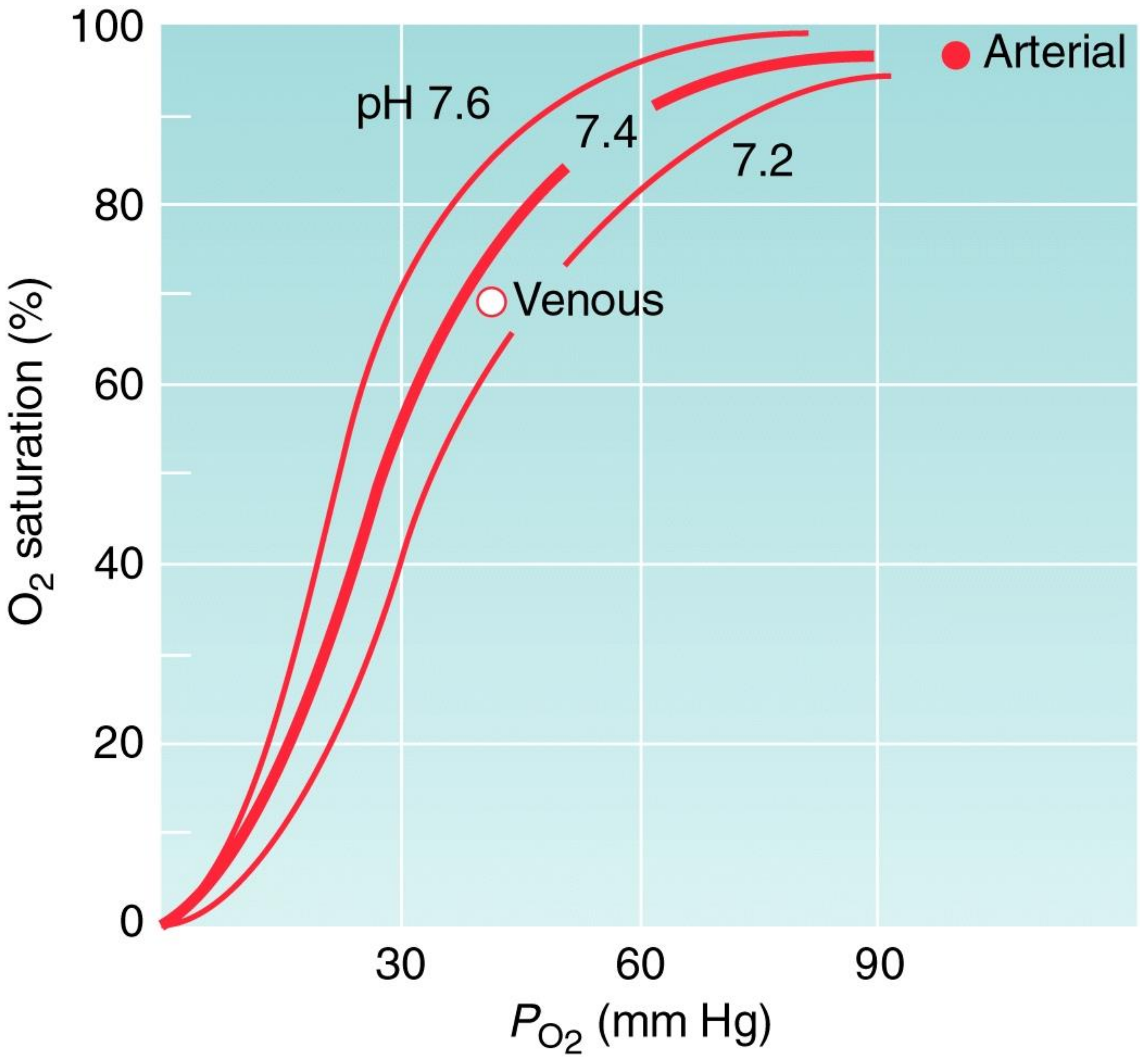


Hemoglobin (%)
100
80
60
40
20
0
Fetal hemoglobin ($\gamma$ chain)
Adult hemoglobin ($\beta$ chain)
Embryonic hemoglobin ( chain)
Hemoglobin $A_2$ ($\delta$ chain)
3
6
Birth
3
6
Duration of pregnancy (months)
Age (months)

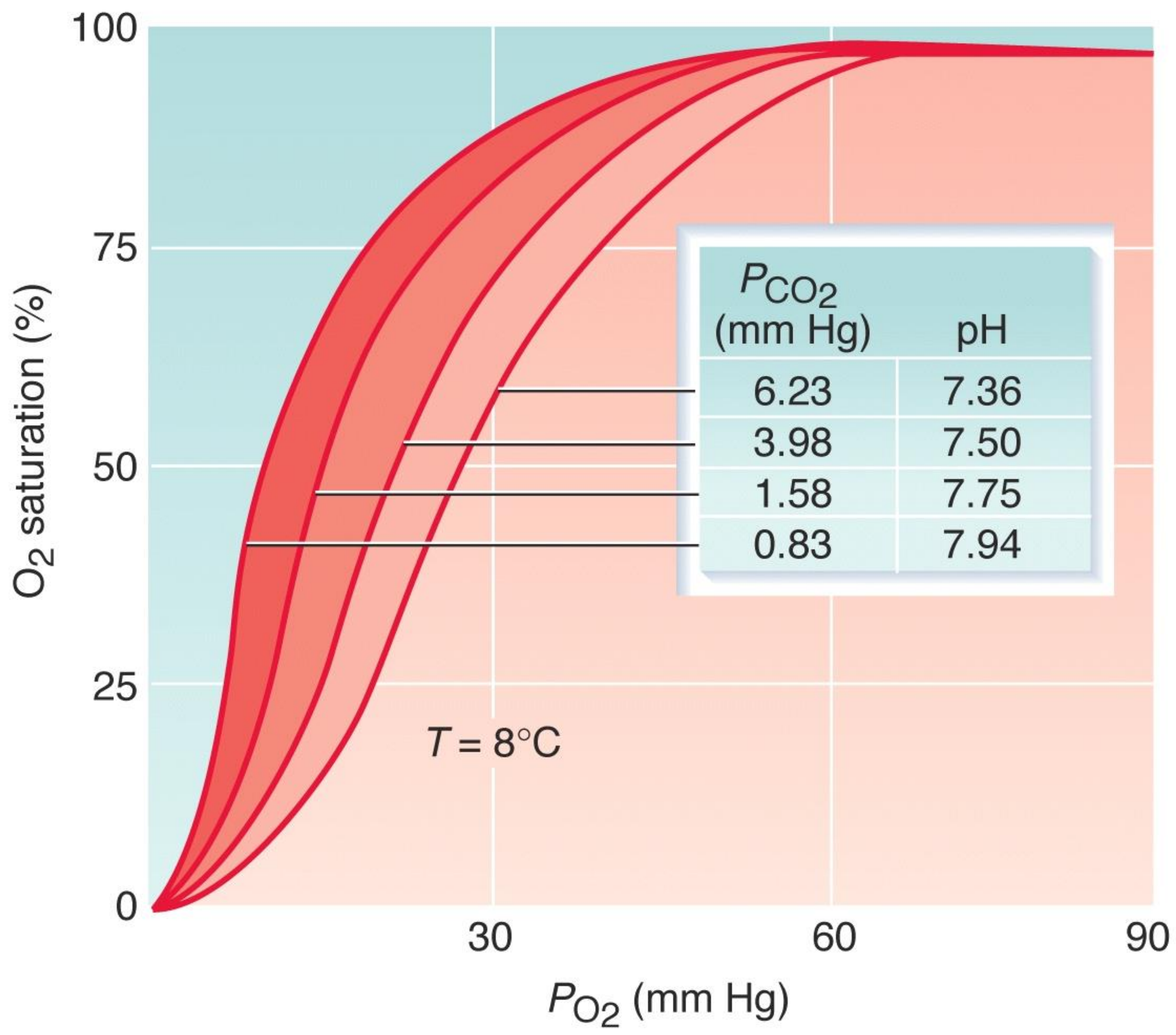

100
80
60
40
20
5
O2 saturation (%)
15
30
45
60
PO2 (mm Hg)
Fetus (near term)
Postnatal (61 days)
Postnatal (81 days)

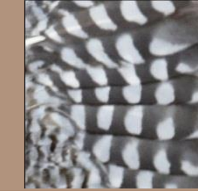


Myoglobin
Hemoglobin
P50
P50
O2 saturation (%)
PO2 (mm Hg)
0
20
40
60
80
100
30
60
90

100
80
60
40
20
0
30
60
90
$O_2$ saturation (%)
$P_{O_2}$ (mm Hg)
pH 7.6
7.4
7.2
Arterial
Venous


100
75
50
25
0
$O_2$ saturation (%)
30
60
90
$P_{O_2}$ (mm Hg)
$T$ = 8°C
$P_{CO_2}$ (mm Hg)
pH
6.23 7.36
3.98 7.50
1.58 7.75
0.83 7.94



# 11.1 Gas Demands: General Problems and Evolutionary Solutions

- Four steps in external respiration
  - **Ventilation**
    - Bulk transport of external media across a gas exchange surface
  - **Respiratory exchange**
    - Gas diffusion between the environmental medium and internal body fluids
  - **Circulation**
    - Bulk transport of the ECF
  - **Cellular exchange**
    - Gas diffusion between the cell’s immediate surroundings and its mitochondria

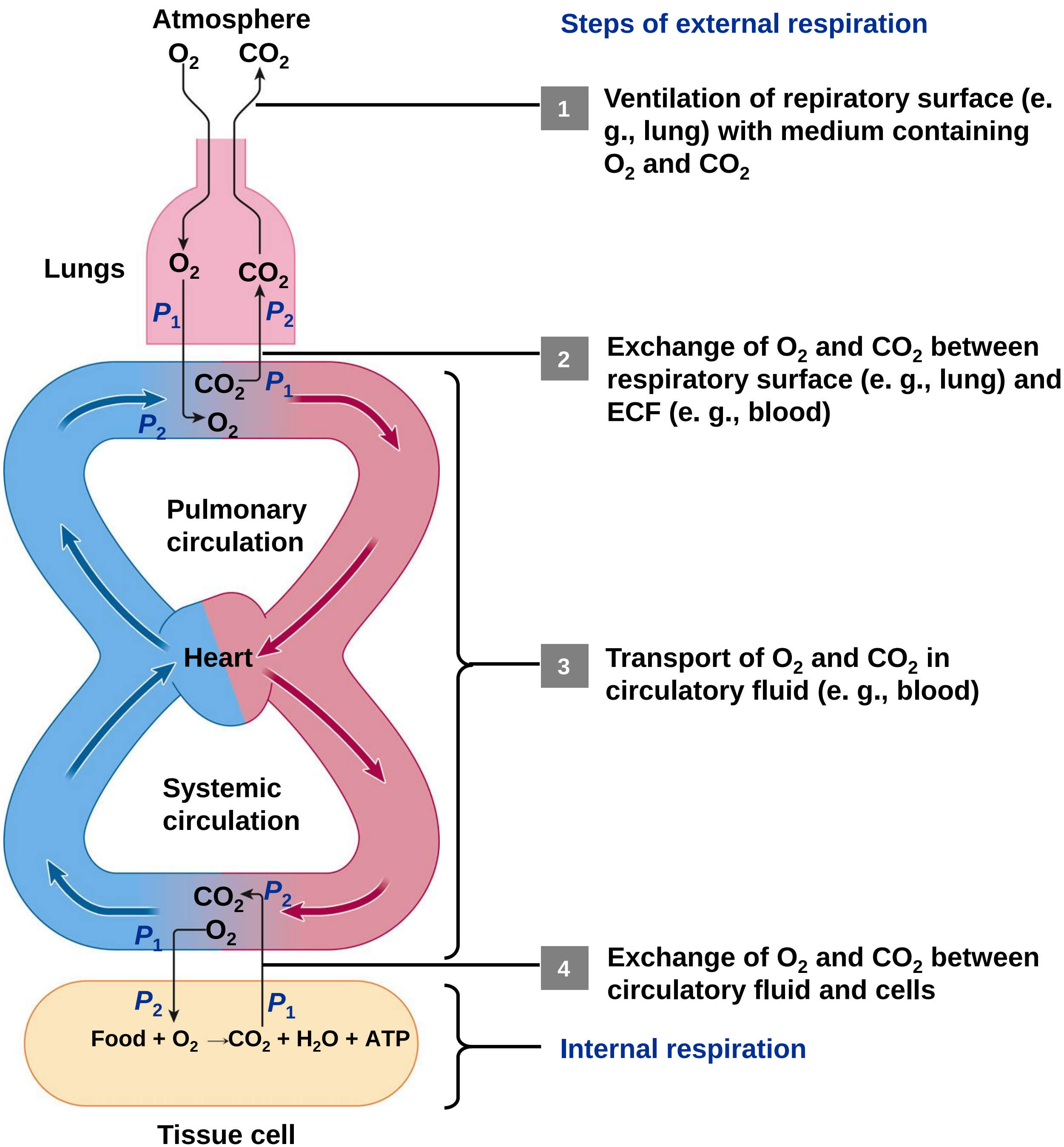



Figure 11-1 p494

# 11.1 Gas Demands: General Problems and Evolutionary Solutions

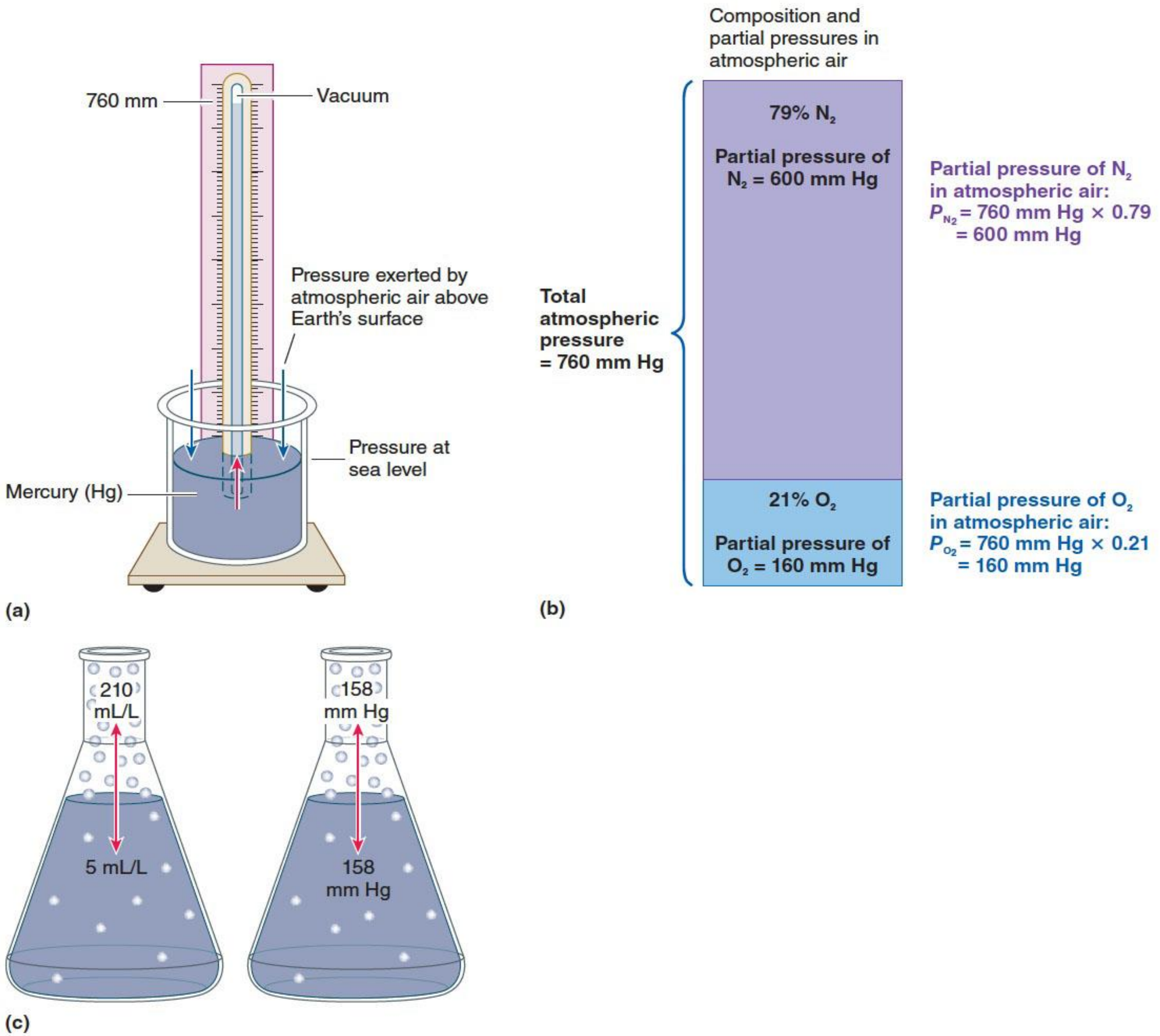
- Gas diffusion follows Fick's law

  - For gases, **concentration gradient** is replaced by **partial pressure gradient**

  - The **partial pressure** of a gas ($P_{gas}$) is the pressure exerted independently by the gas within a mixture of gases
    - Example: $Po_2$ in dry atmospheric air (21% $O_2$) is 0.21 x 760 mmHg = 160 mmHg

  - Water that is in **equilibrium** with air has the **same gas partial pressures** as the air
    - **Concentrations may be different**, depending on the solubility of the gas

# 11.1 Gas Demands: General Problems and Evolutionary Solutions



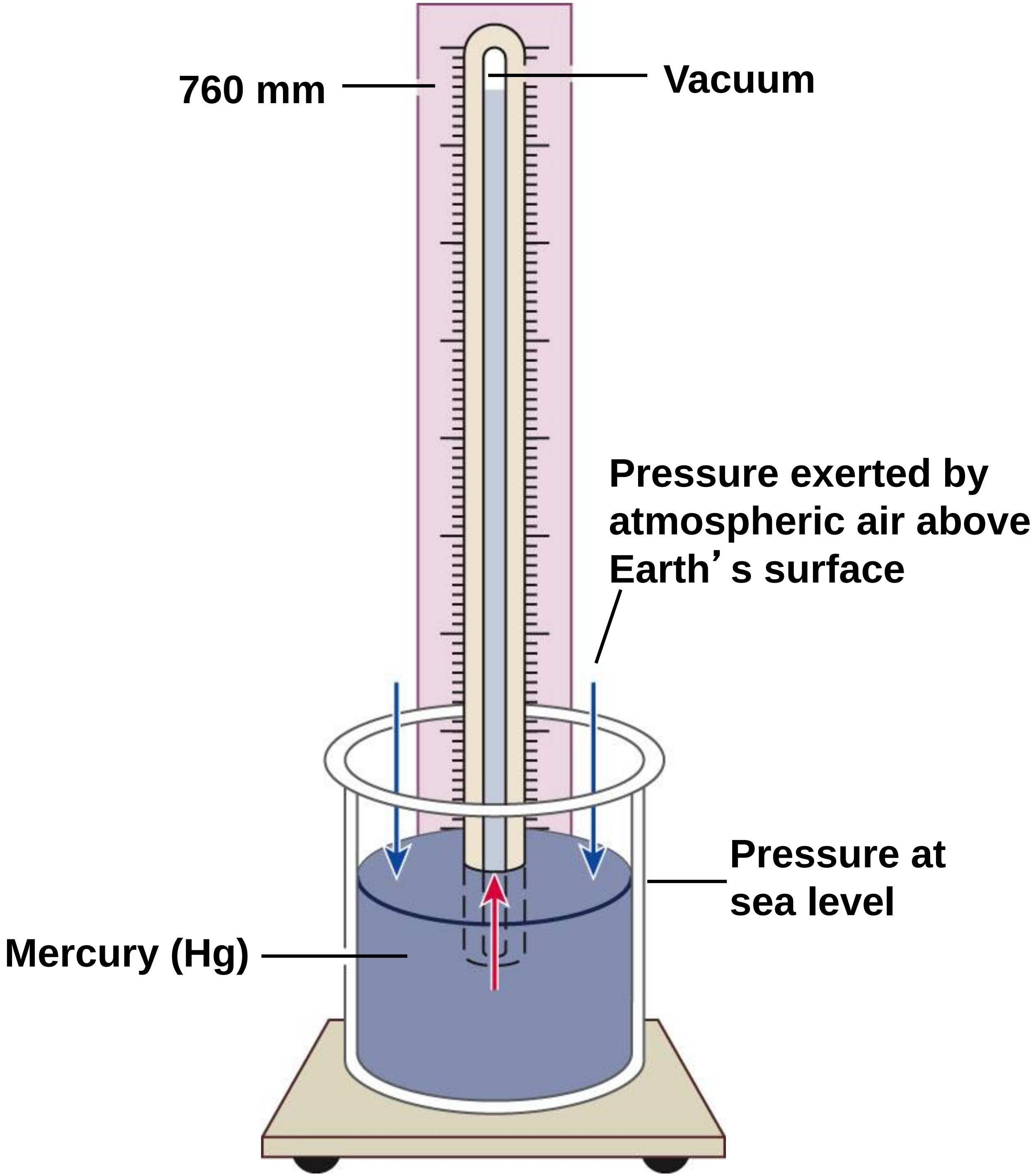
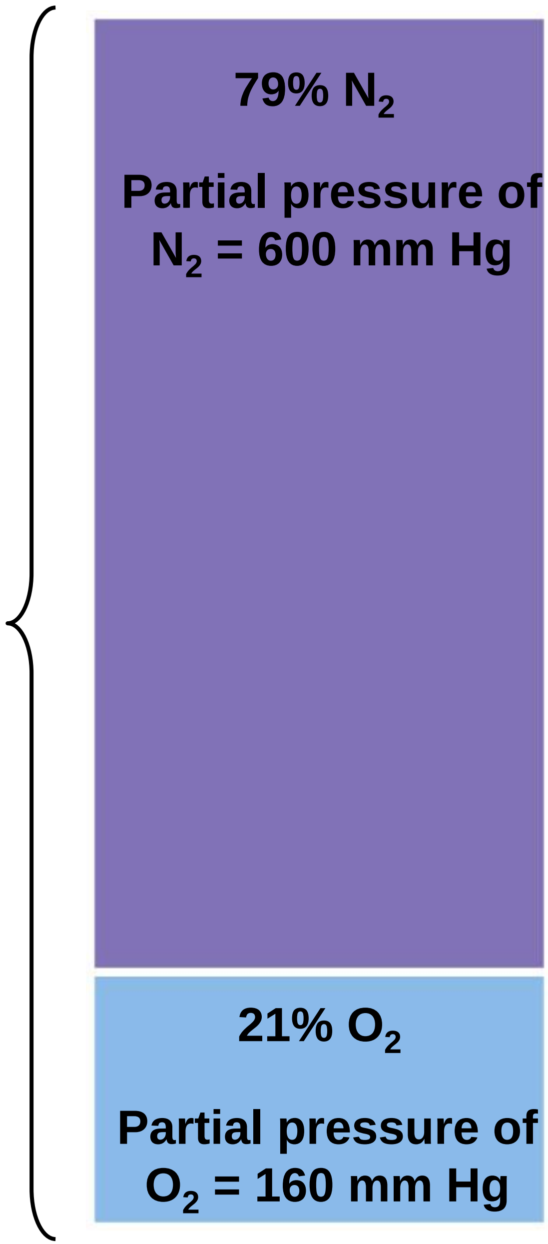



Figure 11-2a p495

**Composition and partial pressures in atmospheric air**

**Total atmospheric pressure = 760 mm Hg**



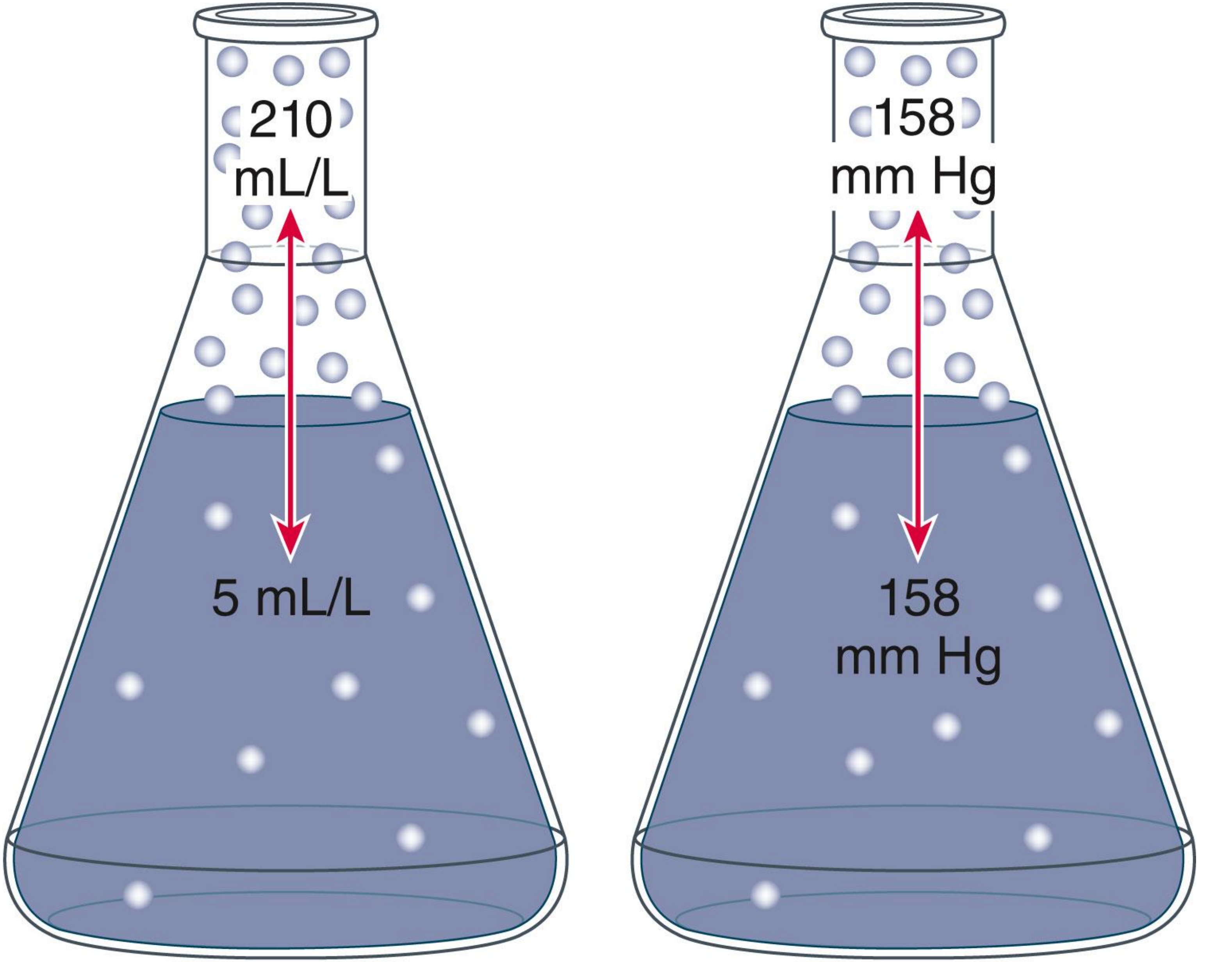

**Partial pressure of $N_2$ in atmospheric air:**

$P_{N_2}$ **= 760 mm Hg x 0.**
**= 600 mm Hg**

**Partial pressure of $O_2$ in atmospheric air:**

$P_{O_2}$ **= 760 mm Hg x 0.21**
**= 160 mm Hg**

Figure 11-2b p495



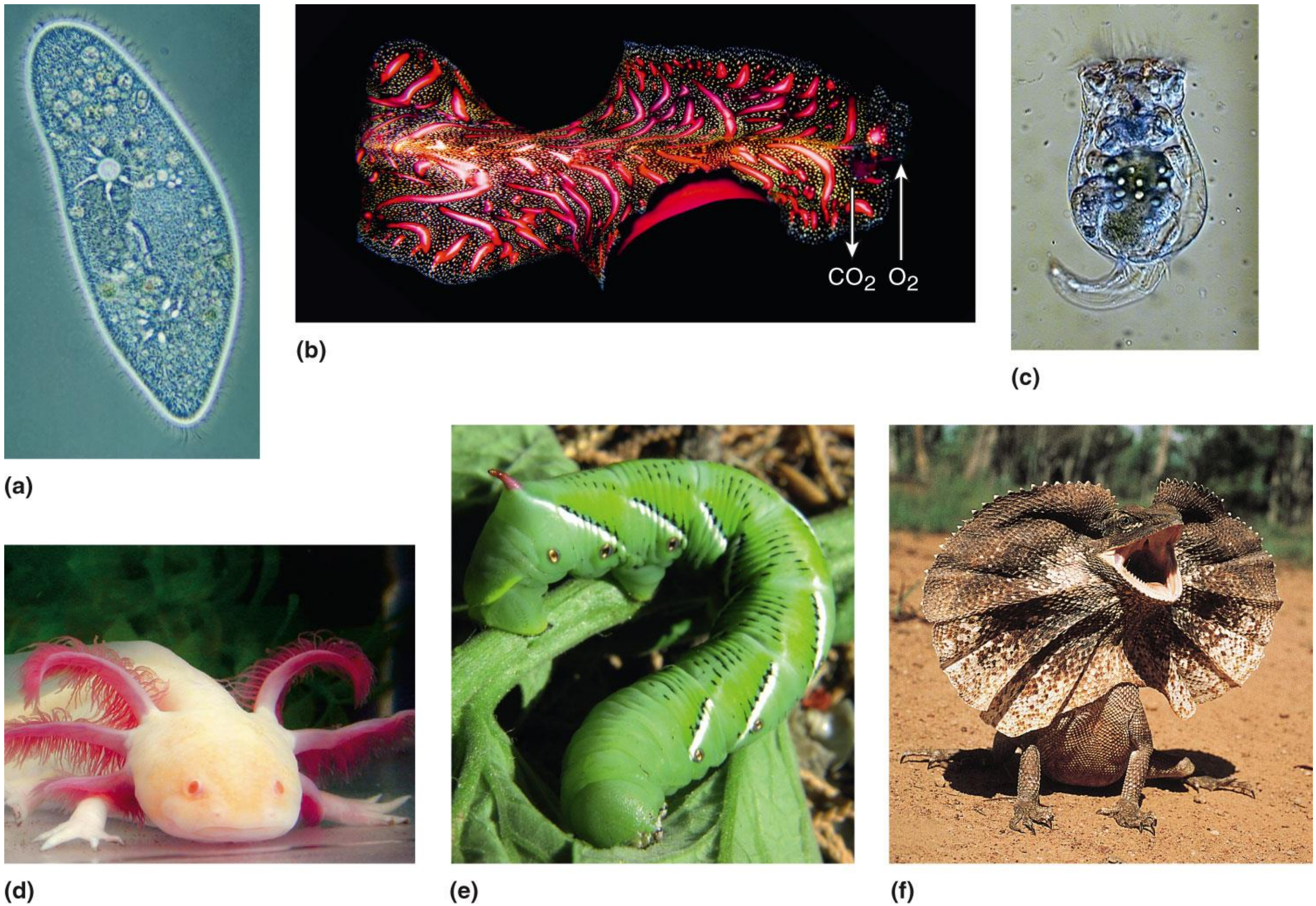

(c)

Figure 11-2c p495

# 11.1 Gas Demands: General Problems and Evolutionary Solutions

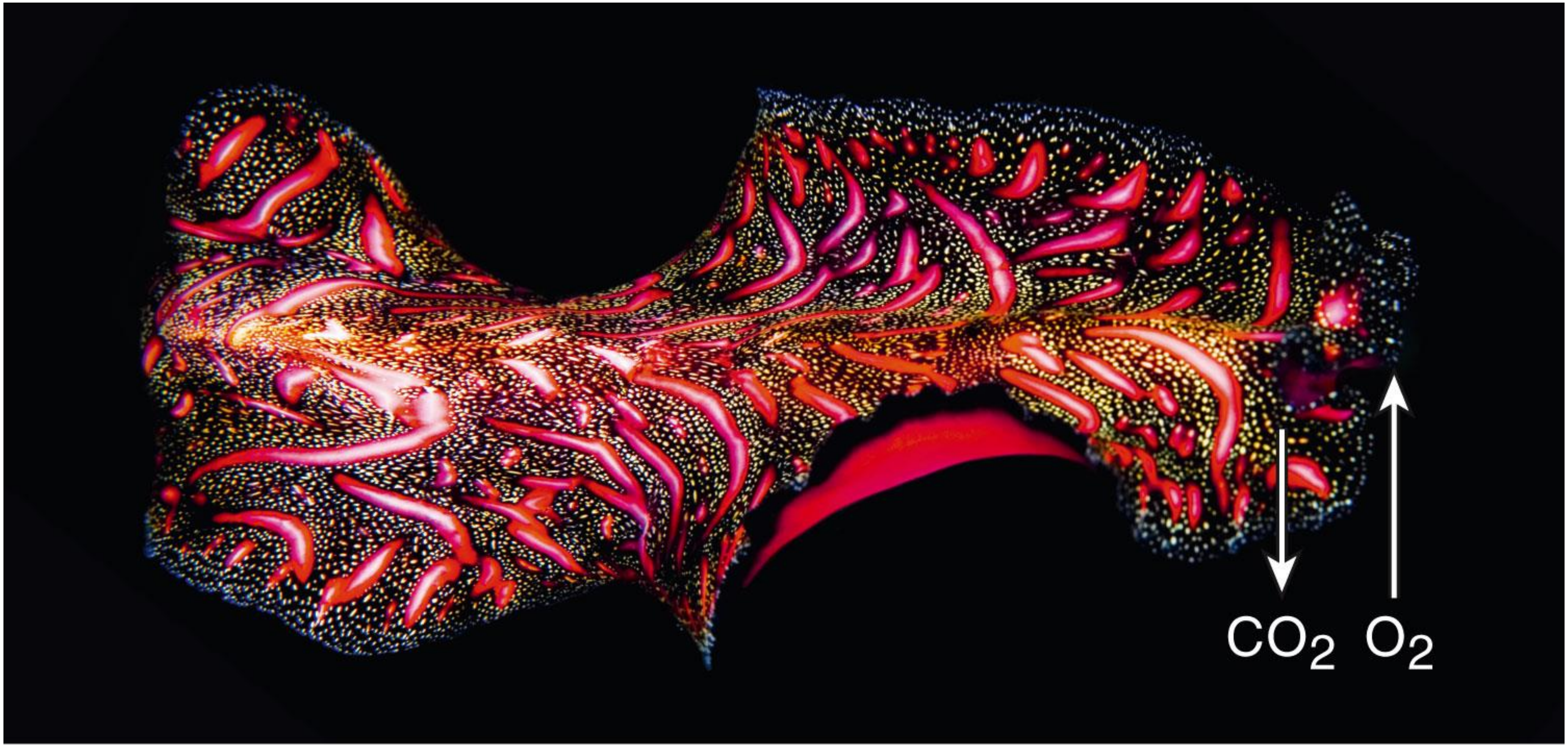
- Diversity of gas exchange structures
  - **Plasma membrane** of unicellular organisms
  - **Skin** of small multicellular organisms
    - Some have **cilia** to create feeding and breathing currents
  - **Evaginated** surfaces (**gills)** of large aquatic animals
  - **Invaginated** surfaces (**tracheae** or **lungs**) of terrestrial animals

# 11.1 Gas Demands: General Problems and Evolutionary Solutions



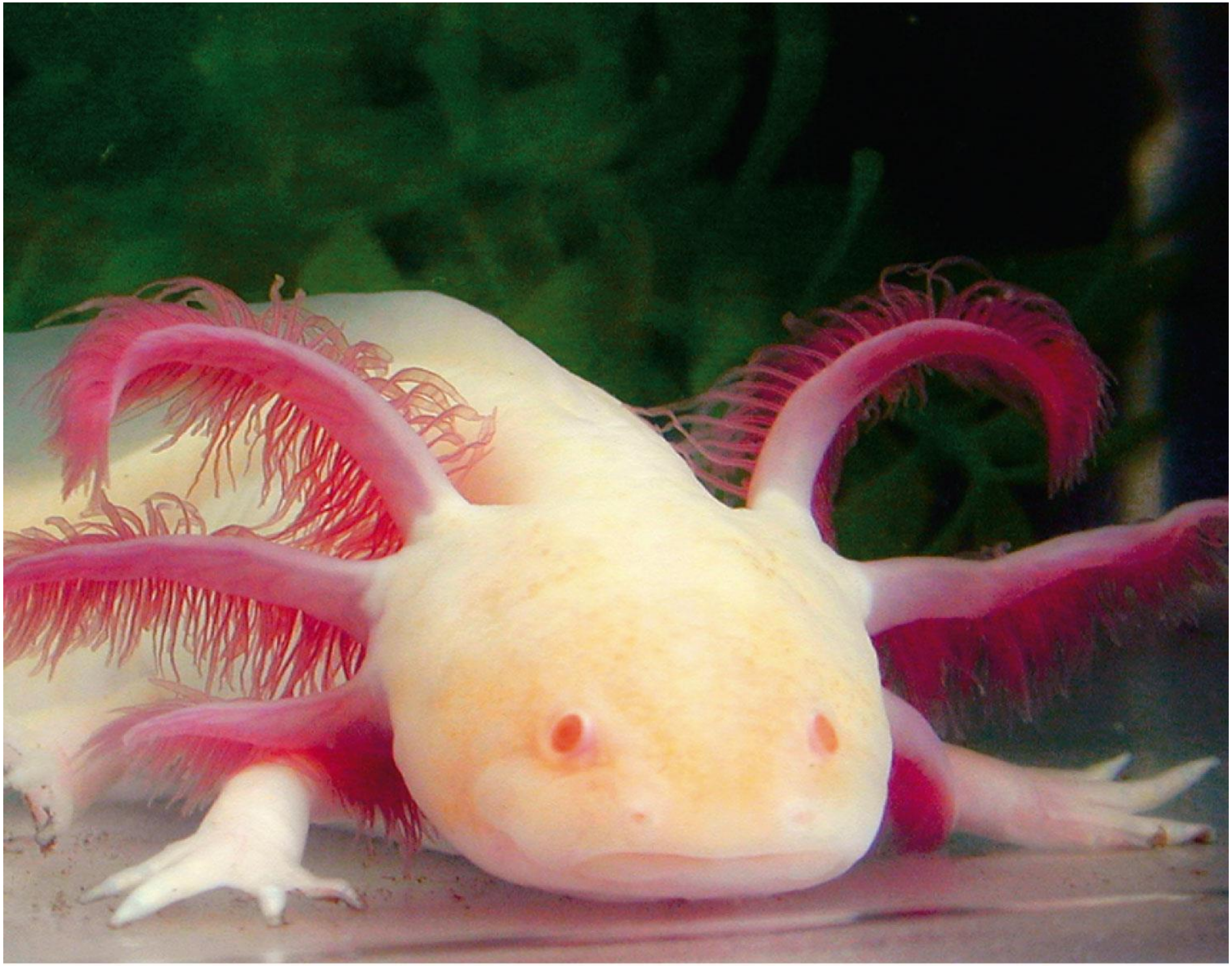
(a)

Figure 11-3a p496




(b)

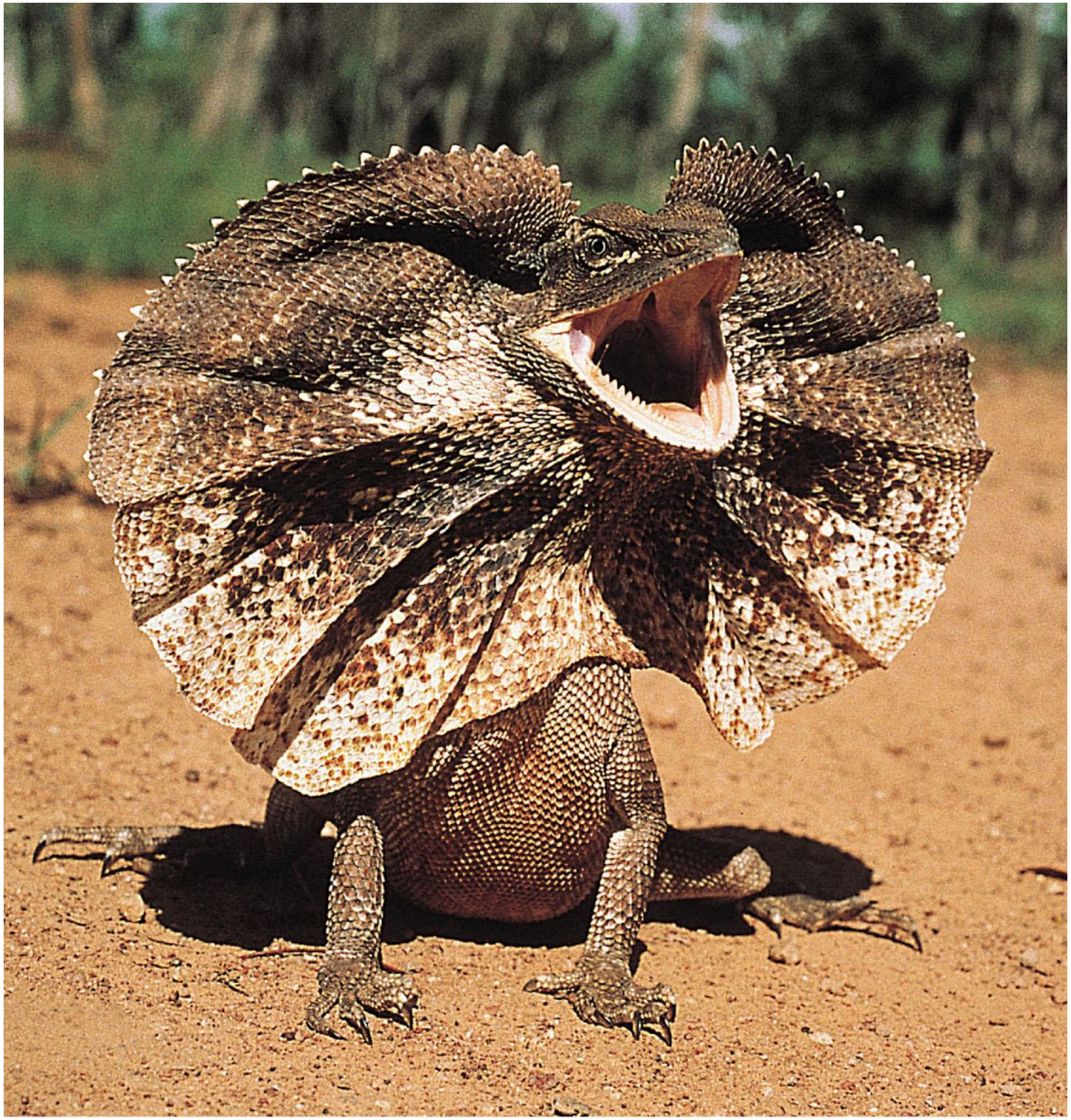
Figure 11-3b p496



(d)

(e)

Figure 11-3e p496



(f)

Figure 11-3f p496

# 11.1 Gas Demands: General Problems and Evolutionary Solutions

- Breathing can be **tidal** or **flow-through**
  - **Tidal breathing**
    - External medium is moved in and out of the same opening through **inhalation** and **exhalation**
    - Fresh medium is only brought in half the time and is mixed with depleted medium
  - **Flow-through breathing**
    - External medium enters one opening and leaves through a separate opening
    - Flow of fresh medium can be continuous and very little mixing occurs
    - **More efficient gas exchange** than tidal breathing

# 11.2 Water Respirers

- Water is a more difficult medium than air for gas exchange
  - **Higher viscosity** than air
  - $O_2$ is **less soluble** in water
  - Rate of **diffusion** of gases is slower
  - Solubility of $O_2$ decreases with increasing **salinity**
  - Solubility of $O_2$ decreases with increasing **temperature**
  - $O_2$ content in water is more variable due to **habitat variation**
  - Environmental water contains many **more components** than air

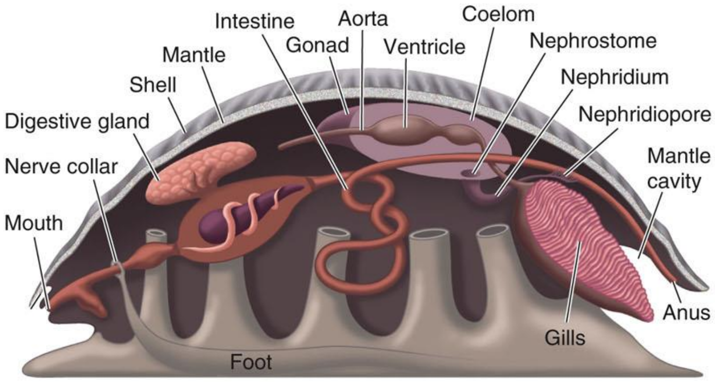
# 11.2 Water Respirers

- Integumentary respiration
  - Flatworms and Cnidaria
  - Enhanced by **internal circulation** (e.g. earthworm)
  - Important in **amphibians**, **aquatic reptiles** and **most fishes**
    - During hibernation, frogs and turtles exchange all of their respiratory gases across the skin
    - Eels exchange 60% of gases through highly vascular skin

# 11.2 Water Respirers

- Gills
  - **Evaginations of tissue** protruding into the external medium
  - **Delicate** structures composed of thin cell layers
    - Protected by shells, toxins, withdrawal, exoskeletons, bony plates
  - **Highly perfused** by a circulatory system
  - May have **flow-through** breathing mechanisms

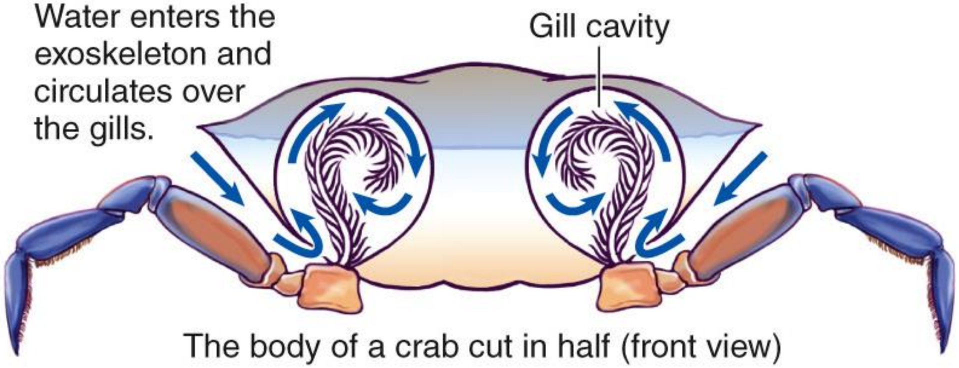
# 11.2 Water Respirers



(a)


(a)


(b)

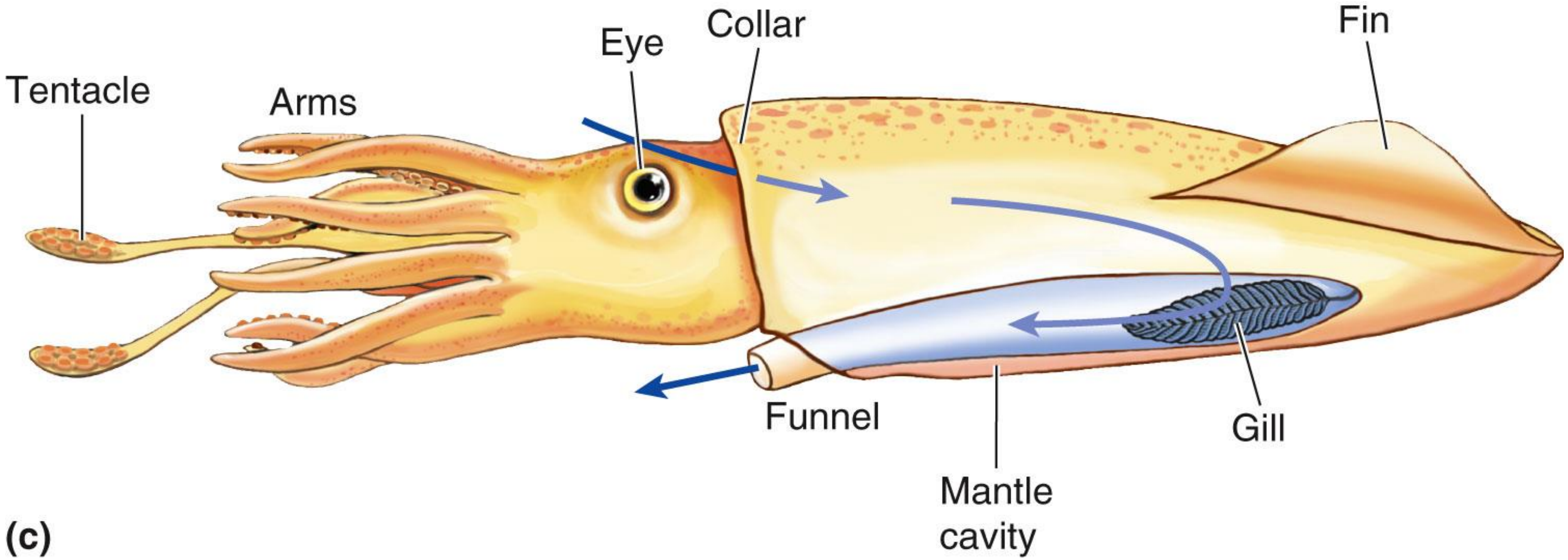


(b)

# 11.2 Water Respirers

- Muscle-driven breathing
  - **Cephalopods**
    - During **inhalation**, the funnel closes and **mantle cavity expands**, drawing water in
    - During exhalation, the mantle opening seals up, the **mantle contracts**, and the funnel opens, expelling water out the siphon
    - Also used for **jet propulsion**

# 11.2 Water Respirers

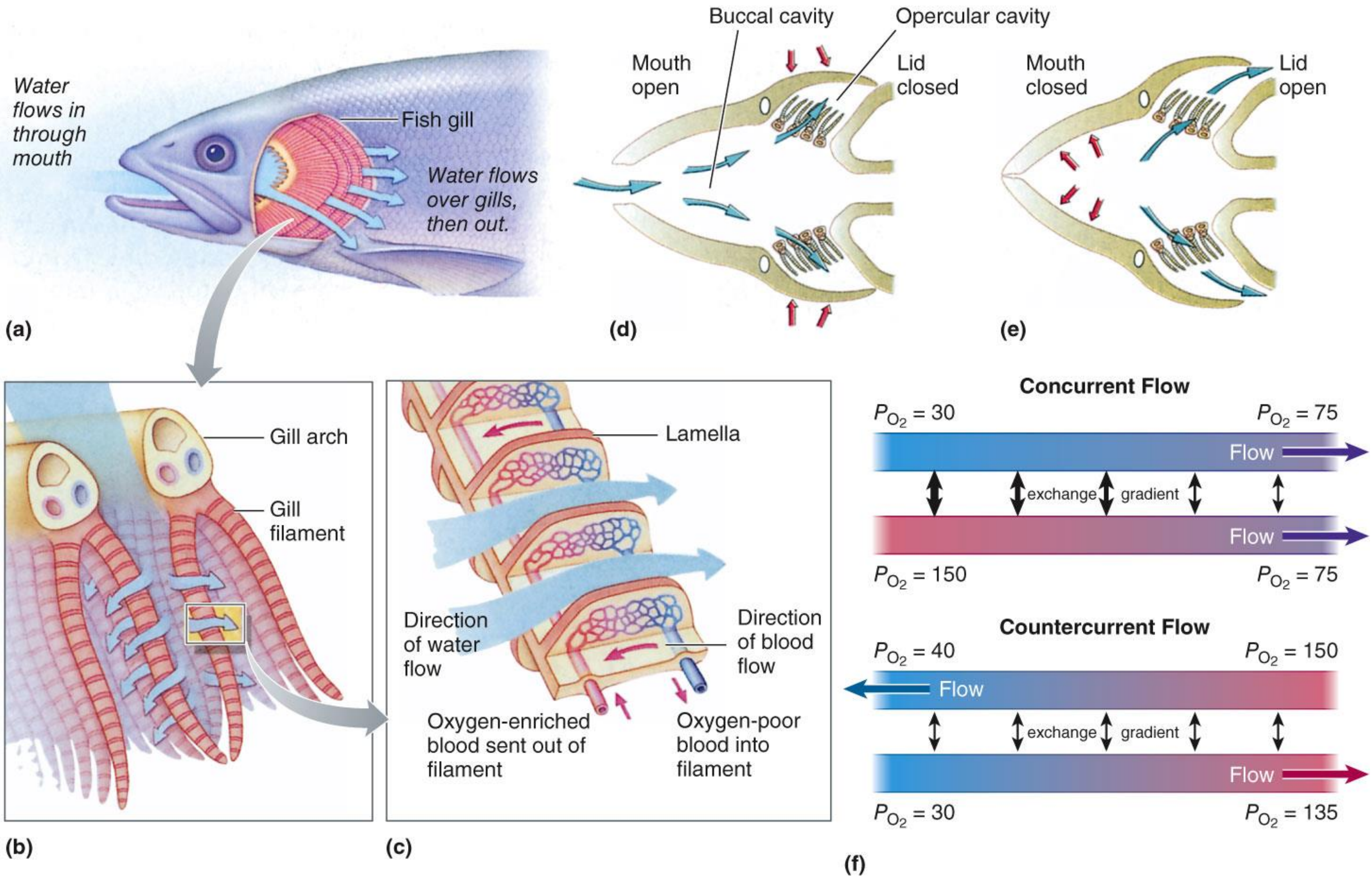



(c)

# 11.2 Water Respirers

- Muscle-driven breathing in fishes
  - **Skeletal muscle pumps** in buccal and opercular cavities
  - Mouth opens and $O_2$-rich water is drawn into the mouth by **negative pressure**
  - Then the mouth closes, the **opercular cavity constricts** and opercula open, forcing water through the gills and out the opercular exit
  - **Lamprey** uses **tidal flow** in and out of the opercular opening, because its mouth remains attached to the host while feeding

# 11.2 Water Respirers



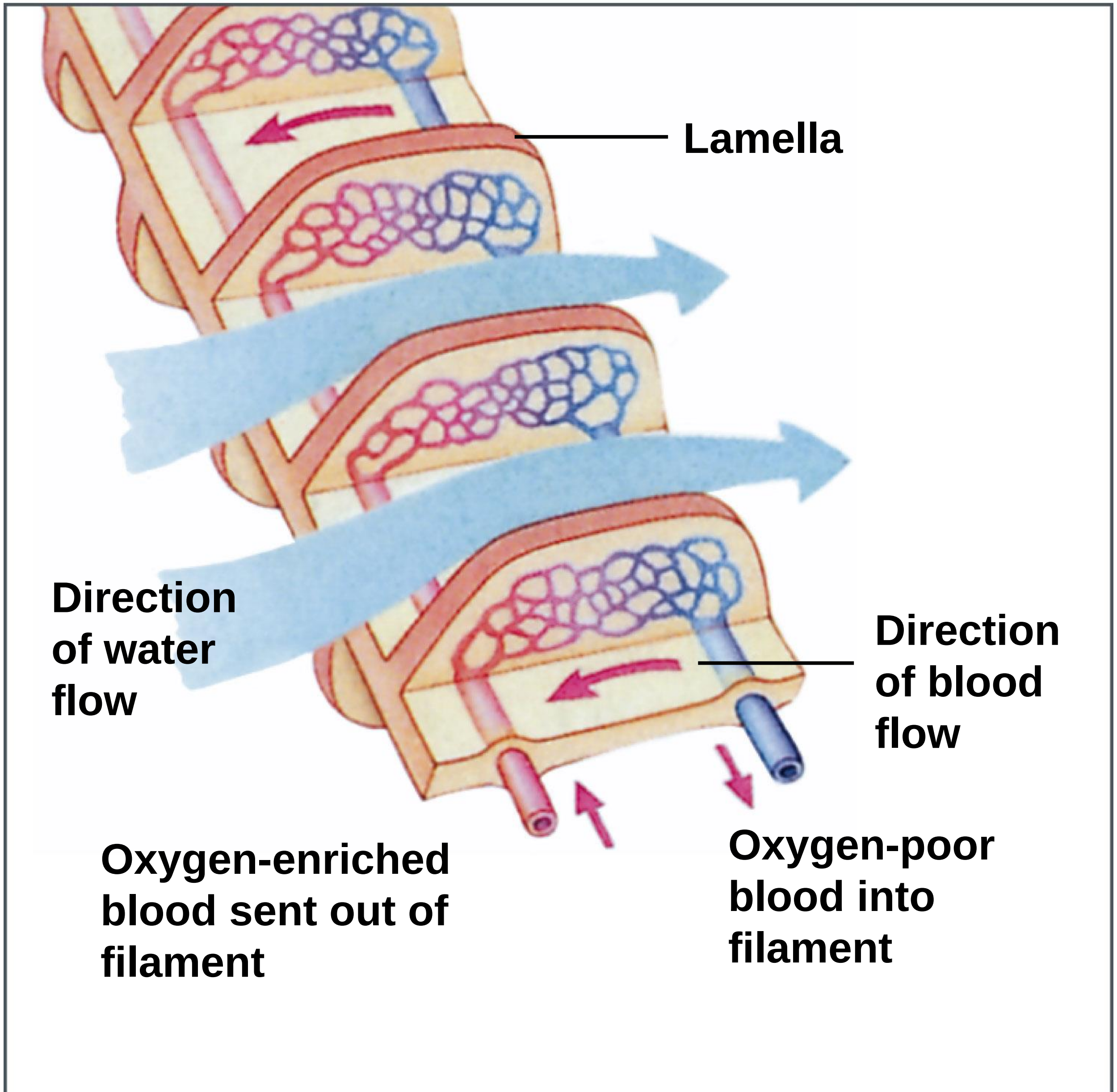



Figure 11-6c p501

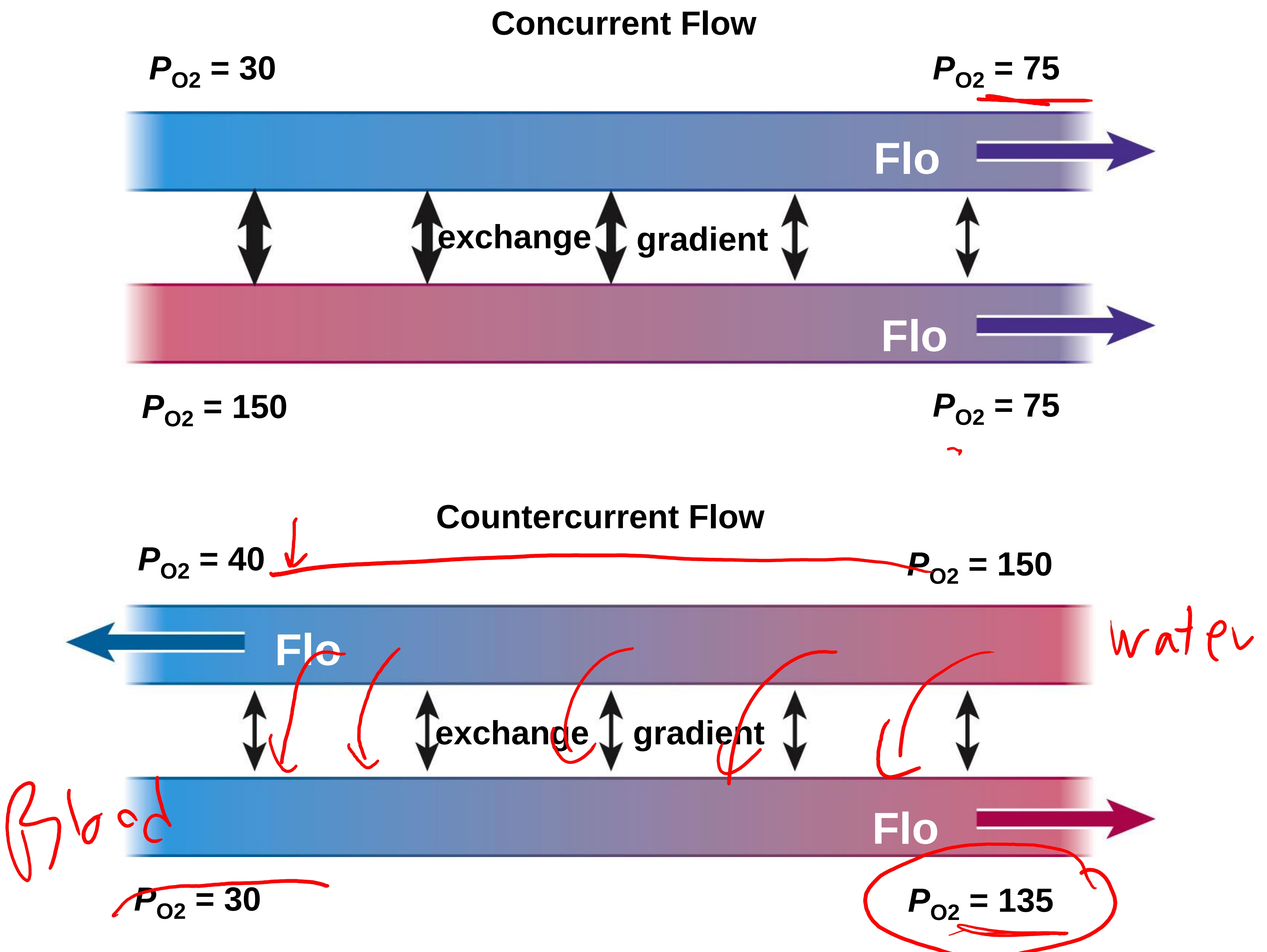



Figure 11-6f p501

# 11.2 Water Respirers

- Muscle-driven breathing in fishes
  - In **ram ventilation**, bulk transport is created by the animal's swimming motion
    - **Obligate ram breathers** (e.g. tuna and sharks) must swim in order to breathe
    - **Facultative ram breathers** (e.g. rainbow trout) switch from buccal-opercular breathing to ram ventilation when swimming above certain velocities

# 11.2 Water Respirers

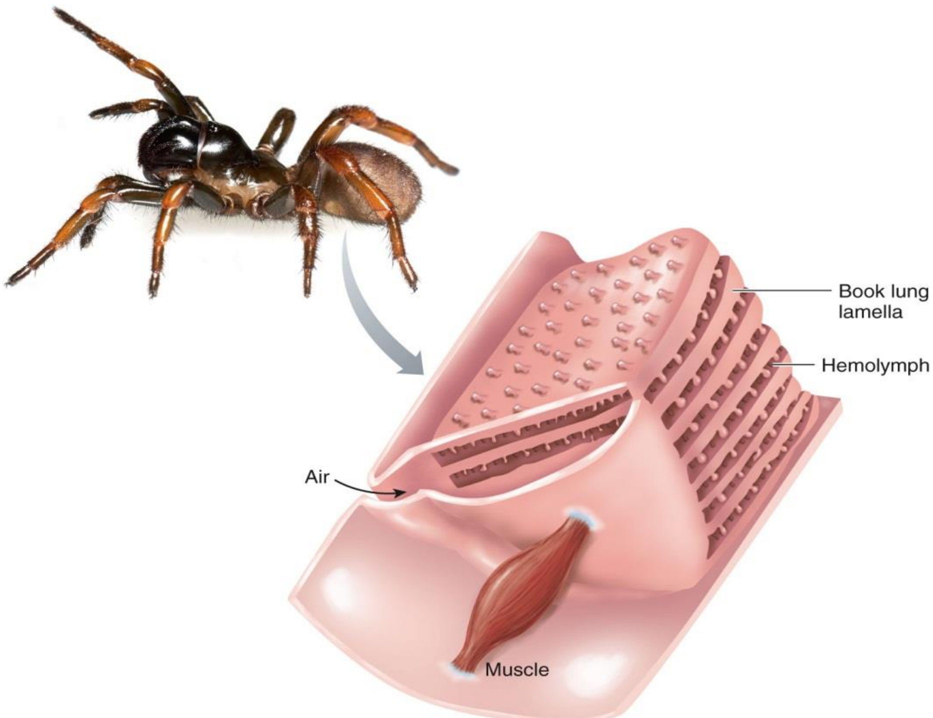
- Muscle-driven breathing in fishes
  - **Countercurrent blood flow** enhances gas pressure gradients
    - Blood flows in a direction **opposite** to that of water flow
    - Blood continually encounters water whose $O_2$ content is higher
    - Provides much **greater efficiency** of gas exchange

# 11.3 Air Respirers: Overview and Nonvertebrates

- Air respirers vs. water respirers
  - Air is much **less viscous** than water, allowing **easier bulk transport**
  - Air **contains more $O_2$** than water
    - Reduced need for surface area
    - Permits less efficient tidal breathing
  - Thin **respiratory surfaces** exposed to air must be kept **moist**
    - Remain in a moist environment or
    - Have covered or fully internal gas exchange structures

# 11.3 Air Respirers: Overview and Nonvertebrates

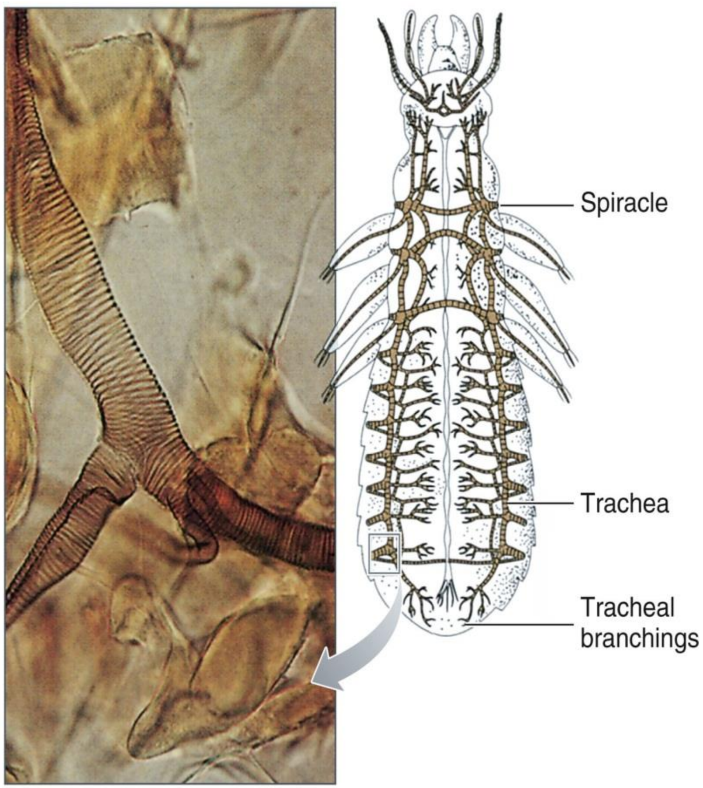
- Arthropods
  - Scorpions and some spiders have **book lungs**
    - **Stacks of lamellae** invaginating from the cuticle into the abdomen



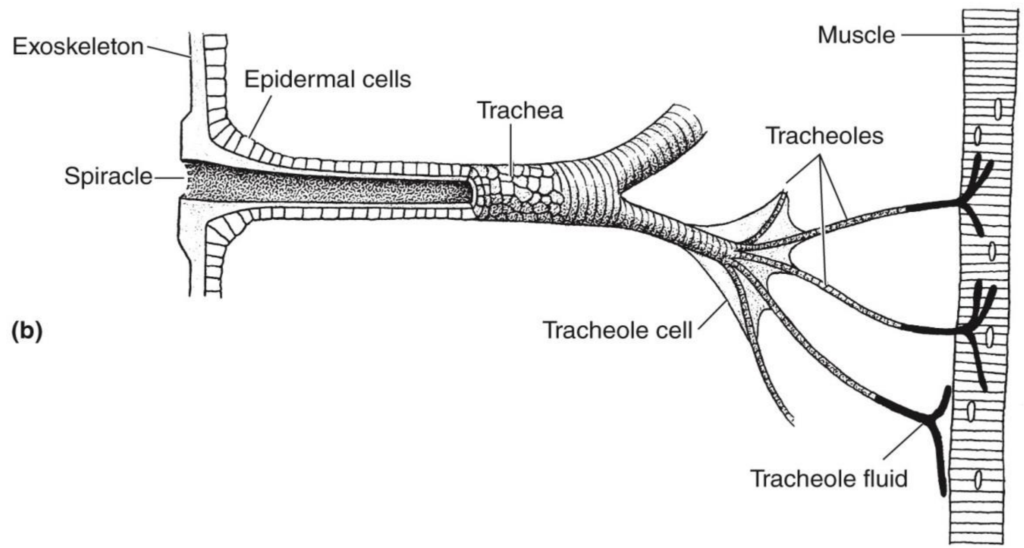
# 11.3 Air Respirers: Overview and Nonvertebrates

- Arthropods
  - Insects and many spiders have **tracheae.**
    - Tubular extensions into the tissues reinforced with rings of chitin
    - Break up into finer branches (**tracheoles**)
    - Tracheae connect to outside through openings in the exoskeleton (**spiracles**)
    - **Distribution of tracheae** reflects the $O_2$ demands of tissues
    - Larger and flying insects have active tidal pumping of air

# 11.3 Air Respirers: Overview and Nonvertebrates




(a)

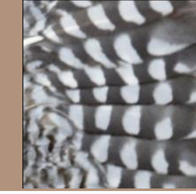



(b)

# 11.4 Air Respirers: Vertebrates

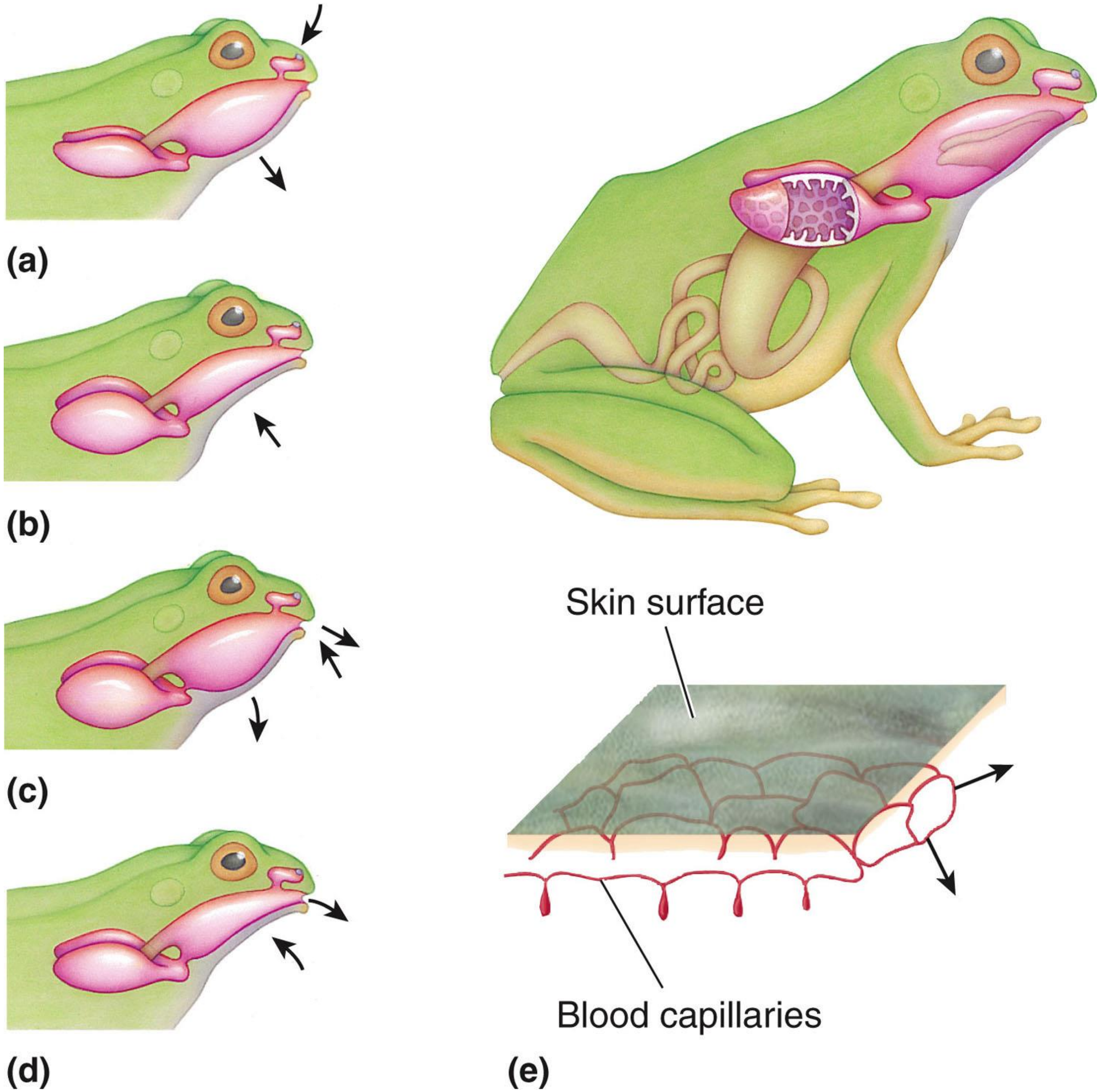
- Bimodal breathers
  - The first **air breathers** evolved in tropical lowlands where stagnant ponds were subject to **hypoxia** or **desiccation.**
  - **Bimodal breathers** have gills and other respiratory exchange structures (e.g. skin)
  - **Lungs in fishes** were simple ventral evaginations of the pharynx

# 11.4 Air Respirers: Vertebrates



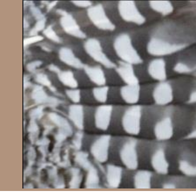
- Amphibians
  - **Bimodal** or **trimodal breathers** (gills, lungs, integument) to support aquatic and terrestrial lifestyles
  - In frogs, **larval stages** have **gills**; **adults** have simple, noncompartmentalized **lungs**
  - Air is forced into lungs by **positive pressure** from a **buccal pump**
  - Several inspiratory oscillations fill lungs; empty in one long exhalation
  - Adaptation to air-breathing included a decrease in affinity of **hemoglobin** to $O_2$

# 11.4 Air Respirers: Vertebrates



# 11.4 Air Respirers: Vertebrates

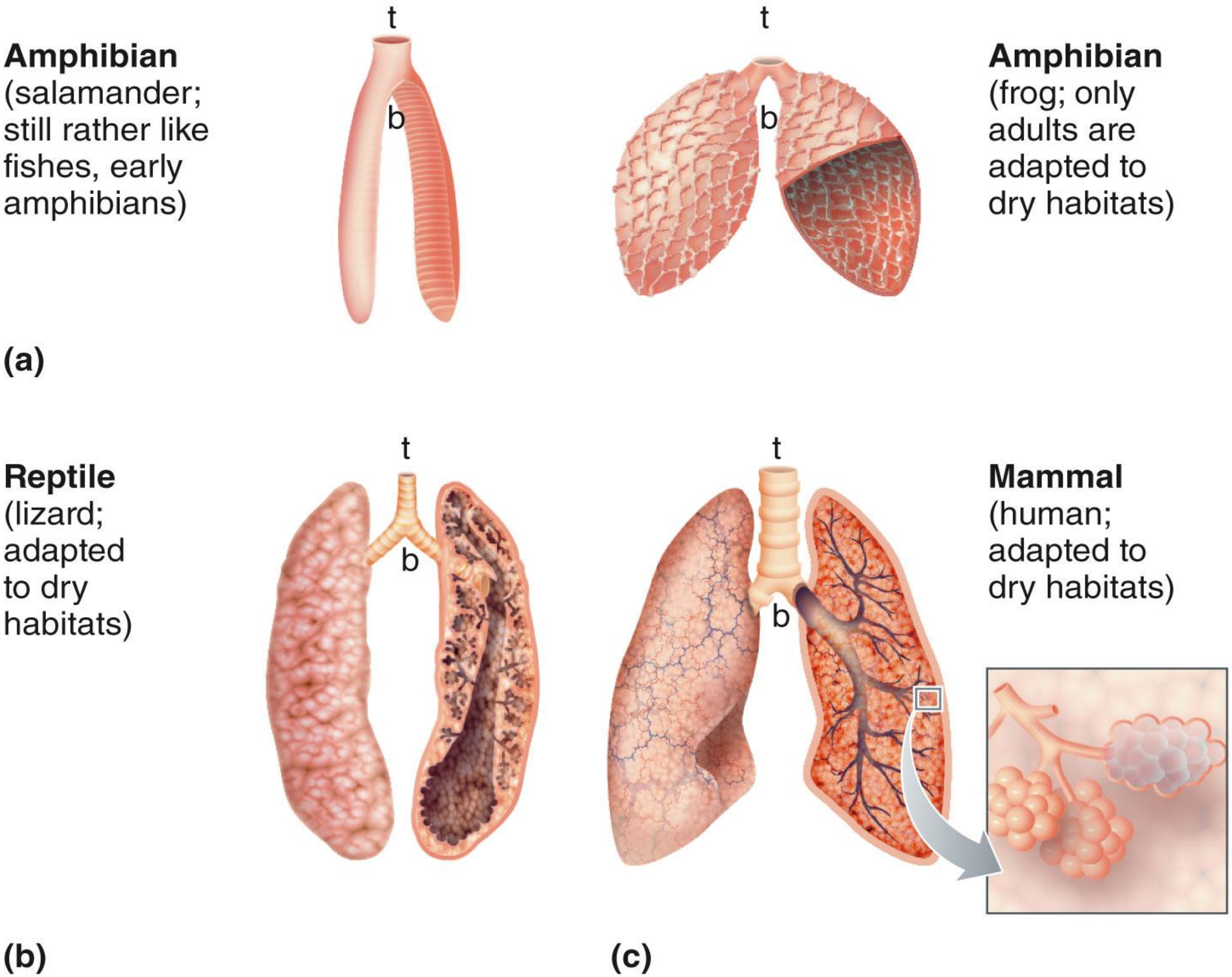
- Reptiles
  - Lungs in reptiles, birds and mammals are **compartmentalized** and fill by **negative pressure**
  - Reptile lungs are expandable, tidally ventilated sacs
  - Vascularized ingrowths or dividing walls (**septa**) subdivide pulmonary lumen
    - Air sacs are called **ediculae** (spherical) or **faveoli** (oblong)



# 11.4 Air Respirers: Vertebrates

- Reptiles
  - **Lizards** and **snakes** rely on costal (rib) muscles for expansion of lungs
  - **Turtles** (with fixed ribs) use limb extension
  - **Crocodilians** have a connective tissue **diaphragm** adhering tightly to the anterior surface of the liver
    - **Diaphragmaticus muscle** contracts during inhalation
    - **Flow-through** system in secondary and tertiary bronchi

# 11.4 Air Respirers: Vertebrates



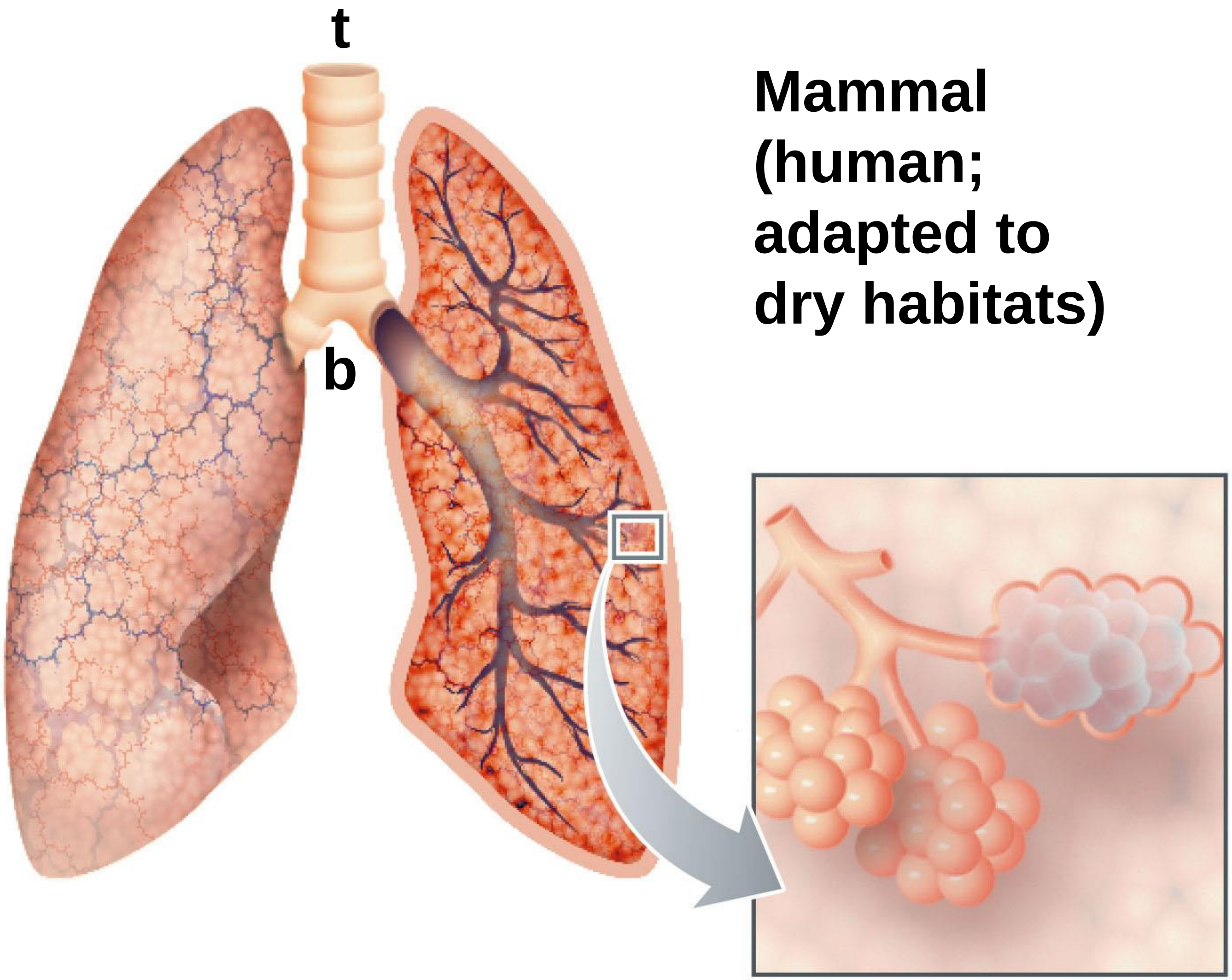



Figure 11-9c p506

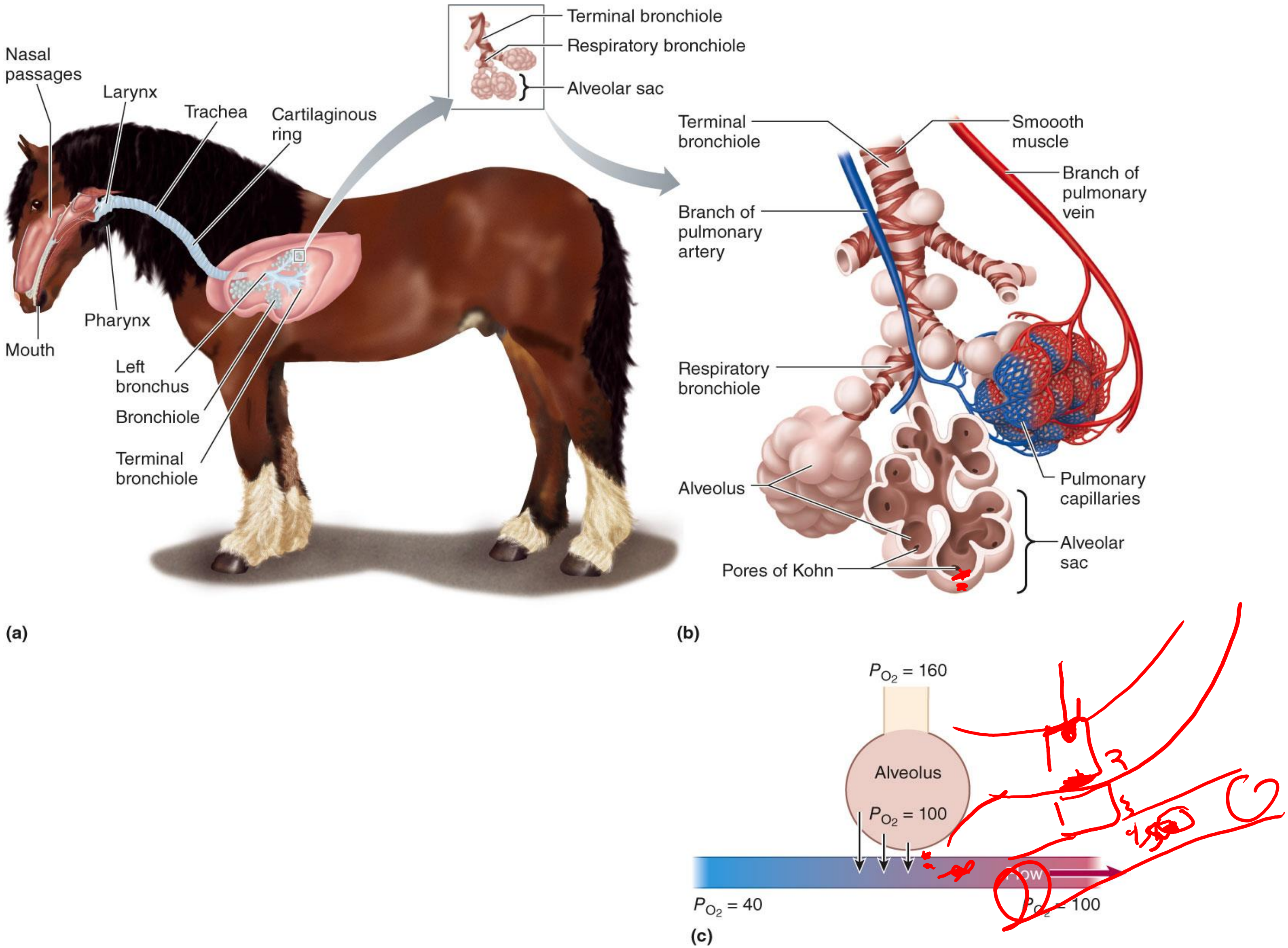
# 11.4 Air Respirers: Vertebrates

- Birds and mammals
  - **Surface area** of lungs for gas exchange is expanded to support increased metabolic rates
    - Very small **alveoli** in mammals
    - **Parabronchi** with **air capillaries** in birds
  - Oxygenated blood from lung is completely **separated** from systemic venous blood by **four-chambered heart**
  - Small percentage of skin breathing in most mammals

# 11.4 Air Respirers: Vertebrates

- Mammalian airways
  - **Nasal passages**
    - **Maxilloturbinals** retain heat and water
  - **Pharynx** is a common passageway for air and food
  - **Trachea** and esophagus exit pharynx
    - Reflexes close off trachea during swallowing
  - **Bronchi**
    - Trachea divides into **right** and **left bronchi**, each entering a lung
    - Bronchi **branch** within lungs
    - Trachea and large bronchi are supported by **cartilaginous rings**
  - **Bronchioles** -- smaller branches
    - Walls contain **smooth muscle** innervated by the **autonomic nervous system**
    - **Terminal bronchioles** open into **alveoli**

# 11.4 Air Respirers: Vertebrates



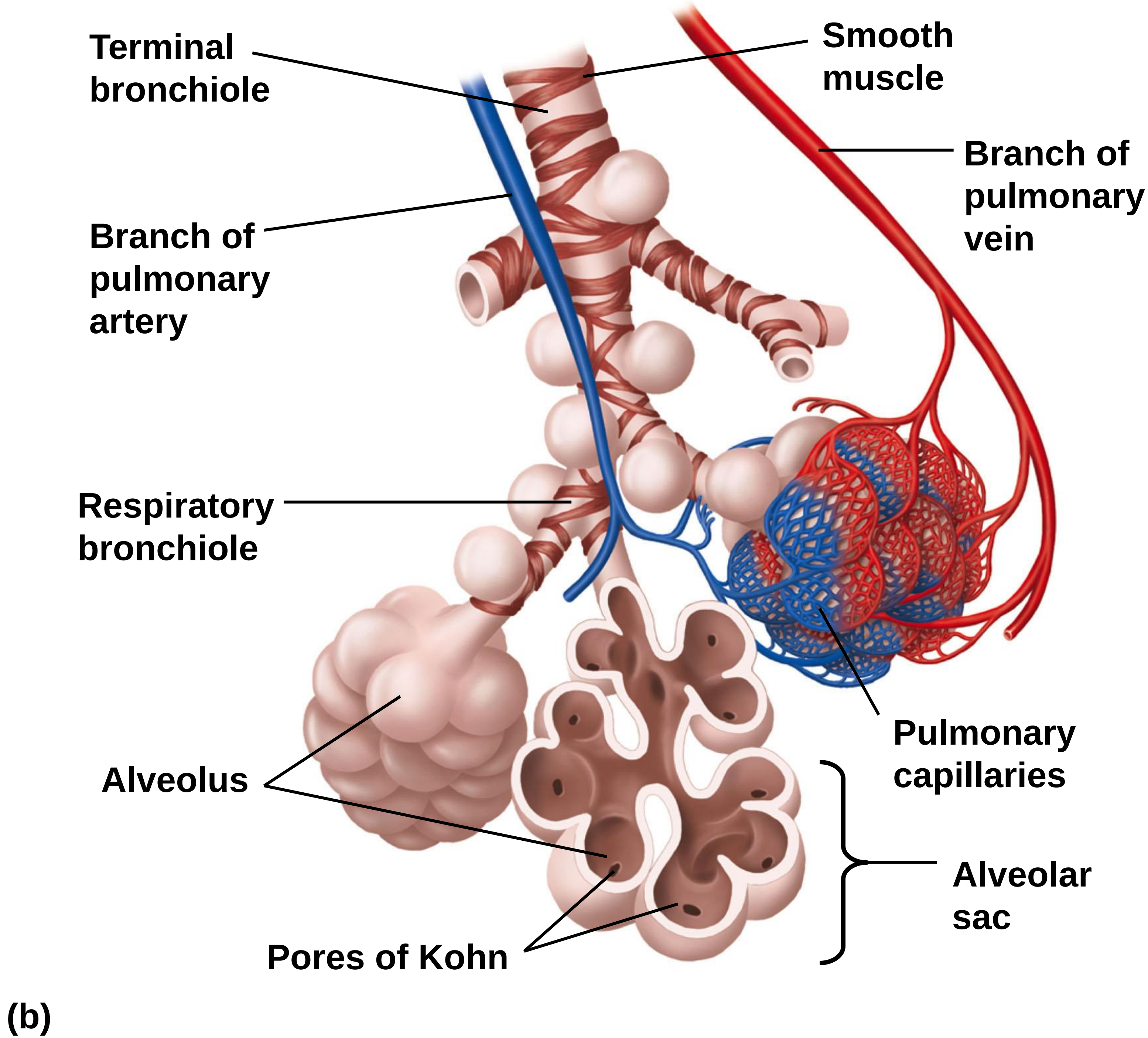
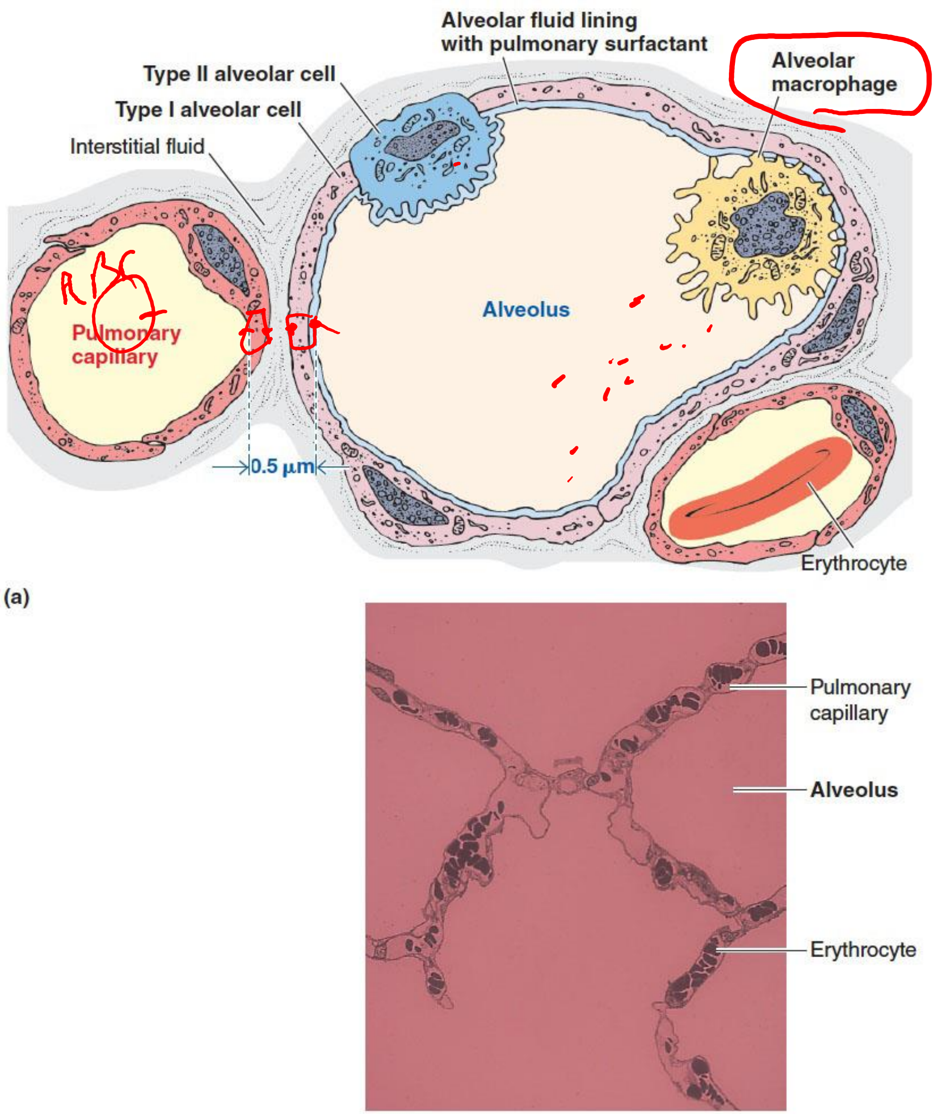



Figure 11-11b p508

# 11.4 Air Respirers: Vertebrates

- Alveoli
  - Very small, tidally ventilated sacs
  - **Gas exchange**
    - Large surface area
    - Single layer of highly flattened **Type I alveolar cells**
    - Dense **network of capillaries** surrounding alveoli
    - Thin **interstitial space**
    - Achieve **partial pressures** of gases in blood comparable to those in inspired air
  - **Type II alveolar cells** secrete **pulmonary surfactant**
    - Facilitates alveolar expansion
  - **Pores of Kohn** permit airflow between adjacent alveoli (**collateral ventilation**)

# 11.4 Air Respirers: Vertebrates

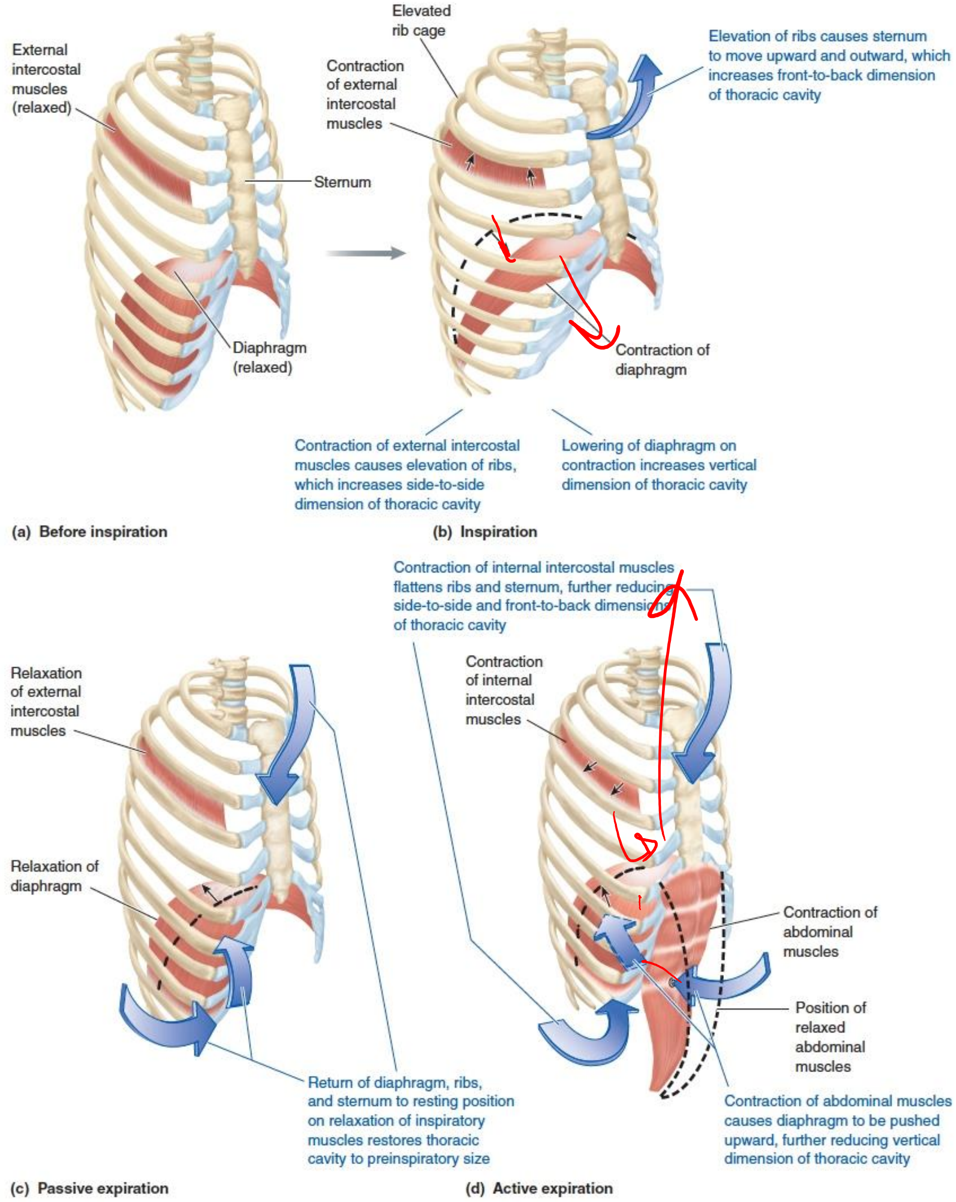



**(b)** Transmission electron micrograph of several alveoli and surrounding pulmonary capillaries

# 11.4 Air Respirers: Vertebrates

- Respiratory cycle
  - **Inspiration** involves **contraction** of inspiratory muscles
    - **Diaphragm** contracts downward
    - **External intercostal muscles** expand ribs outward, enlarging the thoracic cavity
  - **Exhalation** normally involves **relaxation** of inspiratory muscles and **elastic recoil** of chest wall and lungs
  - **Active exhalation** involves contraction of **abdominal wall muscles** and **internal intercostal muscles**

# 11.4 Air Respirers: Vertebrates



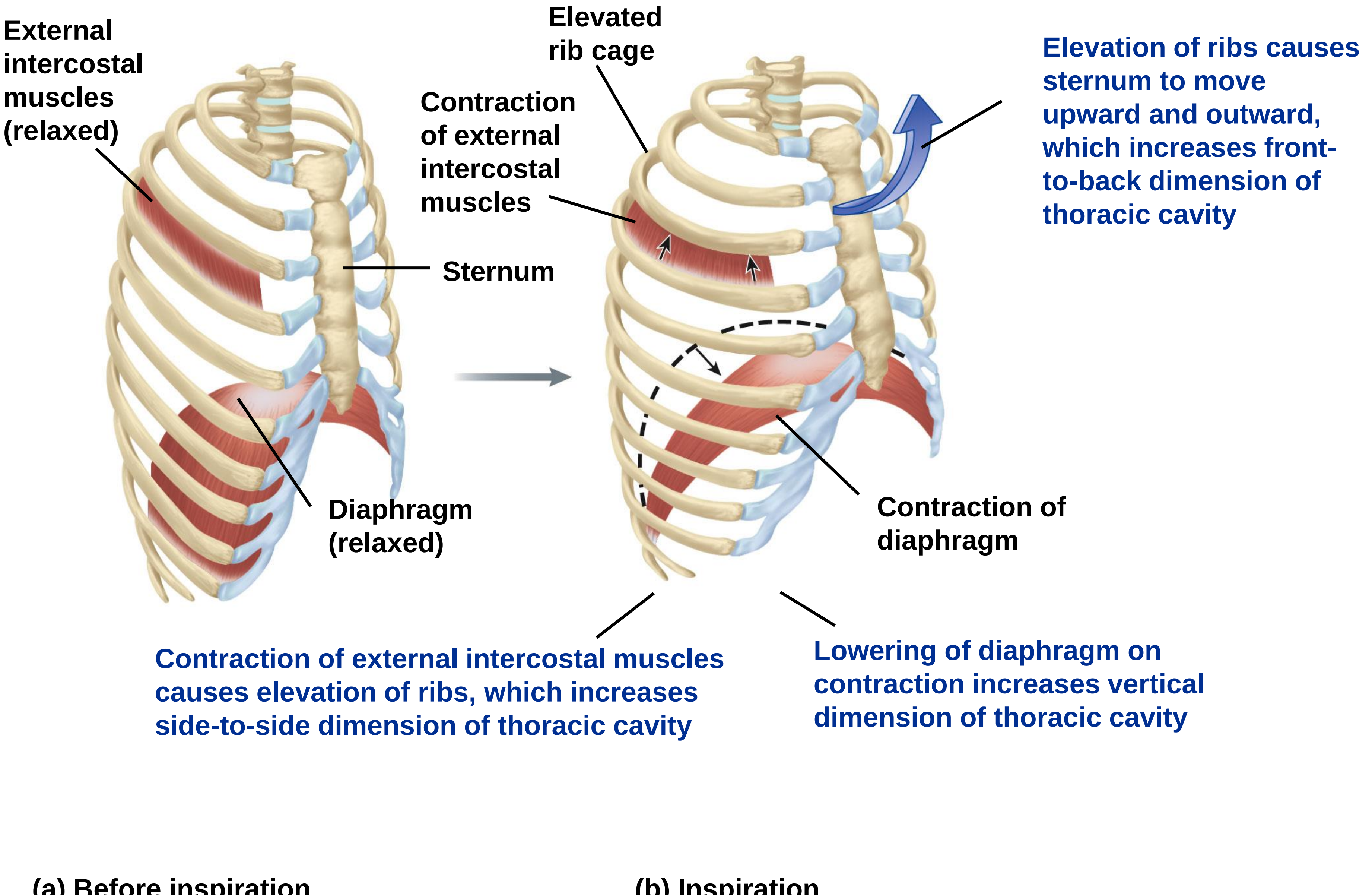
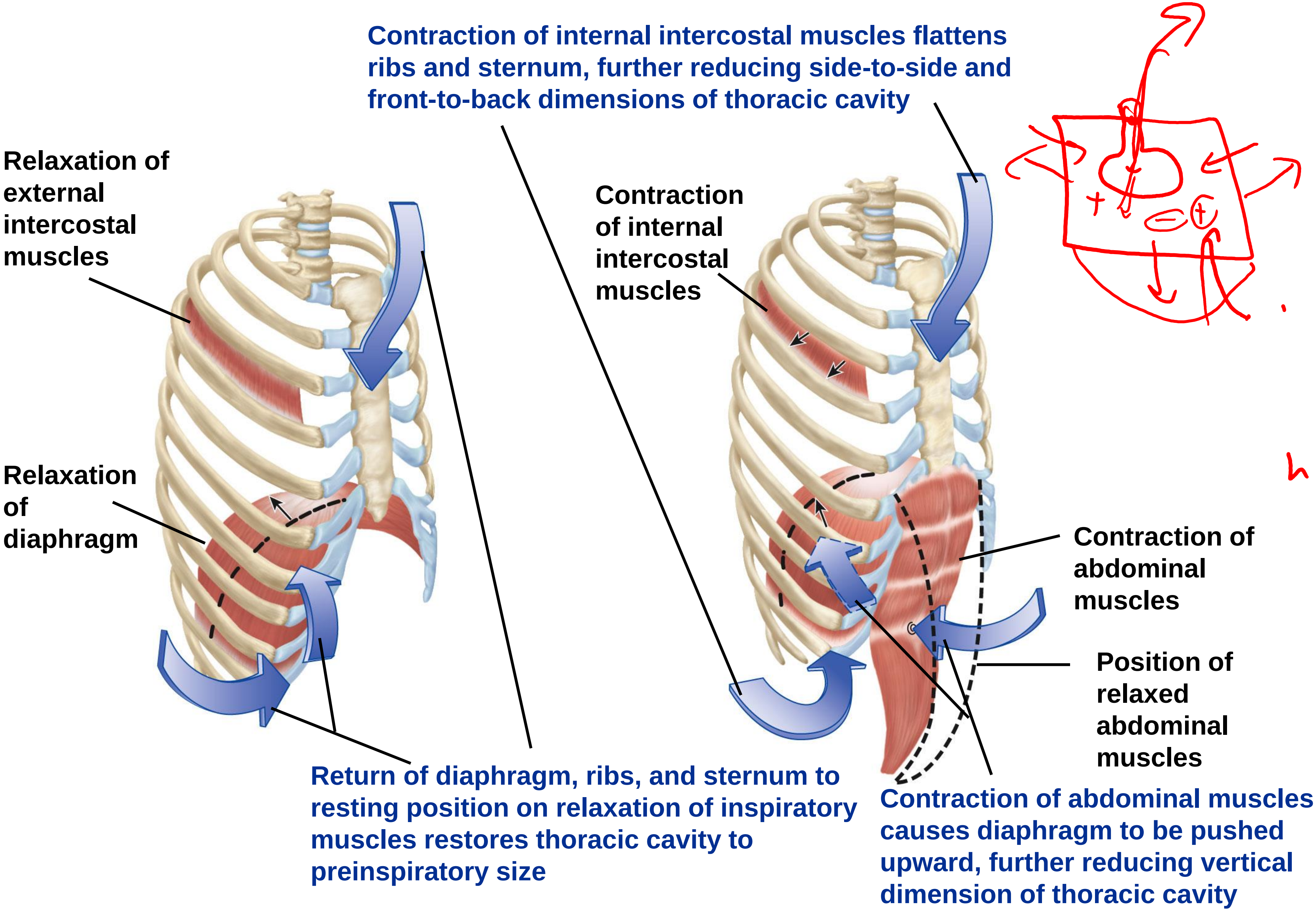



Figure 11-14ab p512




**(c) Passive expiration**

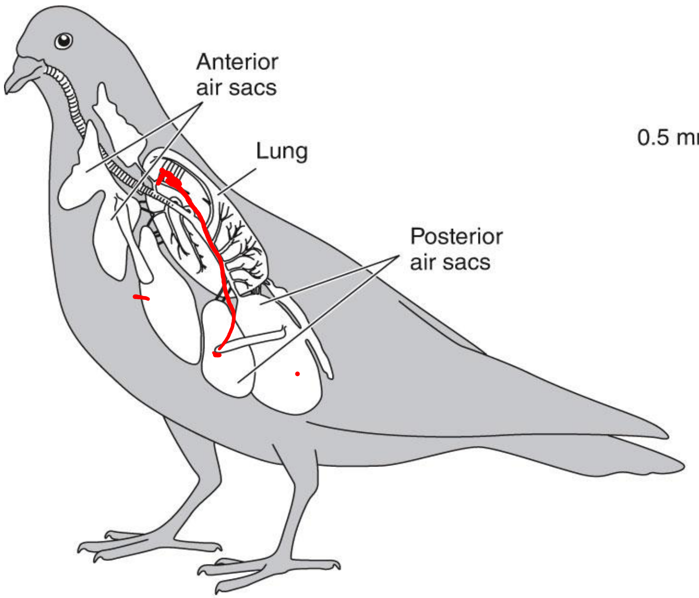
**(d) Active expiration**

**Figure 11-14cd p512**

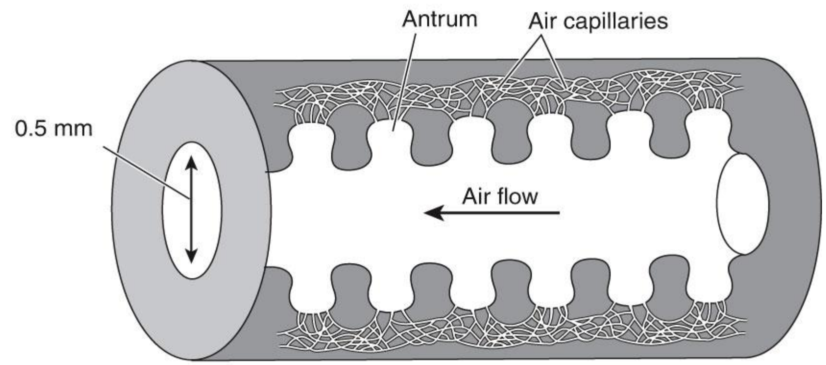
# 11.4 Air Respirers: Vertebrates

- Birds
  - Complete **separation** of ventilation and gas exchange
  - Lungs are **smaller** than in mammals and **inelastic**
  - Ventilation of expandable **air sacs** perform tidal function without gas exchange
  - Air enters **nasal passages**, **trachea**, **bronchi** and **air sacs**
  - Bronchi gives rise to **secondary bronchi**
    - Air flows from **dorsobronchi** to **ventrobronchi** through parallel **parabronchi**
  - **Air capillaries** branch from parabronchi

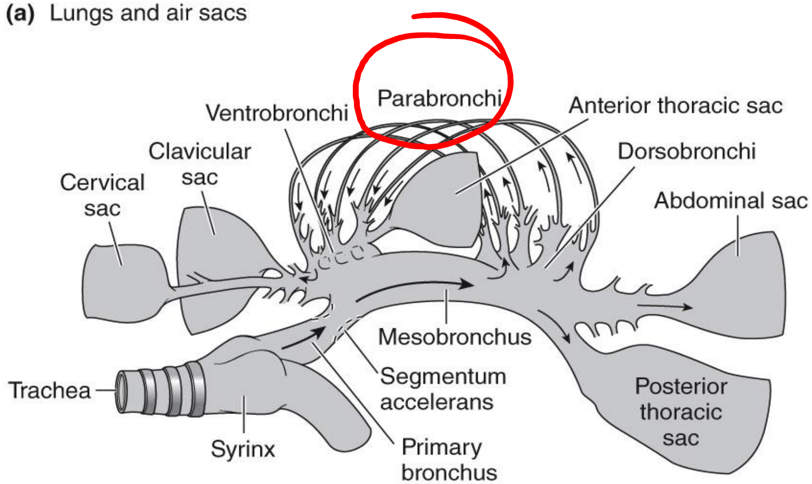
# 11.4 Air Respirers: Vertebrates



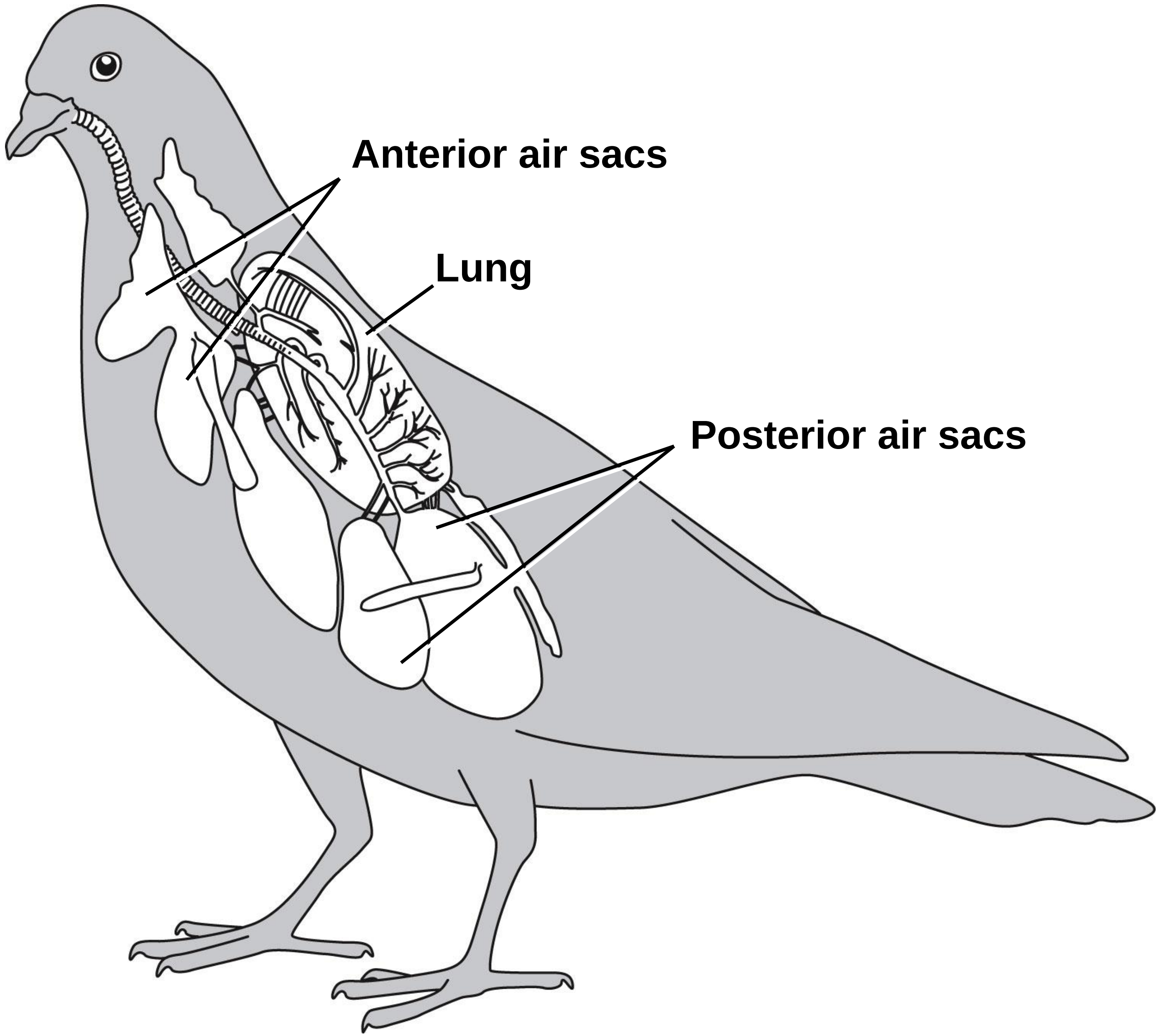

**(a)** Lungs and air sacs




**(c)** Parabronchus and air capillaries

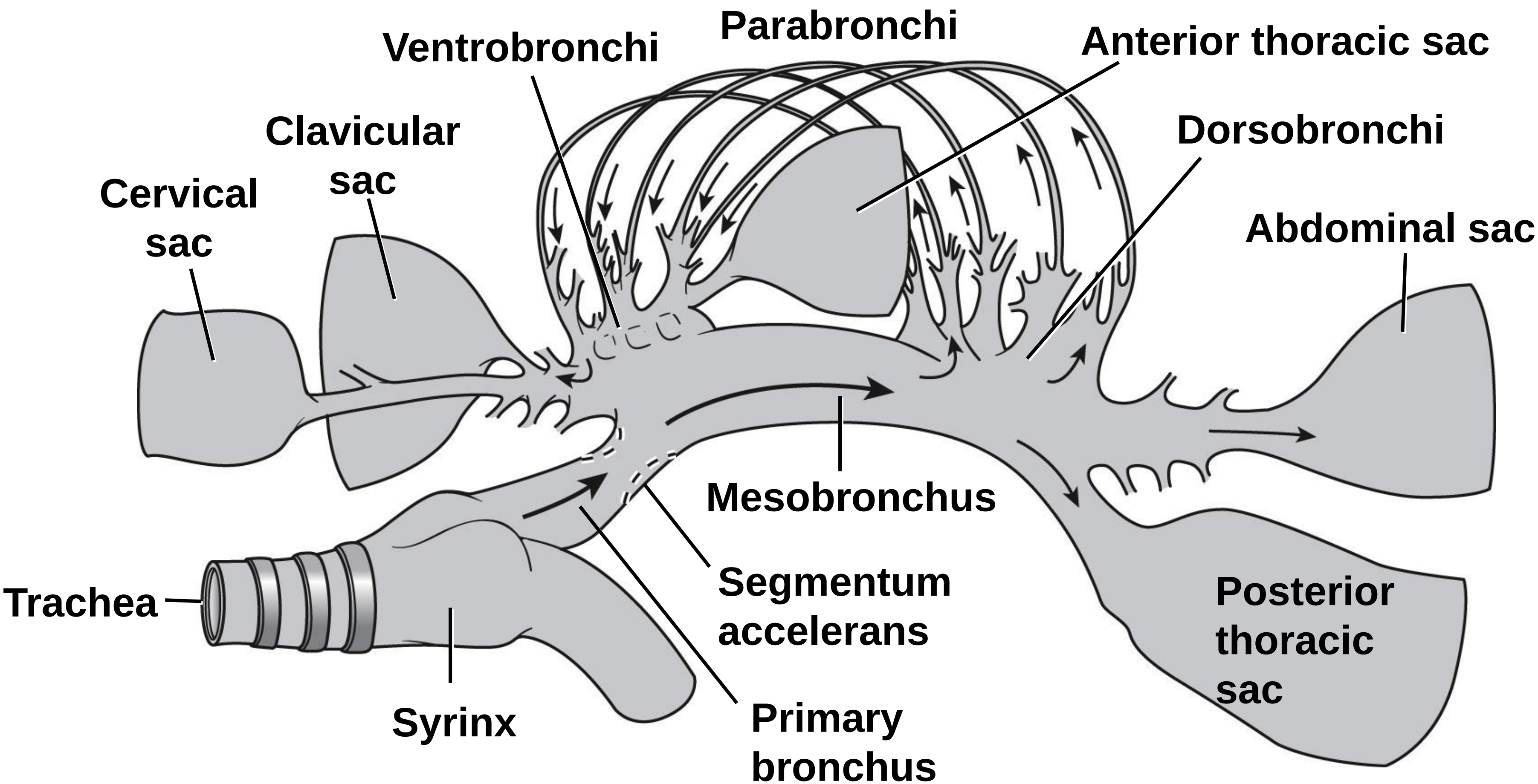



**(b)** Schematic of air sacs and bronchi showing aerodynamic valve (segmentum accelerans; see text p. 515)



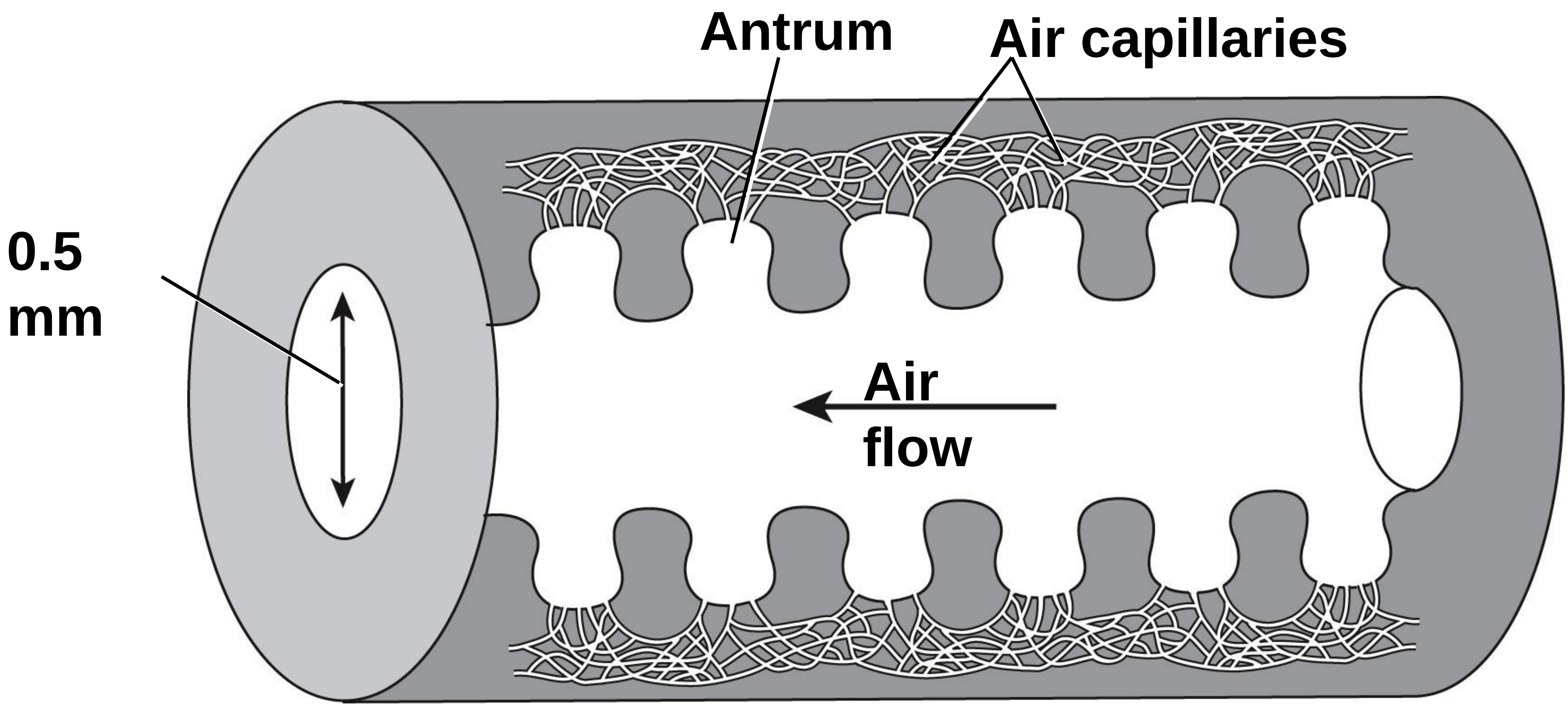

(a) Lungs and air sacs

Figure 11-15a p513




(b) Schematic of air sacs and bronchi showing aerodynamic valve (segmentum accelerans; see text p. 515)

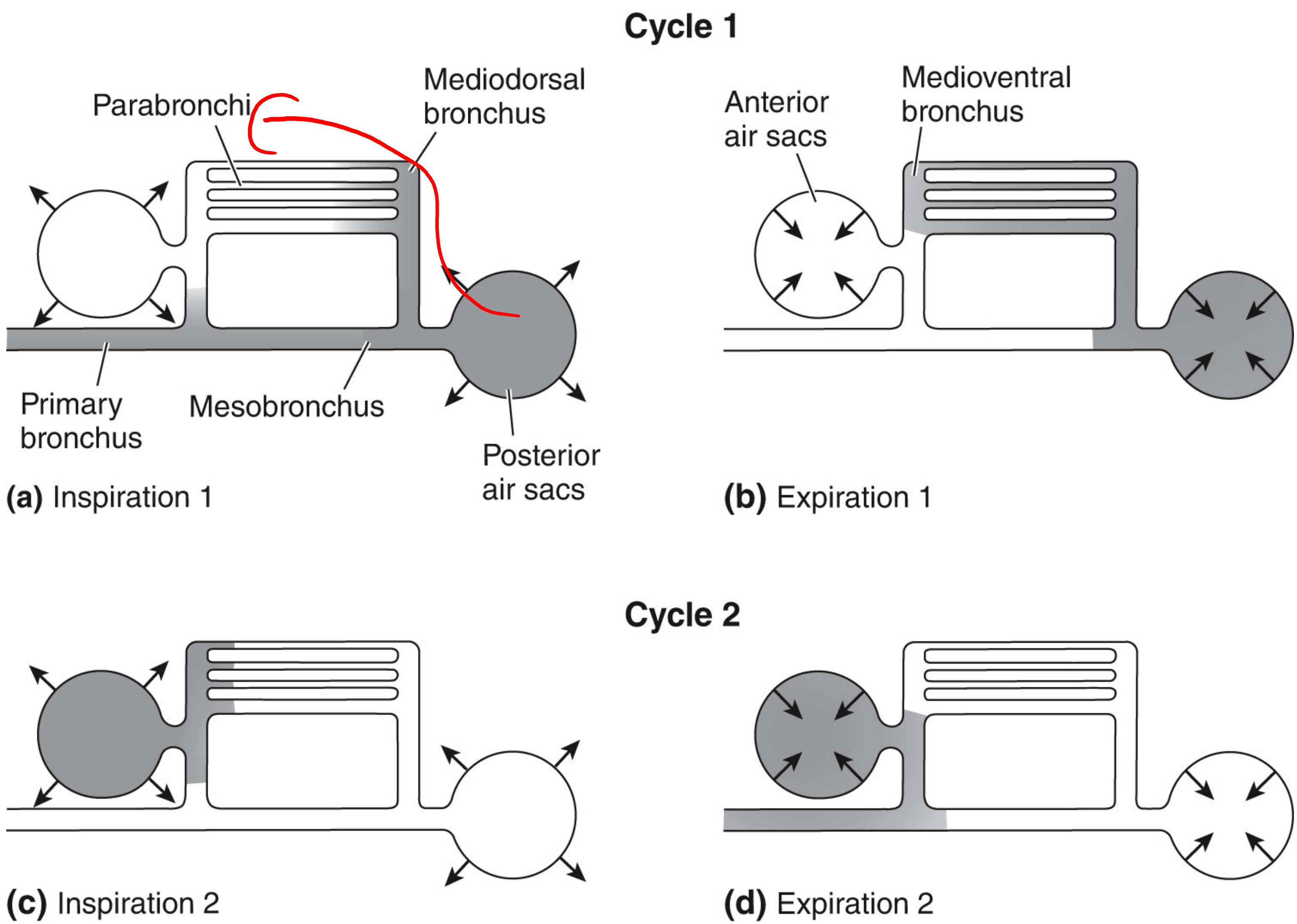
Figure 11-15b p513




(c) Parabronchus and air capillaries

Figure 11-15c p513

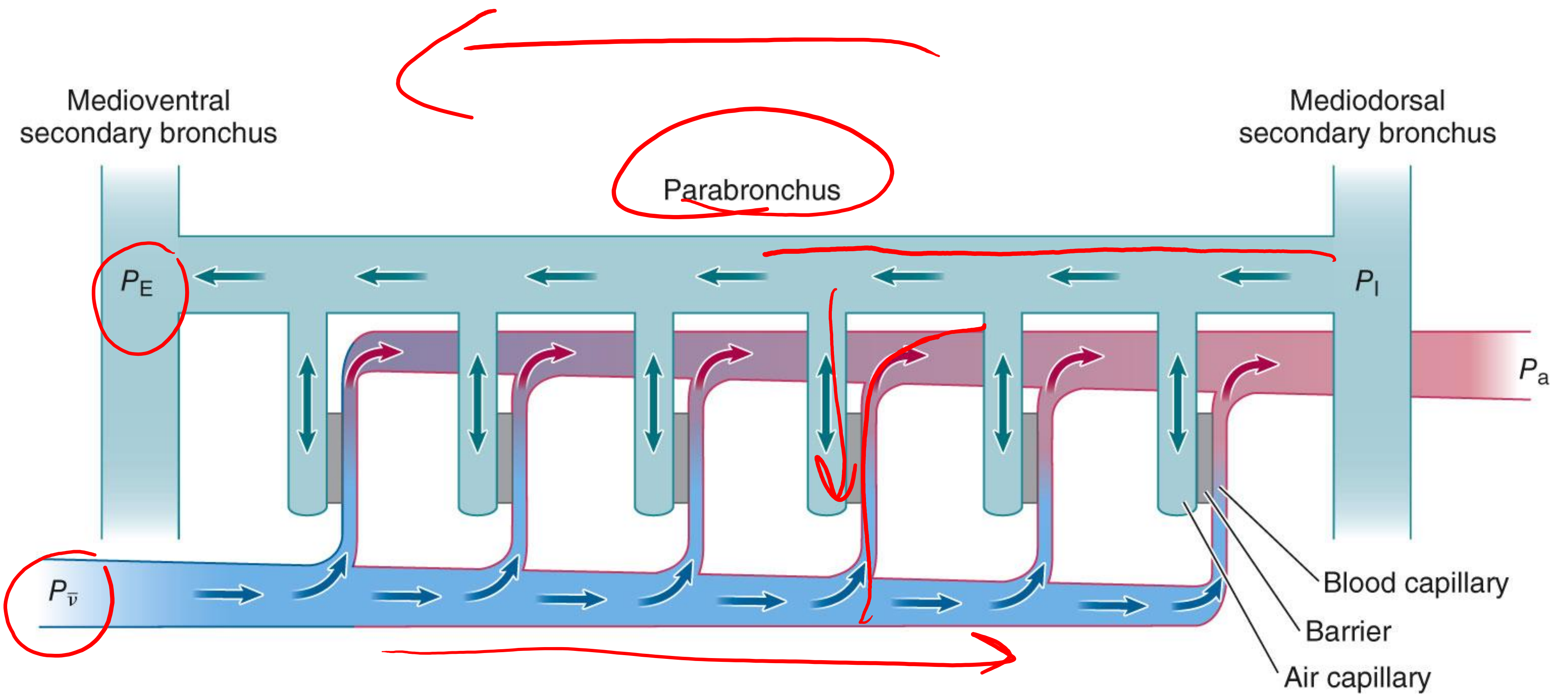
# 11.4 Air Respirers: Vertebrates



# 11.4 Air Respirers: Vertebrates

- **Air capillaries** vs. **alveoli**
  - Air capillaries are **narrower** than alveoli
  - Epithelial cells are **thinner**
  - **Flow-through** design
  - **Rigid** -- resist damage
  - **Greater blood volume** in pulmonary capillaries
  - **Crosscurrent blood flow** in parabronchi provides more efficient uptake of $O_2$

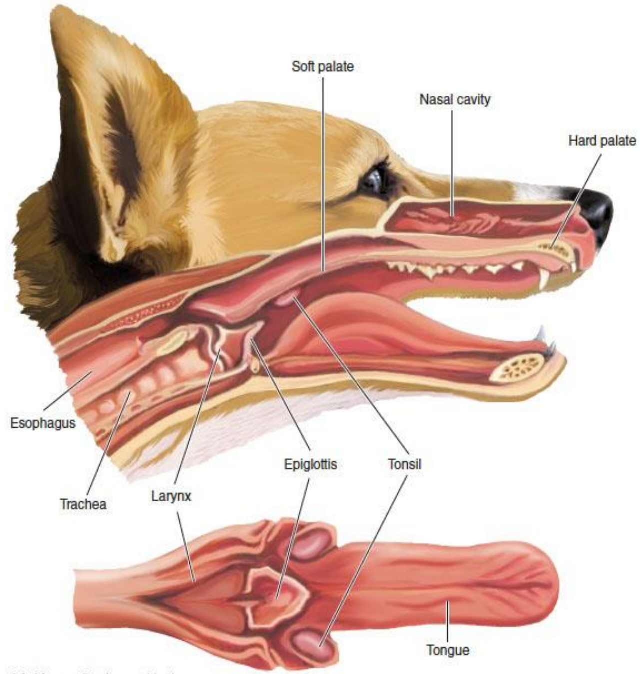
# 11.4 Air Respirers: Vertebrates



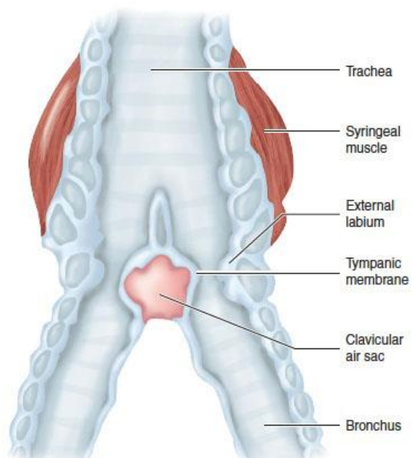
# 11.4 Air Respirers: Vertebrates

- **Nonrespiratory functions** of aerial respiratory systems
  - Regulation of **water loss** and **heat exchange**
    - Moistening of inspired air is essential to prevent desiccation of respiratory surfaces
  - **Improved venous return** -- respiratory pump
  - **Acid-base balance**
  - **Defense** against inhaled foreign matter
  - **Removal**, **modification**, **activation** or **inactivation** of substances passing through the pulmonary circulation
  - **Olfaction**
  - **Vocalization**
    - **Larynx** in mammals
    - **Syrinx** in birds -- the number of syringial muscles relates to complexity of song

# 11.4 Air Respirers: Vertebrates

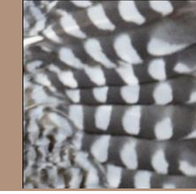



**(a)** Mammalian larynx (dog)



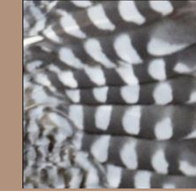

**(b)** Bird syrinx

# 11.5 Breathing: Respiratory Mechanics in Mammals



- Air flows according to **pressure gradients**
  - **Atmospheric pressure** (760 mmHg at sea level)
    - Decreases with increasing altitude
  - **Intra-alveolar pressure** -- seeks equilibrium with atmospheric pressure
  - **Intrapleural pressure**
    - Usually less than atmospheric pressure
    - (4 mmHg less on average)

# 11.5 Breathing: Respiratory Mechanics in Mammals



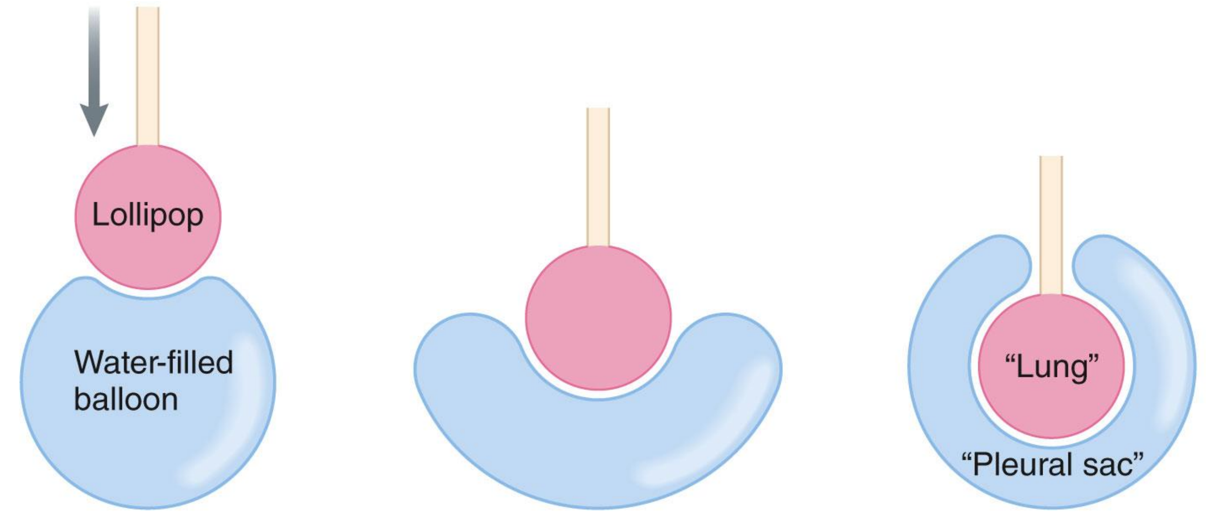
- Influence of intrapleural pressure

  - **Pleural sac** separates lungs from the thoracic wall
    - **Pleural cavity** contains **intrapleural fluid**
    - Polar water molecules in intrapleural fluid resist being pulled apart -- hold pleural surfaces together

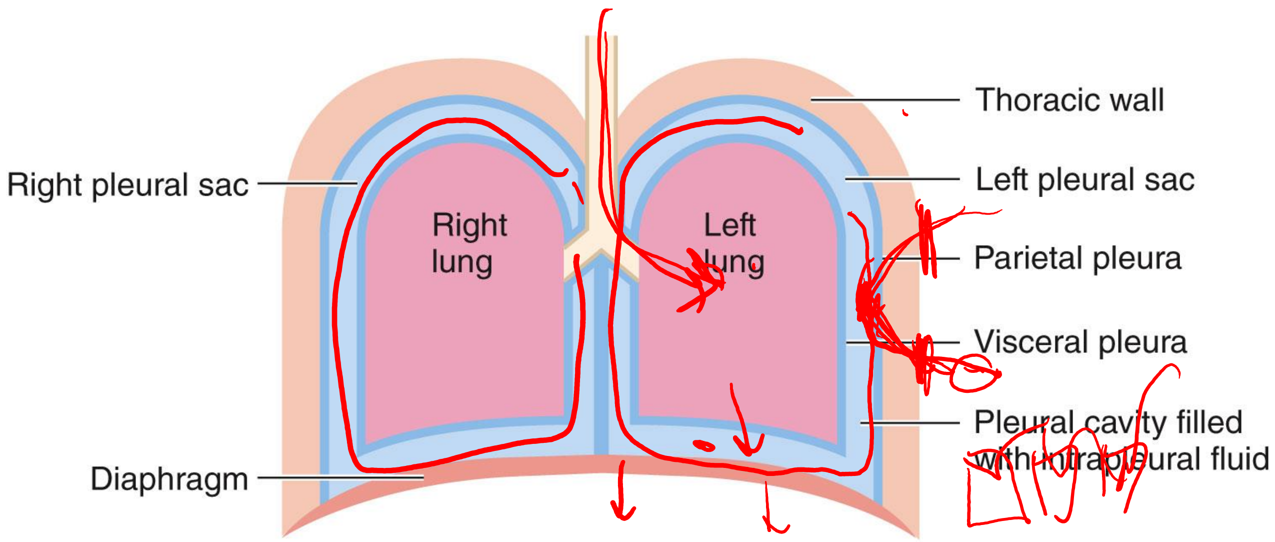
  - Lungs are stretched and follow movements of the chest wall because of **transmural pressure gradient**

  - **Intrapleural pressure** and **intra-alveolar pressure decrease** when the chest wall expands during **inspiration** and **increase** during **expiration**
    - **Boyle's law** -- At any constant temperature, the pressure exerted by a gas varies inversely with the volume of the gas

# 11.5 Breathing: Respiratory Mechanics in Mammals

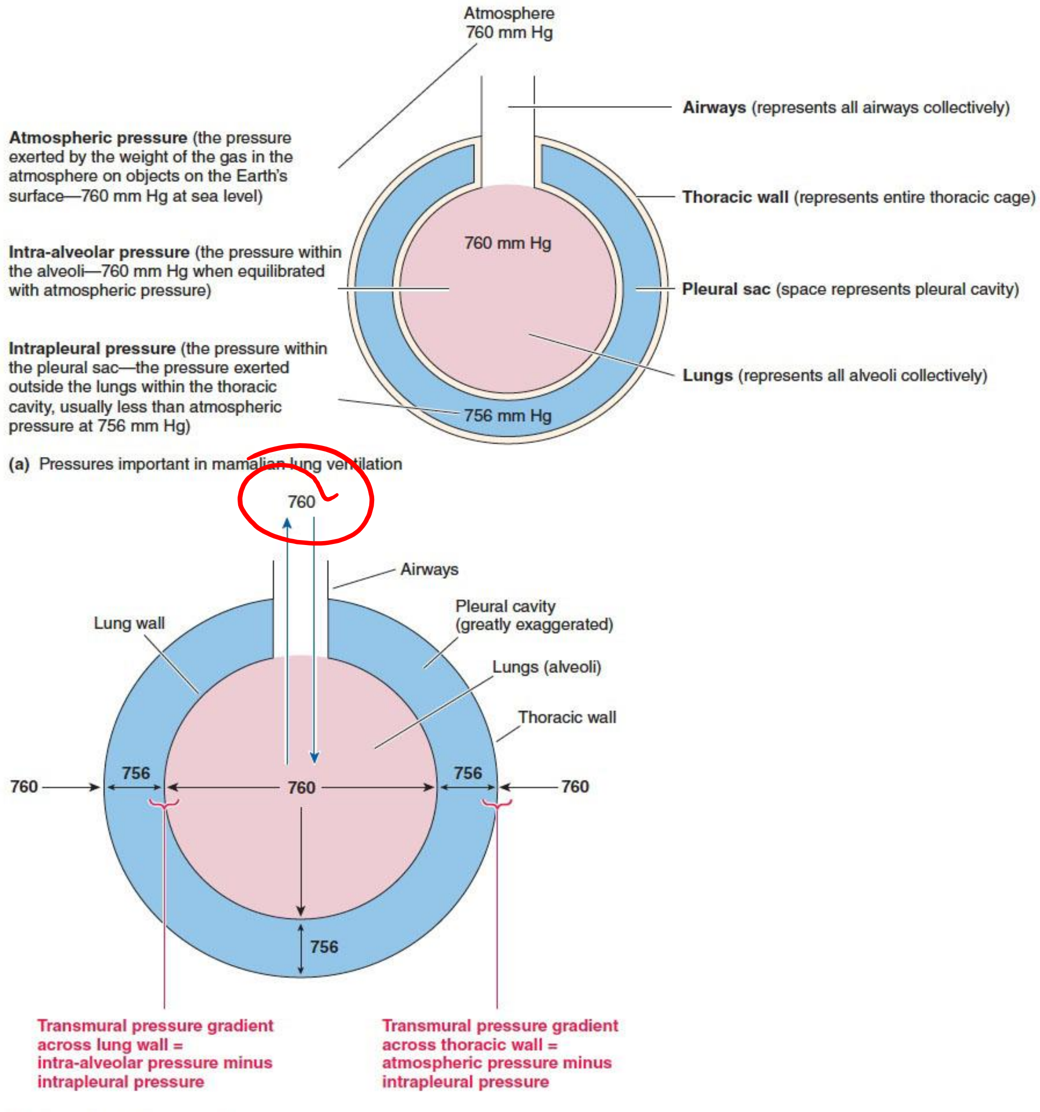



**(a)** Analogy of relationship between lung and pleural sac




**(b)** Relationship of lungs to pleural sacs, thoracic wall, and diaphragm

# 11.5 Breathing: Respiratory Mechanics in Mammals




**(a)** Pressures important in mammalian lung ventilation



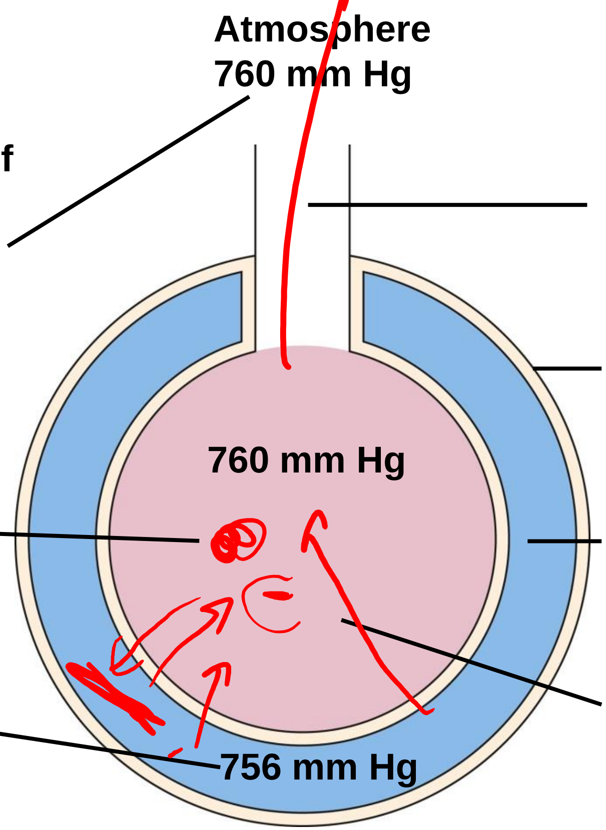
Numbers are mm Hg pressure.

**(b)** Transmural pressure gradient

Atmospheric pressure (the pressure exerted by the weight of the gas in the atmosphere on objects on the Earth's surface—760 mm Hg at sea level)

Intra-alveolar pressure (the pressure within the alveoli—760 mm Hg when equilibrated with atmospheric pressure)

Intrapleural pressure (the pressure within the pleural sac—the pressure exerted outside the lungs within the thoracic cavity, usually less than atmospheric pressure at 756 mm Hg)



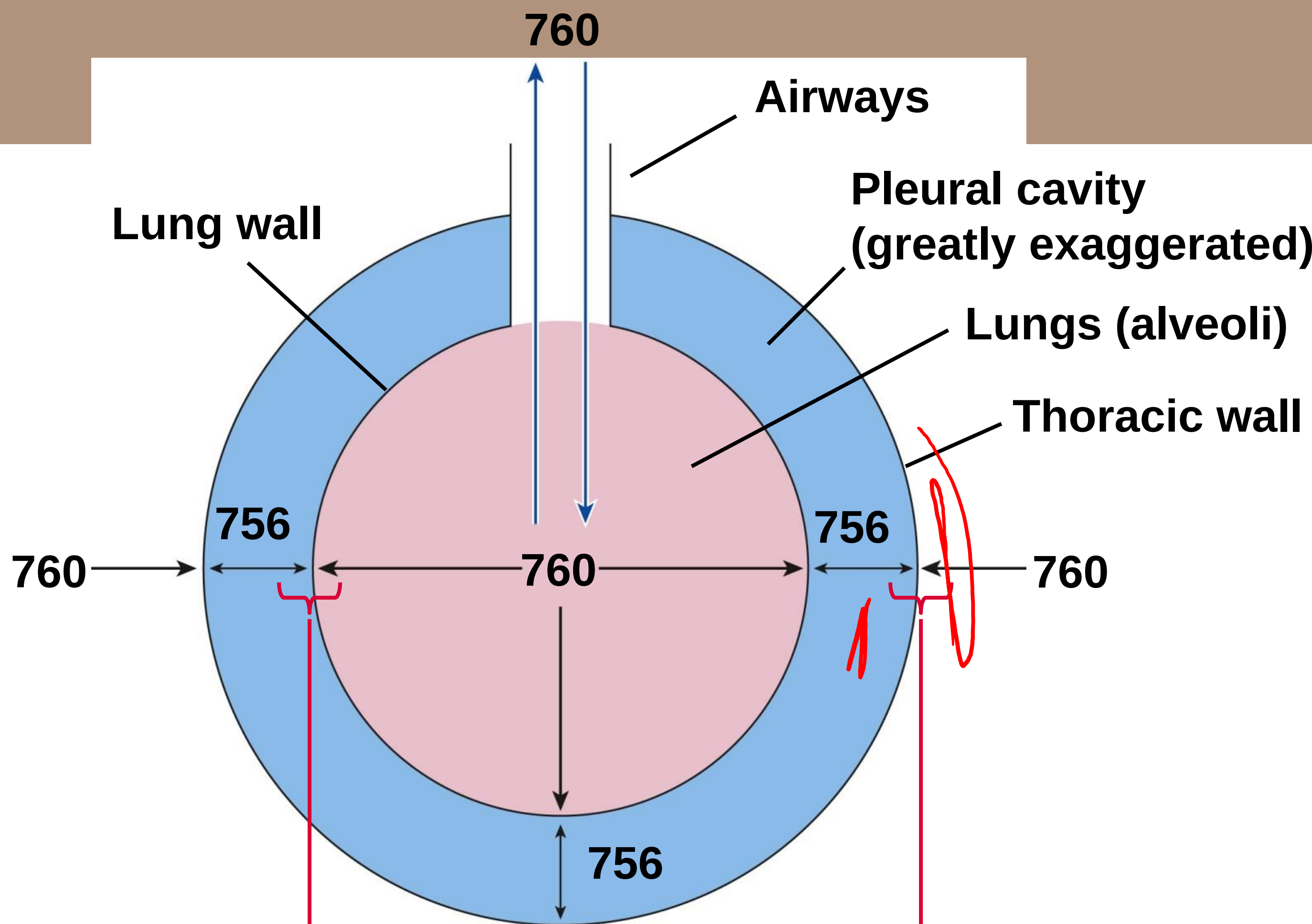

Airways (represents all airways collectively)

Thoracic wall (represents entire thoracic cage)

Pleural sac (space represents pleural cavity)

Lungs (represents all alveoli collectively)

(a) Pressures important in mamalian lung ventilation




Transmural pressure gradient across lung wall = intra-alveolar pressure minus intrapleural pressure

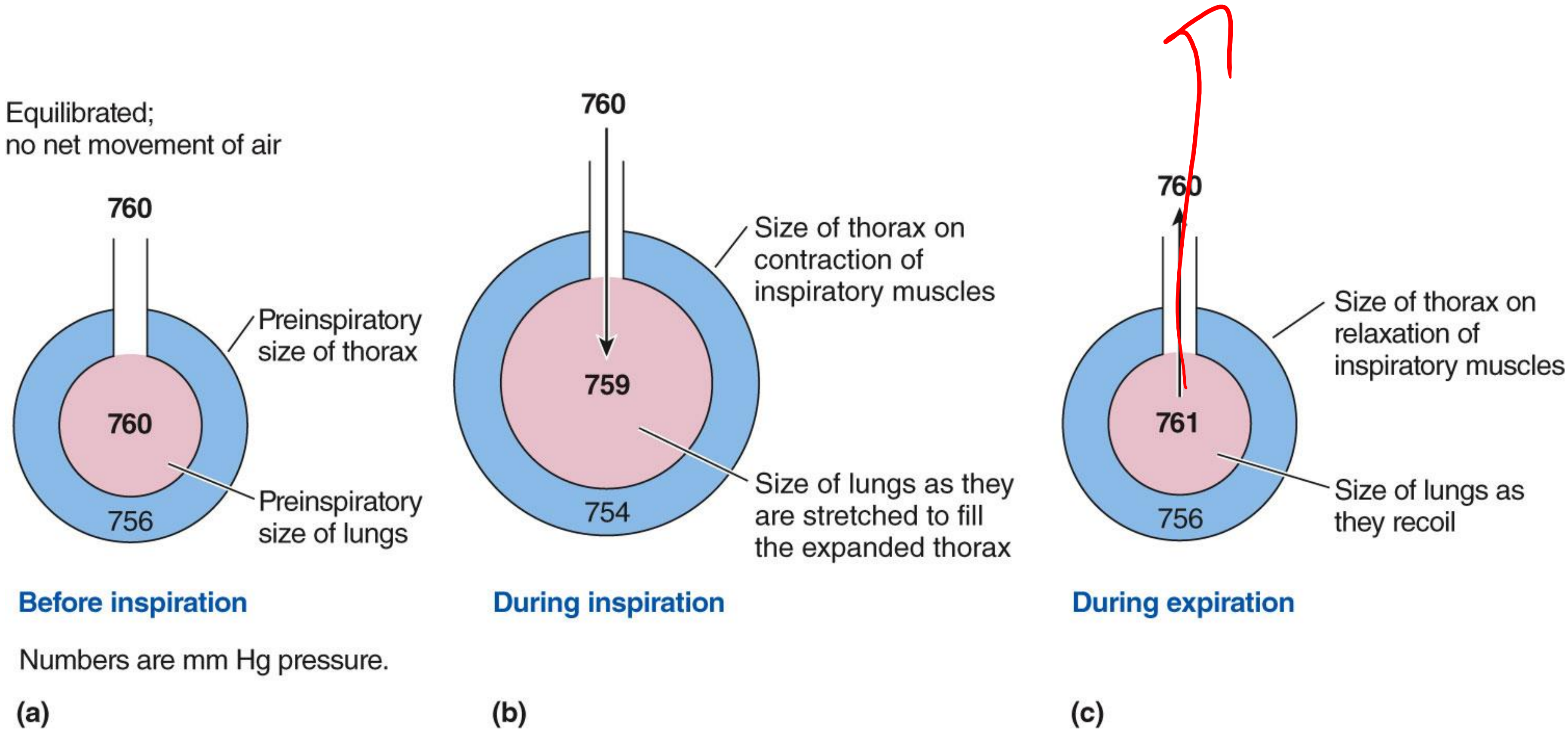
Transmural pressure gradient across thoracic wall = atmospheric pressure minus intrapleural pressure

Numbers are mm Hg pressure.

(b) Transmural pressure gradient

Figure 11-19b p518

# 11.5 Breathing: Respiratory Mechanics in Mammals

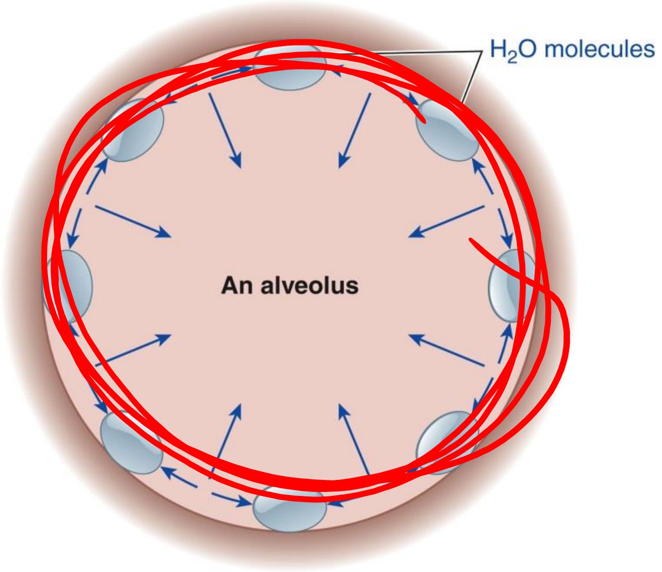


# 11.5 Breathing: Respiratory Mechanics in Mammals

- **Airway resistance** is normally low
  - Depends on **radius** of the conducting system
  - Pressure gradients of 1 - 2 mmHg produce adequate rates of air flow
  - Diseases causing **narrowing of airways** greatly **increase resistance** and the **work of breathing**
    - **Chronic obstructive pulmonary diseases (COPD)** -- chronic bronchitis, asthma, emphysema
    - **Equine restrictive lung diseases**

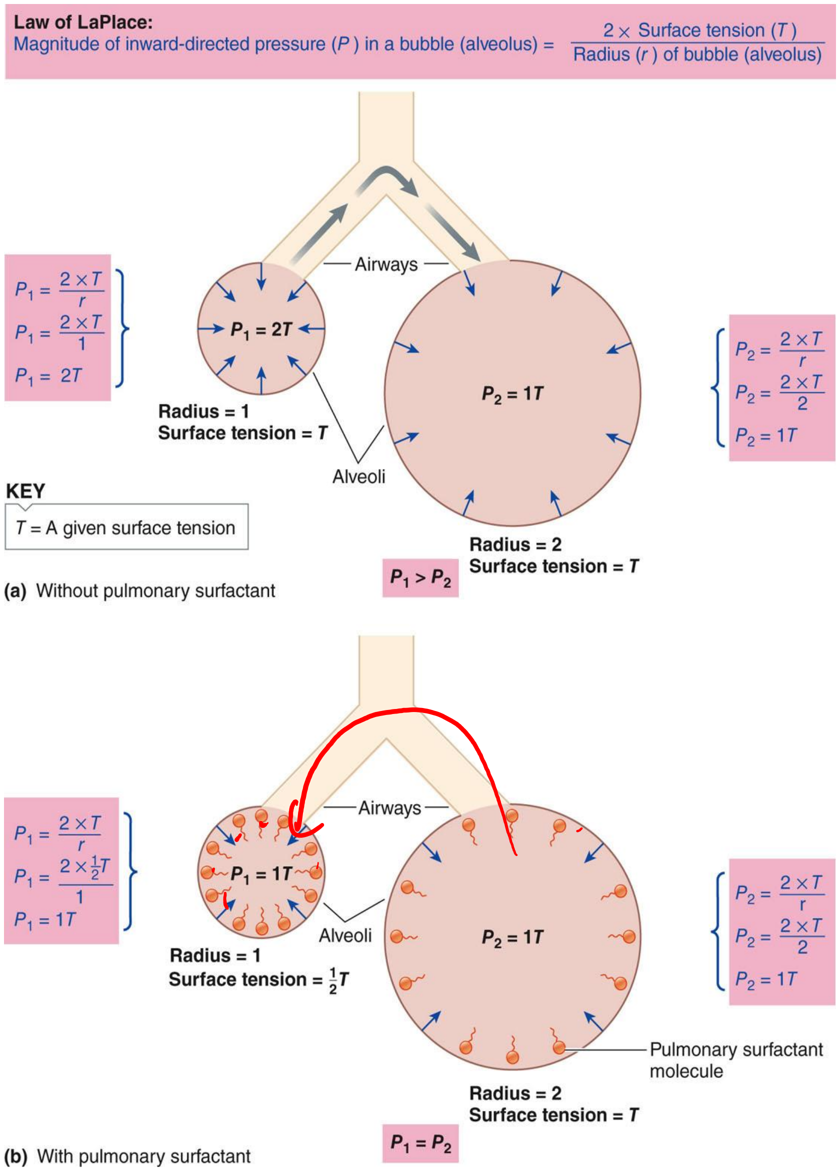
# 11.5 Breathing: Respiratory Mechanics in Mammals

- **Elasticity** of lungs depends on **connective tissue** and **alveolar surface tension**
  - Pulmonary connective tissue contains large amounts of **elastin** -- rebound after being stretched
  - Alveolar surface tension is reduced by **pulmonary surfactant**




    - Increases pulmonary compliance
    - Reduces the lungs' tendency to recoil
    - Prevents collapse of smaller alveoli (predicted by LaPlace's law:  $P = 2T/r$)

# 11.5 Breathing: Respiratory Mechanics in Mammals



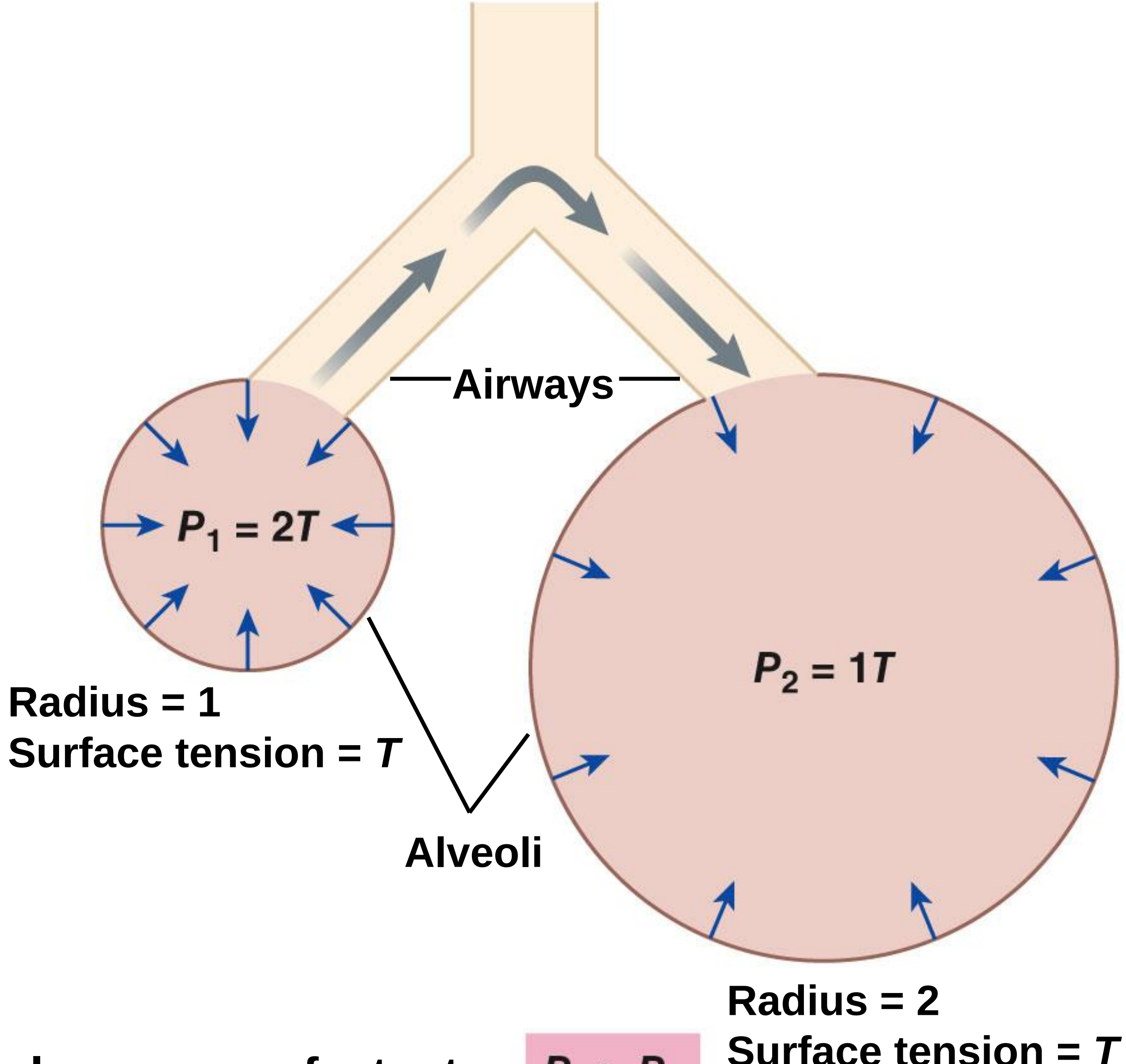
**Law of LaPlace:**

Magnitude of inward-directed pressure ($P$) in a bubble (alveolus) = $\frac{\text{2 x Surface tension } (T)}{\text{Radius } (r) \text{ of bubble (alveolus)}}$

$P_1 = \frac{2 \times T}{r}$

$P_1 = \frac{2 \times T}{1}$

$P_1 = 2T$




$P_2 = \frac{2 \times T}{r}$

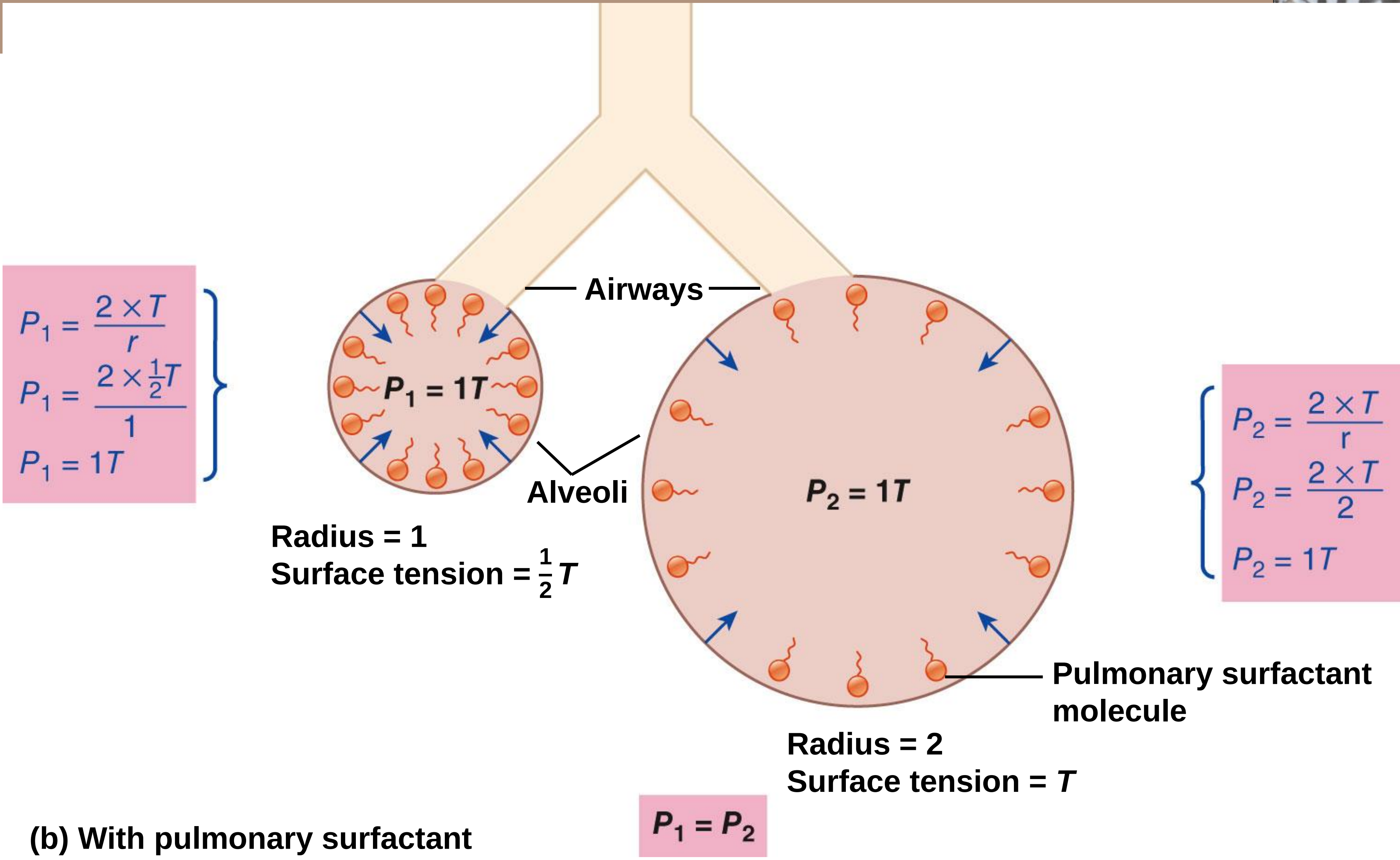
$P_2 = \frac{2 \times T}{2}$

$P_2 = 1T$

(a) Without pulmonary surfactant

$P_1 > P_2$

Figure 11-23a p522

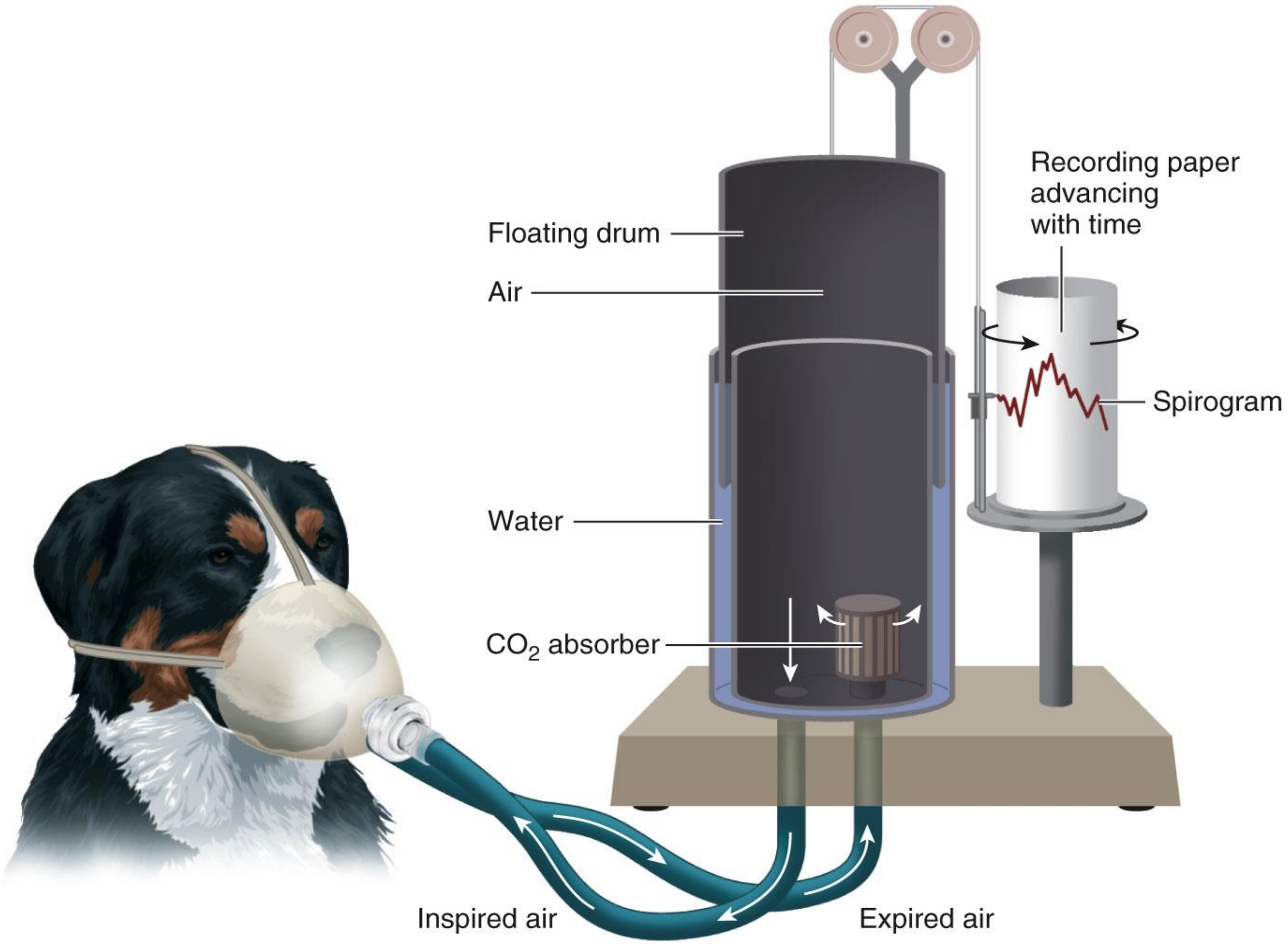



(b) With pulmonary surfactant

Figure 11-23b p522

# 11.6 Breathing: Lung Volumes in Mammals

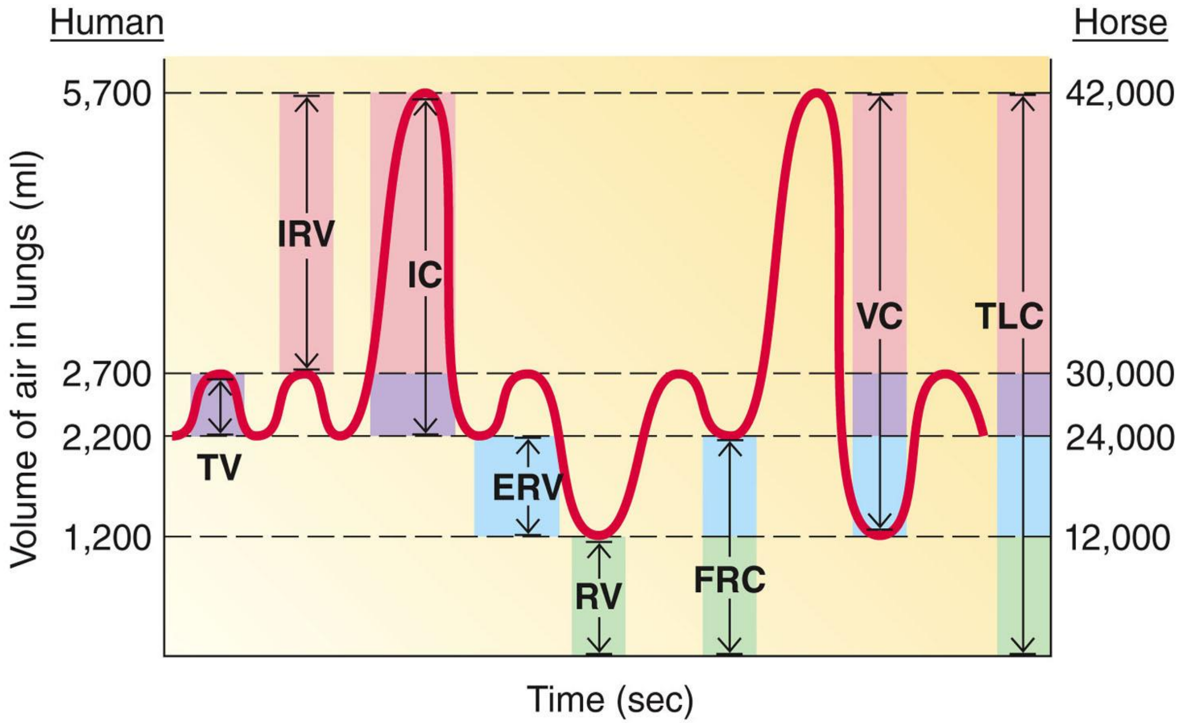
- Measurement of lung volumes with a **spirometer**



# 11.6 Breathing: Lung Volumes in Mammals

- Lung volumes and capacities
  - **Total lung capacity** (TLC) = Maximum amount of air that the lungs can hold (~5.7 L in humans)
  - **Tidal volume** (TV) = Volume of air entering or leaving the lungs during a single breath (resting TV ~ 0.5 ml)
  - **Functional residual capacity** (FRC) = Volume of air in the lungs at the end of a normal passive expiration (~2.2 L)
  - **Residual volume** (RV) = Minimum volume of air remaining in the lungs after a maximal expiration (~1.2 L)
  - **Vital capacity** (VC) = Maximum volume of air that can be moved out during a single breath following maximal inspiration (~4.5 L)

# 11.6 Breathing: Lung Volumes in Mammals




| | Human | Horse |
|---|---|---|
| TV = Tidal volume | 500 mL | 6,000 mL |
| IRV = Inspiratory reserve volume | 3,000 mL | 12,000 mL |
| IC = Inspiratory capacity | 3,500 mL | 18,000 mL |
| ERV = Expiratory reserve volume | 1,000 mL | 12,000 mL |
| RV = Residual volume | 1,200 mL | 12,000 mL |
| FRC = Functional residual capacity | 2,200 mL | 24,000 mL |
| VC = Vital capacity | 4,500 mL | 30,000 mL |
| TLC = Total lung capacity | 5,700 mL | 42,000 mL |

**(b)** Spirogram and table of values for adult male human and horse

# 11.6 Breathing: Lung Volumes in Mammals

- **Pulmonary ventilation** (minute ventilation)

Pulmonary ventilation = tidal volume x respiratory rate
(L/min) (L/breath) (breaths/min)

- Scales with **body size**

  - **Tidal volume** increases with increasing body size ($m_b$), while **respiratory rate** decreases with increasing body size:

$$TV = 0.0062 m_b^{1.01} \qquad RR = 53.5 m_b^{-0.26}$$

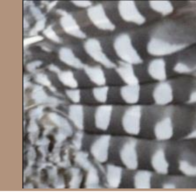
# 11.6 Breathing: Lung Volumes in Mammals

- Please note some significant errors on page 523

3. Functional Reserve Capacity (FRC)

Pulmonary ventilation = tidal volume x respiratory rate
(L/min) (L/breath) (breaths/min)

# 11.6 Breathing: Lung Volumes in Mammals



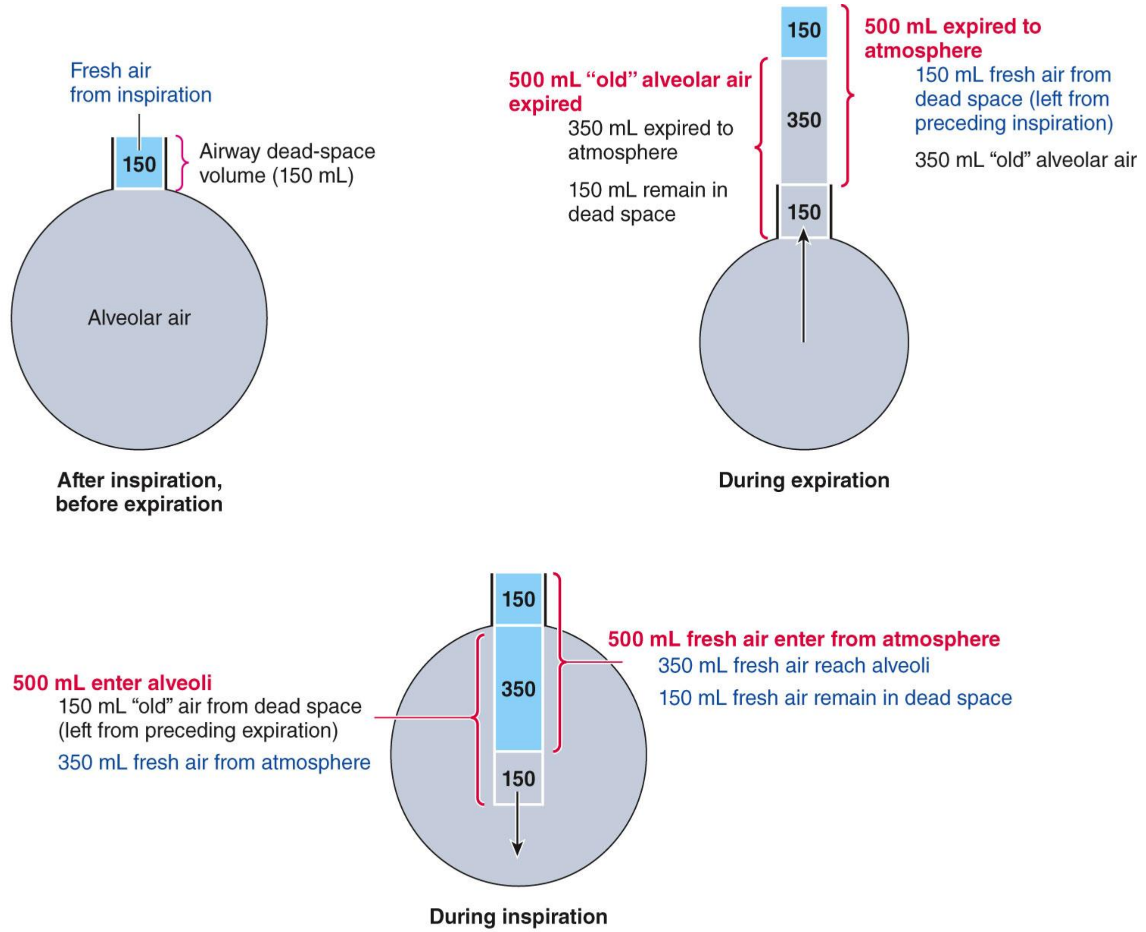
| Animal at Rest | Pulmonary Ventilation (PV) | = | Resting Tidal Volume (rTV) | × | Respiratory Rate |
|---|---|---|---|---|---|
| Rat (0.22 kg) | 0.12 L/min | = | 0.001 L/breath | × | 120 breaths/min |
| Human (70 kg) | 6.0 L/min | = | 0.4 L/breath | × | 15 breaths/min |
| Giraffe (400 kg) | 30 L/min | = | 3.3 L/breath | × | 9 breaths/min |
| Horse (450 kg) | 72 L/min | = | 6 L/breath | × | 12 breaths/min |
| Elephant (7,000 kg) | 235 L/min | = | 47 L/breath | × | 5 breaths/min |
| **Active Animals** | | | **Active TV** | | |
| Human, fast run: | 150 L/min | = | 2.5 L/breath | × | 60 breaths/min |
| Horse, fast trot: | 1,500 L/min | = | 25 L/breath | × | 60 breaths/min |

# 11.6 Breathing: Lung Volumes in Mammals

- **Alveolar ventilation**
  - When increasing pulmonary ventilation (e.g. during activity), it is advantageous to have a **greater increase in tidal volume** than respiratory rate
    - Not all inspired air reaches the alveoli for gas exchange
    - **Anatomic dead space** = Volume of conducting passages (~0.15 L)
    - **Alveolar ventilation** = Volume of air exchanged between the atmosphere and alveoli per minute

Alveolar ventilation = (TV – dead space) x RR

# 11.6 Breathing: Lung Volumes in Mammals




The numbers in the figure represent ml of air.

**KEY**

- "Old" alveolar air that has exchanged $O_2$ and $CO_2$ with the blood
- Fresh atmospheric air that has not exchanged $O_2$ and $CO_2$ with the blood

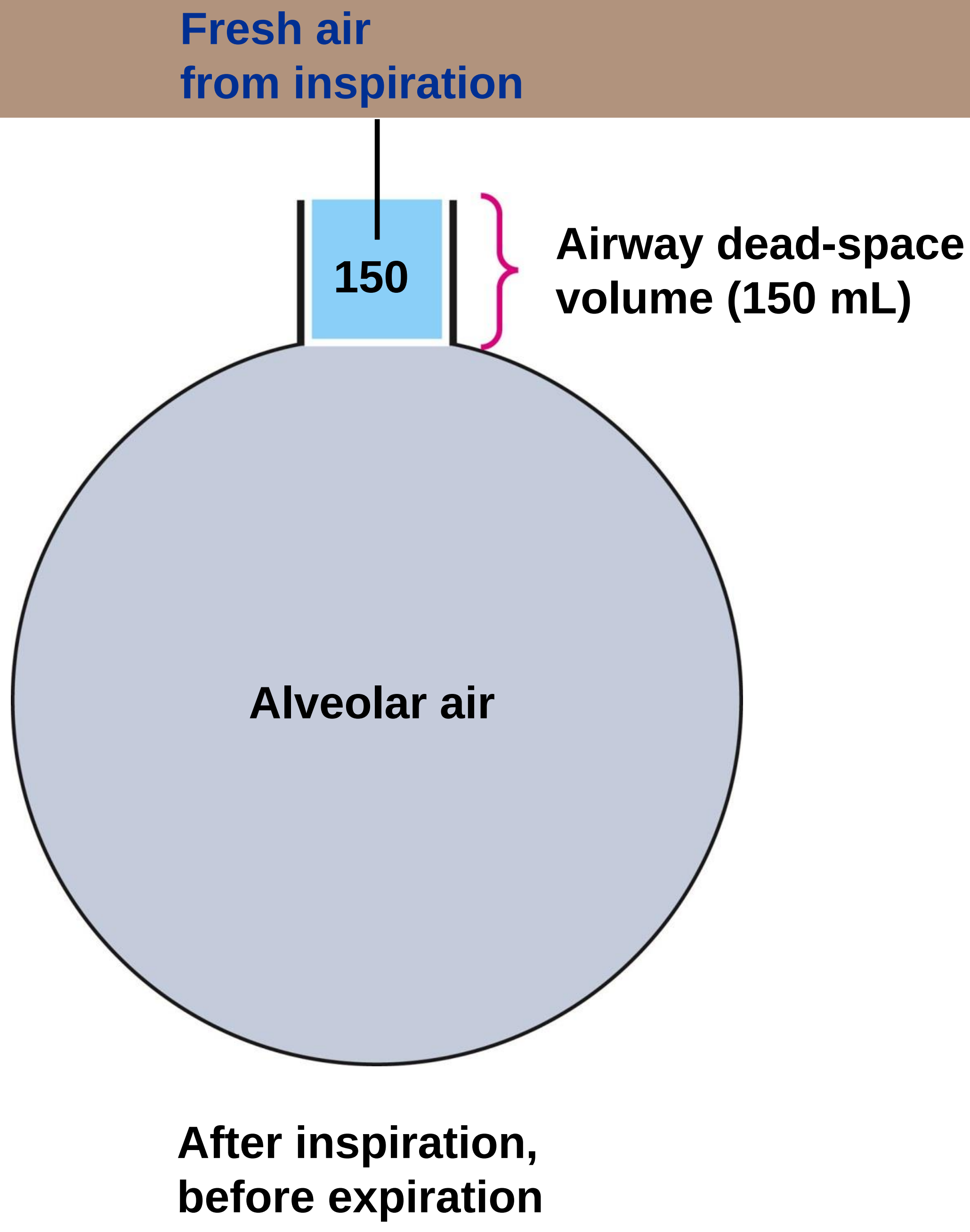



Figure 11-26a p526

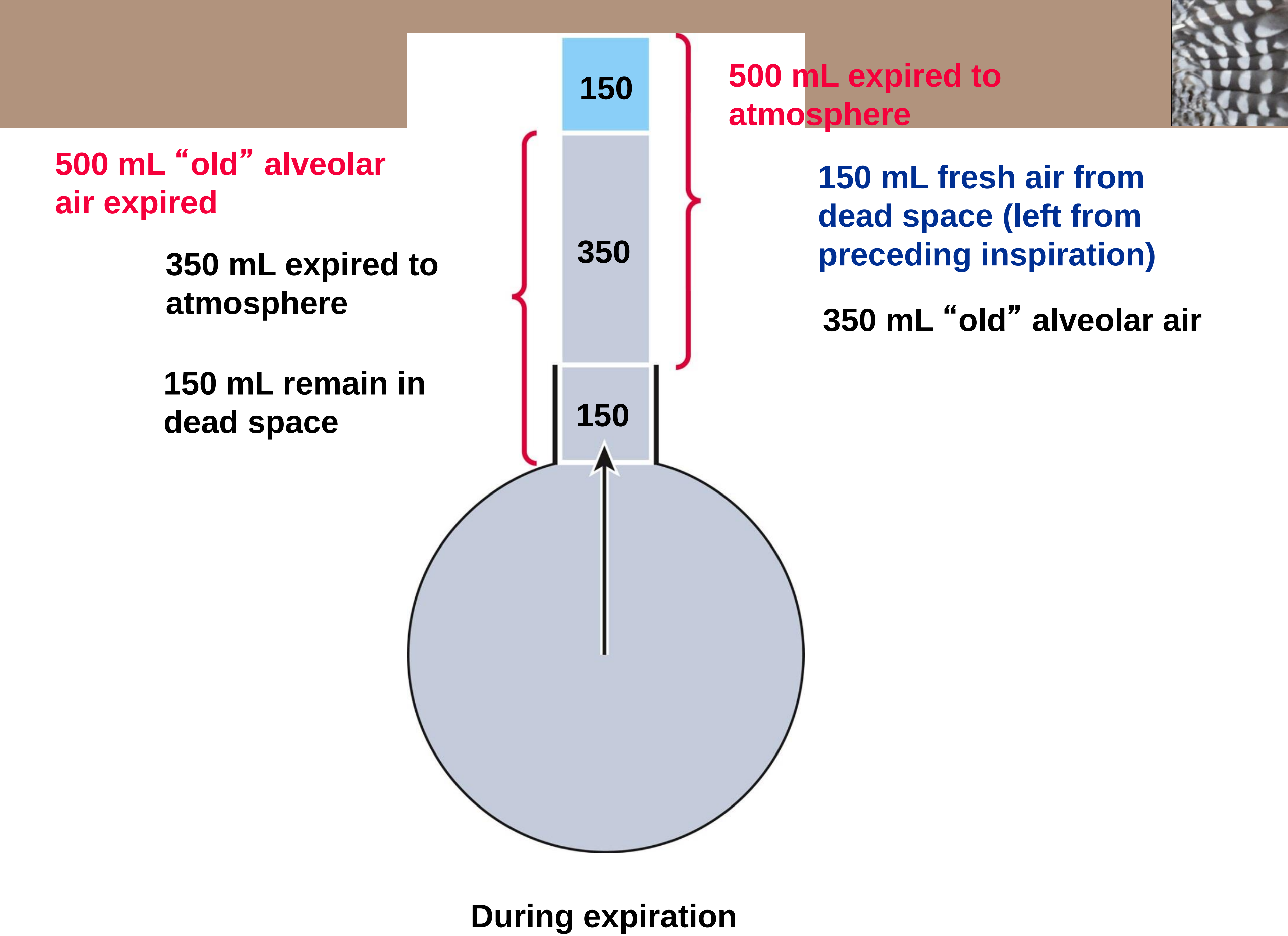
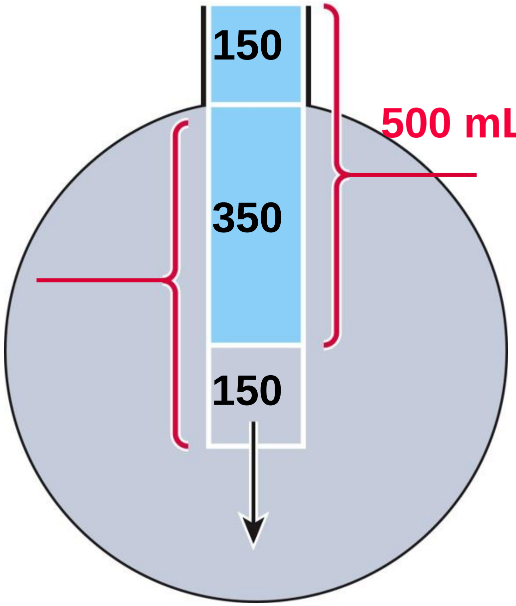



Figure 11-26b p526

500 mL enter alveoli

150 mL “old” air from dead space (left from preceding expiration)

350 mL fresh air from atmosphere




500 mL fresh air enter from atmosphere

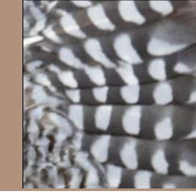
350 mL fresh air reach alveoli

150 mL fresh air remain in dead space

During inspiration

Figure 11-26c p526

# 11.7 Breathing: Flow-through versus Tidal Respirers



- Comparative efficiency
  - **Flow-through systems** (e.g. fishes) have much **lower dead-space** volumes than tidal systems
  - **Partial flow-through systems** in **birds** have **higher dead-space volumes**
    - Due to the larger size of the trachea
    - To compensate, a bird has a **higher TV** and **lower RR** than a mammal of comparable size
  - Only **2% of total energy** is expended on quiet breathing in mammals
    - 25-fold **increase in energy requirement** for pulmonary ventilation during **strenuous activity** increases percentage to 5%
    - ~20% of total energy is expended on respiration in **fish**

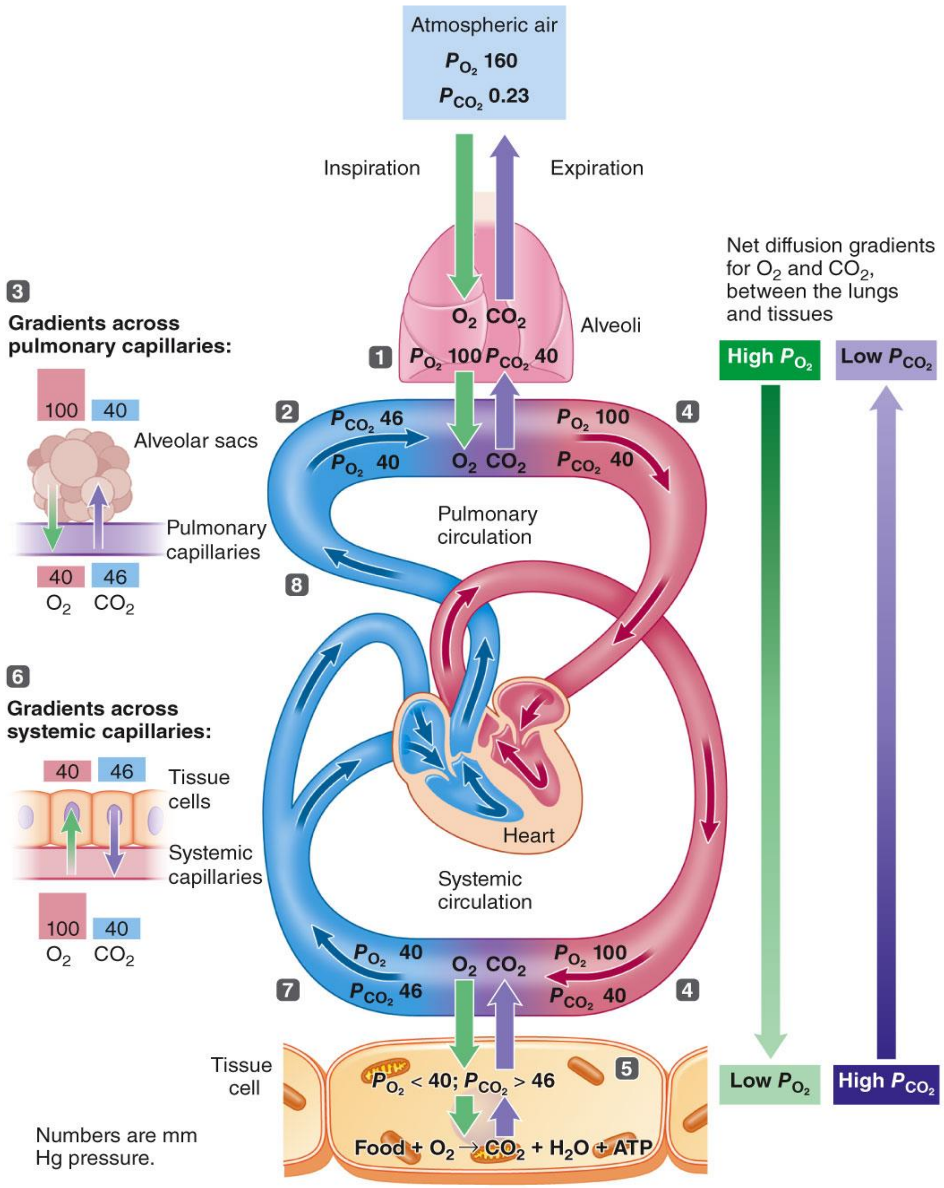
# 11.7 Breathing: Flow-through versus Tidal Respirers

- Comparative efficiency
  - The tidal lung of mammals can only achieve a blood $Po_2$ equal to that of expired air
    - **25% efficiency** of $O_2$ extraction from air
  - In **birds** (partially tidal with dead spaces and crosscurrent blood flow), efficiency is 30 - 40%
  - Countercurrent blood flow in **fish, crustaceans and amphibians** yields **90% $O_2$ extraction efficiency** from water (however, $O_2$ content is lower in water)

# 11.8 Gas Exchange at Vertebrate Respiratory Organs and Body Tissues

- Lung air $Po_2$ is lower than inspired atmospheric air
  - **Saturated with water** (partial pressure of water vapor is 47 mmHg at body temperature)
  - Inspired air is **mixed with old air** in dead space
  - Average **alveolar $Po_2$** is **100 mmHg**
  - $O_2$ diffuses into pulmonary capillary blood about as fast as it is inhaled
  - $Pco_2$ is higher in lung air than in inspired air
    - Average alveolar $Pco_2$ is 40 mmHg

# 11.8 Gas Exchange at Vertebrate Respiratory Organs and Body Tissues




1 Alveolar $P_{O_2}$ remains relatively high and alveolar $P_{CO_2}$ remains relatively low because a portion of the alveolar air is exchanged for fresh atmospheric air with each breath.

2 In contrast, the systemic venous blood entering the lungs is relatively low in $O_2$ and high in $CO_2$, having given up $O_2$ and picked up $CO_2$ at the systemic capillary level.

3 The partial pressure gradients established between the alveolar air and pulmonary capillary blood induce passive diffusion of $O_2$ into the blood and $CO_2$ out of the blood until the blood and alveolar partial pressures become equal.

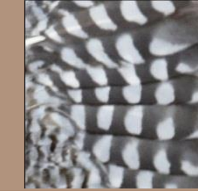
4 The blood leaving the lungs is thus relatively high in $O_2$ and low in $CO_2$. It arrives at the tissues with the same blood-gas content as when it left the lungs.

5 The partial pressure of $O_2$ is relatively low and that of $CO_2$ is relatively high in the $O_2$-consuming, $CO_2$-producing tissue cells.

6 Consequently, partial pressure gradients for gas exchange at the tissue level favor the passive movement of $O_2$ out of the blood into non-circulatory cells to support their metabolic requirements and also favor the simultaneous transfer of $CO_2$ into the blood.

7 Having equilibrated with the tissue cells, the blood leaving the tissues is relatively low in $O_2$ and high in $CO_2$.

8 The blood then returns to the lungs to once again fill up on $O_2$ and dump off $CO_2$.



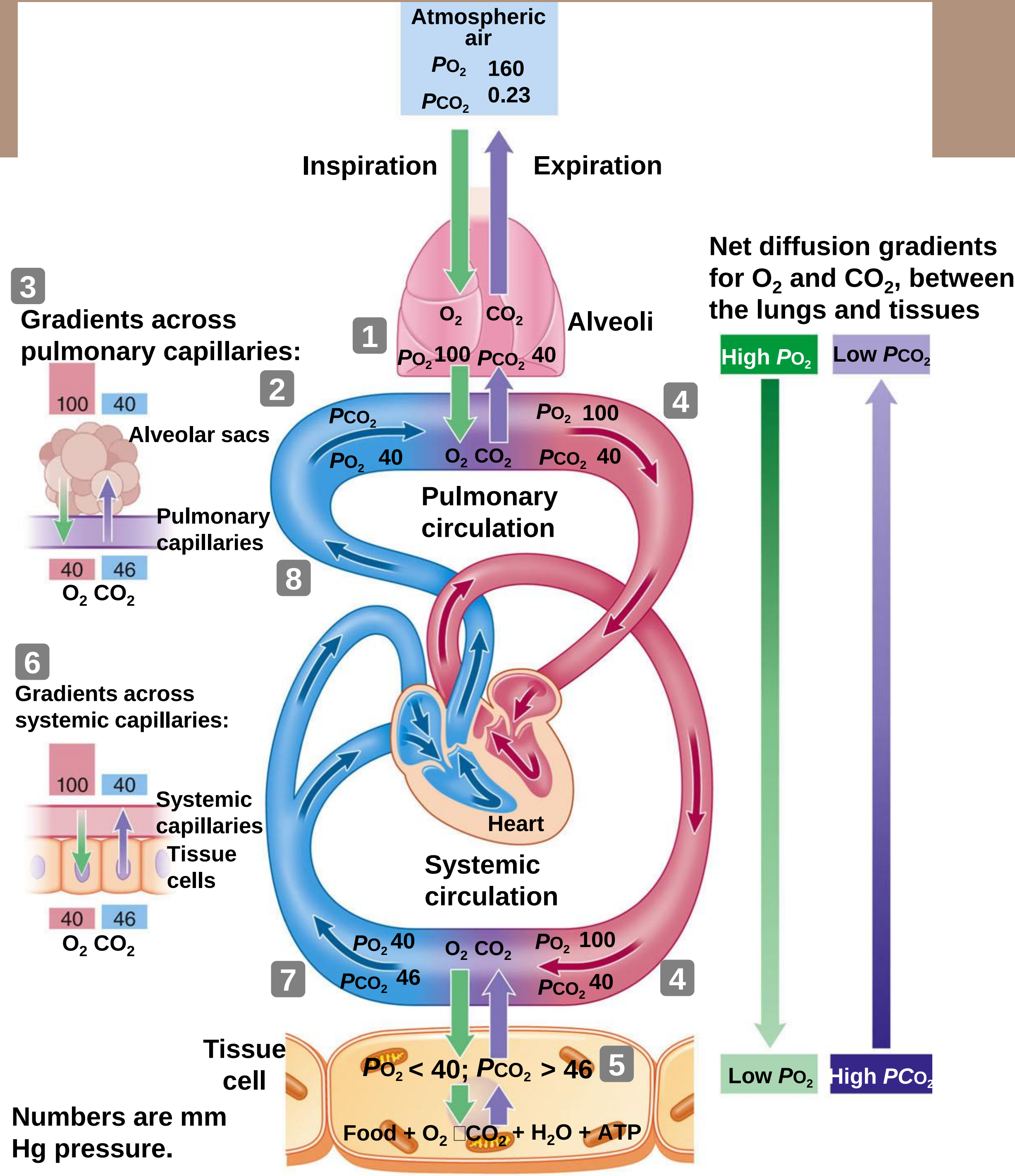
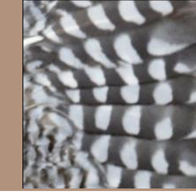



Figure 11-27 p528

# 11.8 Gas Exchange at Vertebrate Respiratory Organs and Body Tissues



- Gas exchange in the lungs
  - **$O_2$ diffuses from alveolar air into capillary blood**, equilibrating at $Po_2$ of 100 mmHg
  - **$CO_2$ diffuses from capillary blood into alveolar air**, equilibrating at $Pco_2$ of 40 mmHg
  - **Increased perfusion** of lung or gill capillaries improves gas exchange
  - **Increased thickness** of gas exchange barriers slows diffusion and **reduces gas exchange**
    - Low or high environmental pH causes **mucification** and **inflammation** of gill epithelium
    - **Pulmonary edema**, **pulmonary fibrosis** and **pneumonia** interfere with gas exchange in air breathers

# 11.8 Gas Exchange at Vertebrate Respiratory Organs and Body Tissues

- Gas exchange in the tissues
  - **Cellular $Po_2$** is **40 mmHg** and **$Pco_2$** is **46 mmHg**
  - **$O_2$ diffuses from systemic capillary blood into cells**, equilibrating at 40 mmHg
  - **$CO_2$ diffuses from cells into capillary blood**, equilibrating at 46 mmHg
  - **Increased metabolic activity** will lower capillary blood and tissue $Po_2$ and raise blood and tissue $Pco_2$

# 11.9 Circulatory Transport and Gas Exchange

- $O_2$ is transported in blood bound to **metal-containing respiratory pigments**

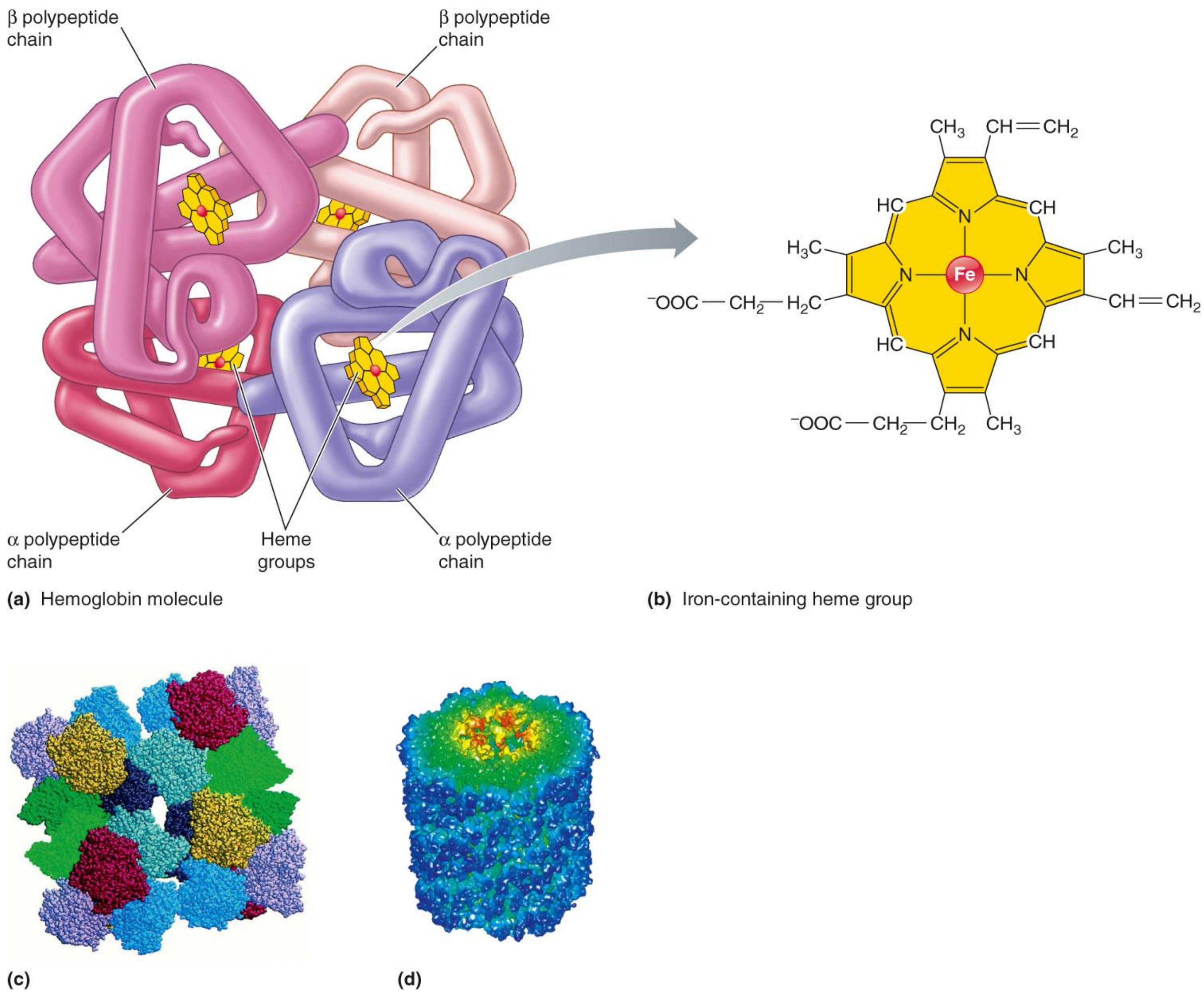
  - **Hemoglobin**
    - Annelids, mollusks, crustaceans, vertebrates
    - Highly folded polypeptide chain (**globin**) and iron-containing **heme** group
    - Red when oxygenated; blue when deoxygenated
  - **Hemocyanin**
    - Arthropods, annelids, mollusks
    - Large proteins bound to copper ions
    - Blue when oxygenated; colorless when deoxygenated

  - **Hemerythrin**
    - Brachiopods, sipunculids, one annelid
    - Red iron pigment, not in heme complex

    https://en.wikipedia.org/wiki/Hemerythrin
  - **Chlorocruorin** and **erythrocruorin**
    - Some annelids
    - Large iron/heme proteins; green or red
    - https://en.wikipedia.org/wiki/Chlorocruorin

https://en.wikipedia.org/wiki/Leghemoglobin

# 11.9 Circulatory Transport and Gas Exchange




**(a)** Hemoglobin molecule

**(b)** Iron-containing heme group

**(c)**

**(d)**

# 11.9 Circulatory Transport and Gas Exchange

- $O_2$ transport in vertebrates

  - Amount of **$O_2$ dissolved** is **proportional to $Po_2$** of blood (3 ml $O_2$/liter of blood at $Po_2$ of 100 mmHg)

  - The majority of $O_2$ is **bound to hemoglobin**
    - Most vertebrate hemoglobin is **tetrameric** and capable of binding to four $O_2$ molecules

$$\underset{\text{deoxyhemoglobin}}{HbH_4^{+} + 4\,O_2} \longleftrightarrow \underset{\text{oxyhemoglobin}}{Hb(O_2)_4 + 4\,H^{+}}$$

  - **Myoglobin** is a monomer that stores $O_2$ in muscle cells

  - **Neuroglobin** (neurons) and **cytoglobin** (fibroblasts)

# 11.9 Circulatory Transport and Gas Exchange

- Please note another significant error on page 532

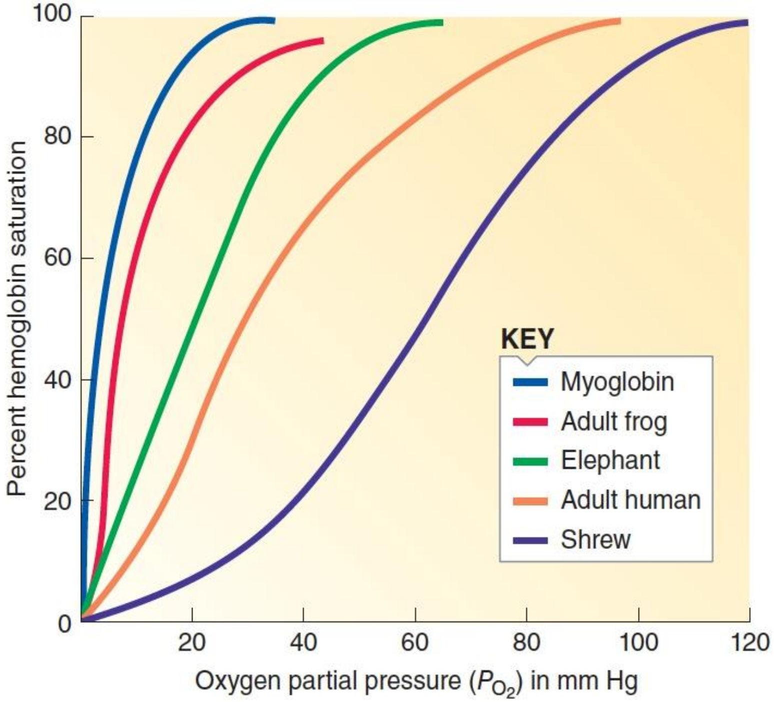
$$HbH_4^+ \;+\; 4\,O_2 \;\longleftrightarrow\; Hb(O_2)_4 \;+\; 4\,H^+$$

deoxyhemoglobin — oxyhemoglobin

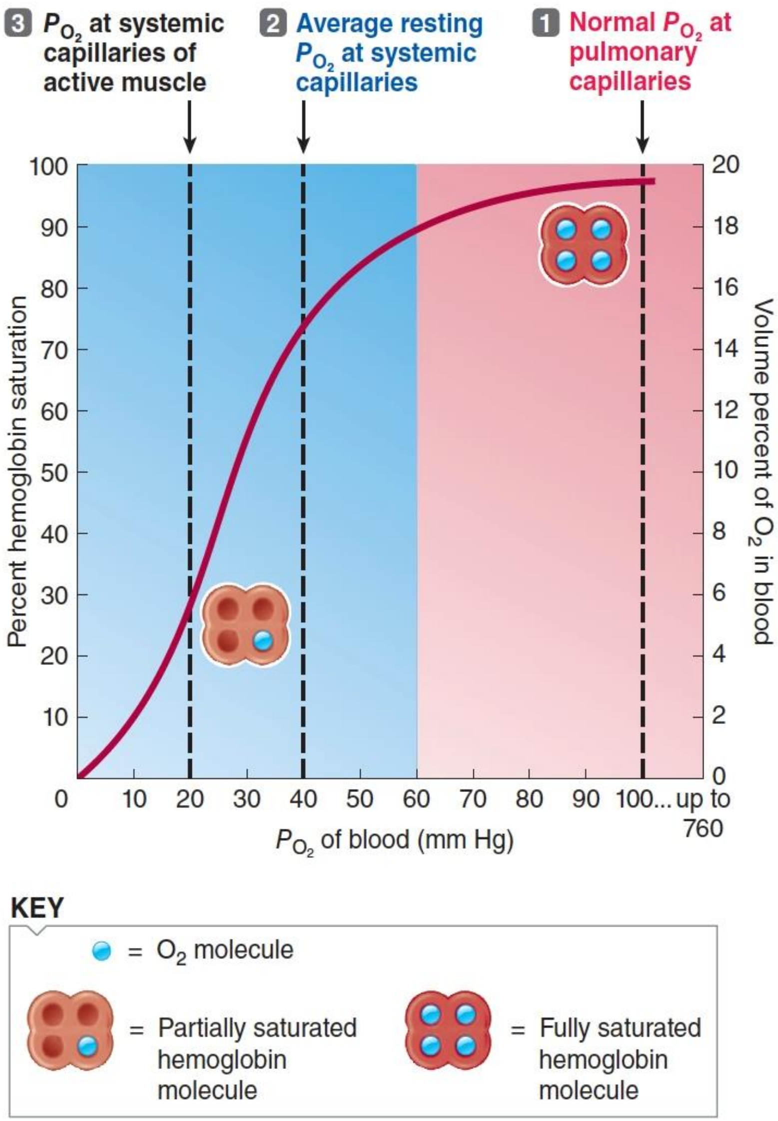
# 11.9 Circulatory Transport and Gas Exchange

- Hemoglobin saturation
  - Binding of $O_2$ to hemoglobin is **reversible** and subject to the **law of mass action**
  - The most important factor determining **% hemoglobin saturation** is $\mathbf{Po_2}$
  - Hemoglobin **binds** $\mathbf{O_2}$ **in the lungs** and **unloads** $\mathbf{O_2}$ **in the tissues**
  - **Affinity** of hemoglobin for $O_2$ (measured as $\mathbf{P_{50}}$) **increases with body size** and is higher in animals adapted to **high altitude** or **low oxygen** environments

# 11.9 Circulatory Transport and Gas Exchange



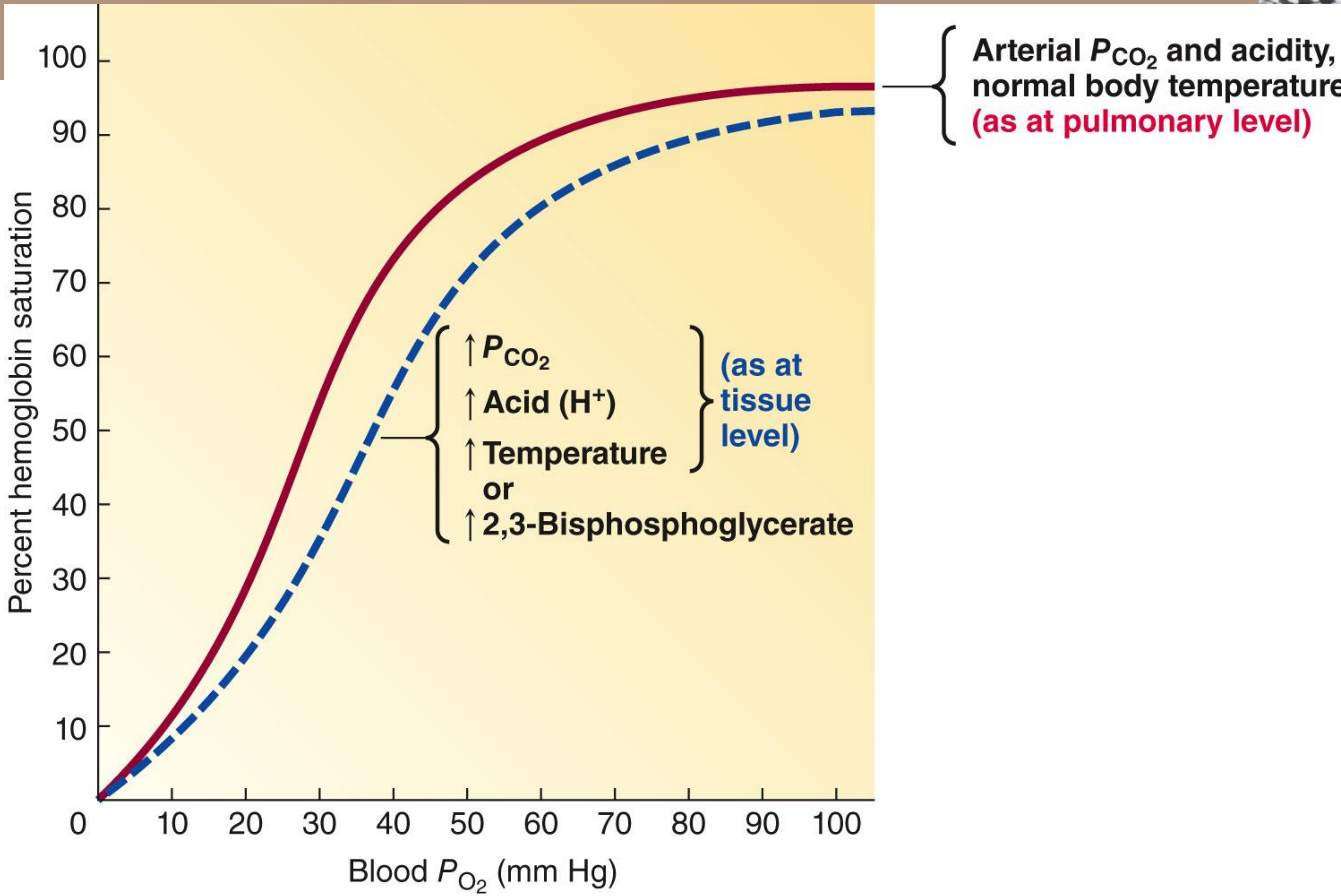

(a)




(b)

# 11.9 Circulatory Transport and Gas Exchange

- Factors that **decrease affinity** of Hb for $O_2$ promote **greater unloading** of $O_2$ in the tissues
  - Increased **$Pco_2$**
  - Increased **acidity** (Bohr effect)
    - Acidity also lowers **maximal $O_2$-binding capacity** (Root effect)
  - Increased **temperature**
  - **Organic phosphates**
    - 2,3-diphosphoglycerate (DPG) in most mammals
    - Inositol pentaphosphate (IPP) in birds
    - Nucleoside triphosphates in fishes




(a)

Figure 11-31a p538

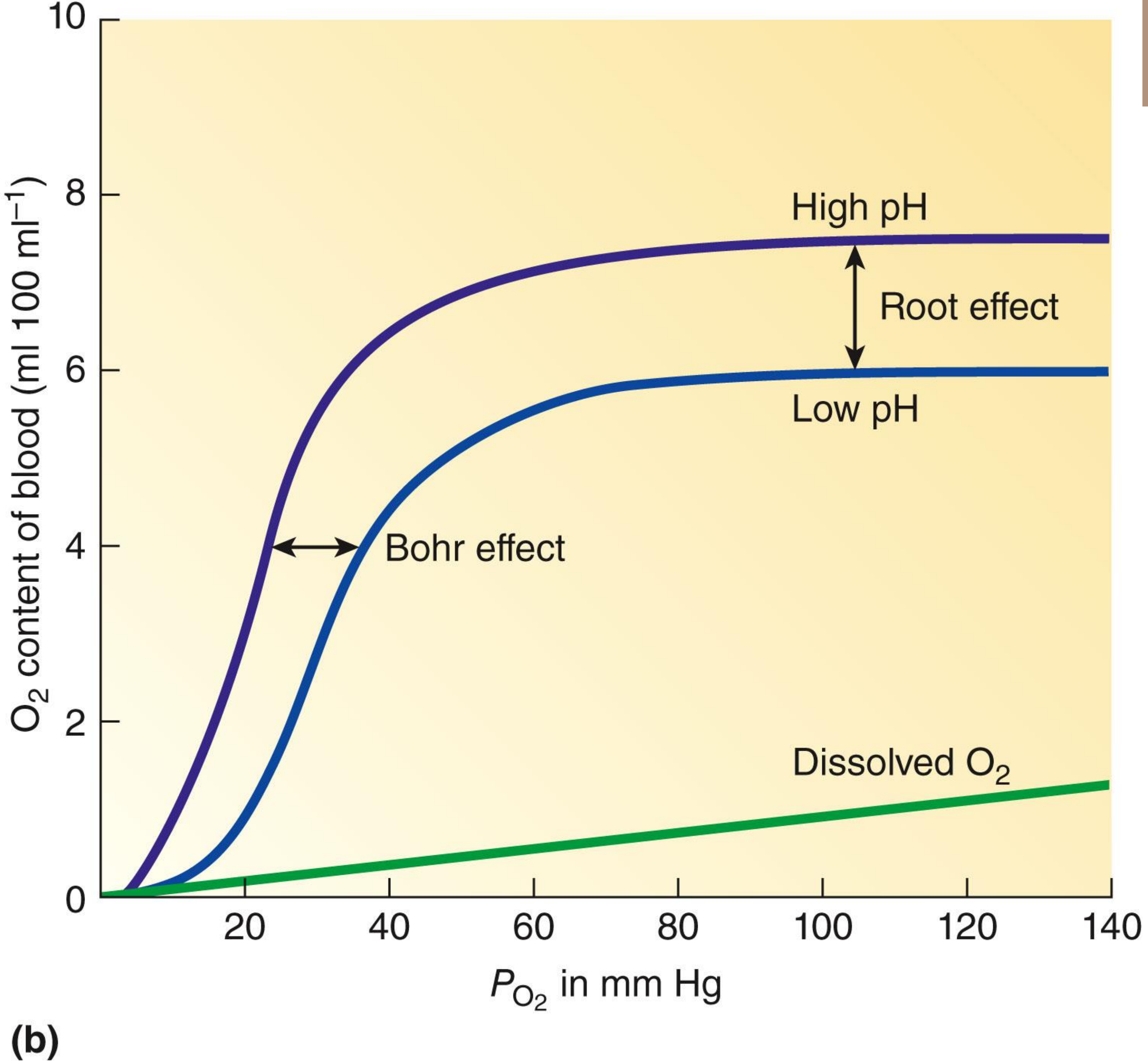


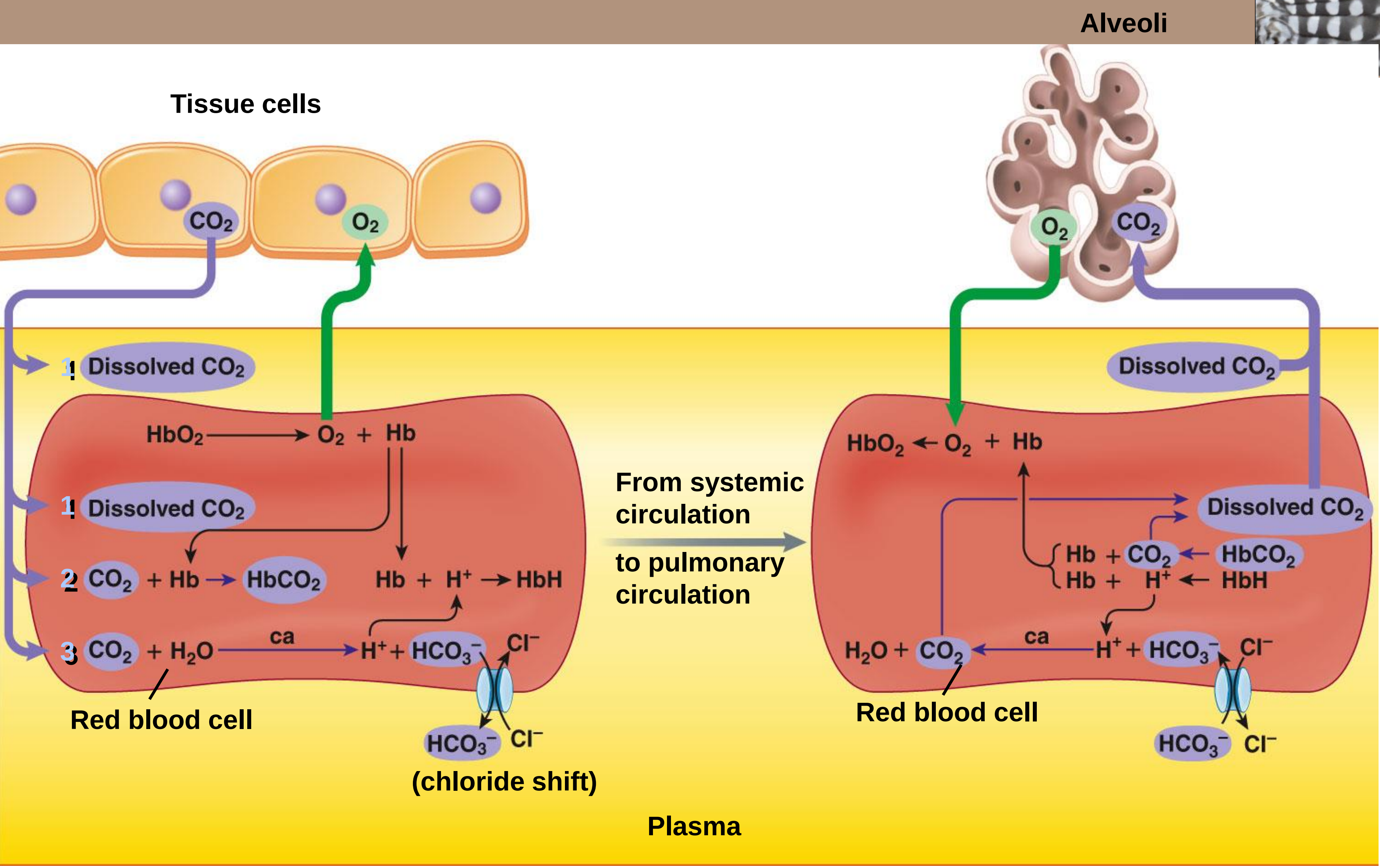

Figure 11-31b p538

# 11.9 Circulatory Transport and Gas Exchange

- Carbon dioxide transport in blood
  - **Dissolved** (5 - 10%)
  - **Bound to hemoglobin** (25 - 30%)
    - Forms **carbaminohemoglobin** ($HbCO_2$)
    - Binds with the globin
  - **Bicarbonate ion ($HCO_3^-$)** (60 - 70%)

$$CO_2 + H_2O \longleftrightarrow \underset{\text{carbonic acid}}{H_2CO_3} \longleftrightarrow H^+ + \underset{\text{bicarbonate ion}}{HCO_3^-}$$

- Enzyme for the first step is **carbonic anhydrase** found in lungs, kidneys and gills
- Chloride ions enter red blood cells in exchange for efflux of bicarbonate ion (**chloride shift**)
- Deoxygenated hemoglobin picks up $CO_2$ and $H^+$ (**Haldane effect**)



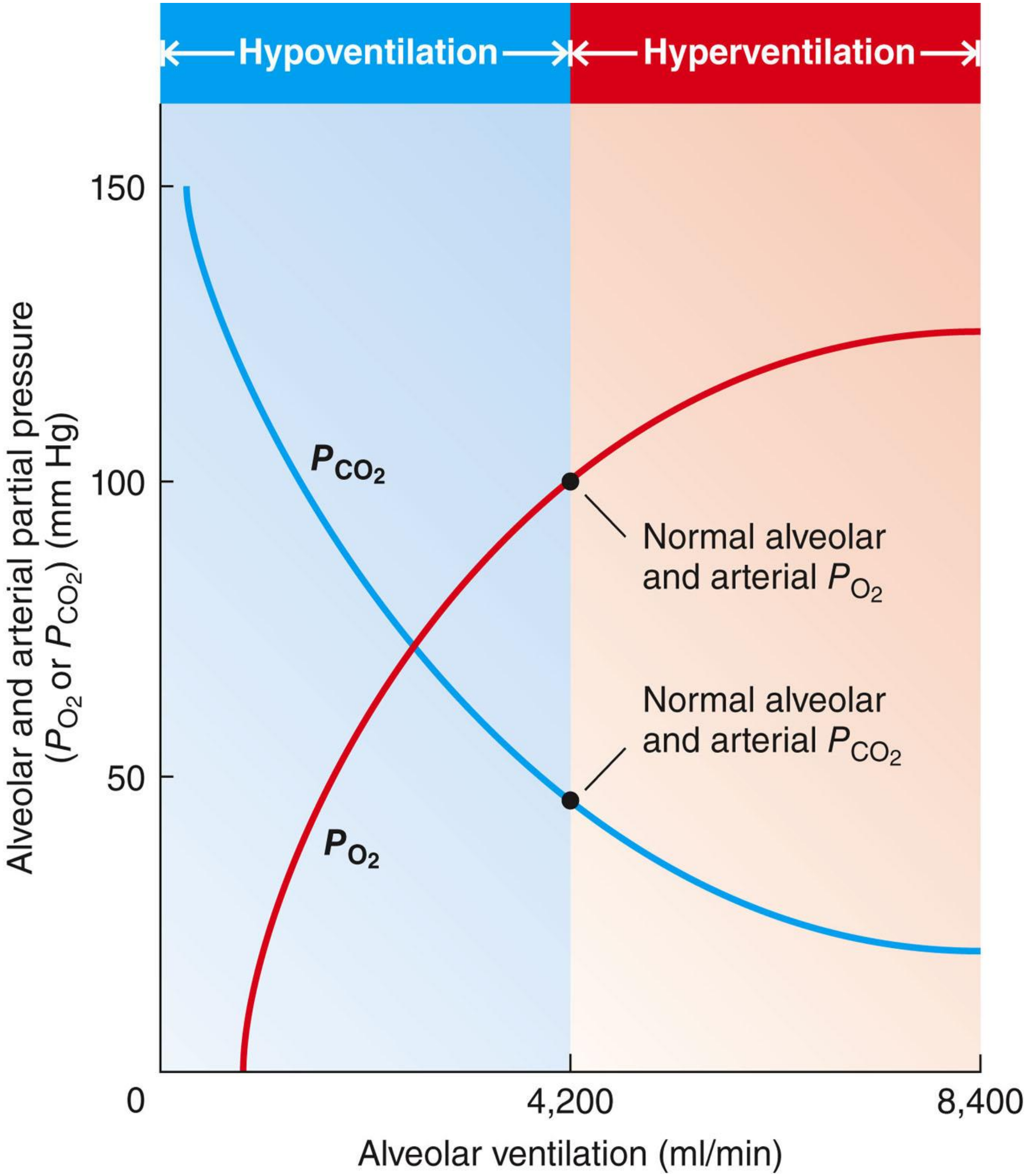

ca = Carbonic anhydrase

Figure 11-33 p541

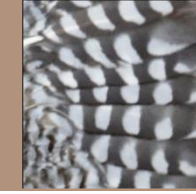
# 11.9 Circulatory Transport and Gas Exchange

- Abnormalities in arterial $Po_2$
  - **Hypoxic hypoxia** (e.g. high altitude)
  - **Anemic hypoxia** (e.g. carbon monoxide poisoning)
  - **Circulatory hypoxia** (e.g. congestive heart failure)
  - **Histotoxic hypoxia** (e.g. cyanide poisoning)
- Abnormalities in arterial $Pco_2$
  - **Hypercapnia** = excess $CO_2$ in arterial blood
    - Caused by **hypoventilation**
  - **Hypocapnia** = below normal arterial $Pco_2$
    - Caused by **hyperventilation**
  - Changes in blood $CO_2$ mainly affect **acid-base balance**

# 11.9 Circulatory Transport and Gas Exchange



# 11.10 Control of Respiration

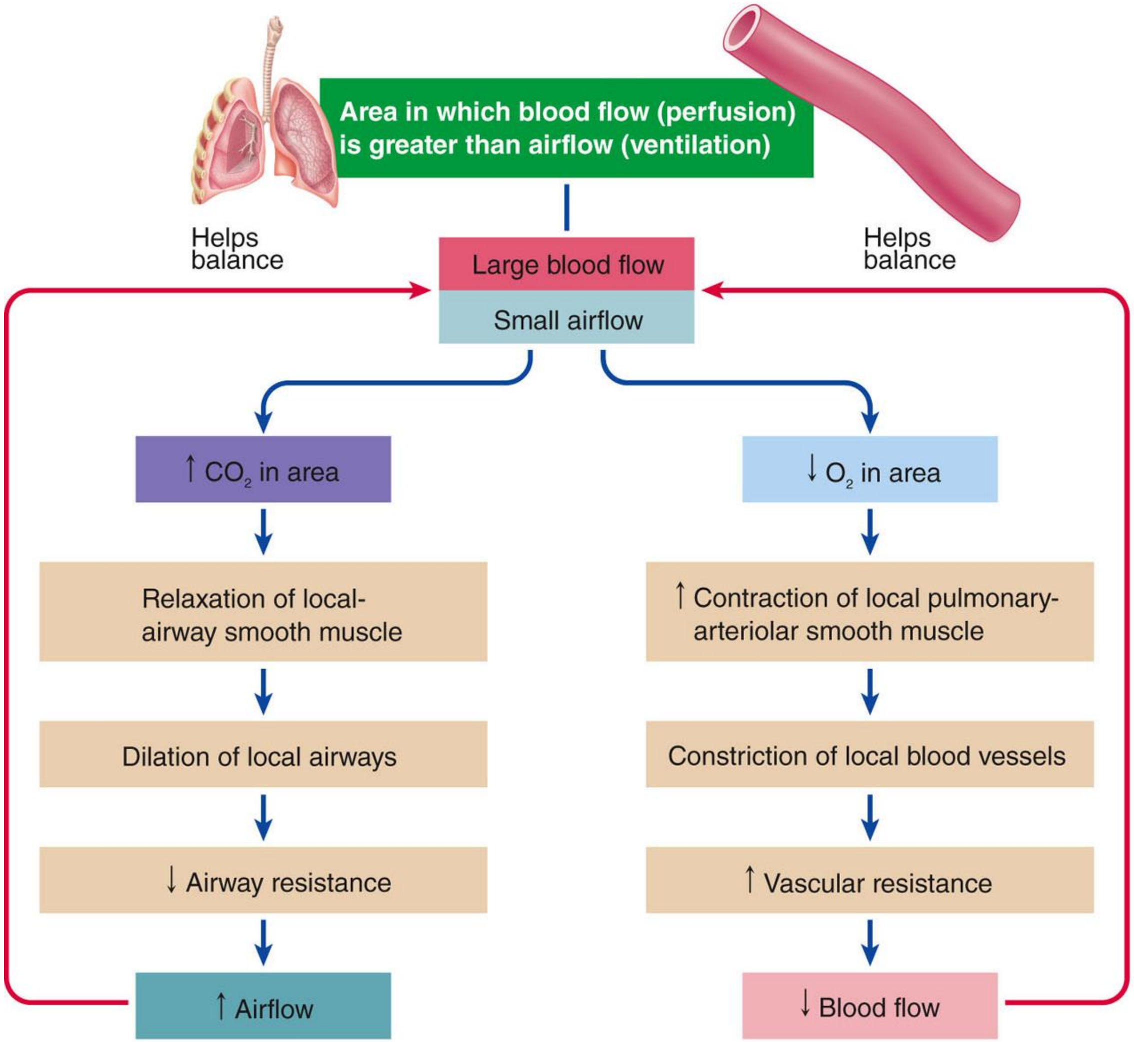


- Control of respiration in insects
  - **Metathoracic ganglia** control **closer muscles** which reduce opening of spiracles

- Extrinsic regulation of airways in mammals
  - **Parasympathetic** stimulation promotes **bronchoconstriction**, increasing airway resistance
  - **Sympathetic** stimulation promotes **bronchodilation**, decreasing airway resistance

- Intrinsic regulation of airways in mammals
  - **Ventilation rates match perfusion rates** by adjustment of airway smooth muscle and arterioles
  - **Local increase in $CO_2$** induces **relaxation** of airway smooth muscle
  - **Local decrease in $O_2$** causes **vasoconstriction** of pulmonary arterioles

# 11.10 Control of Respiration

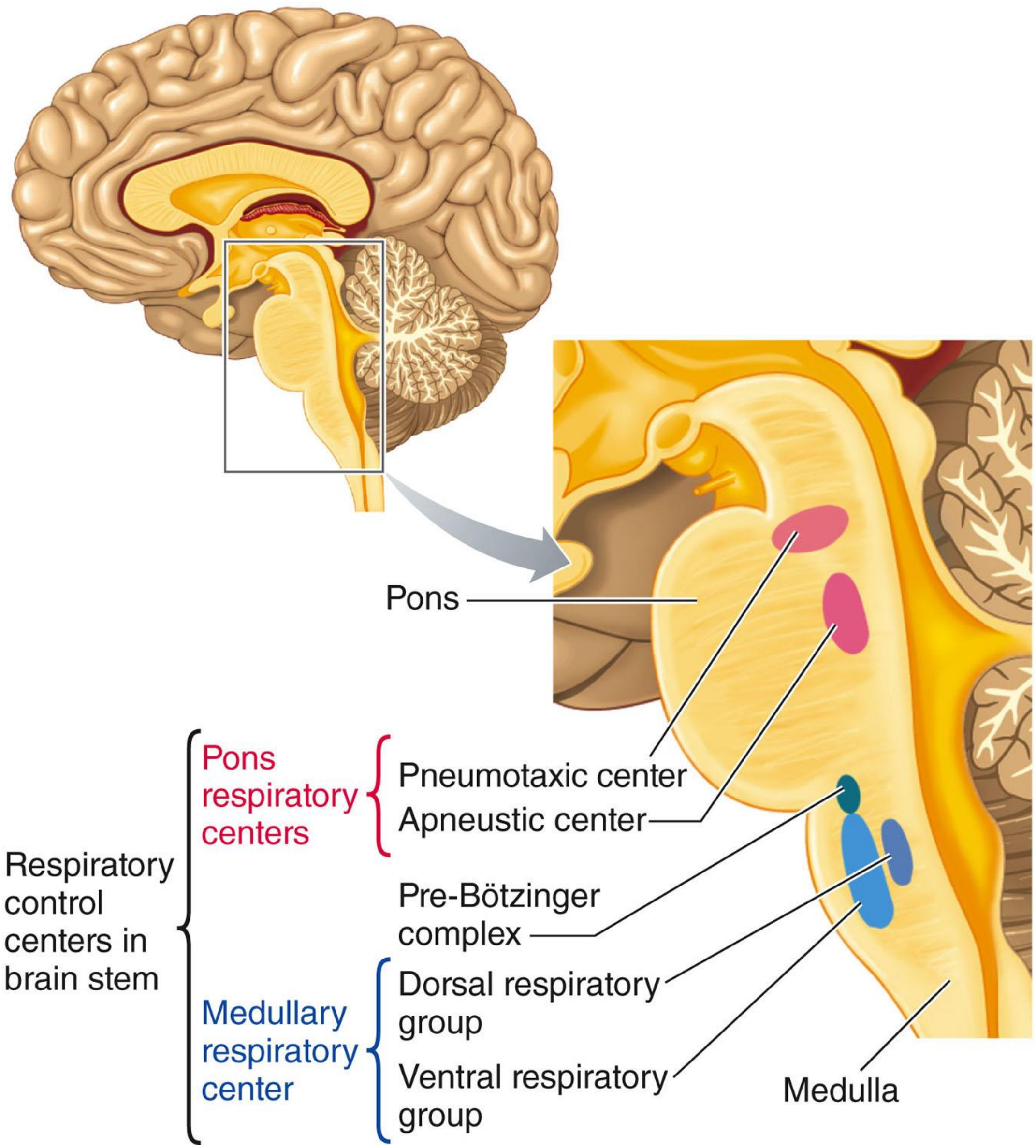



**(a)** Local controls to adjust ventilation and perfusion to lung area with large blood flow and small airflow

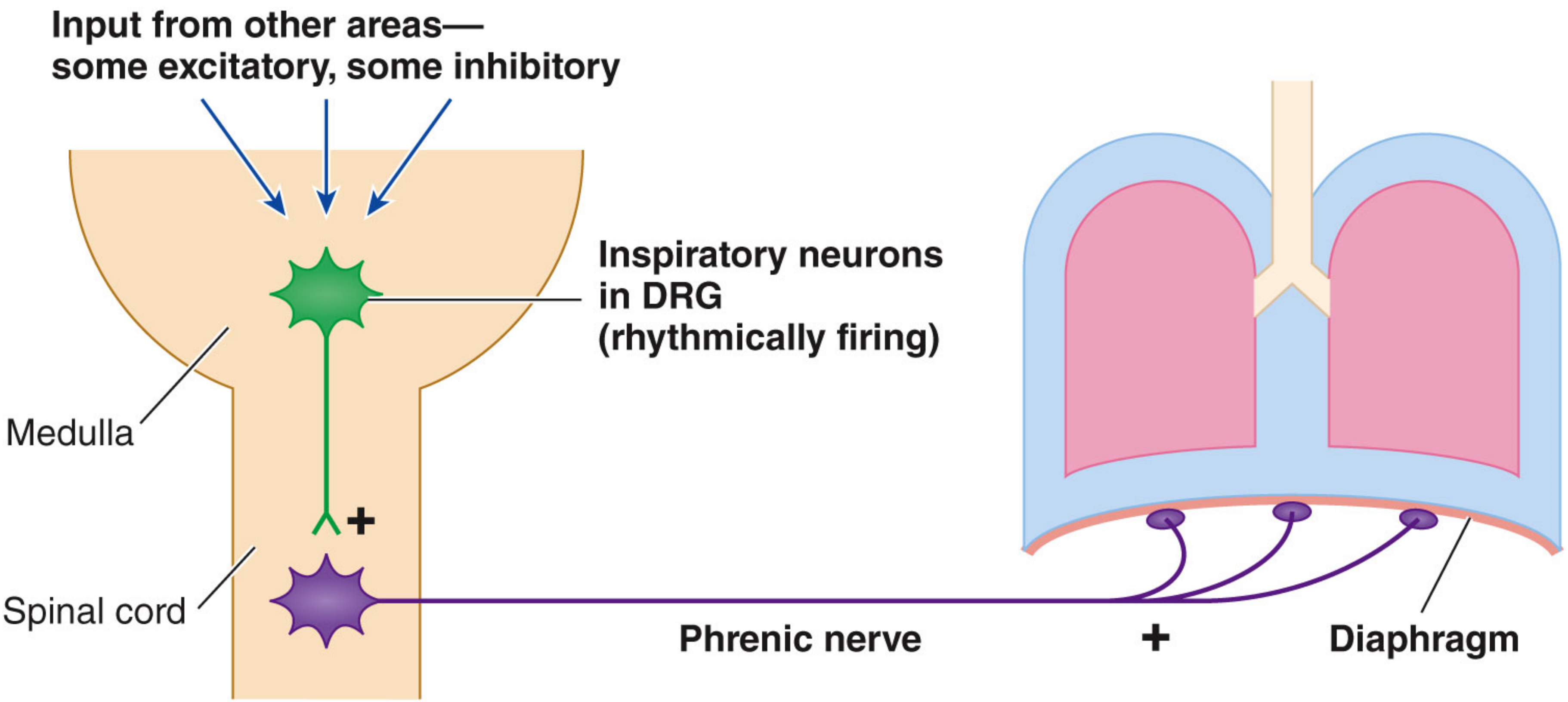
# 11.10 Control of Respiration

- **Medullary respiratory center**
  - **Dorsal respiratory group** (DRG) contains **inspiratory neurons** that terminate on motor neurons supplying inspiratory muscles
  - **Ventral respiratory group** (VRG) contains **inspiratory neurons** and **expiratory neurons**
    - Utilized only during **active breathing** when demands for ventilation increase
  - Generation of a **respiratory rhythm** lies in the **pre-Botzinger complex**
    - Neurons display **pacemaker** activity
  - **Pneumotaxic center** and **apneustic center** in the **pons** fine tune the breathing pattern

# 11.10 Control of Respiration



# 11.10 Control of Respiration

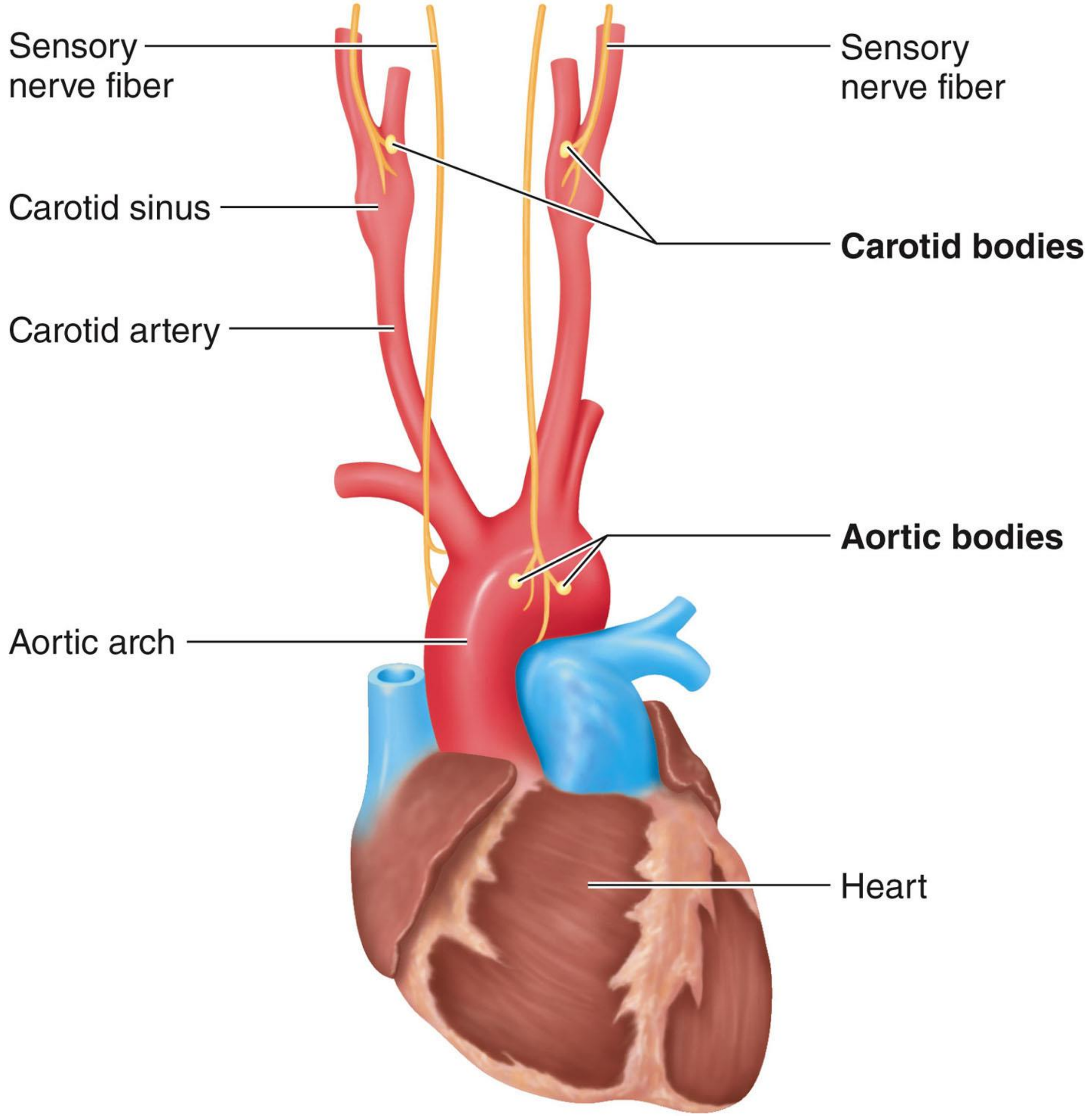



Not shown are intercostal nerves to external intercostal muscles.

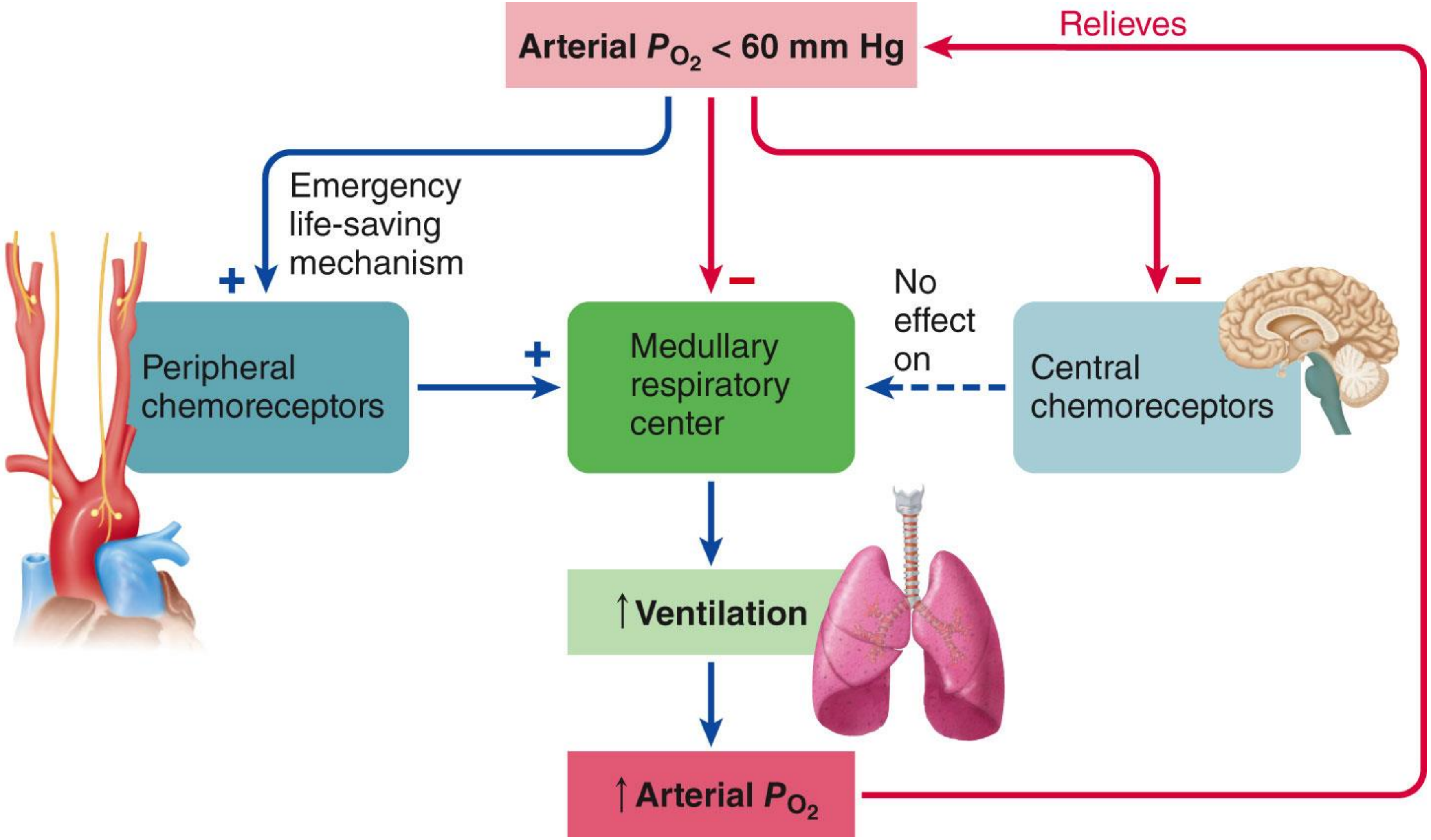
# 11.10 Control of Respiration

- Arterial blood gases are precisely regulated.
  - The **medullary respiratory center** adjusts rate and depth of ventilation in response to inputs from **central** and **peripheral chemoreceptors.**
  - Arterial $Po_2$ is monitored by **peripheral chemoreceptors** in **carotid** and **aortic bodies**
    - In **water-breathing vertebrates**, $Po_2$ is the **primary homeostatic variable**
  - Increased arterial $Pco_2$, detected by **central chemoreceptors**, is the most powerful stimulus to breathing in air-breathers

# 11.10 Control of Respiration



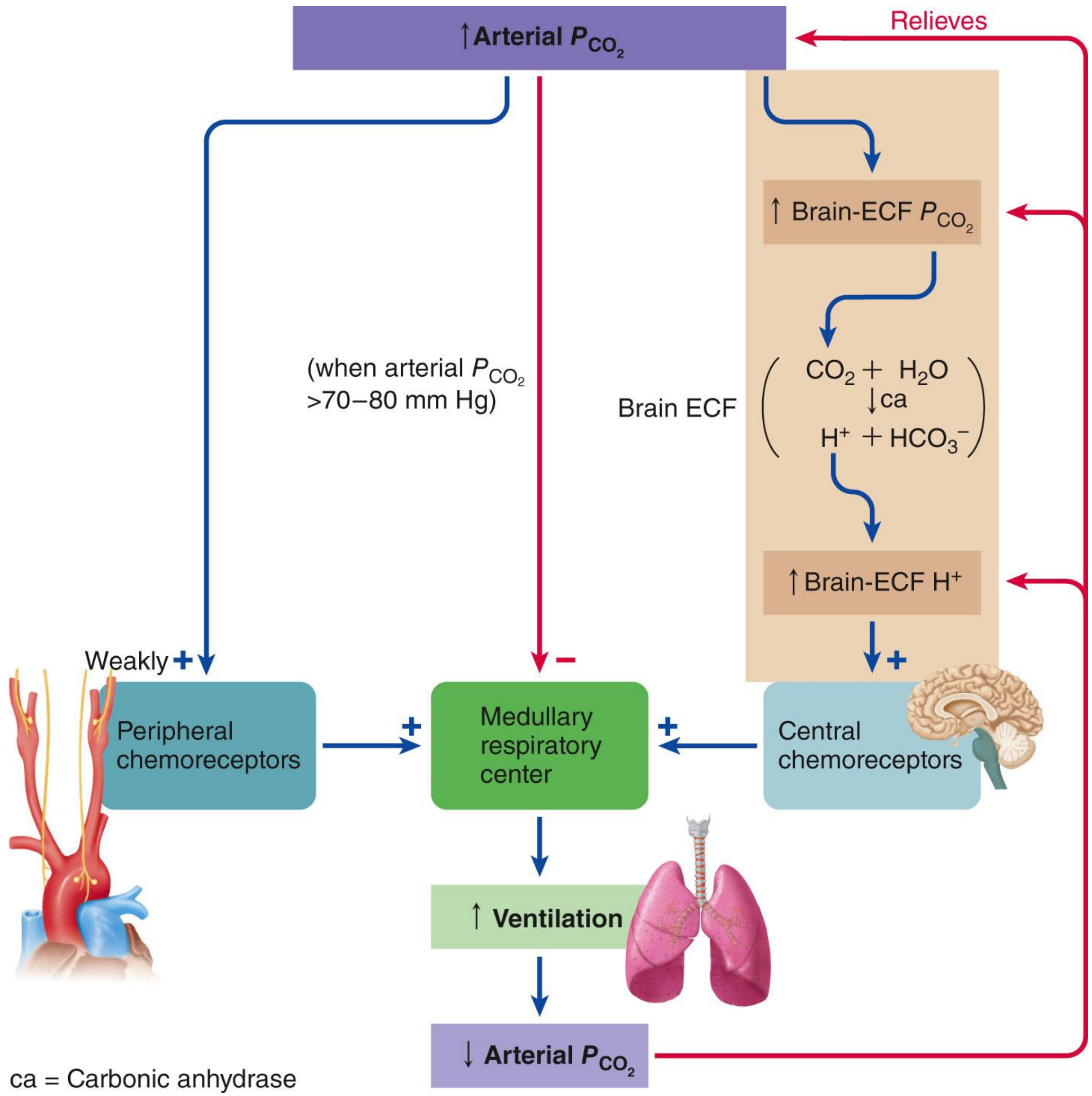
# 11.10 Control of Respiration



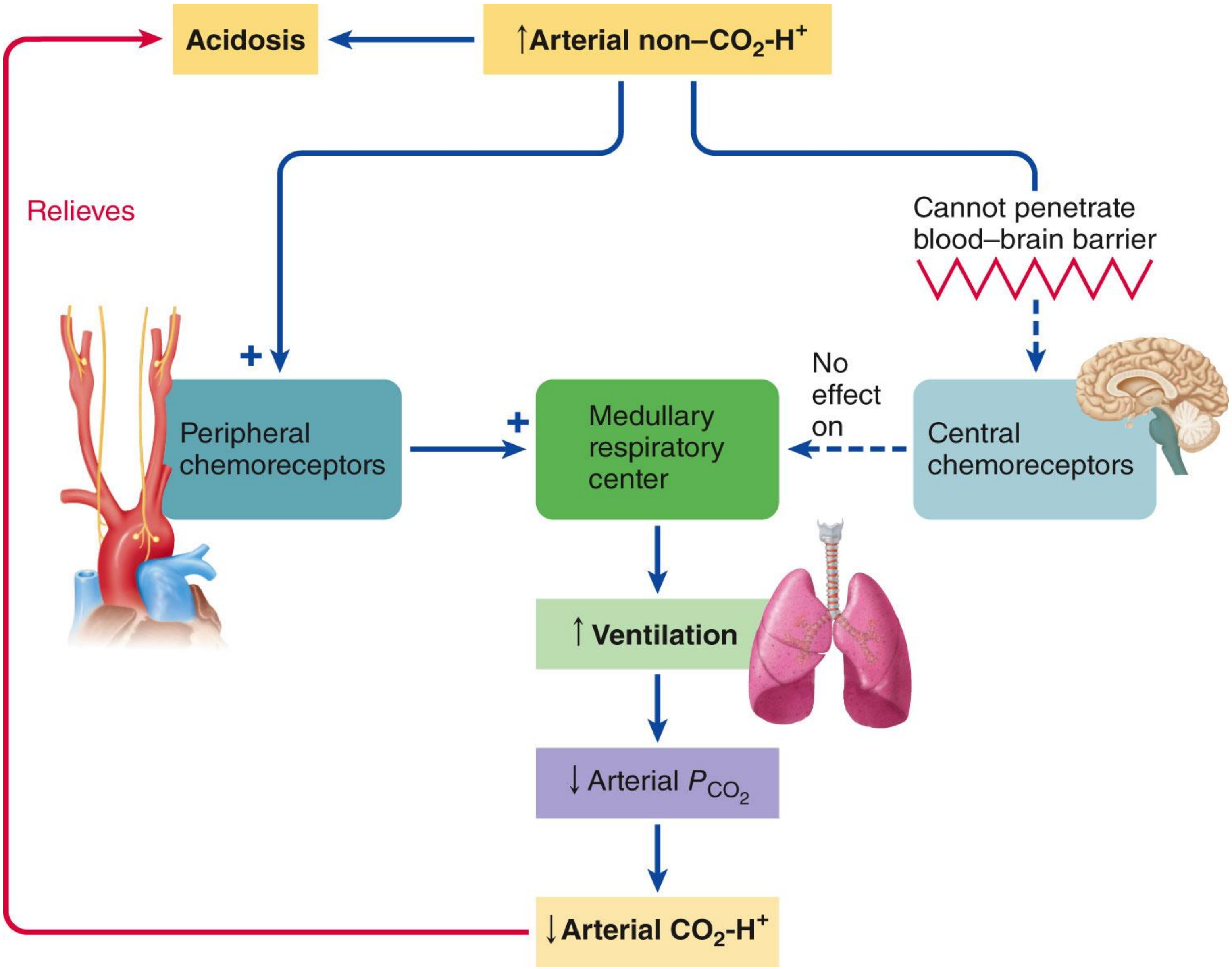
# 11.10 Control of Respiration

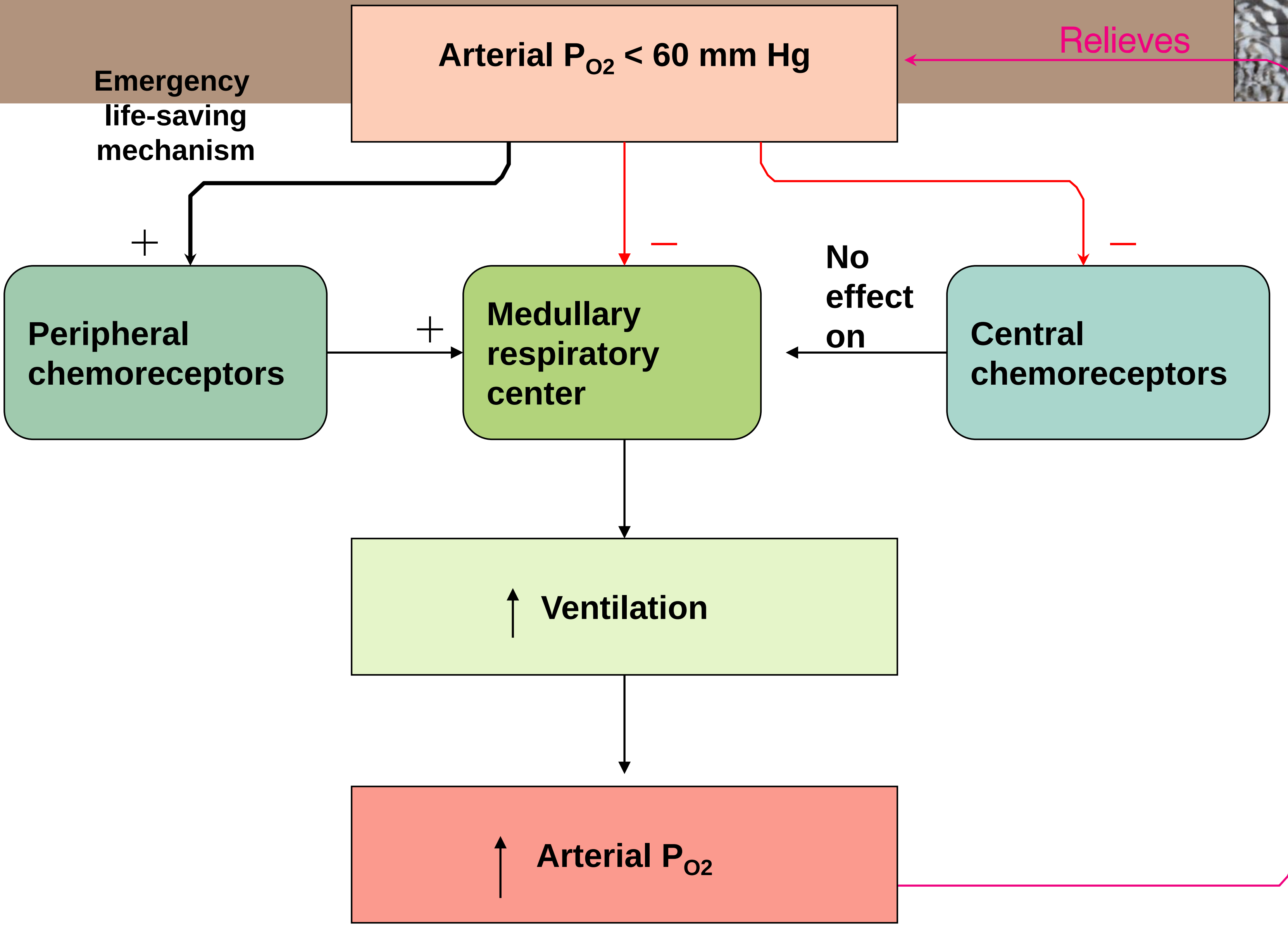
- Role of $H^+$ in respiratory control
  - Central chemoreceptors are **most sensitive** to $CO_2$-induced **$H^+$ production** in the brain **extracellular fluid**
  - **Peripheral chemoreceptors** are also highly responsive to **arterial $H^+$ concentration**
    - Major role in response to changes in $H^+$ unrelated to $P_{CO_2}$ (e.g. lactate or keto acids)
  - Important in regulating **acid-base balance**

# 11.10 Control of Respiration



# 11.10 Control of Respiration






Stepped Art

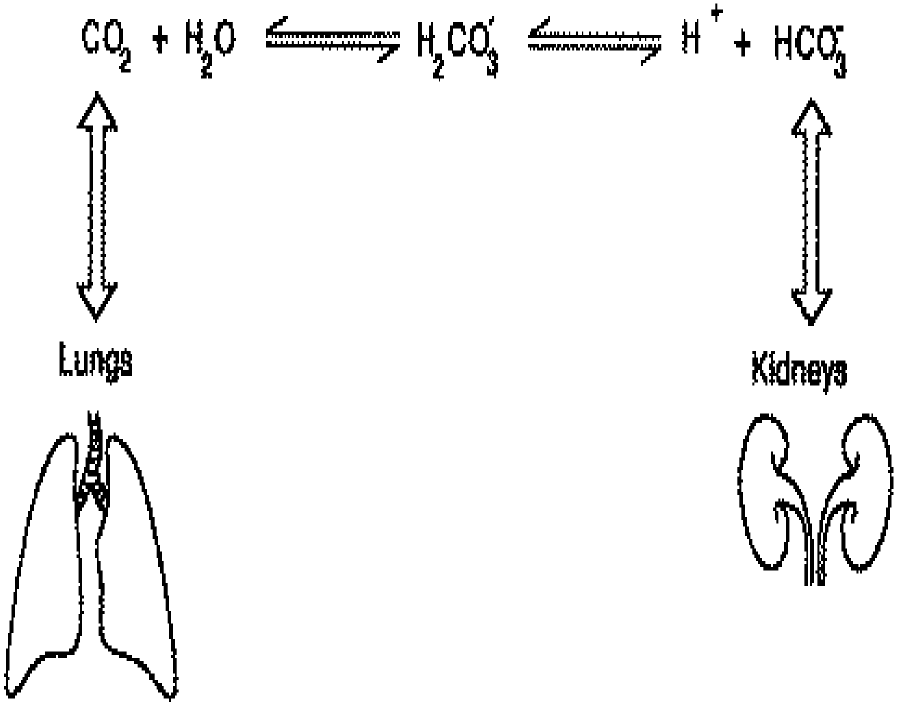
Fig. 11-39, p.551

# 11.10 Control of Respiration

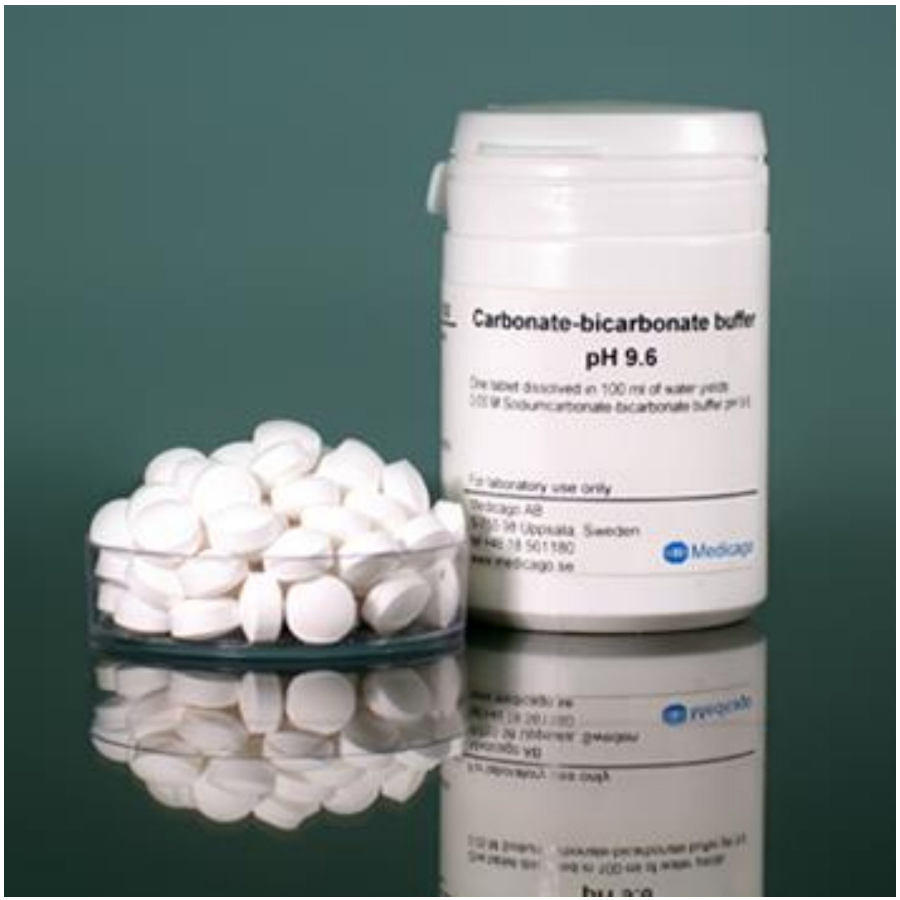
- Ventilation increases abruptly at the onset of **exercise.**
  - Occurs **without** changes in arterial $Po_2$ or $Pco_2$
  - Possible factors increasing ventilation during exercise
    - **Reflexes** originating from **body movements**
    - Anticipatory activation by **epinephrine**
    - Anticipatory activation by the **cerebral cortex**

# ABGs

- Base Excess
  - Amt of blood buffer
  - Normal +/- 2 mEq/L
  - High value—alkalosis
    - Citrate excess from rapid blood transfusions
    - IV HCO3 infusion DKA\
    - Ingestion large amt bicarb solutions (antacids)



# ABGs



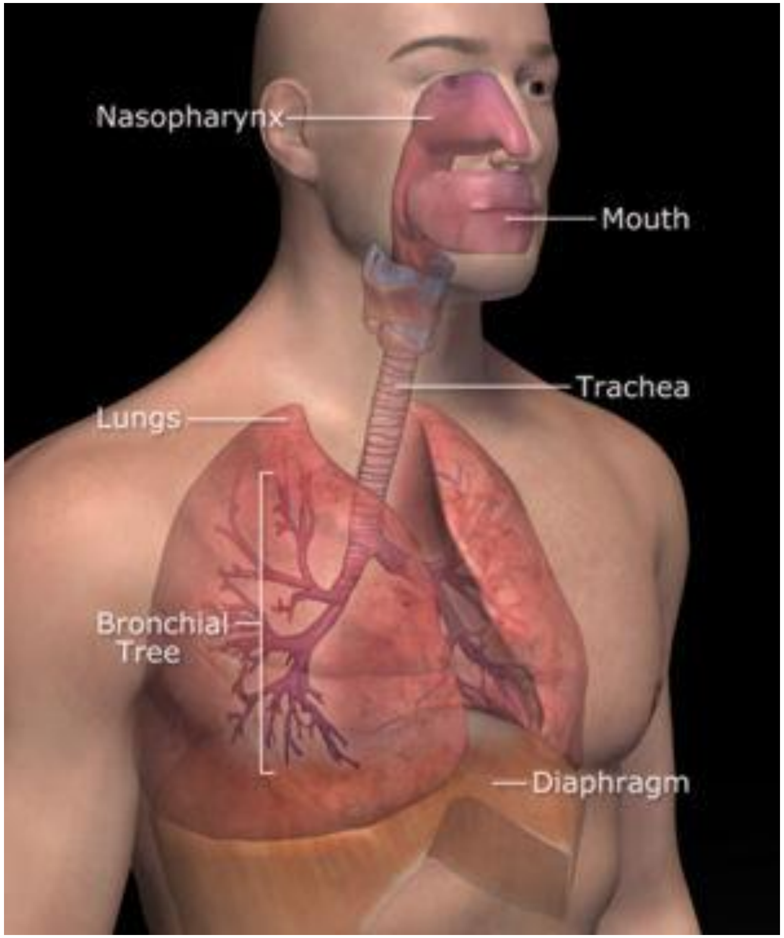

- Base excess
  - Low value—acidosis
    - Lg amts of bicarb ion excretion
    - ie: diarrhea
  -

# ABGs

- Bicarbonate
  - Major renal component
  - Kidneys excrete & retain to maintain normal balance
  - Principal buffer ECF
  - Normal 22-26 mEq/L
  - Metabolic acidosis < 22 mEq/L
  - Metabolic alkalosis > 26 mEq/L

# Acid-Base Imbalances

- Either respiratory or metabolic, depend on their underlying cause
- Corrects AB imbalances through process known as compensation



# Respiratory Acidosis

pH < 7.35
PaCO2 >45 mm Hg
PaO2 < 80 mm Hg
Bicarb level normal if uncompensated
Bicarb level > 26 mEq/L if compensated

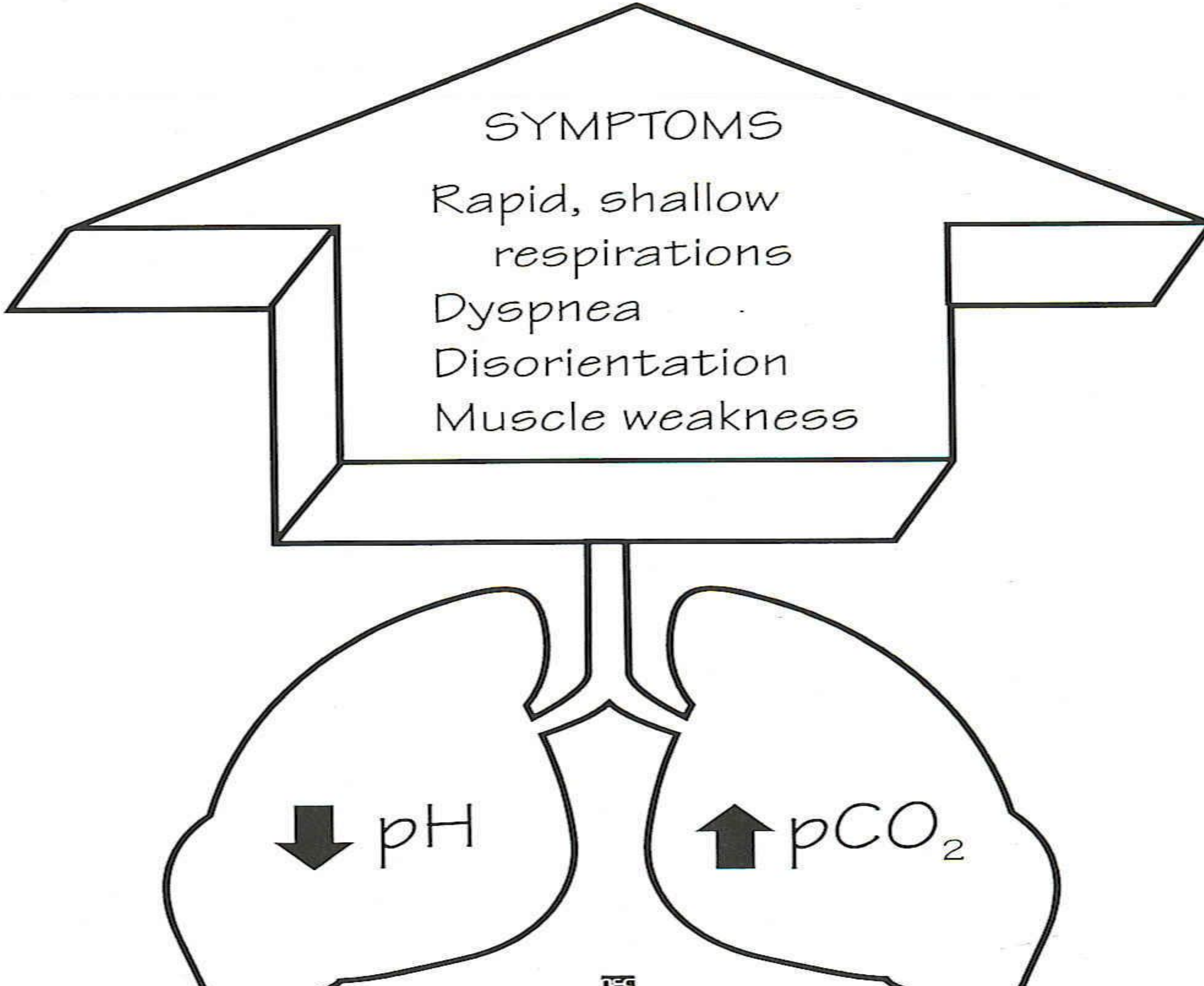
Hypoventilation→CSF & brain cells become acidic→neurological changes→ hypoxemia→further neurological impairment
Hyperkalemia & hypercalcemia can occur
Kidneys hold to bicarb & release hydrogen ions UA—may take 24 hrs

# Respiratory Acidosis Causes

- Hypoventilation resulting primary respiratory problems
  - Chest wall injury
  - Respiratory failure
  - Cystic fibrosis
  - Pneumonia
  - Atelectasis (obstruction of small airways often caused by mucus)

- Hypoventilation resulting from factors other than resp system
  - Obesity
  - Head injury
  - Drug overdose (OD) with resp depressant
  - Paralysis of resp muscles caused by neurological alterations

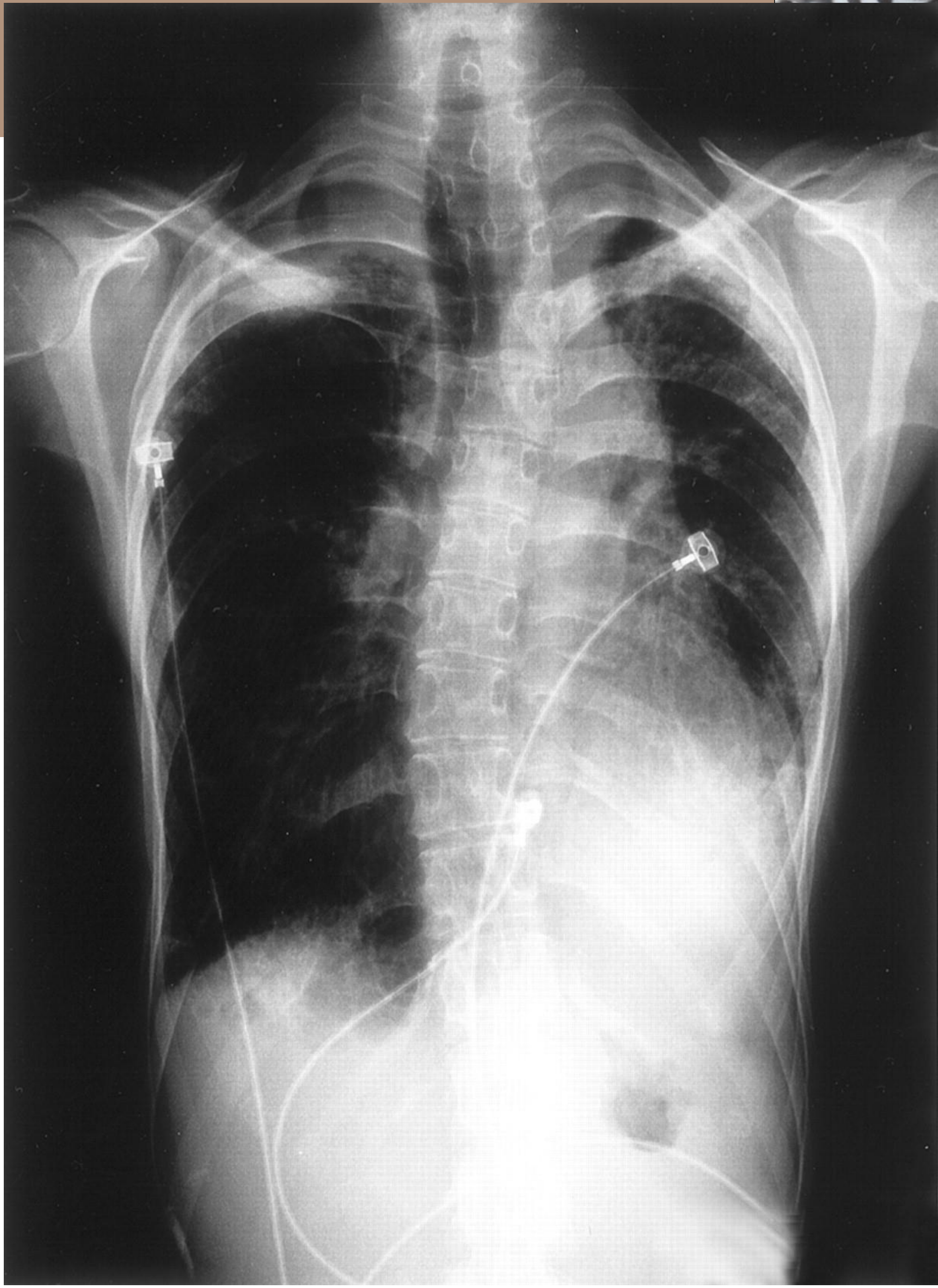
# RESPIRATORY ACIDOSIS



# Respiratory Acidosis

S/S

- Convulsion
- Coma
- Muscular twitching
- Confusion
- Dizziness
- Lethargy
- HA
- Warm flushed skin
- Ventricular dysrhythmia



# Respiratory Alkalosis

- pH >7.45
- PaCO2 <35 mm Hg
- PaO2 normal
- HCO3 nl if short-lived or uncompensated
- HCO3 <22 mm Hg if compensated

- Begins outside resp system ie: anxiety, panic attack OR within resp system ie: initial phase of asthma attack

- Body does not usually compensate because pH returns to nl before kidneys can respond

# Respiratory Alkalosis

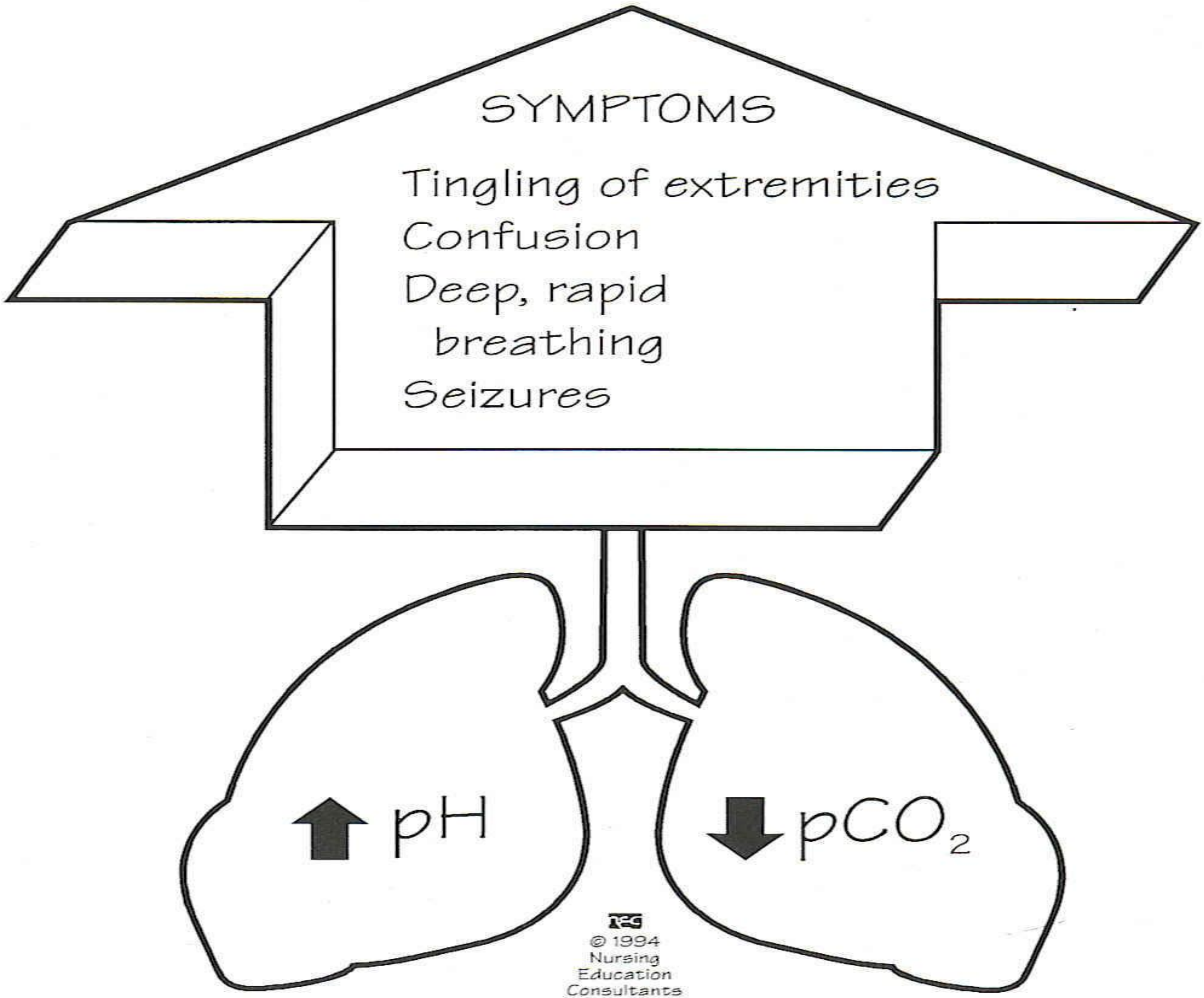
Causes

- Salicylate overdoes
- Anxiety
- Hypermetabolic states ie: fever, exercise
- CNS disorders ie: head injury, infections
- Asthma
- Pneumonia
- Inappropriate vent settings

S/S

- Confusion
- Dizziness
- Convulsions
- Coma
- Tachypnea
- Numbness/tingling of extremities
- dysrhythmias

# RESPIRATORY ALKALOSIS

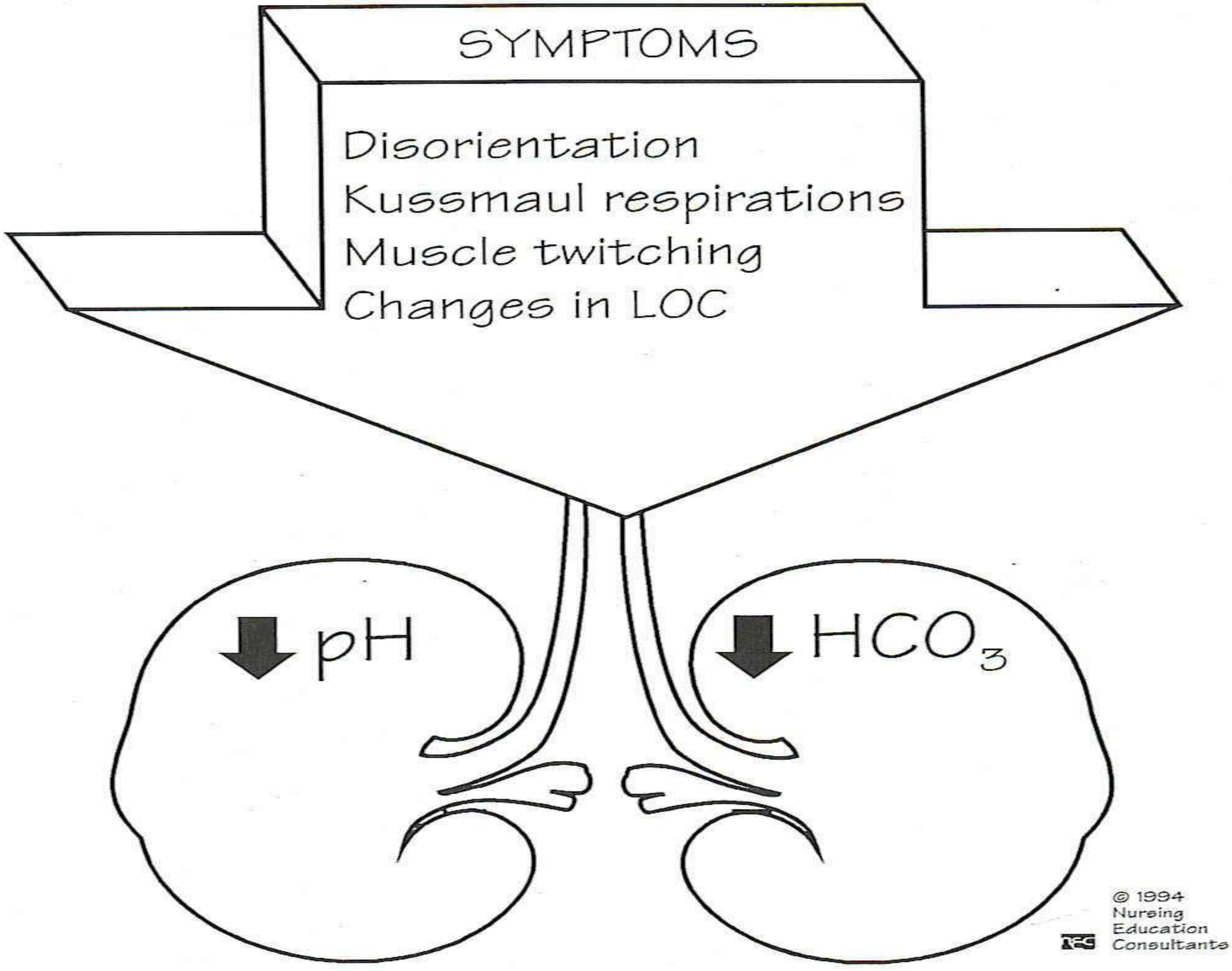


# Metabolic Acidosis

High acid content of bld
Loss of $HCO_3$

pH $<7.35$
$PaCO_2$ normal if uncompensated
$<35$ mm Hg if compensated
$PaO_2$ normal or increased
$HCO_3 < 22$ mEq/L
$O_2$ Sat normal

# METABOLIC ACIDOSIS

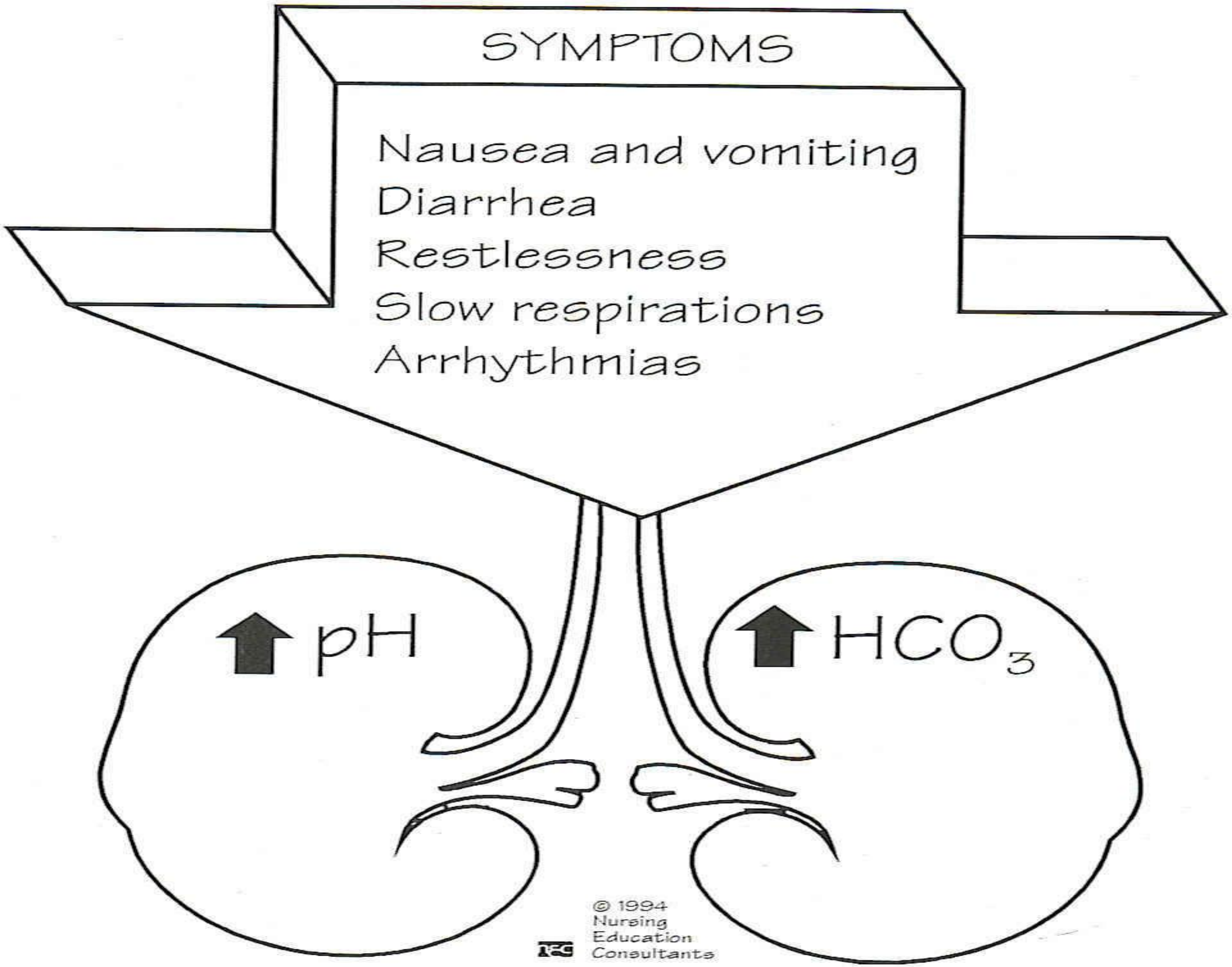


# Metabolic Alkalosis

- pH >7.45
- $PaCO_2$ normal if uncompensated
- $PaCO_2$ >45 mm Hg if compensated (occurs by decreasing RR & no renal disease)
- $PaO_2$ normal
- $HCO_3$ > 26 mEq/L

- Causes
  - Excessive vomiting
  - Prolong gastric sx
  - Excess aldosterone
  - Hypokalemia
  - Hypercalcemia
  - Use of drugs ie: steriods, diuretics, sodium bicarb

# METABOLIC ALKALOSIS



# Question

- Interpret the following ABGs:
  - pH ?
  - PCO2 ? mm Hg
  - PO2 ? mm Hg
  - HCO3 ? mEq/L
  - O2 Sat ? %

Normal blood gas in an artery for humans:

| | |
|---|---|
| pH | 7.35–7.45 |
| $PaCO_2$ | 35–45 mmHg |
| $PaO_2$ | 80–100 mmHg |
| $HCO_3^-$ | 22–26 mmol/L |

https://www.rccc.eu/ppc/calculadoras/ABG%20interpreter%20-%20calculator.htm