The Respiratory System Physiology

Part One

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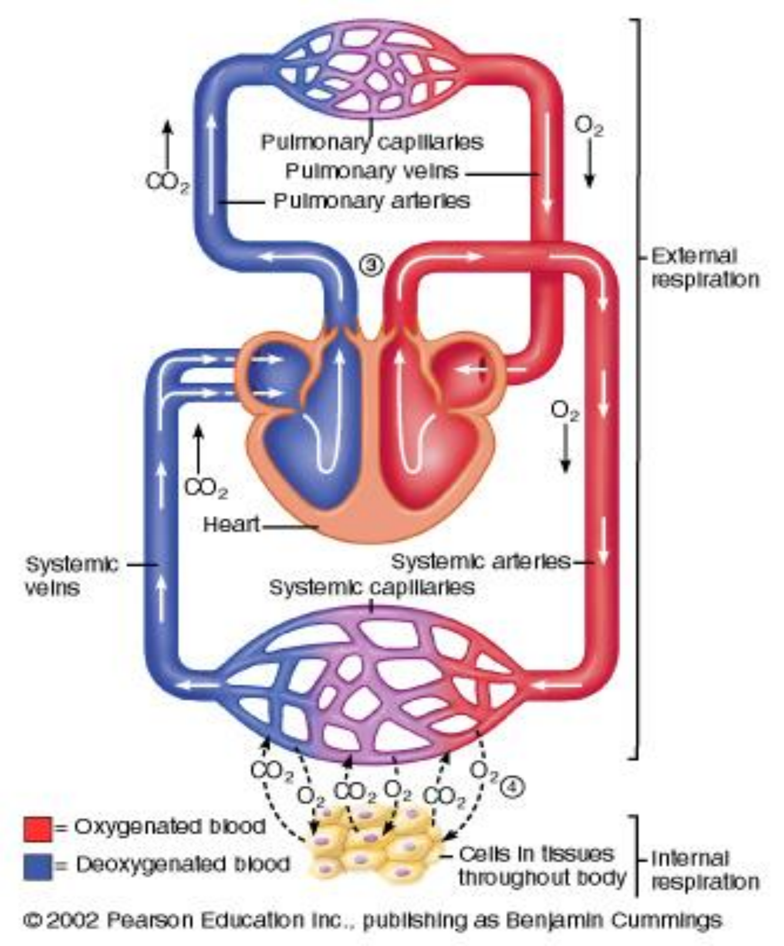
Overall function

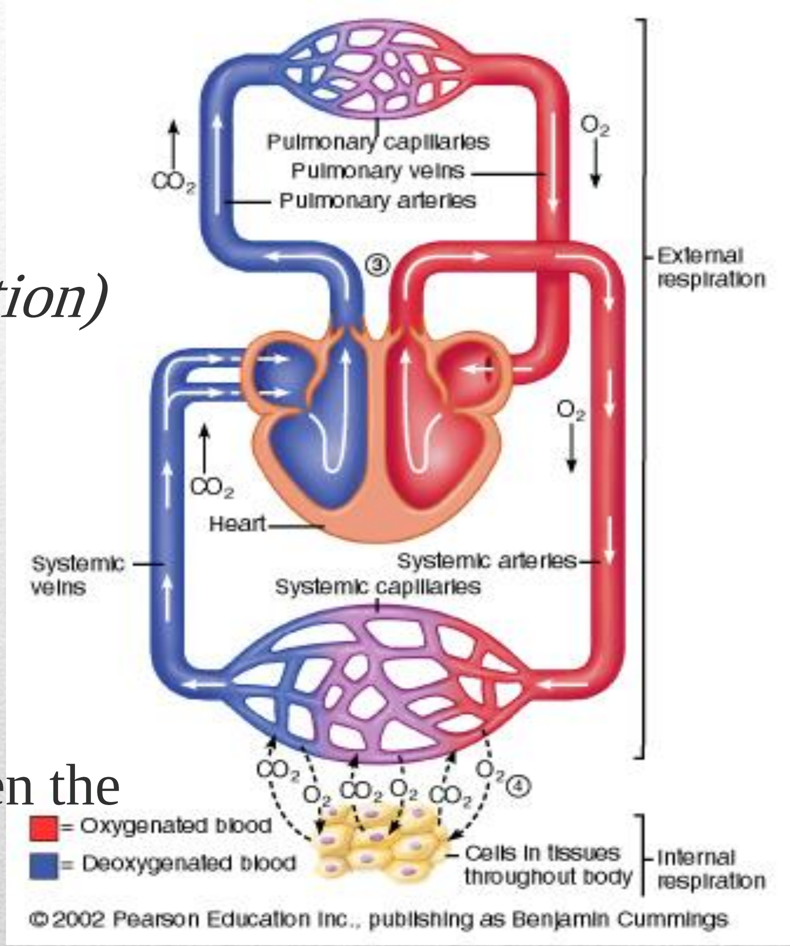
- Movement of gases
- Gas exchange
- Transport of gas (oxygen and carbon dioxide)

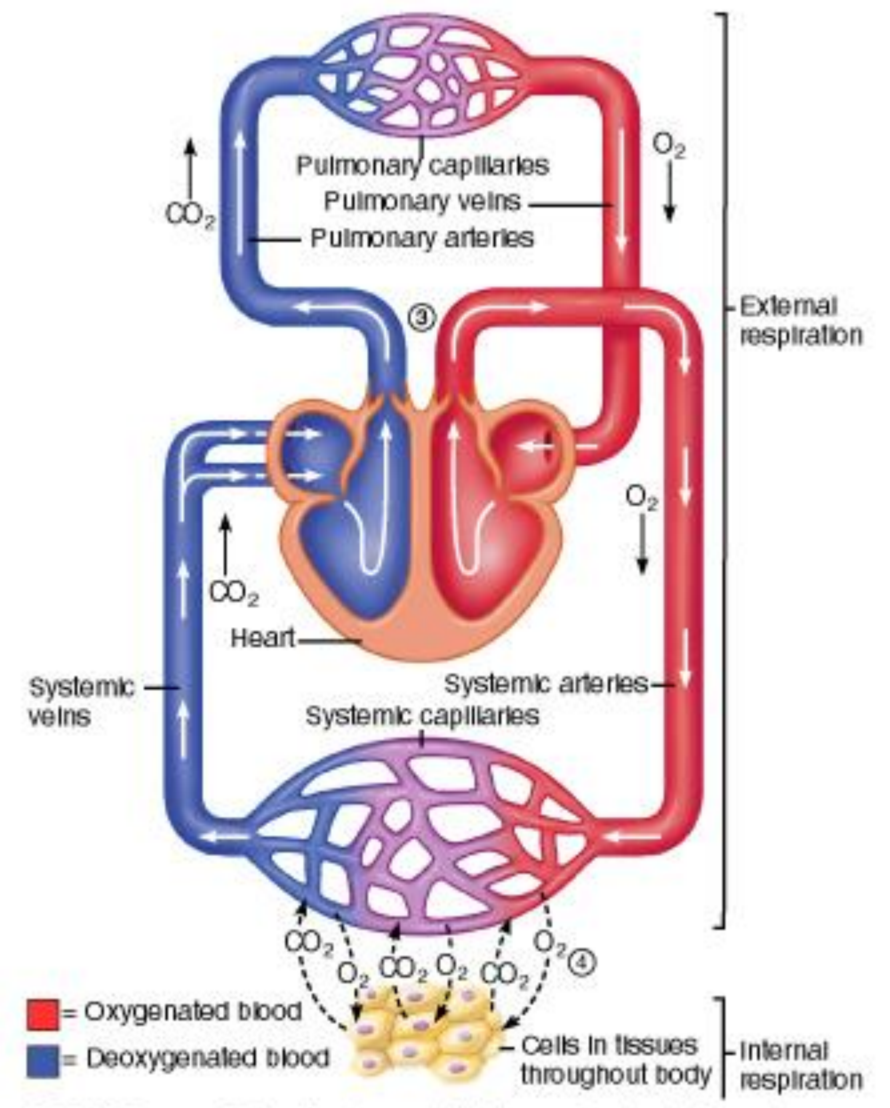


Overview of Respiratory Function

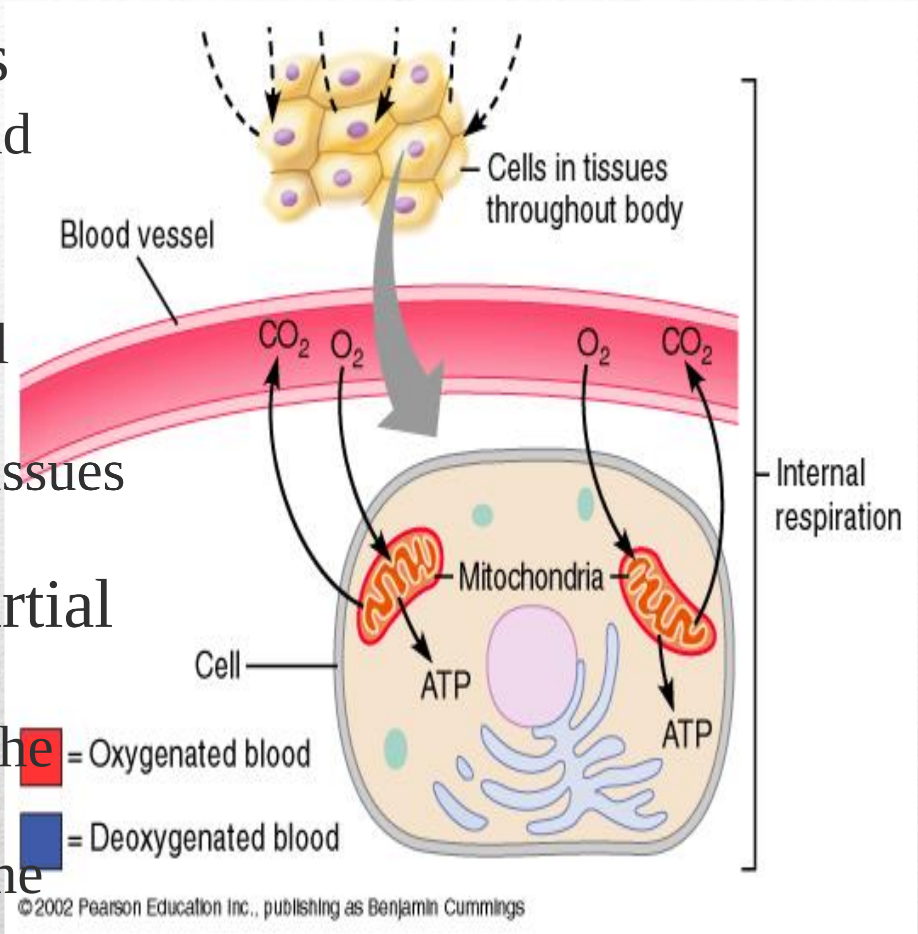
Respiration = the process of gas exchange

- <u>Two levels of respiration:</u>
- *Internal respiration (cellular respiration)*
  - The use of O_2 with mitochondria to generate ATP by oxidative phosphorylation
  - CO_2 is the waste product
- *External respiration (ventilation)*
  - The exchange of O_2 and CO_2 between the atmosphere and body tissues

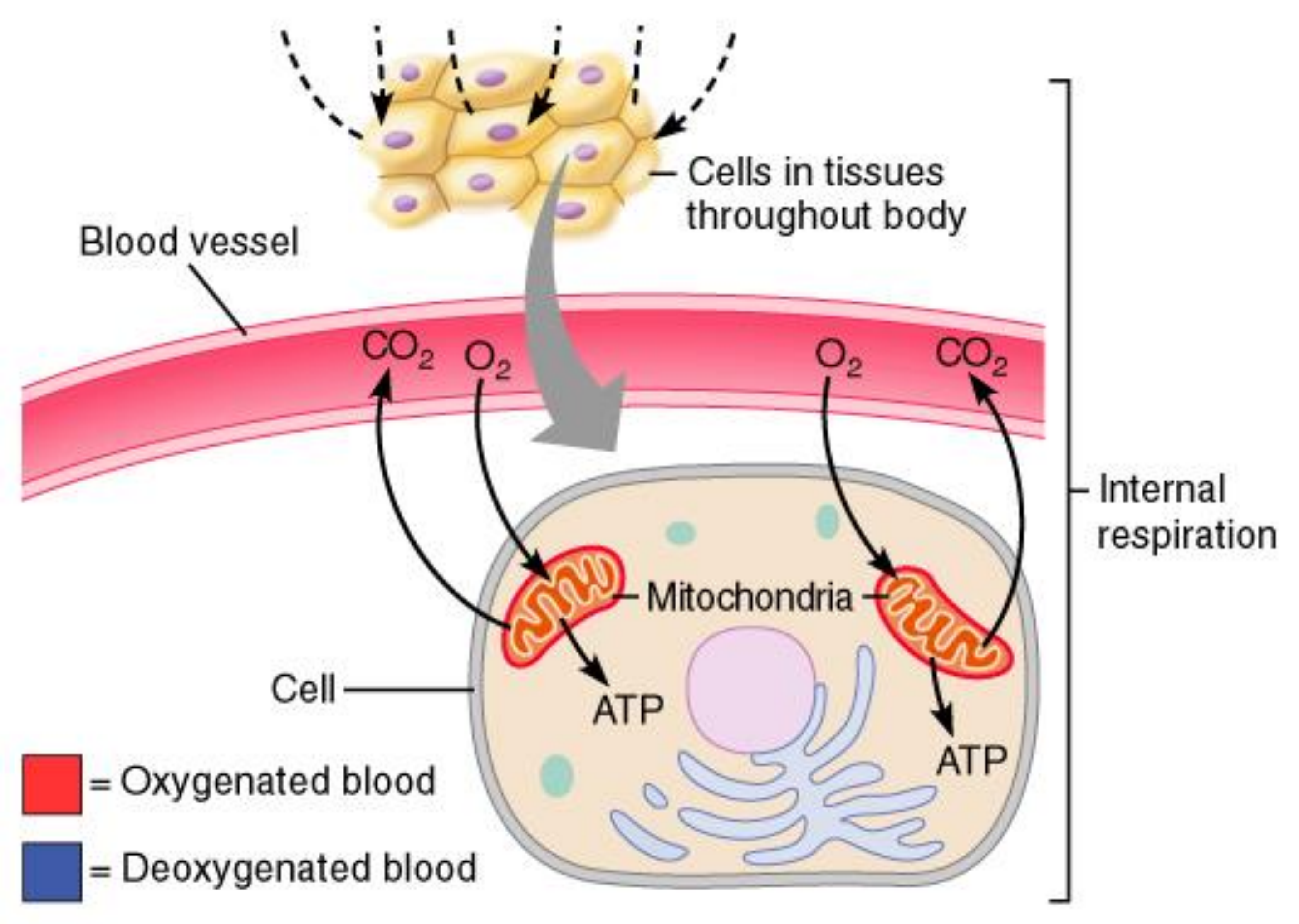



Pulmonary capillaries
Pulmonary veins
Pulmonary arteries
CO_2
O_2
③
External respiration
O_2
CO_2
Heart
Systemic veins
Systemic arteries
Systemic capillaries
CO_2 O_2 CO_2 O_2 CO_2 O_2 ④
= Oxygenated blood
= Deoxygenated blood
Cells in tissues throughout body
Internal respiration

- Involves gas exchange between capillaries and body tissues cells
  - Tissue cells continuously use O_2 and produce CO_2 during metabolism
- Partial pressure (P)
  - The PO_2 is always higher in arterial blood than in the tissues
  - The PCO_2 is always higher in the tissues than in arterial blood
- O_2 and CO_2 move down their partial pressure gradients
  - O_2 moves out of the capillary into the tissues
  - CO_2 moves out of the tissues into the capillary



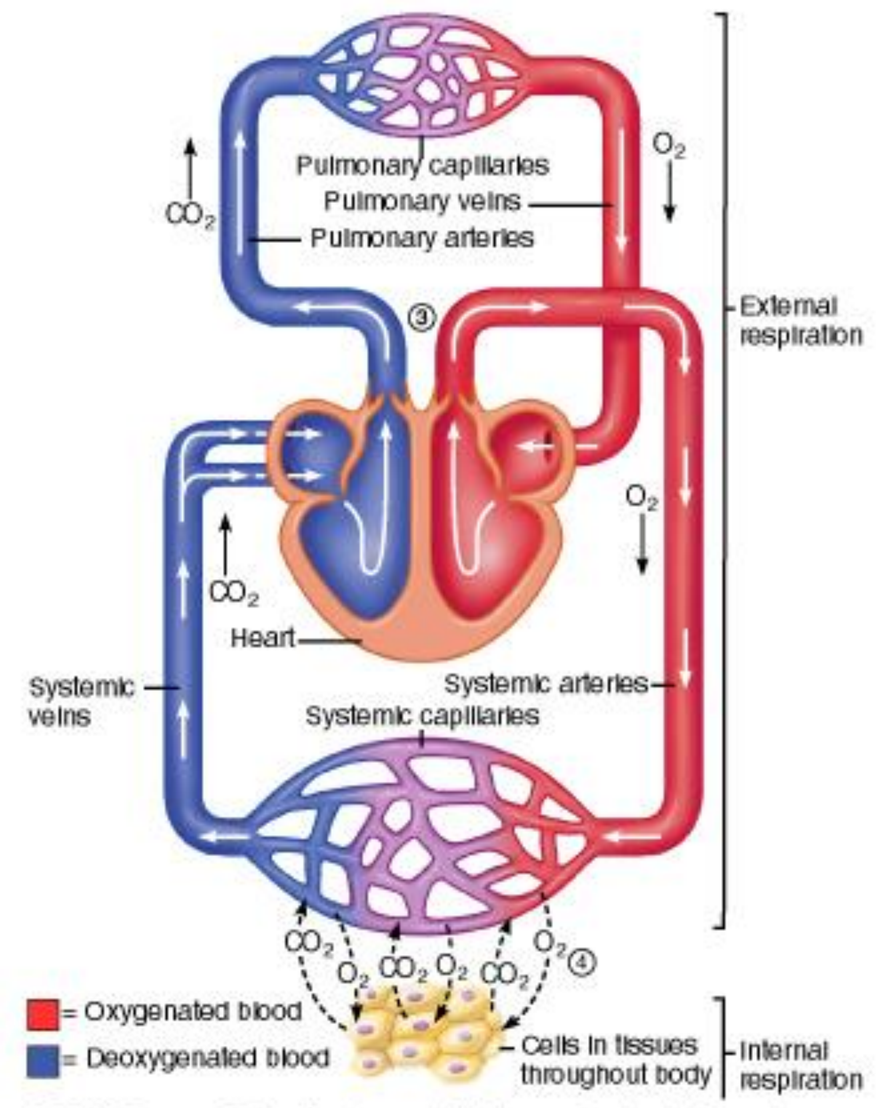
Internal respiration (cellular respiration)


Cells in tissues throughout body
Blood vessel
CO_2
O_2
O_2
CO_2
Internal respiration
Mitochondria
Cell
ATP
ATP
= Oxygenated blood
= Deoxygenated blood

4 Processes:

- Pulmonary Ventilation
  - Movement of air into the lungs (inspiration) and out of the lungs (expiration)
- Exchange of O_2 and CO_2 between lung air spaces and blood
- Transportation of O_2 and CO_2 between the lungs and body tissues
- Exchange of O_2 and CO_2 between the blood and tissues

External respiration (ventilation)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External respiration
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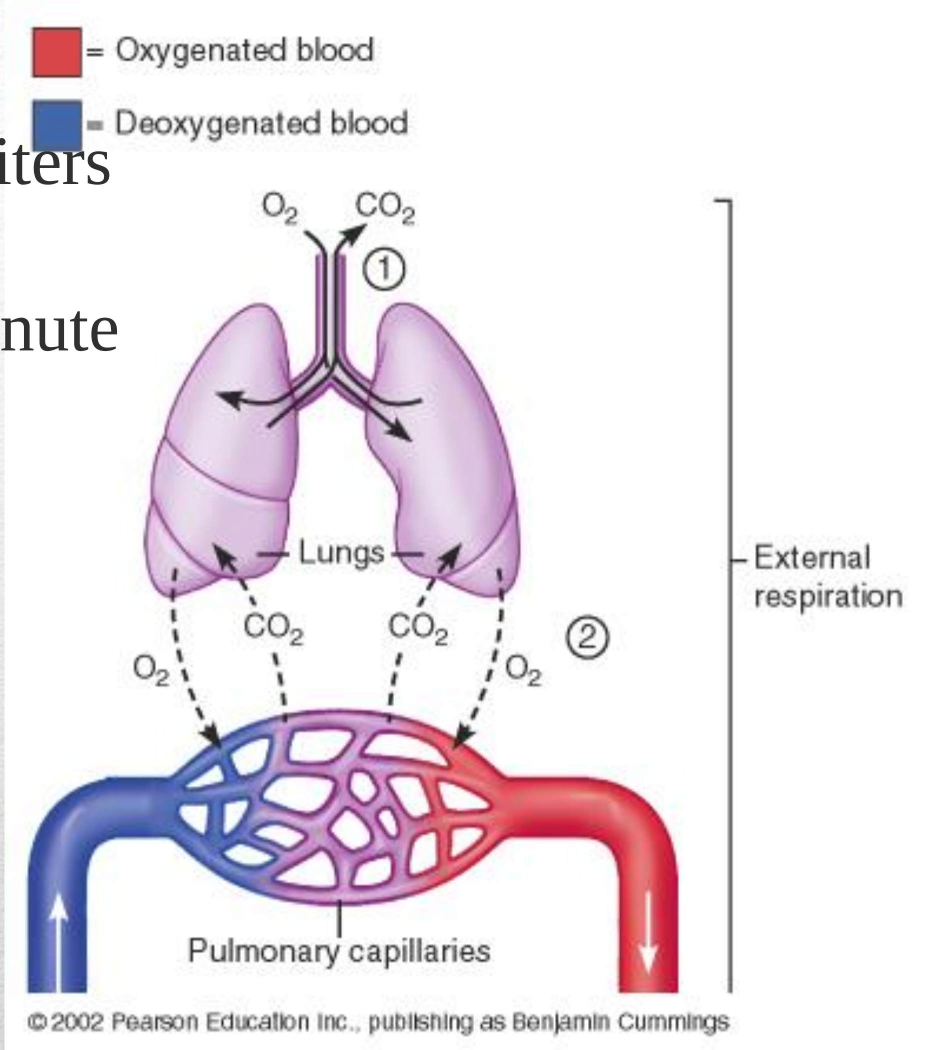
Heart
Systemic veins
Systemic arteries
Systemic capillaries
CO_2 O_2 CO_2 O_2 CO_2 O_2 ④
= Oxygenated blood
= Deoxygenated blood
Cells in tissues throughout body
Internal respiration

Overview of Pulmonary Circulation

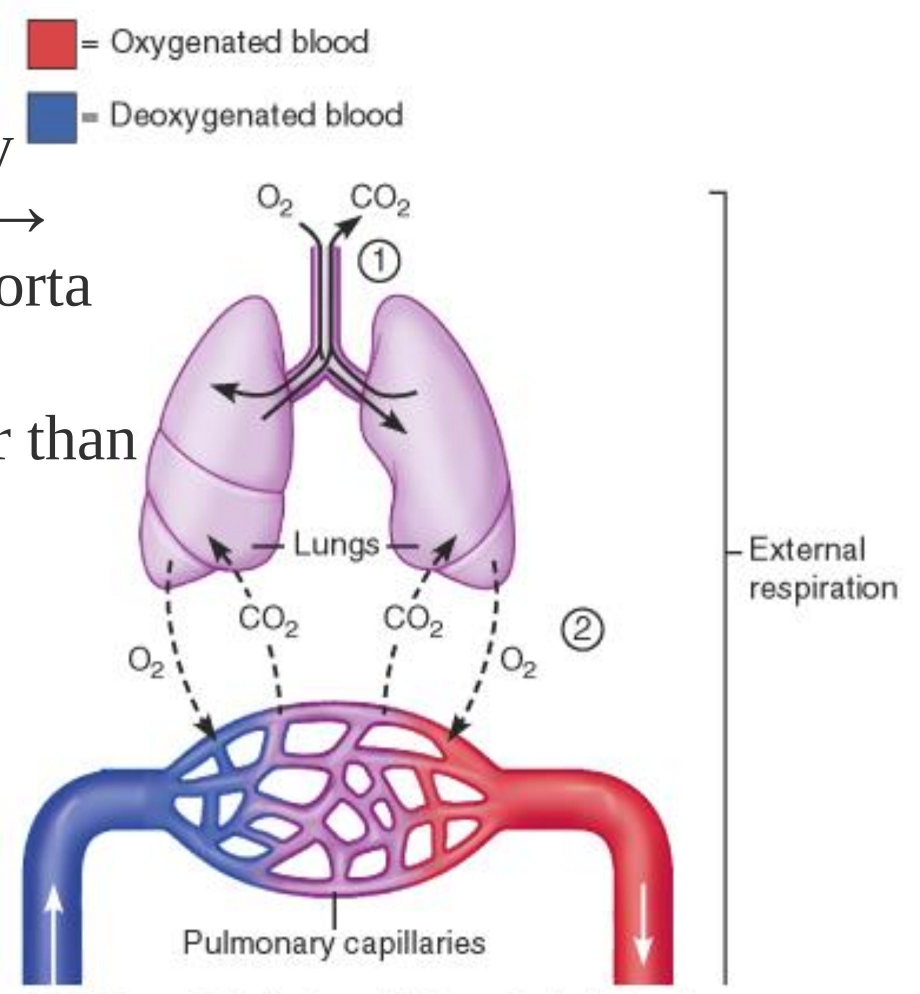
Deoxygenated blood

- Under resting conditions, 5 liters of deoxygenated blood are pumped to the lungs each minute from the right ventricle
- CO_2 blood concentration is higher than O_2 blood concentration in:
    - Systemic veins
    - Right atrium
    - Right ventricle
    - Pulmonary arteries

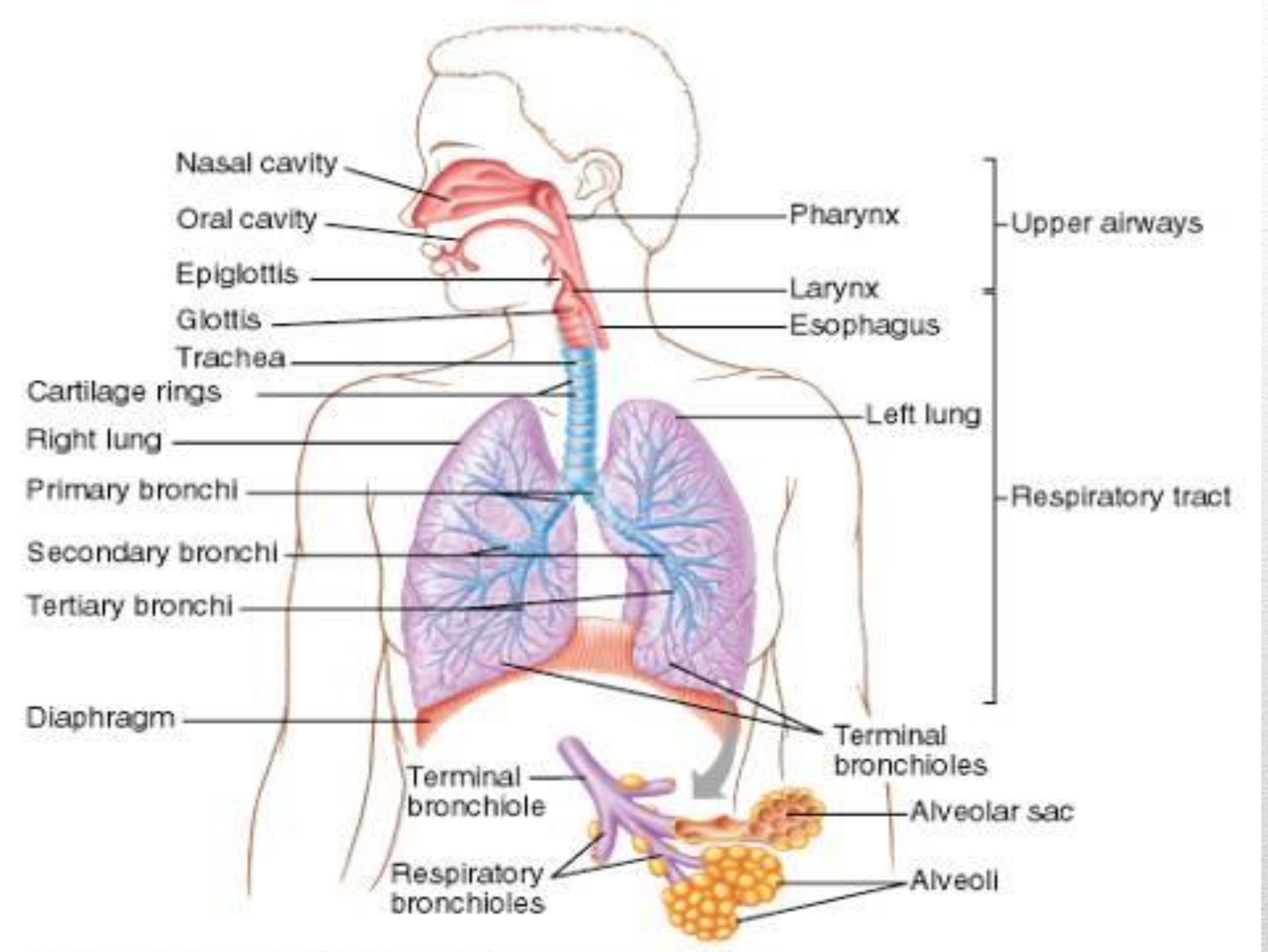


Oxygenated blood

- Transported from the pulmonary capillaries → pulmonary veins → left atrium → left ventricle → aorta → systemic arterial circulation
- O_2 blood concentration is higher than CO_2 blood concentration in:
  - Alveoli
  - Pulmonary capillaries
  - Pulmonary veins
  - Left atrium
  - Left ventricle
  - Systemic arteries

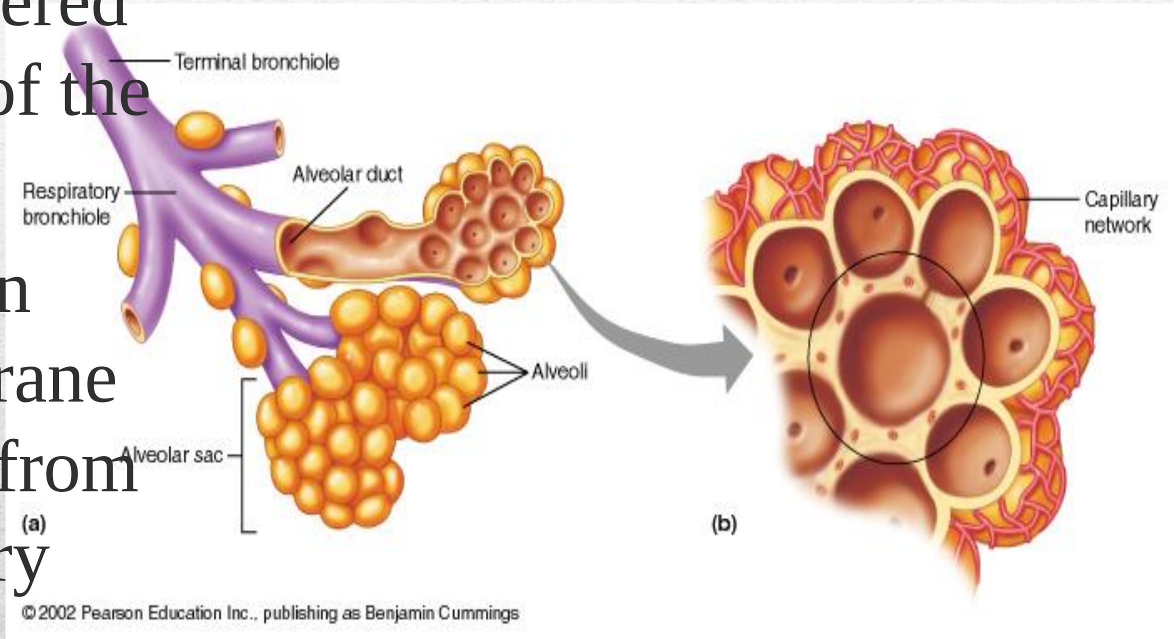


Overview of Pulmonary Circulation

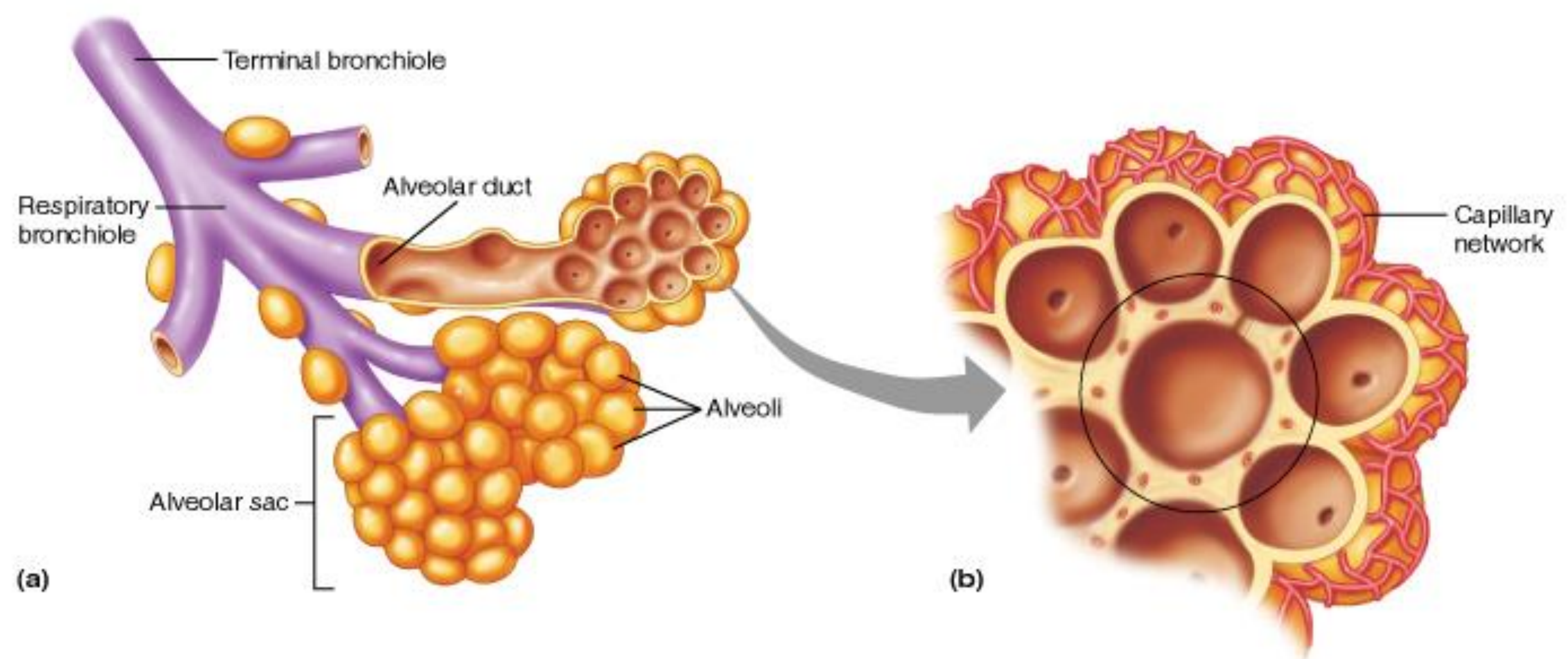


Anatomy of the Respiratory Zone

- Alveoli (singular is alveolus)
  - Tiny air sacs clustered at the distal ends of the alveolar ducts
  - Alveoli have a thin respiratory membrane separating the air from blood in pulmonary capillaries



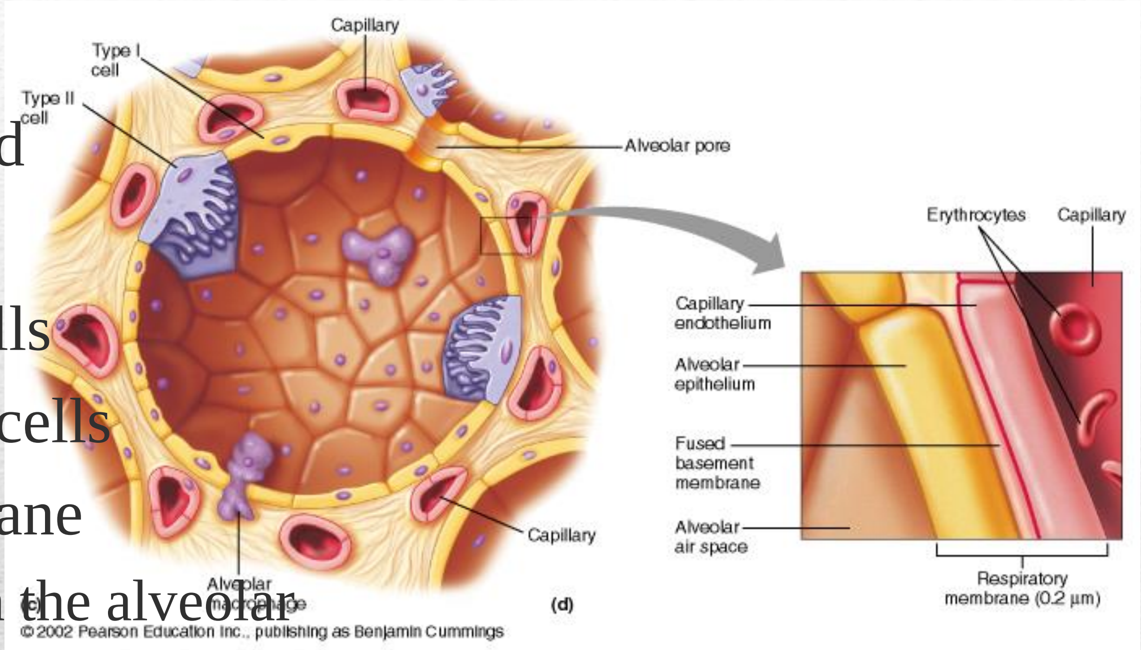
Anatomy of the Respiratory Zone

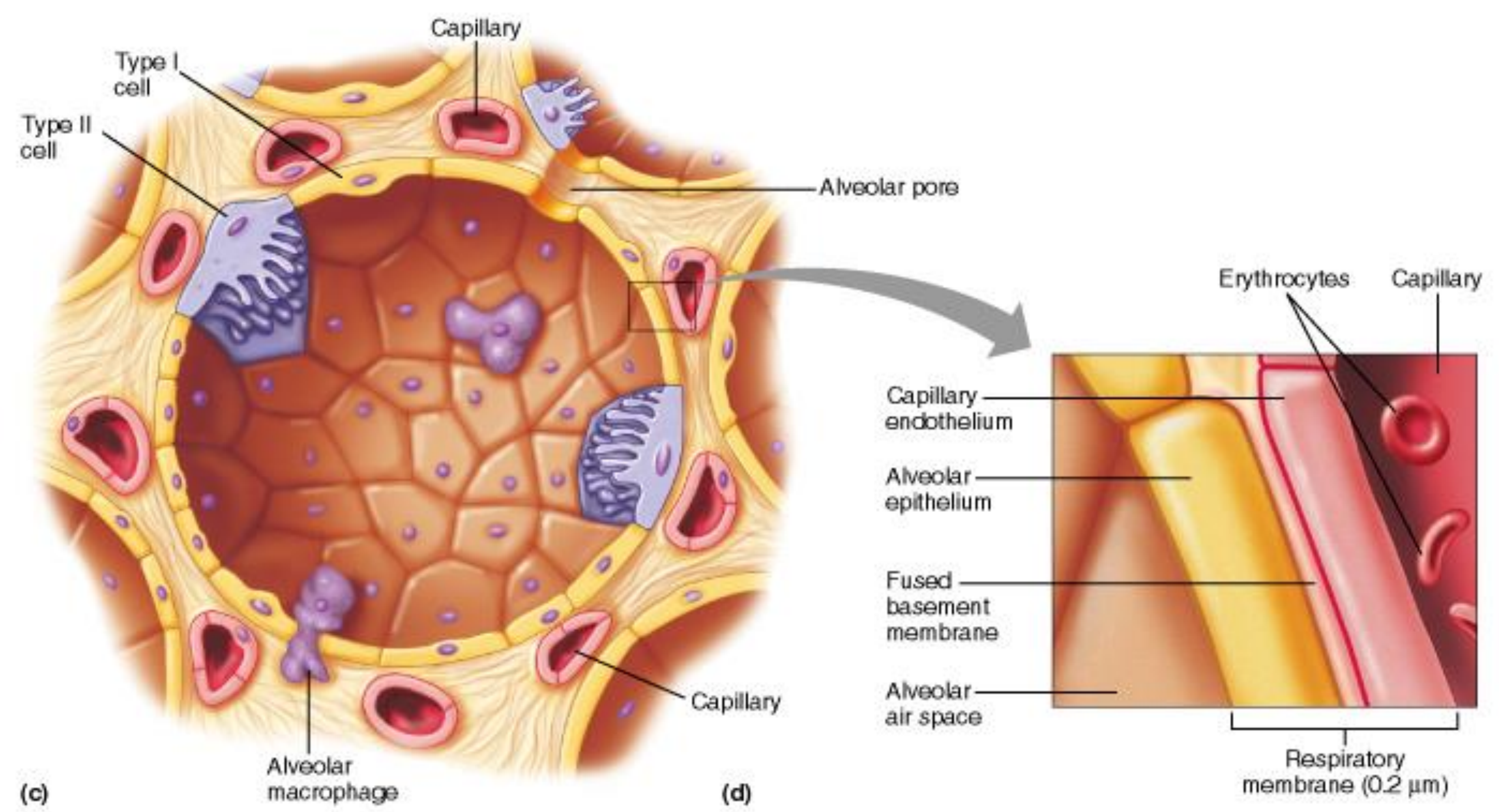

Terminal bronchiole
Respiratory bronchiole
Alveolar duct
Alveoli
Alveolar sac
(a)
(b)
Capillary network

Respiratory Membrane

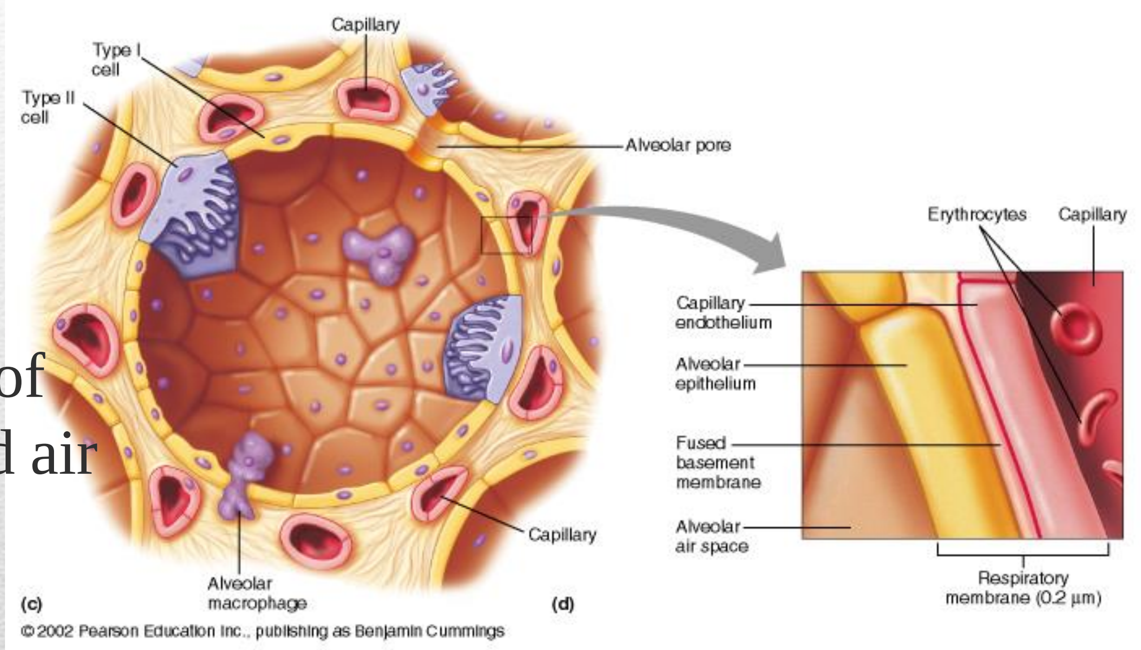
The thin alveolar wall consists of:

- The fused alveolar and capillary walls
- Alveolar epithelial cells
- Capillary endothelial cells
- The basement membrane
  - Sandwiched between the alveolar epithelial cells and the endothelial cells of the capillary




Capillary
Type I cell
Type II cell
Alveolar pore
Capillary
Alveolar macrophage
(c)
(d)
Erythrocytes
Capillary
Capillary endothelium
Alveolar epithelium
Fused basement membrane
Alveolar air space
Respiratory membrane (0.2 µm)

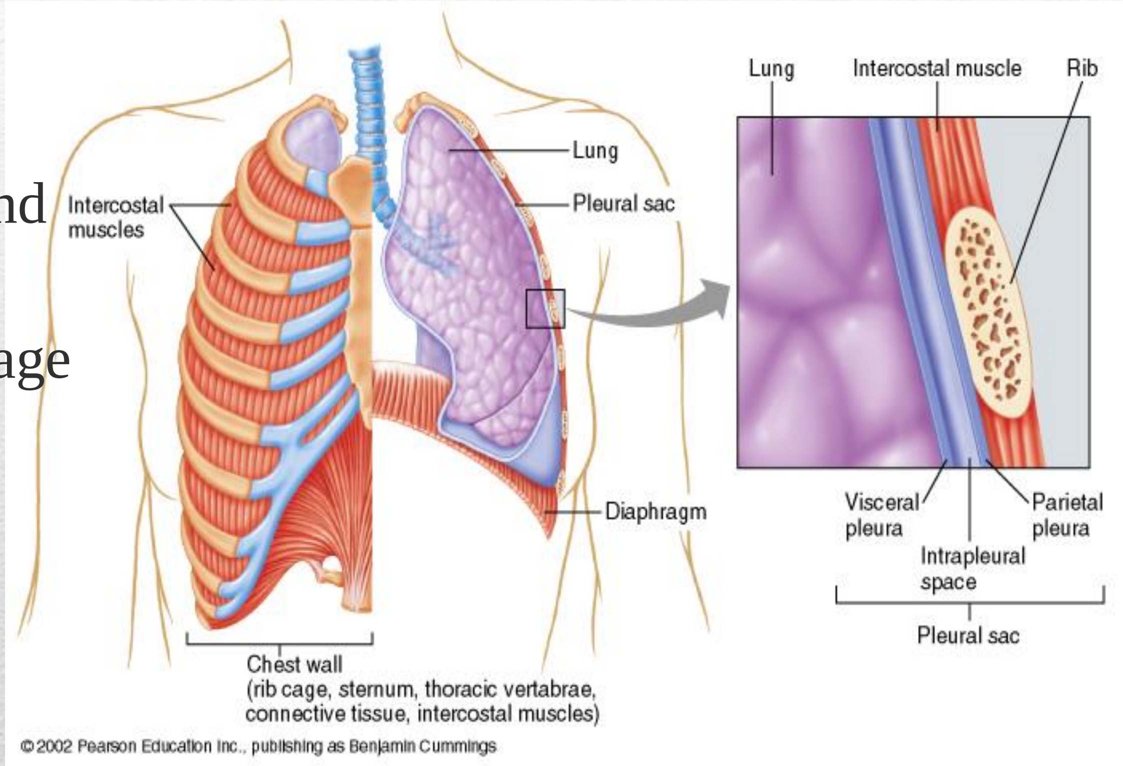
- Gas exchanges occurs across the respiratory membrane
  - It is < 0.1 μm thick
  - Lends to very efficient diffusion
- It is the site of external respiration and diffusion of gases between the inhaled air and the blood
  - Occurs in the pulmonary capillaries

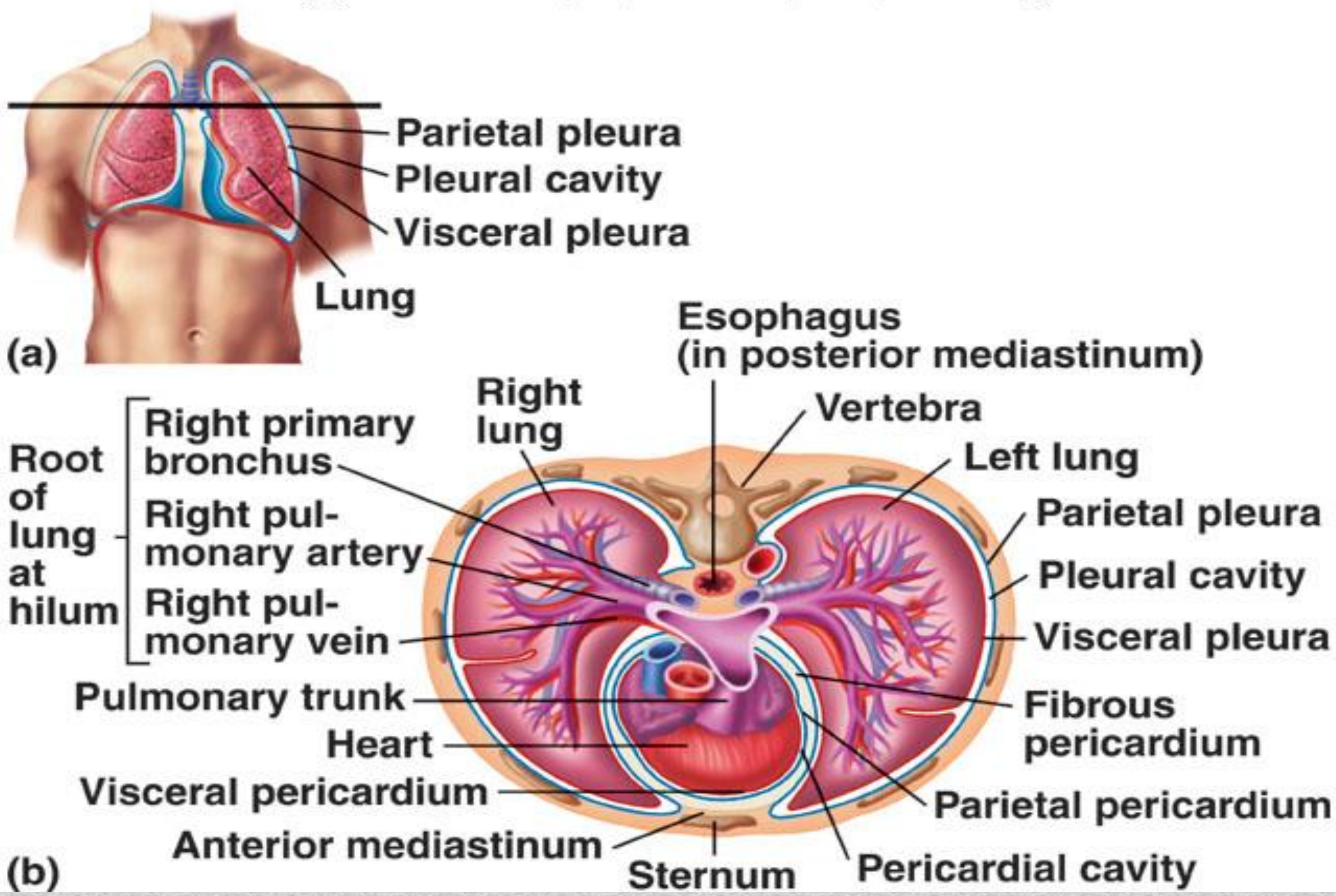


Respiratory Membrane

Structures of the Thoracic Cavity

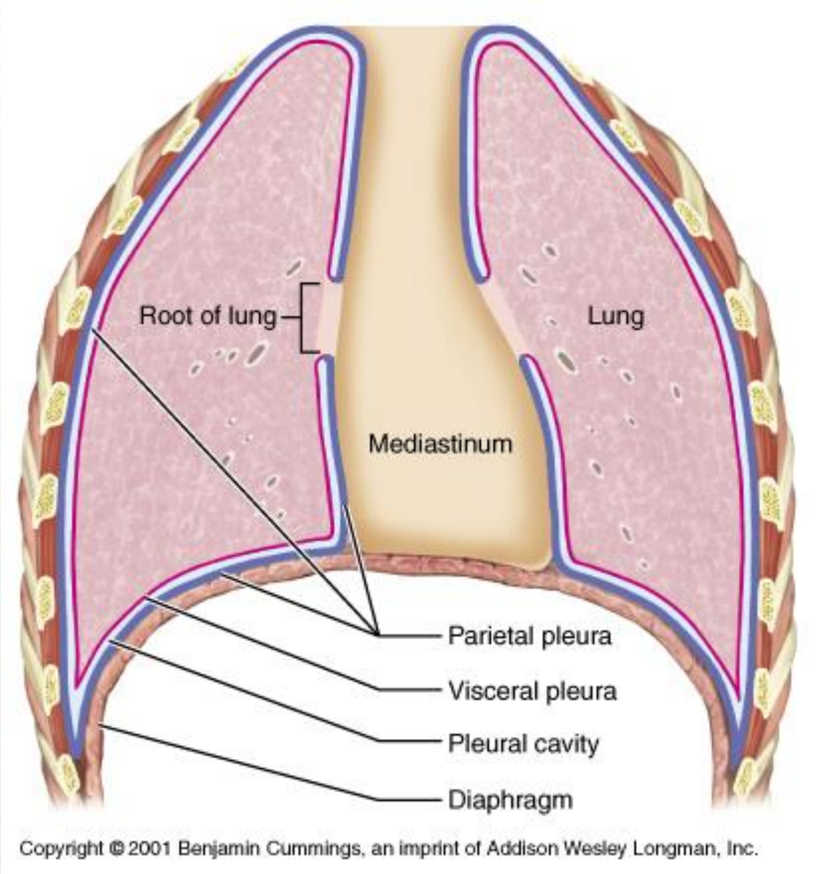
- A container with a single opening, the trachea
- Volume of the container changes
  - Diaphragm moves up and down
  - Muscles move the rib cage in and out
- Volume of the thoracic cavity increases by enlarging all diameters
  - ↑ diameter = ↑ volume




Parietal pleura
Pleural cavity
Visceral pleura
Lung
(a)
Esophagus
(in posterior mediastinum)
Right lung
Vertebra
Left lung
Root of lung at hilum
Right primary bronchus
Right pulmonary artery
Right pulmonary vein
Parietal pleura
Pleural cavity
Visceral pleura
Pulmonary trunk
Heart
Fibrous pericardium
Visceral pericardium
Parietal pericardium
Anterior mediastinum
Sternum
Pericardial cavity
(b)

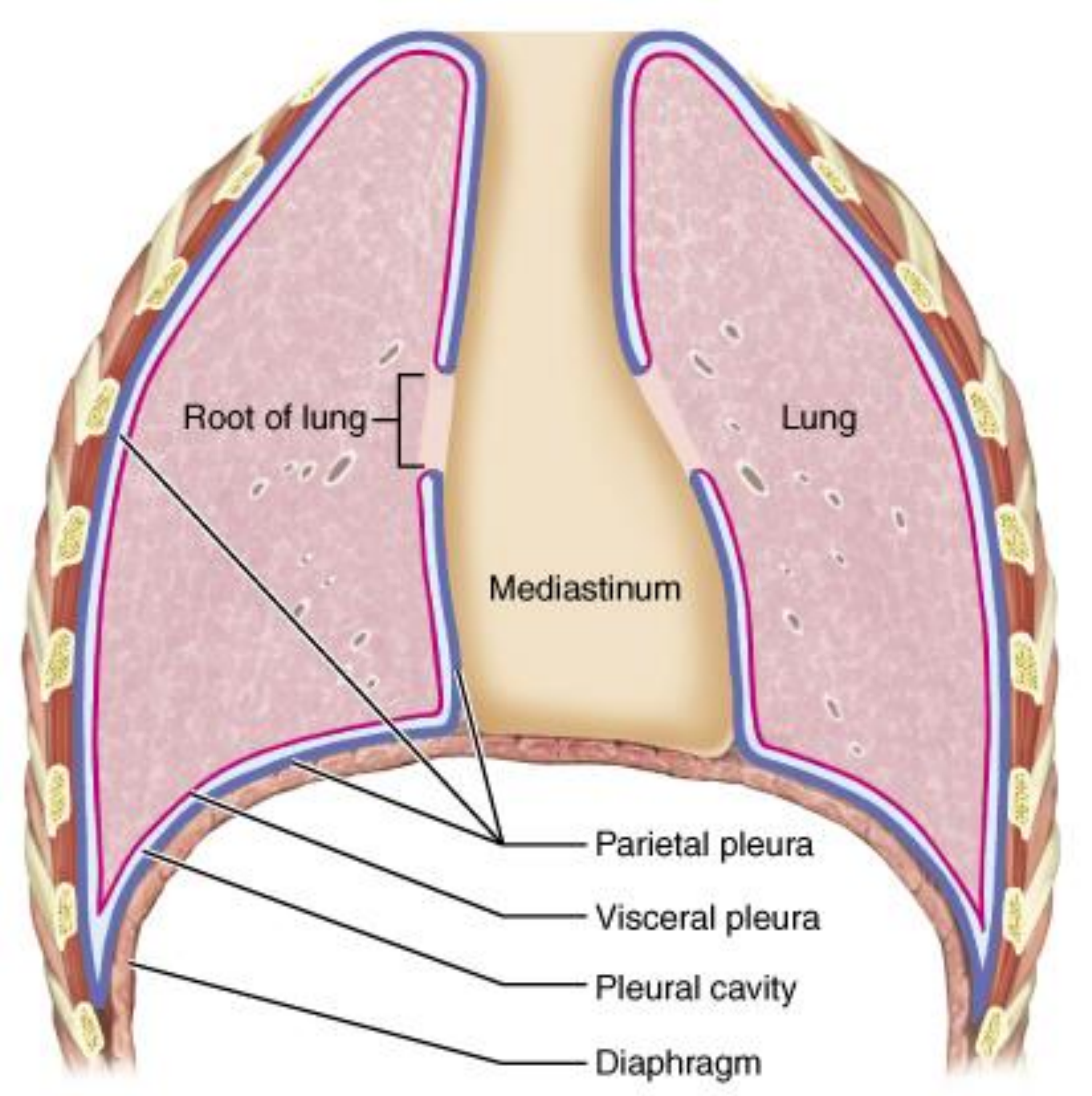
Boyle's Law

- Volume and pressure are *inversely* related
  - ↑ volume = ↓ pressure
- Air always flows from an area of higher pressure to an area of lower pressure
- Decreased pressure in the thoracic cavity in relation to atmospheric pressure causes air to flow into the lungs
  - The process of inspiration



- Pleura
  - Parietal pleura: A membrane that lines the interior surface of the chest wall
  - Visceral pleura: A membrane that lines the exterior surface of the lungs
- Intrapleural space
  - A thin compartment between the two pleurae filled with intrapleural fluid

Structures of the Thoracic Cavity


Root of lung
Lung
Mediastinum
Parietal pleura
Visceral pleura
Pleural cavity
Diaphragm

- Pressure gradient
  - The difference between intrapulmonary and atmospheric pressures
- 4 Pulmonary Pressures
  - Atmospheric pressure
  - Intra-alveolar (Intrapulmonary) pressure
  - Intrapleural pressure
  - Transpulmonary pressure

Pulmonary Pressures

Atmospheric pressure

- The pressure exerted by the weight of the air in the atmosphere (~ 760 mmHg at sea level)

Intra-alveolar (Intrapulmonary) pressure

- The pressure inside the lungs

Intrapleural pressure

- The pressure inside the pleural space

Transpulmonary pressure

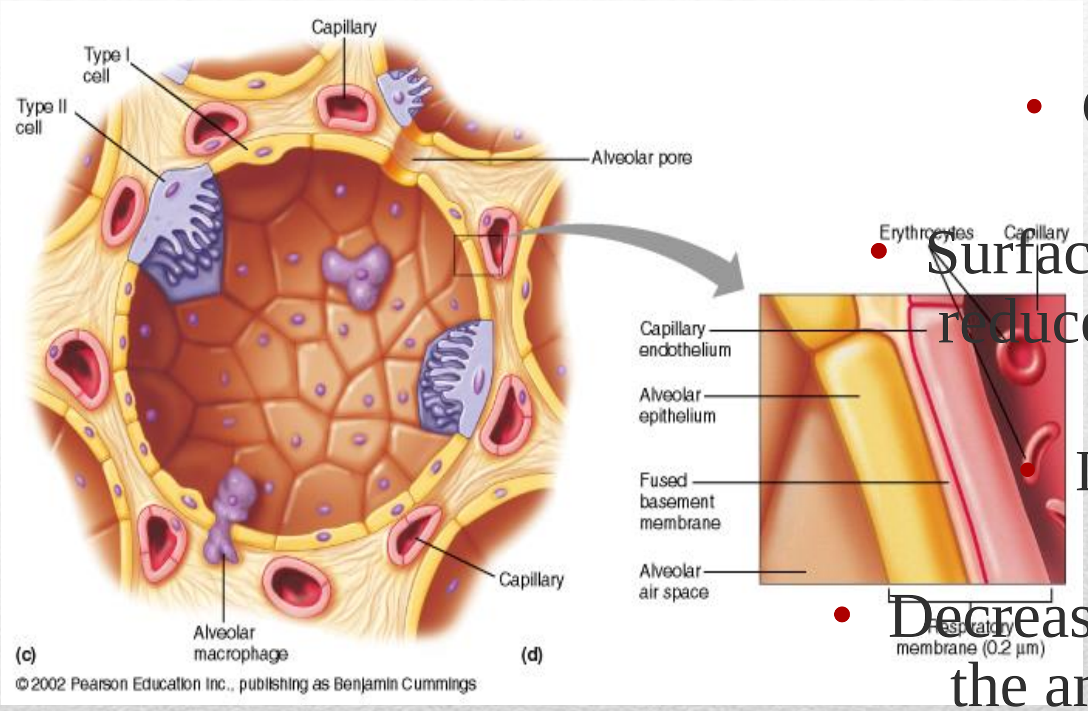
- The difference between the intrapleural and intra-alveolar pressure

Pulmonary Pressures

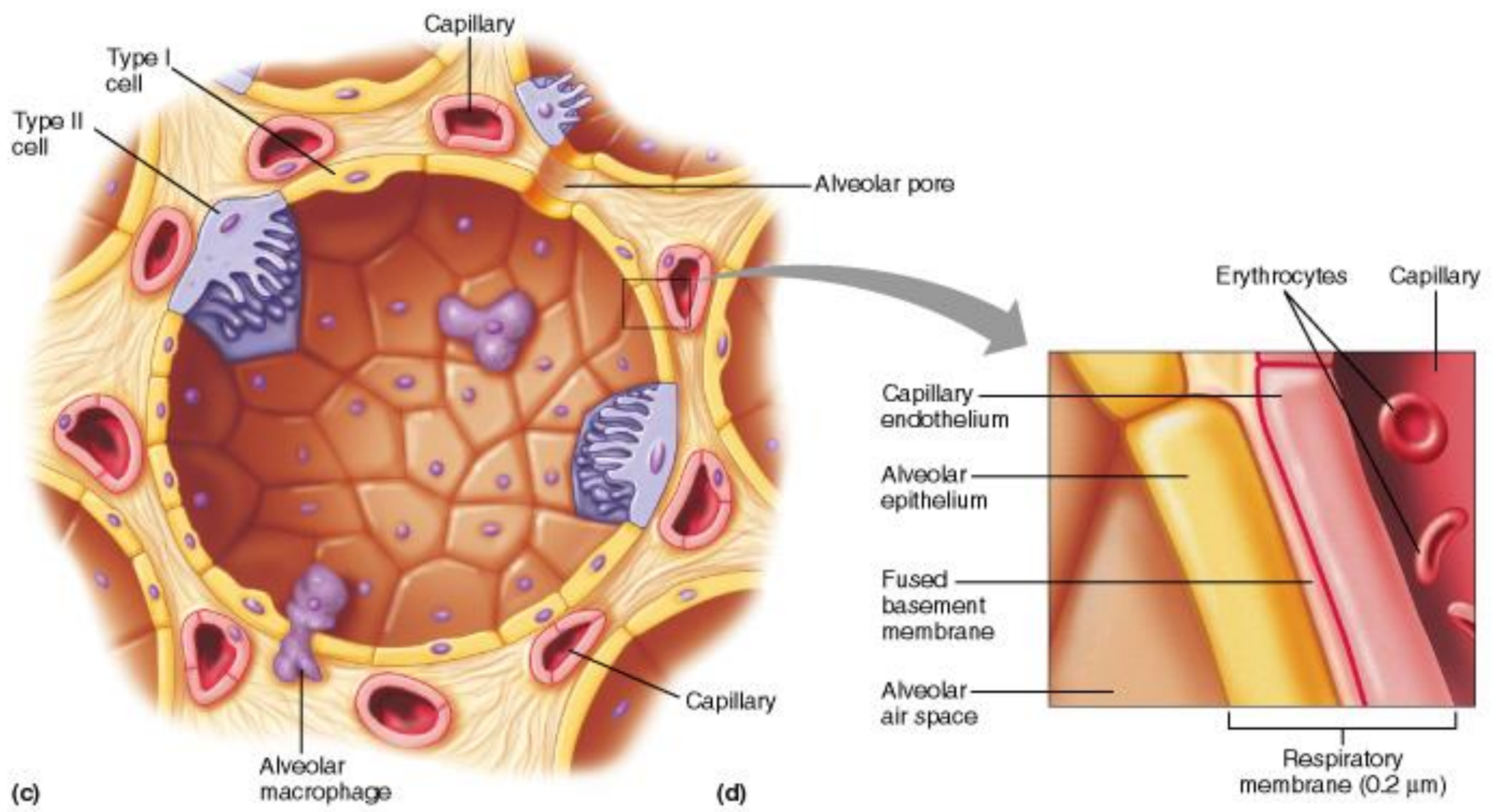
- Intrapleural pressure
  - The pressure inside the pleural space or cavity
  - This cavity contains intrapleural fluid, necessary for surface tension
- Surface tension
  - The force that holds moist membranes together due to an attraction that water molecules have for one another
  - Responsible for keeping lungs patent

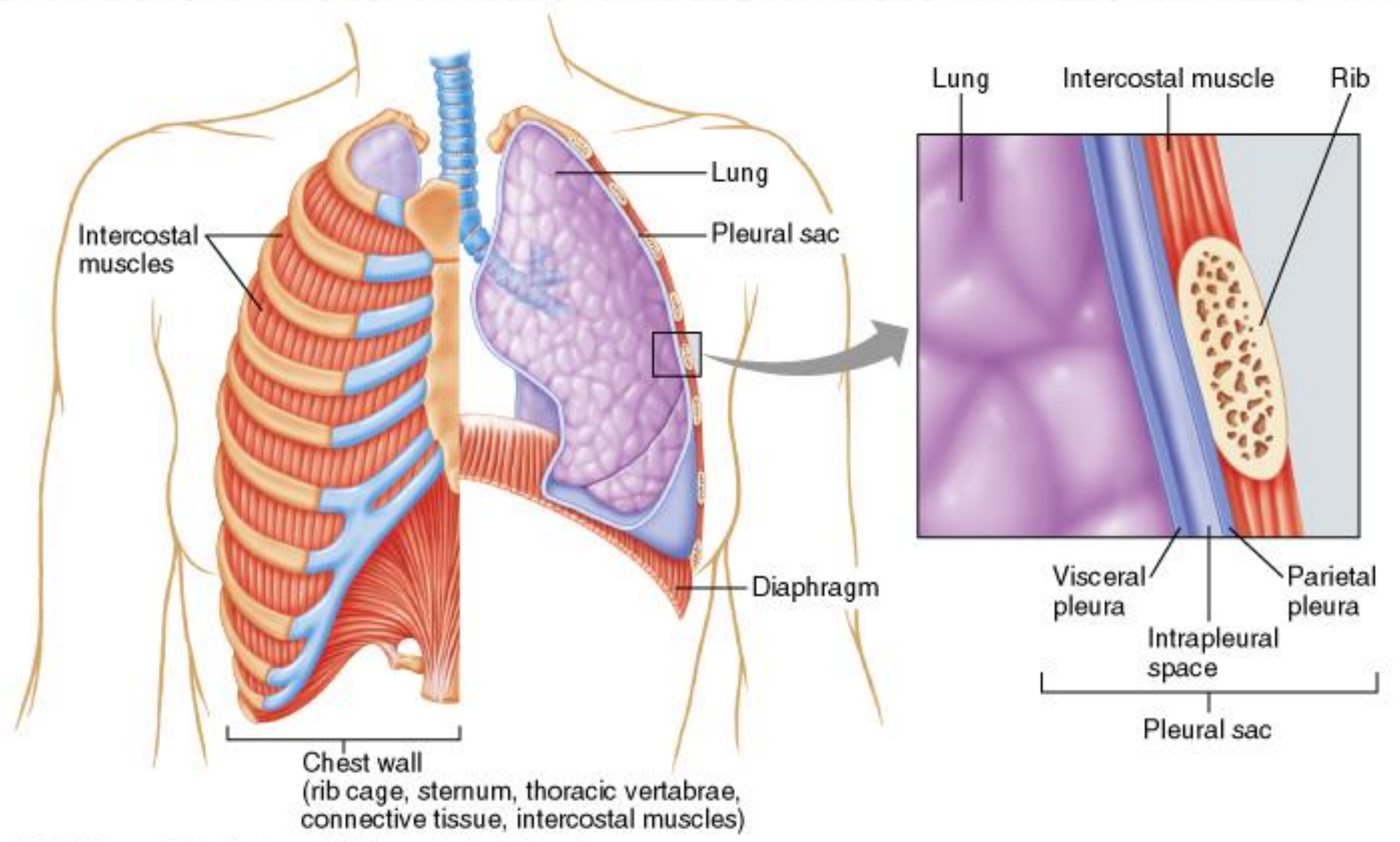
Pleural Pressures

Surface Tension



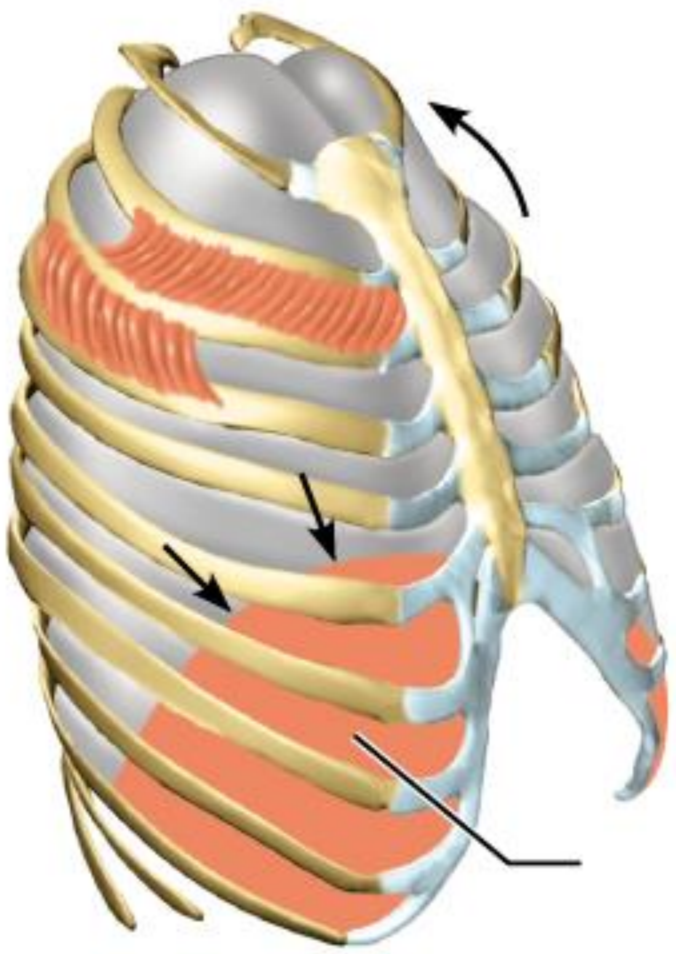
- The force of attraction between liquid molecules
- Type II alveolar cells secrete *surfactant*
- Creates a thin fluid film in the alveoli
- Surfactant (a phospholipoprotein) reduces the surface tension in the alveoli
- It interferes with the attraction between fluid molecules
- Decreasing surface tension reduces the amount of energy required to expand the lungs


Capillary
Type I cell
Type II cell
Alveolar pore
Erythrocytes
Capillary
Capillary endothelium
Alveolar epithelium
Fused basement membrane
Alveolar air space
Respiratory membrane (0.2 µm)
Capillary
Alveolar macrophage
(c)
(d)

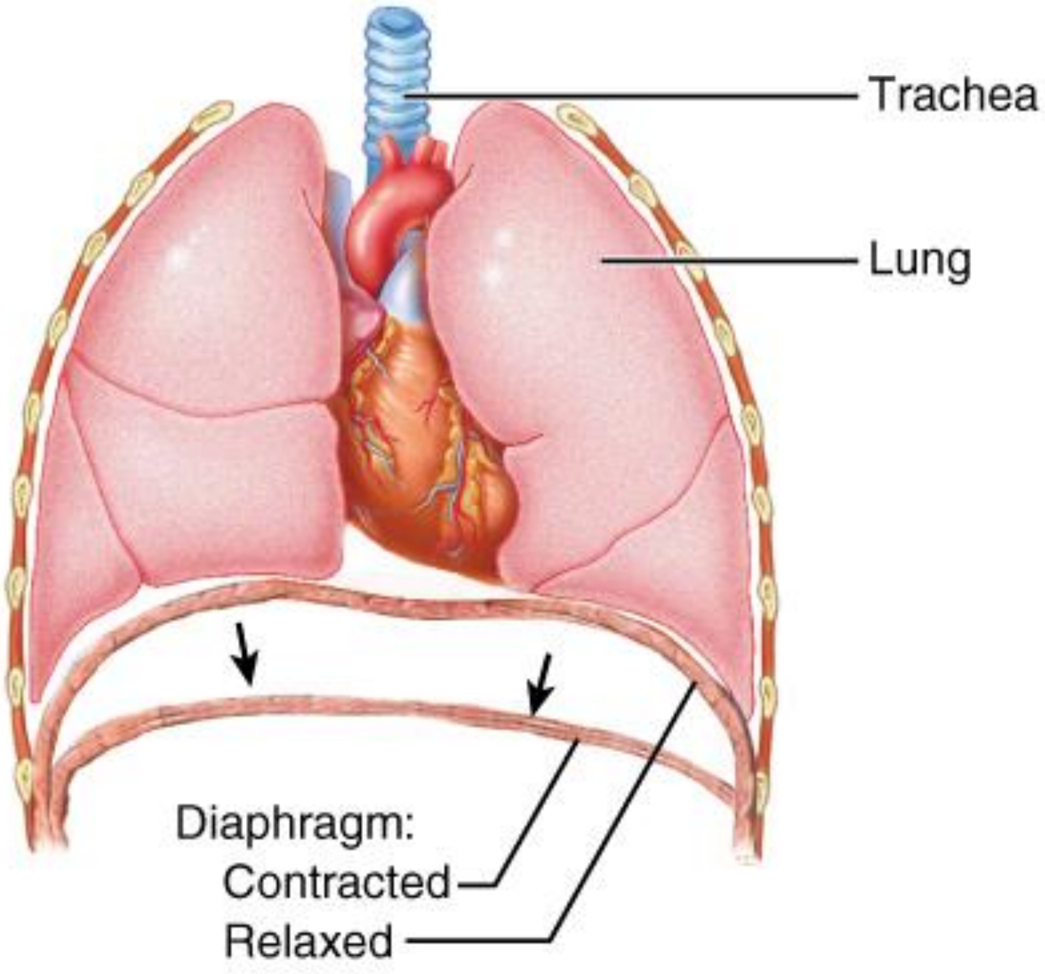

Intercostal muscles
Lung
Pleural sac
Diaphragm
Chest wall
(rib cage, sternum, thoracic vertabrae, connective tissue, intercostal muscles)
Lung
Intercostal muscle
Rib
Visceral pleura
Intrapleural space
Parietal pleura
Pleural sac

- Drawing or pulling air into the lungs
- Atmospheric pressure forces air into the lungs
- The diaphragm moves downward, decreasing intra-alveolar pressure
- The thoracic rib cage moves upward and outward, increasing the volume of the thoracic cavity
- Surface tension
  - Holds the pleural membranes together, which assists with lung expansion
  - Surfactant reduces surface tension within the alveoli

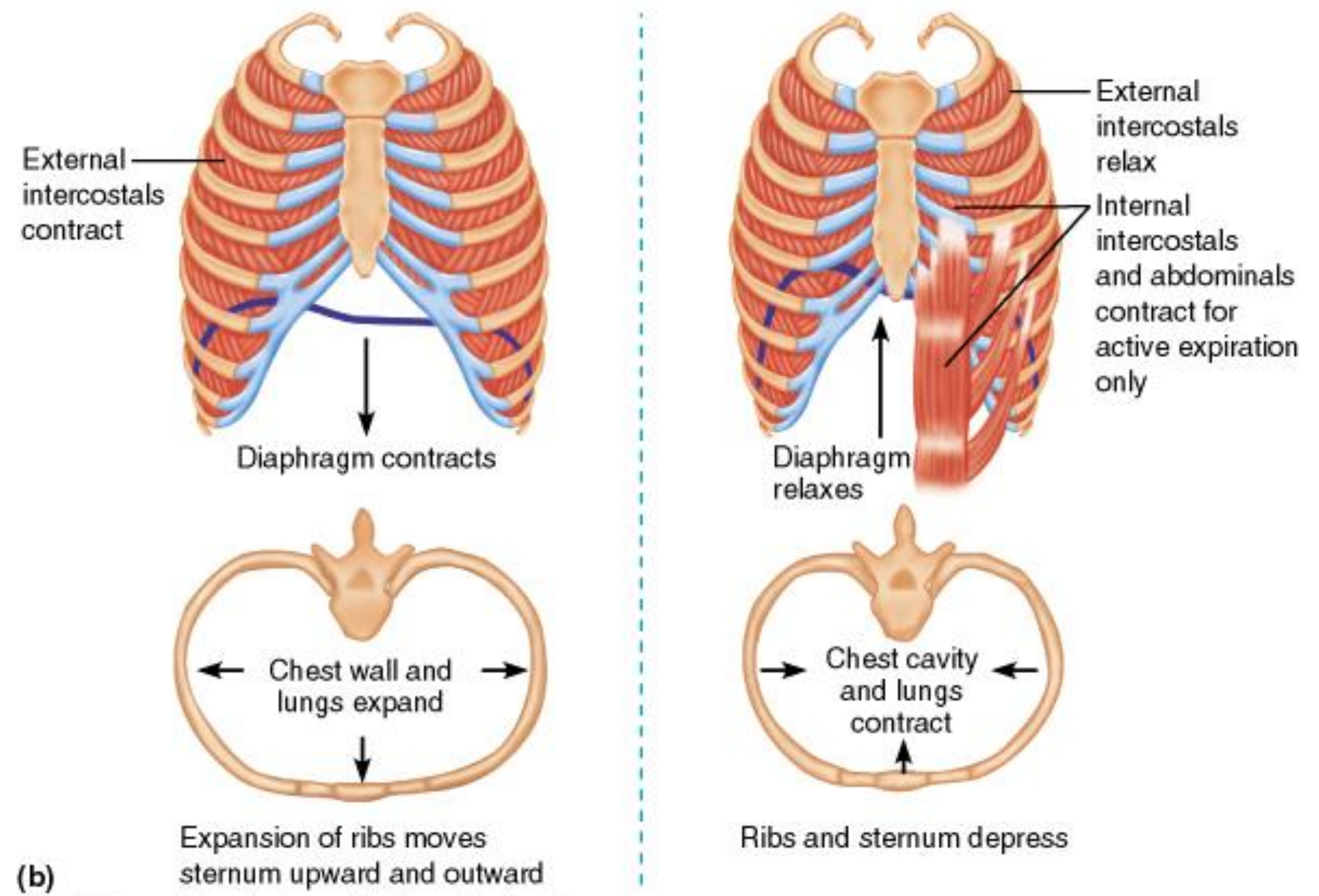
Inspiration



(d) Inspiration

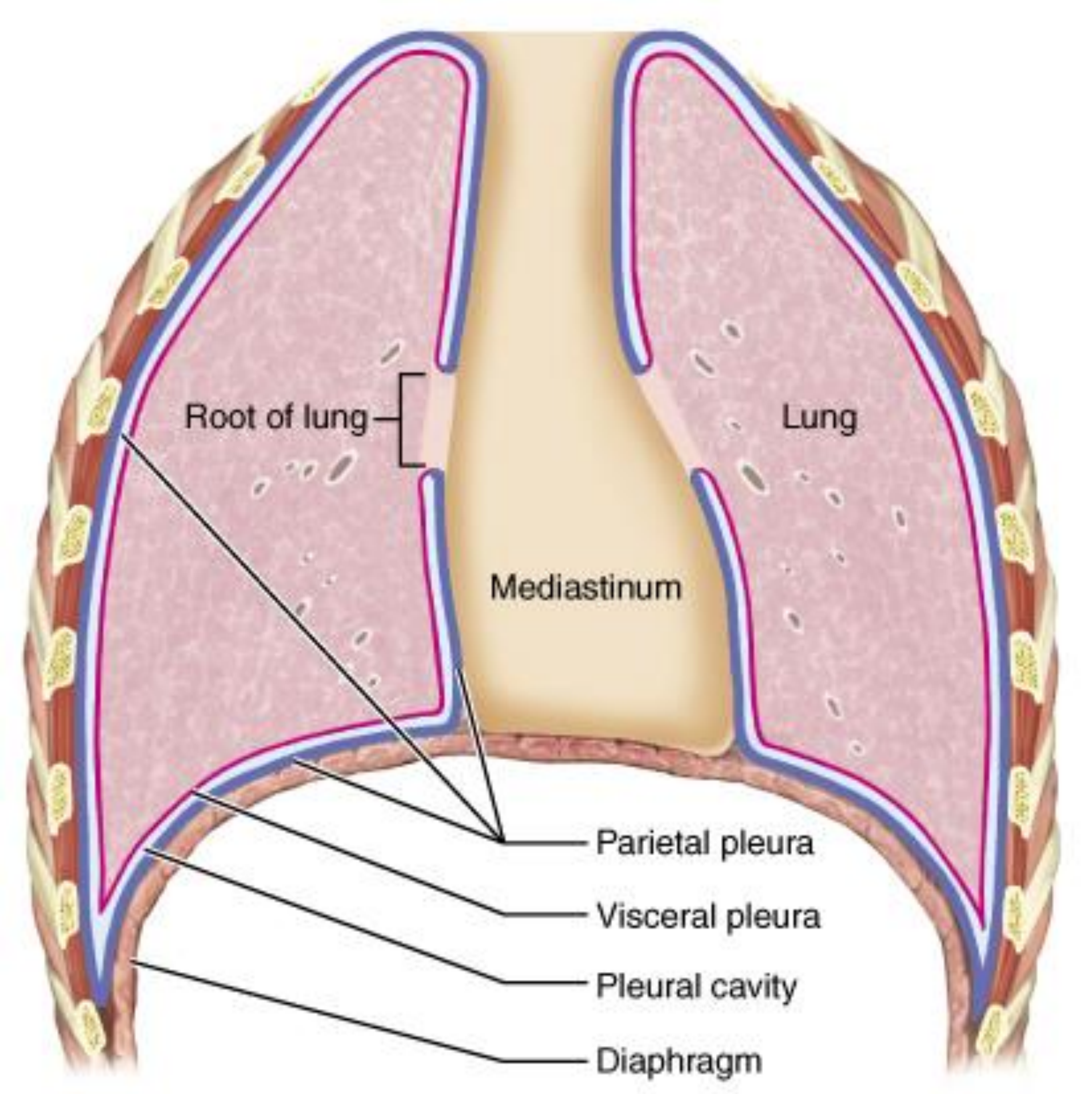


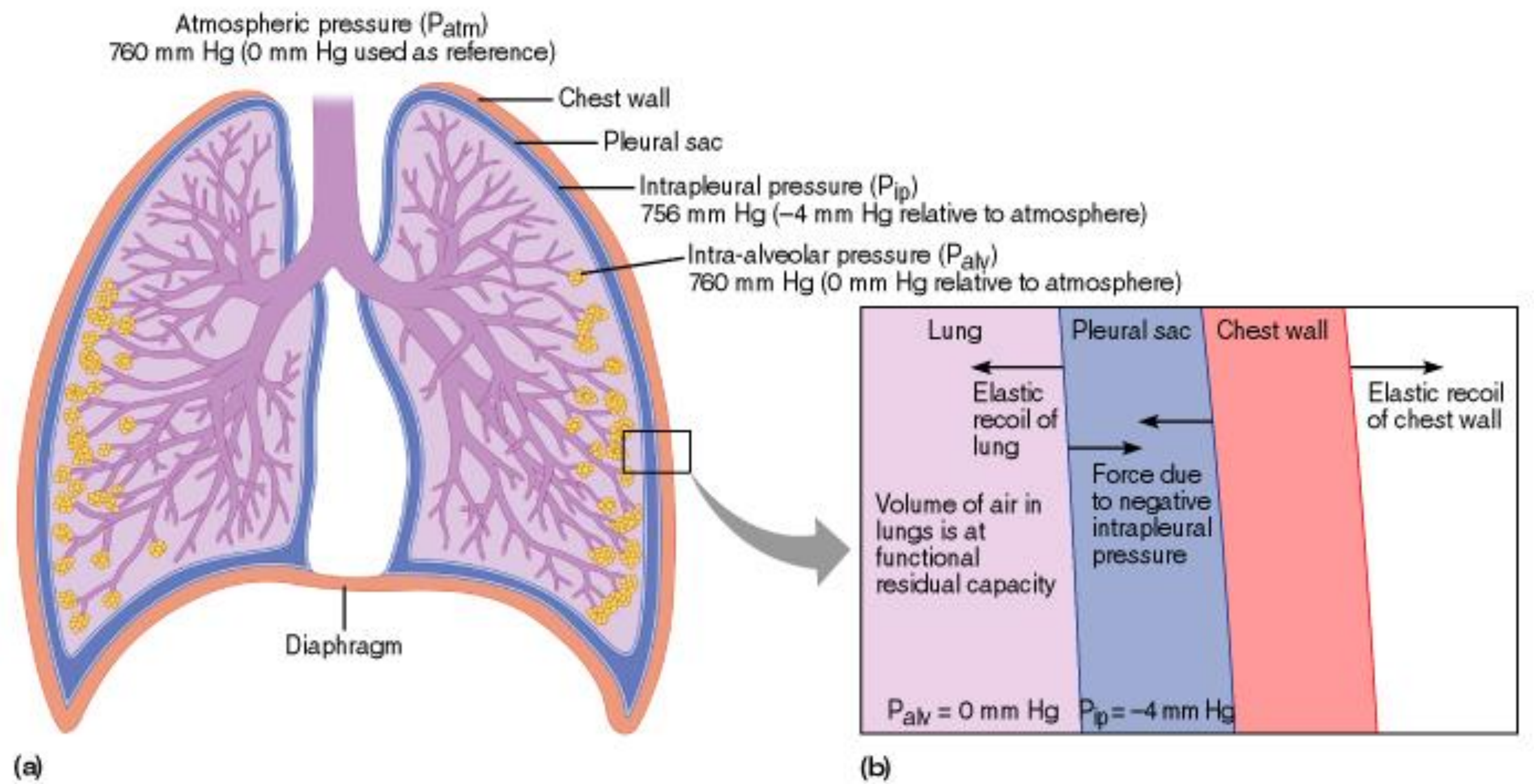
(a) Superoinferior expansion


External intercostals contract
Diaphragm contracts
Chest wall and lungs expand
Expansion of ribs moves sternum upward and outward
(b)
External intercostals relax
Internal intercostals and abdominals contract for active expiration only
Diaphragm relaxes
Chest cavity and lungs contract
Ribs and sternum depress

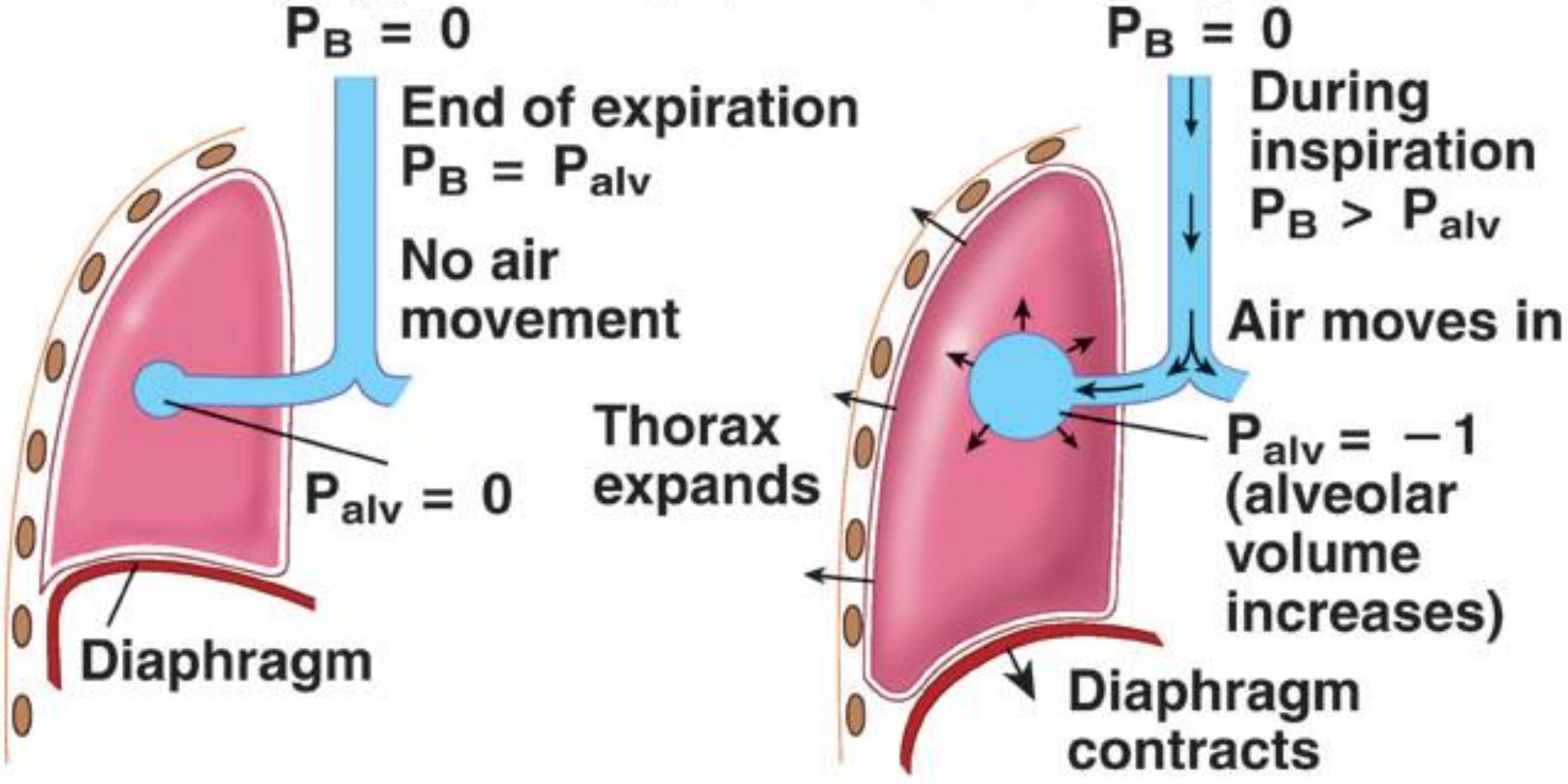
- During inspiration, forces are generated that attempt to pull the lungs away from the thoracic wall
- Surface tension of the intraplueral fluid hold the lungs against the thoracic wall, preventing collapse

Inspiration


Root of lung
Lung
Mediastinum
Parietal pleura
Visceral pleura
Pleural cavity
Diaphragm



Atmospheric pressure (Patm)
760 mm Hg (0 mm Hg used as reference)
Chest wall
Pleural sac
Intrapleural pressure (Pip)
756 mm Hg (–4 mm Hg relative to atmosphere)
Intra-alveolar pressure (Palv)
760 mm Hg (0 mm Hg relative to atmosphere)
Diaphragm
(a)
Lung
Pleural sac
Chest wall
Elastic recoil of lung
Elastic recoil of chest wall
Force due to negative intrapleural pressure
Volume of air in lungs is at functional residual capacity
Palv = 0 mm Hg
Pip = –4 mm Hg
(b)



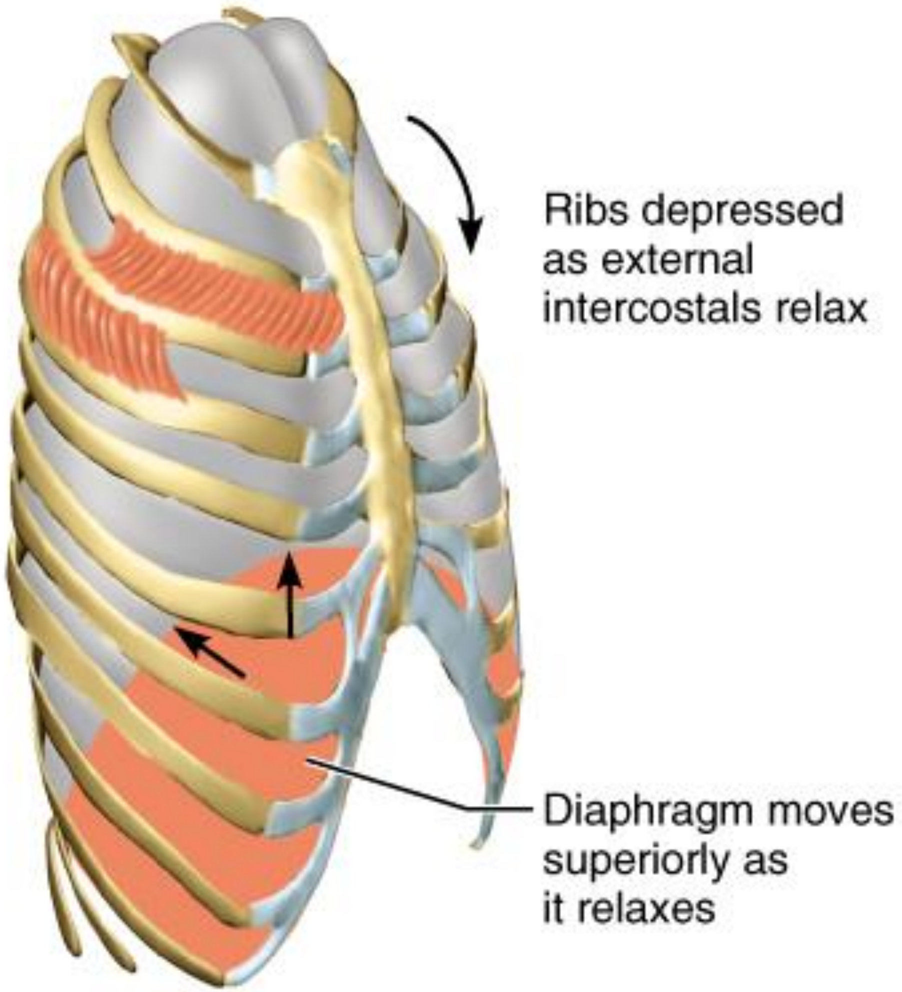
1. Barometric air pressure (P_B) is equal to alveolar pressure (P_{alv}) and there is no air movement.

2. Increased thoracic volume results in increased alveolar volume and decreased alveolar pressure. Barometric air pressure is greater than alveolar pressure, and air moves into the lungs.

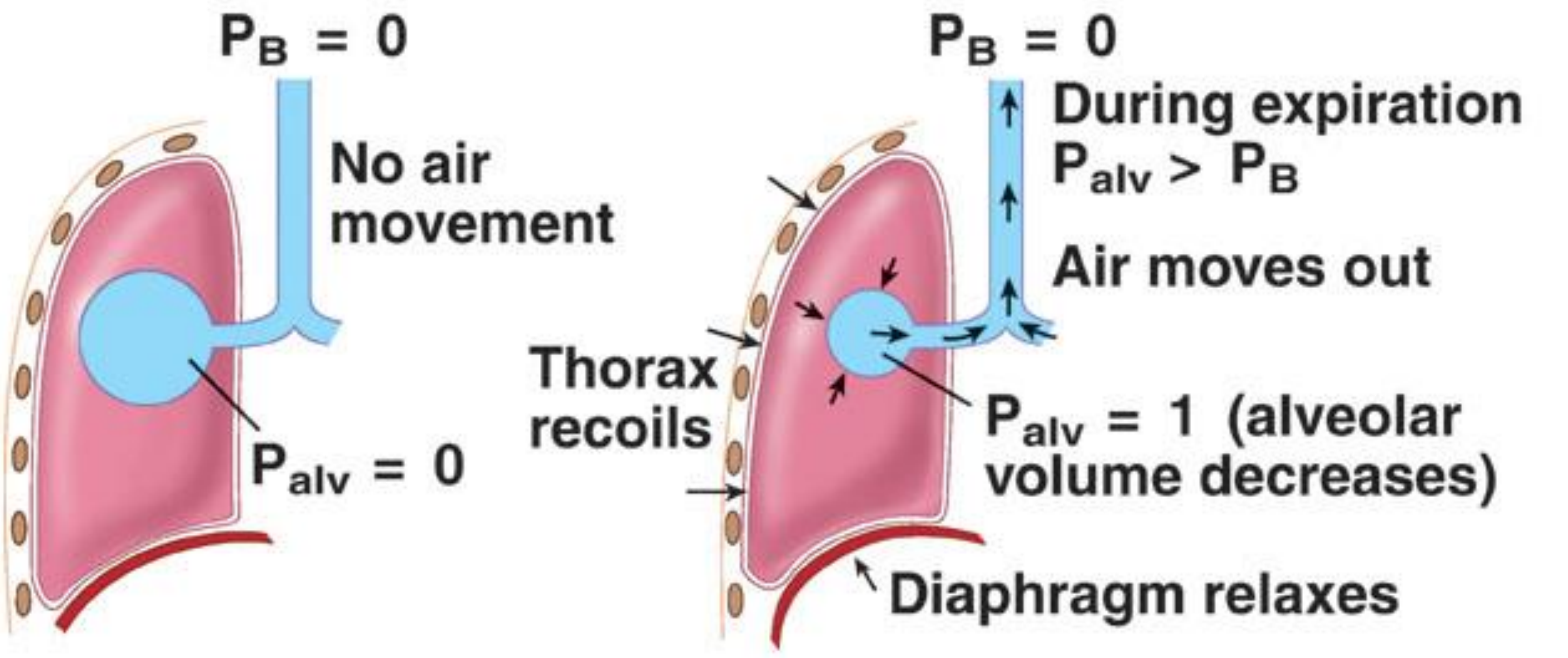
Expiration

- Pushing air out of the lungs
- Results due to the elastic recoil of tissues and due to the surface tension within the alveoli

- Expiration can be aided by:
  - Thoracic and abdominal wall muscles that pull the thoracic cage downward and inward, decreasing intra-alveolar pressure
  - This compresses the abdominal organs upward and inward, decreasing the volume of the thoracic cavity

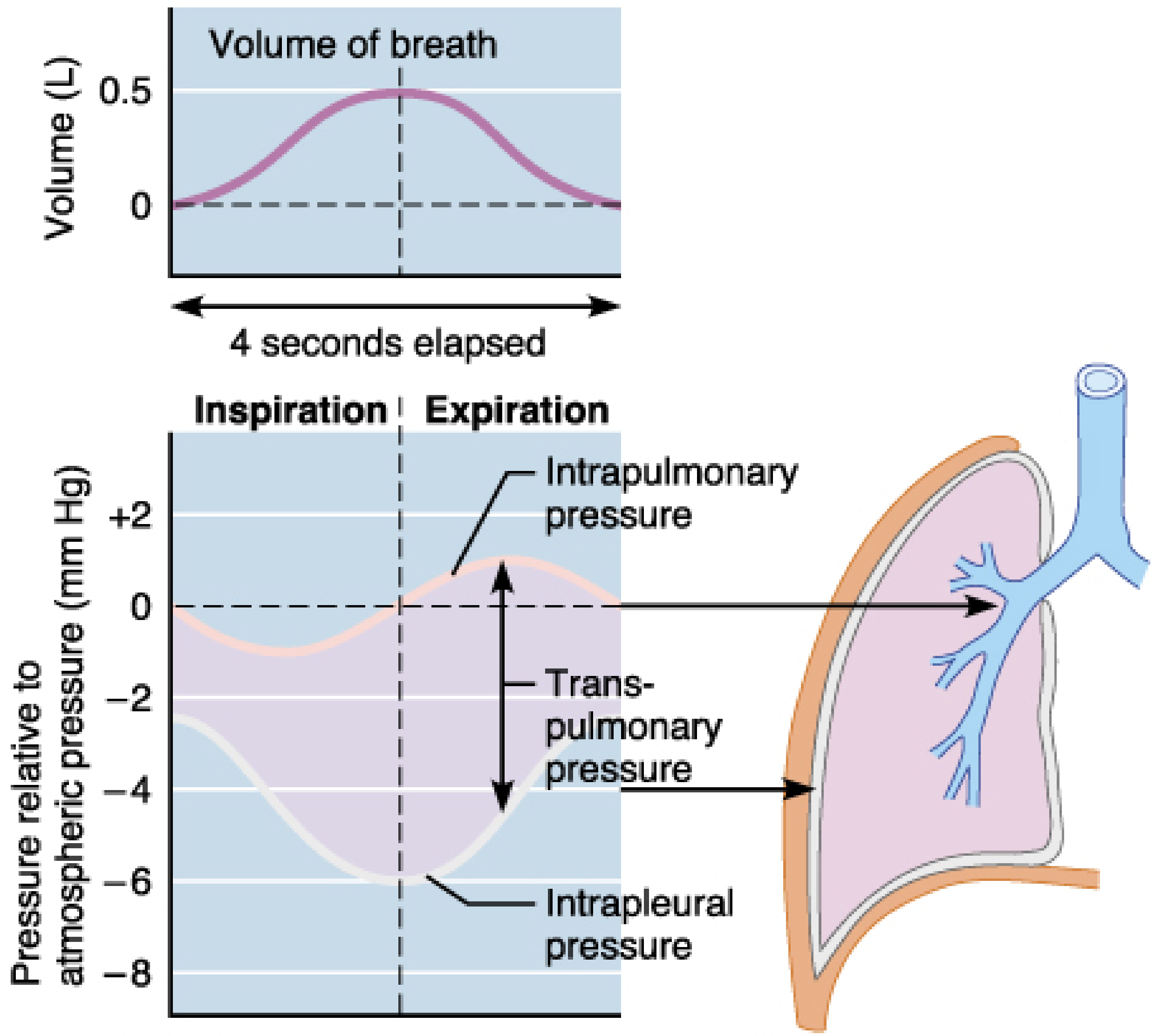

Ribs depressed as external intercostals relax
Diaphragm moves superiorly as it relaxes

Expiration



3. End of inspiration.

4. Decreased thoracic volume results in decreased alveolar volume and increased alveolar pressure. Alveolar pressure is greater than barometric air pressure, and air moves out of the lungs.

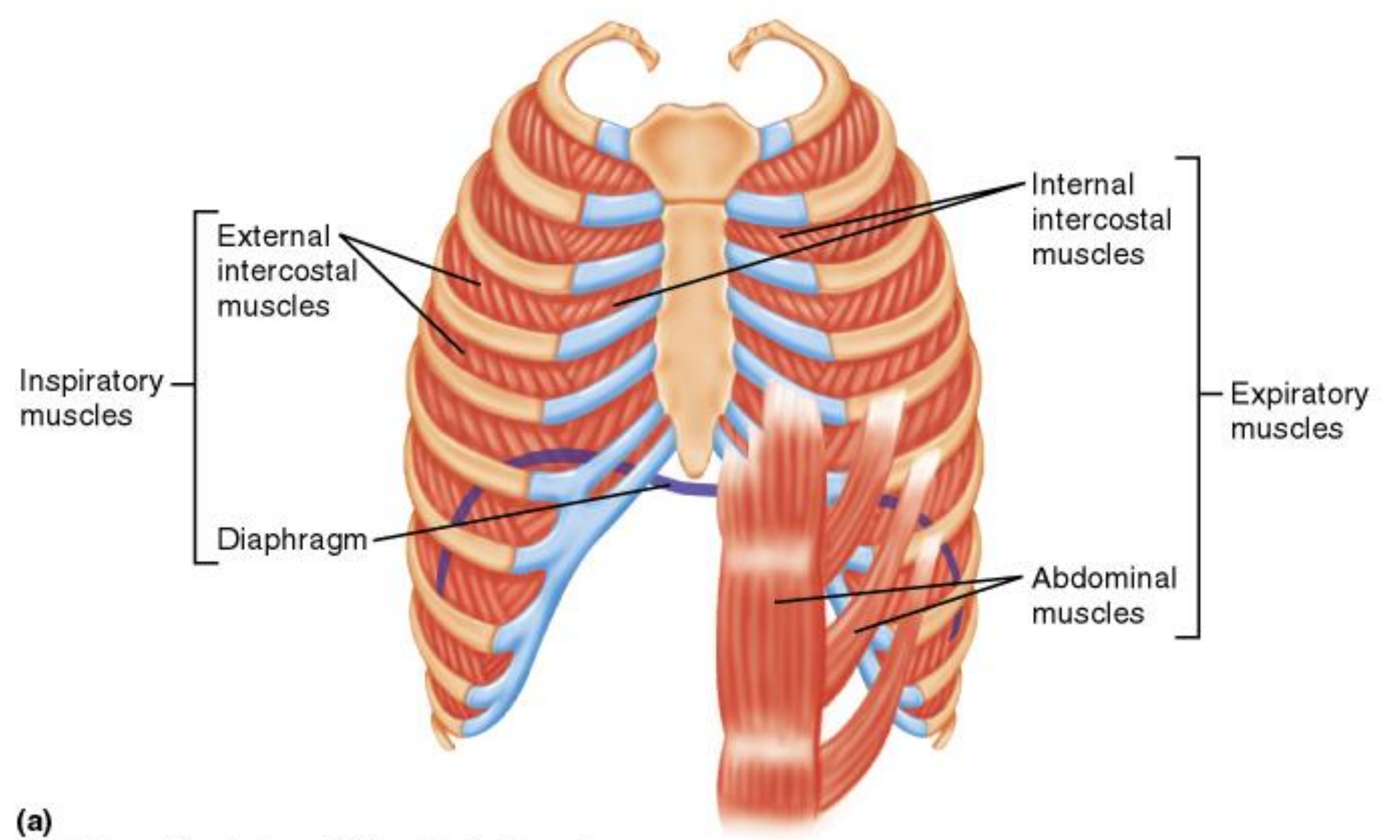


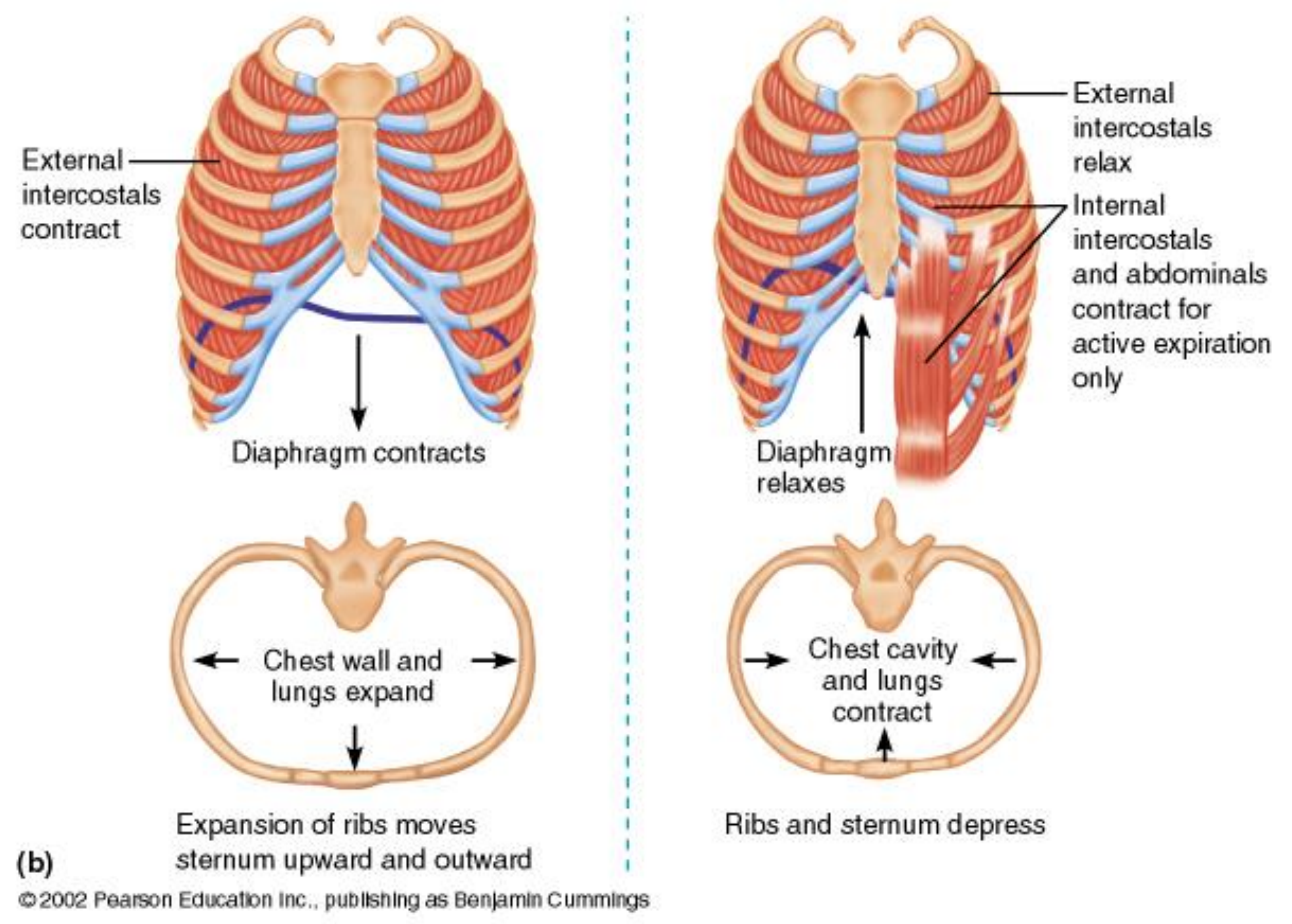
Volume of breath
Volume (L)
0.5
0
4 seconds elapsed
Inspiration
Expiration
Pressure relative to atmospheric pressure (mm Hg)
+2
0
−2
−4
−6
−8
Intrapulmonary pressure
Trans-pulmonary pressure
Intrapleural pressure

Quiet Breathing

- Muscles include:
  - External intercostals
  - Diaphragm
- Contract to expand the rib cage and stretch the lungs = ↑ volume of the thoracic cavity
- ↑ intrapulmonary volume
- ↓ intrapulmonary pressure (relative to atmospheric pressure)
- Decreased pressure inside the lungs pulls air into the lungs down its pressure gradient until intrapulmonary pressure equals atmospheric pressure

Muscles of Breathing - Inspiration


External
intercostal
muscles
Internal
intercostal
muscles
Inspiratory
muscles
Expiratory
muscles
Diaphragm
Abdominal
muscles
(a)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(b)
External intercostals relax
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Diaphragm relaxes
Chest cavity and lungs contract
Ribs and sternum depress
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Forced or Deep Inspiration

- Involves several accessory muscles:
  - Sternocleidomastoid
  - Pectoralis minor
  - Scalenes (neck muscles)
- Maximal ↑ in thoracic volume
- Greater ↓ in intrapulmonary pressure
- More air moves into the lungs
- At the end of inspiration, the intrapulmonary pressure equals atmospheric pressure

Muscles of Breathing - Inspiration

Quiet Breathing

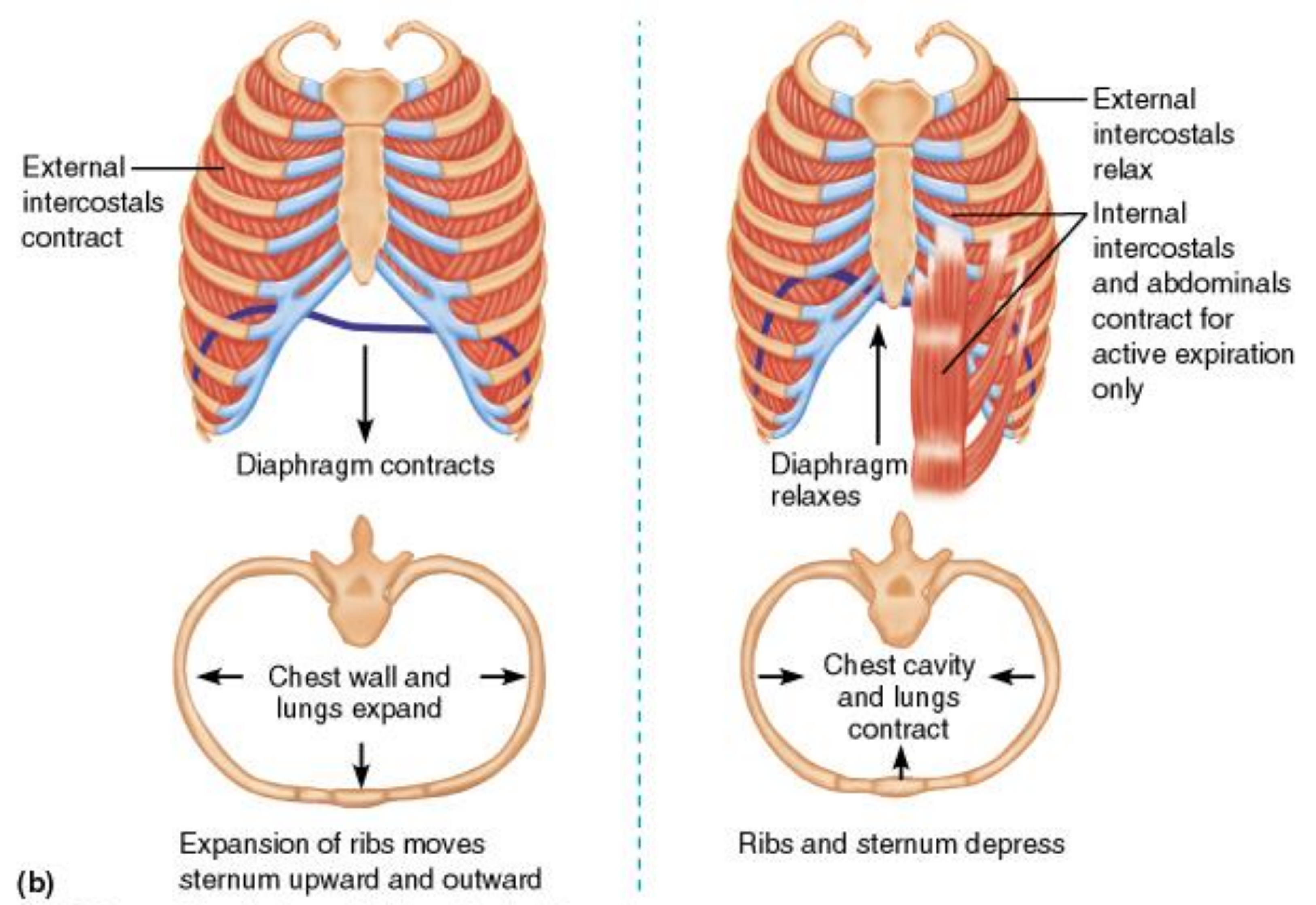
- Passive process
  - Depends on the elasticity of the lungs
- Muscles of inspiration relax
  - The rib cage descends
  - The lungs recoil
- ↓ intrapulmonary volume
- ↑ intrapulmonary pressure
- Alveoli are compressed, thus forcing air out of the lungs

Muscles of Breathing - Expiration

Muscles of Breathing - Expiration

Forced Expiration

- It is an active process
  - Occurs in activities such as blowing up a balloon, exercising, or yelling
- Abdominal wall muscles are involved in forced expiration
  - Function to ↑ the pressure in the abdominal cavity forcing the abdominal organs upward against the diaphragm
- ↓ volume of the thoracic cavity
- ↑ pressure in the thoracic cavity
- Air is forced out of the lungs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Lung compliance

- The ease with which the lungs may be expanded, stretched, or inflated
- Depends primarily on the elasticity of the lung tissue
  - Elasticity refers to the ability of the lung to recoil after it has been inflated

Factors Affecting Pulmonary Ventilation

- Lung and thoracic cavity tissue has a natural tendency to recoil, or become smaller
- Lung recoil is essential for normal expiration and depends on the fibroelastic qualities of lung tissue
- In normal lungs there is a balance between compliance and elasticity

Factors Affecting Pulmonary Ventilation

- Recoil pressure is *inversely* proportional to compliance
- Increased compliance results in decreased recoil
  - Example: Emphysema
  - Results in difficulty resuming the shape of the lung during exhalation
- Decreased compliance results in increased recoil
  - Example: Cysitc fibrosis
  - Results in difficulty expanding the lung because of increased fibrous tissue and mucous

Factors Affecting Pulmonary Ventilation

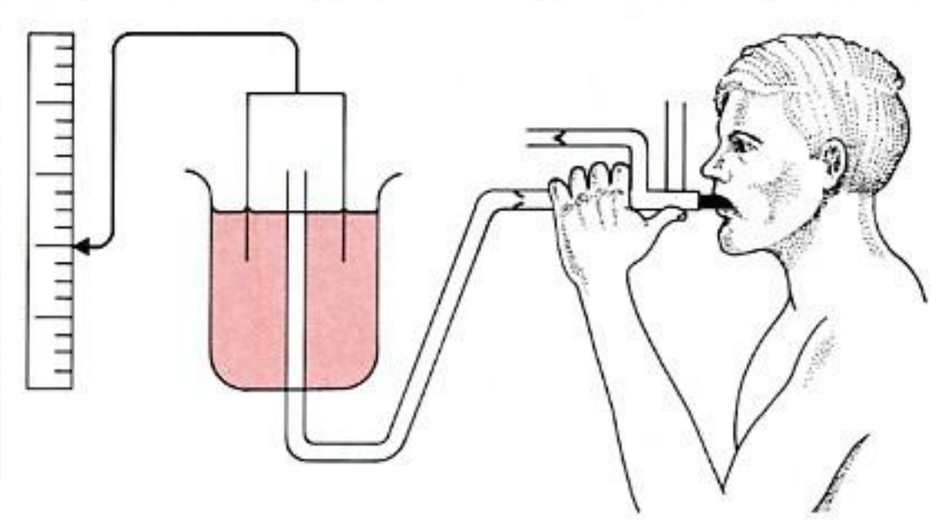
Airway Resistance

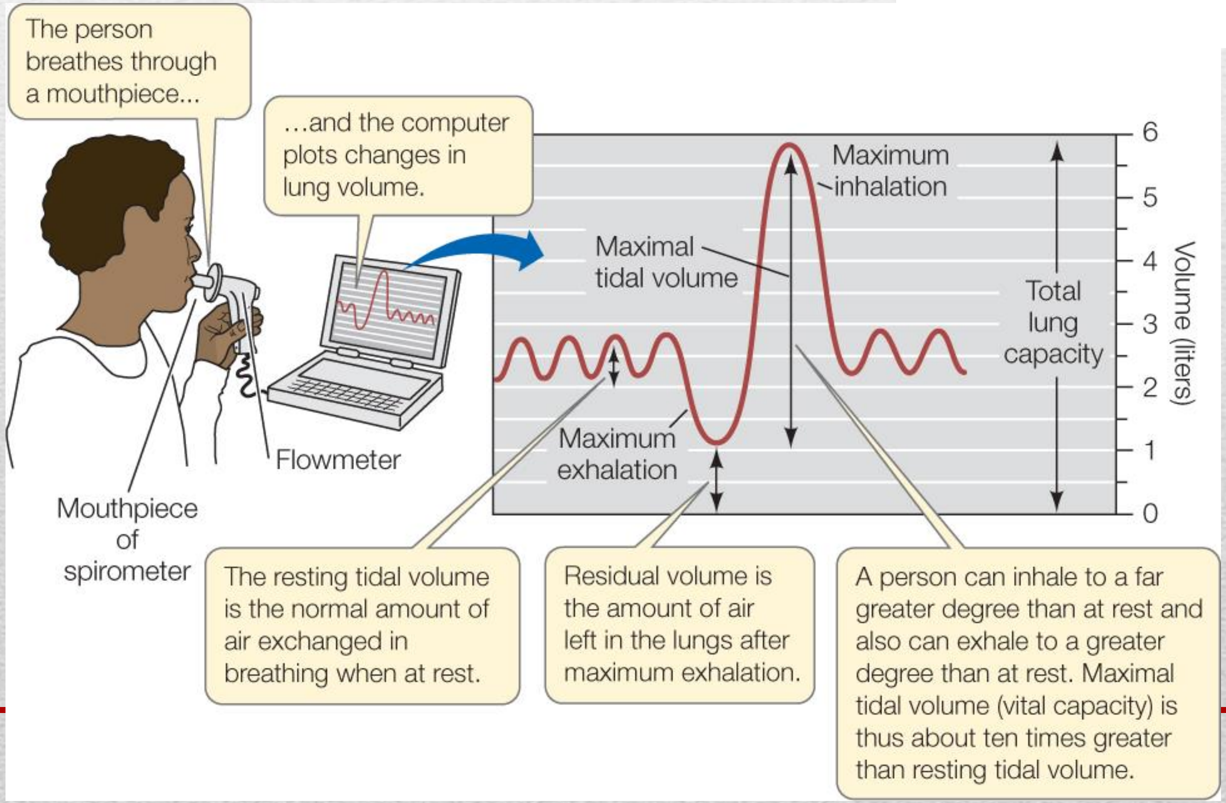
- Opposition to air flow in the respiratory passageways
- Resistance and air flow are *inversely* related
  - ↑ airway resistance = ↓ air flow (and vice versa)
- Airway resistance is most affected by changes in the diameter of the bronchioles
  - ↓ diameter of the bronchioles = ↑ airway resistance
- Examples:
  - Asthma
  - Bronchiospasm during an allergic reaction
- A high resistance to air flow produces a greater energy cost of breathing

Factors Affecting Pulmonary Ventilation

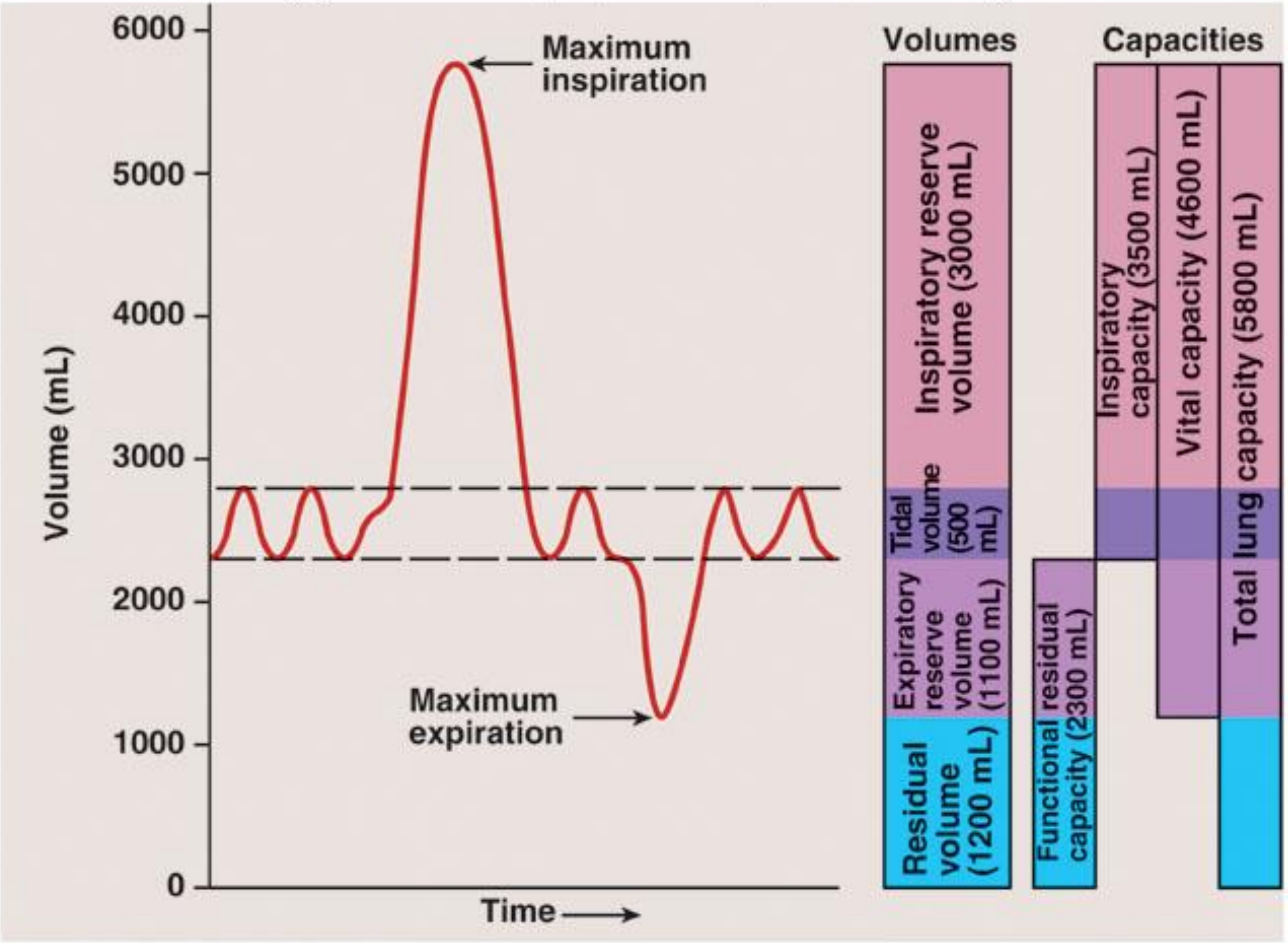
- Tidal Volume (500 mls)
- Respiratory Rate (12 breaths/minute)
- Minute Respiratory Volume (6000 mls/min)

Lung Volumes & Capacities



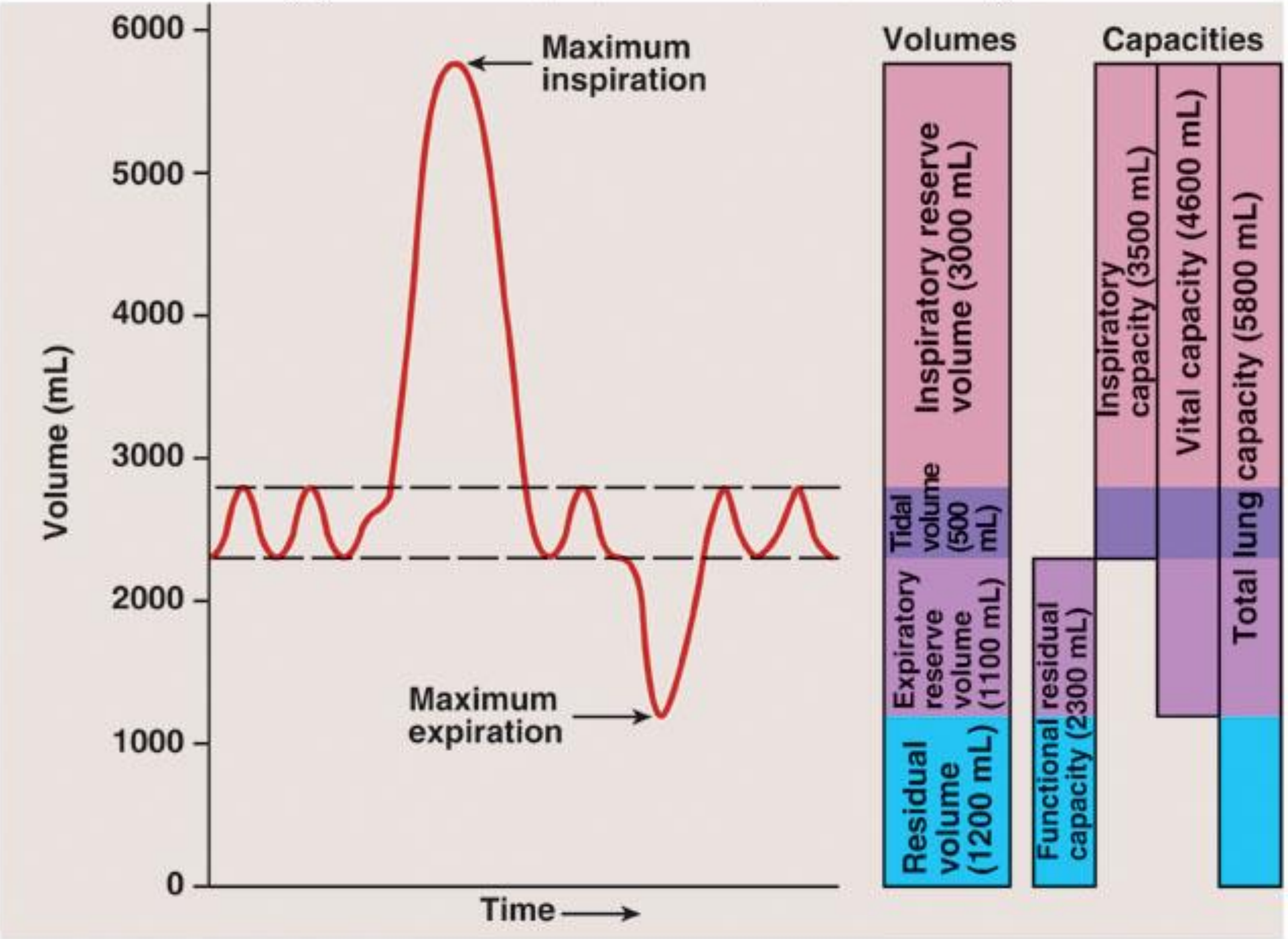


The person breathes through a mouthpiece...
...and the computer plots changes in lung volume.
Maximum inhalation
Maximal tidal volume
Total lung capacity
Maximum exhalation
Flowmeter
Mouthpiece of spirometer
Volume (liters)
6
5
4
3
2
1
0
The resting tidal volume is the normal amount of air exchanged in breathing when at rest.
Residual volume is the amount of air left in the lungs after maximum exhalation.
A person can inhale to a far greater degree than at rest and also can exhale to a greater degree than at rest. Maximal tidal volume (vital capacity) is thus about ten times greater than resting tidal volume.


6000
5000
4000
3000
2000
1000
0
Volume (mL)
Maximum inspiration
Maximum expiration
Time
Volumes
Capacities
Inspiratory reserve volume (3000 mL)
Tidal volume (500 mL)
Expiratory reserve volume (1100 mL)
Residual volume (1200 mL)
Functional residual capacity (2300 mL)
Inspiratory capacity (3500 mL)
Vital capacity (4600 mL)
Total lung capacity (5800 mL)

- Inspiratory Reserve Volume (3000, 2100 mls)
- Inspiratory Capacity (TV + IRV)

Lung Volumes & Capacities


6000
5000
4000
3000
2000
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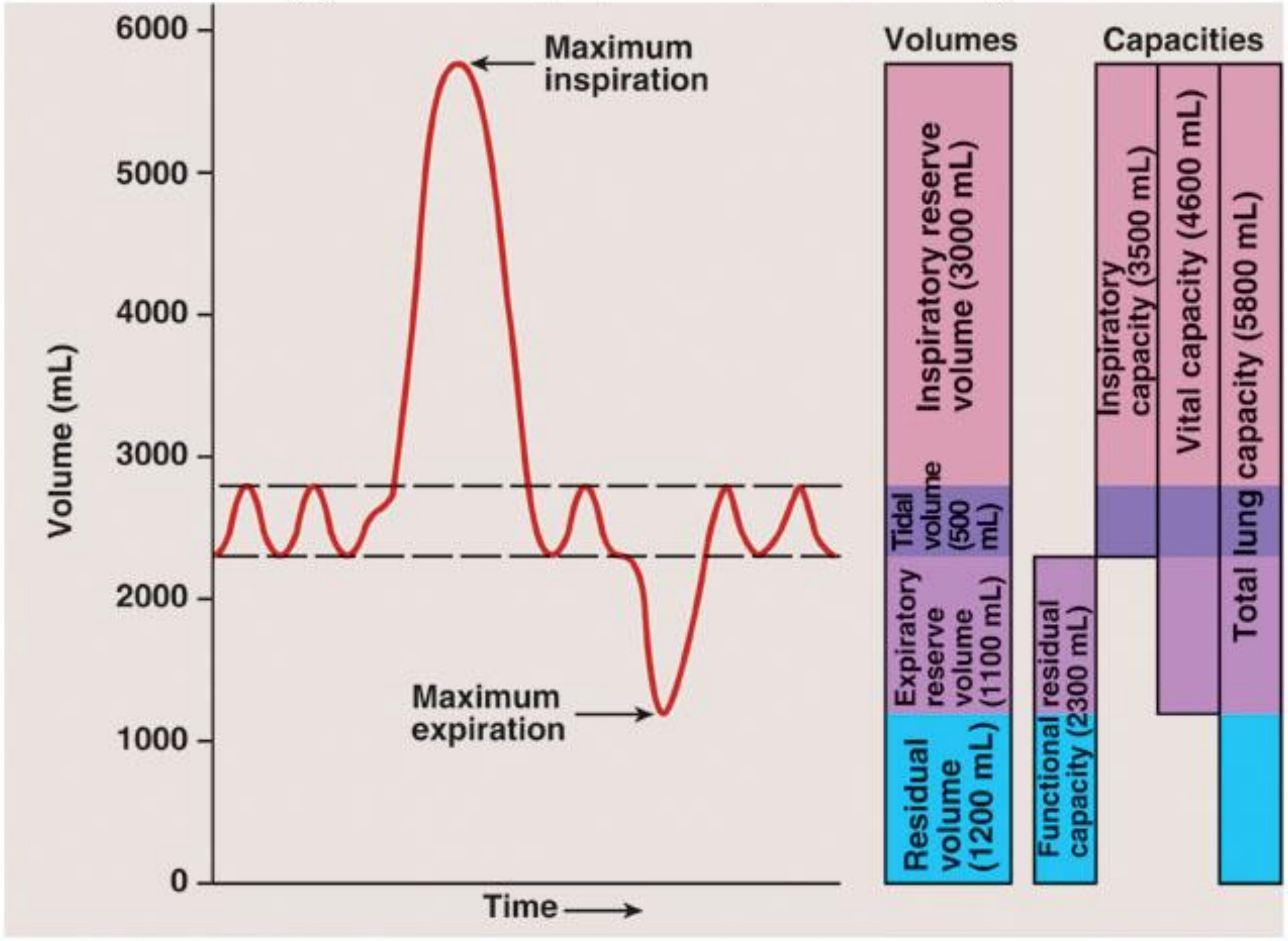
0
Volume (mL)
Time
Maximum inspiration
Maximum expiration
Volumes
Capacities
Inspiratory reserve volume (3000 mL)
Tidal volume (500 mL)
Expiratory reserve volume (1100 mL)
Residual volume (1200 mL)
Functional residual capacity (2300 mL)
Inspiratory capacity (3500 mL)
Vital capacity (4600 mL)
Total lung capacity (5800 mL)

- Expiratory Reserve Volume (1200, 800 mls)
- Residual Volume (1200 mls)
- Functional Residual Capacity (ERV + RV)
  - Air left in lungs after exhaling the tidal volume quietly

Lung Volumes & Capacities



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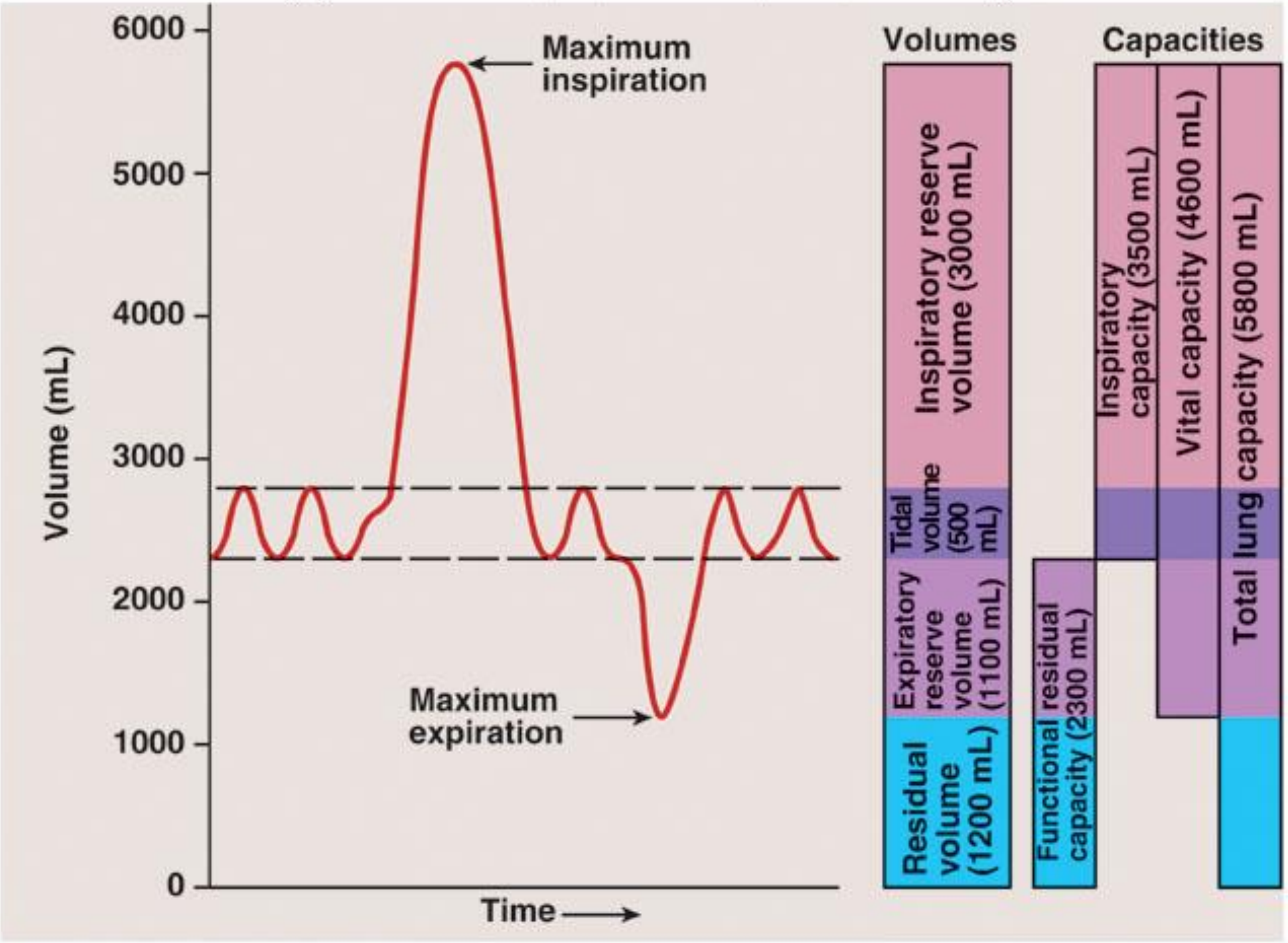
Inspiratory capacity (3500 mL)
Vital capacity (4600 mL)
Total lung capacity (5800 mL)

- Vital Capacity
- IRV + TV + ERV = 4700, 3400 mls
- Maximum amount of air that can be moved in and out of lungs

Lung Volumes & Capacities



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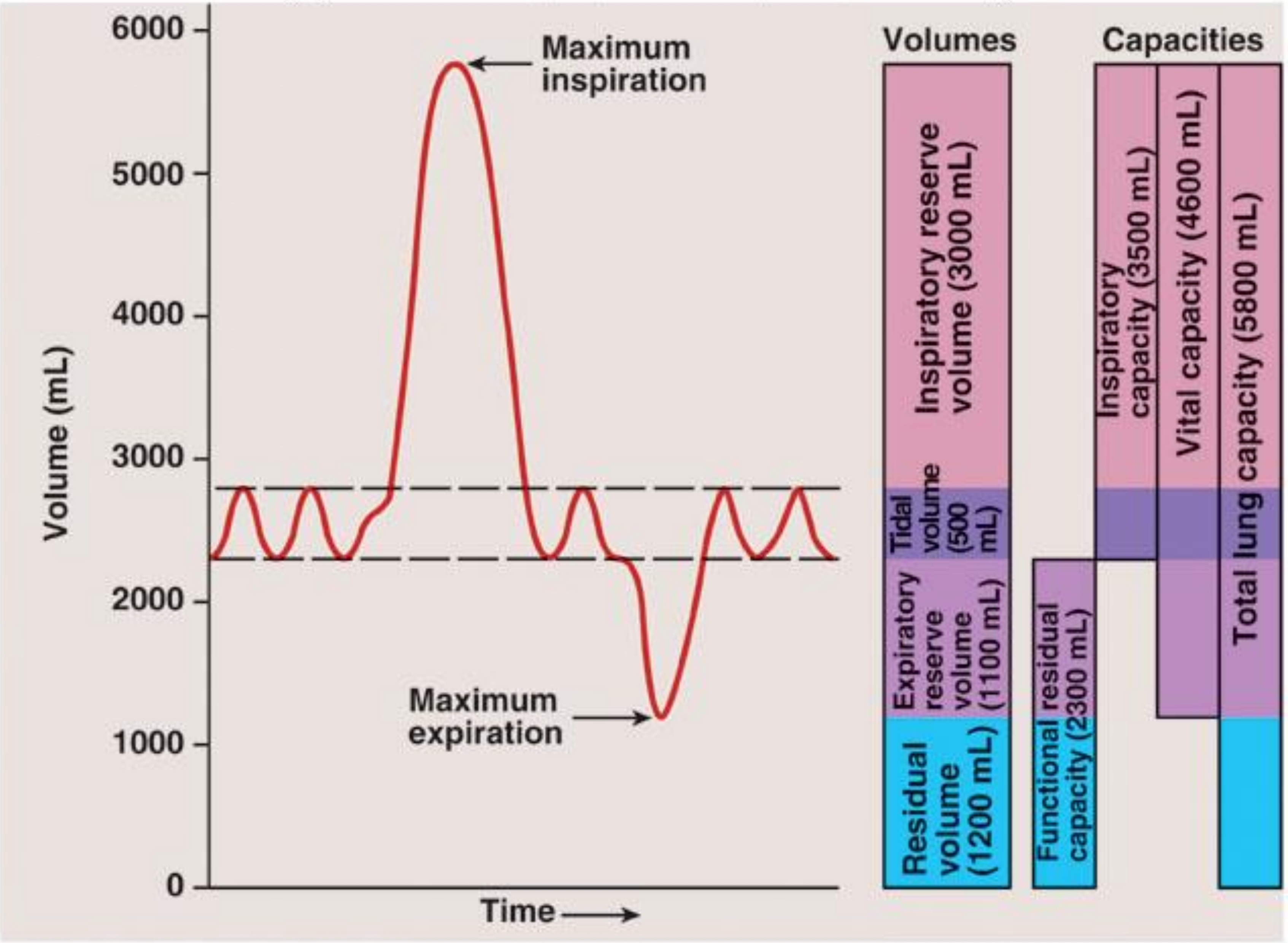
Residual volume (1200 mL)
Functional residual capacity (2300 mL)
Inspiratory capacity (3500 mL)
Vital capacity (4600 mL)
Total lung capacity (5800 mL)

- Total Lung Capacity (5900, 4400)
- Dead air volume (150 mls) – air not in the alveoli

Lung Volumes & Capacities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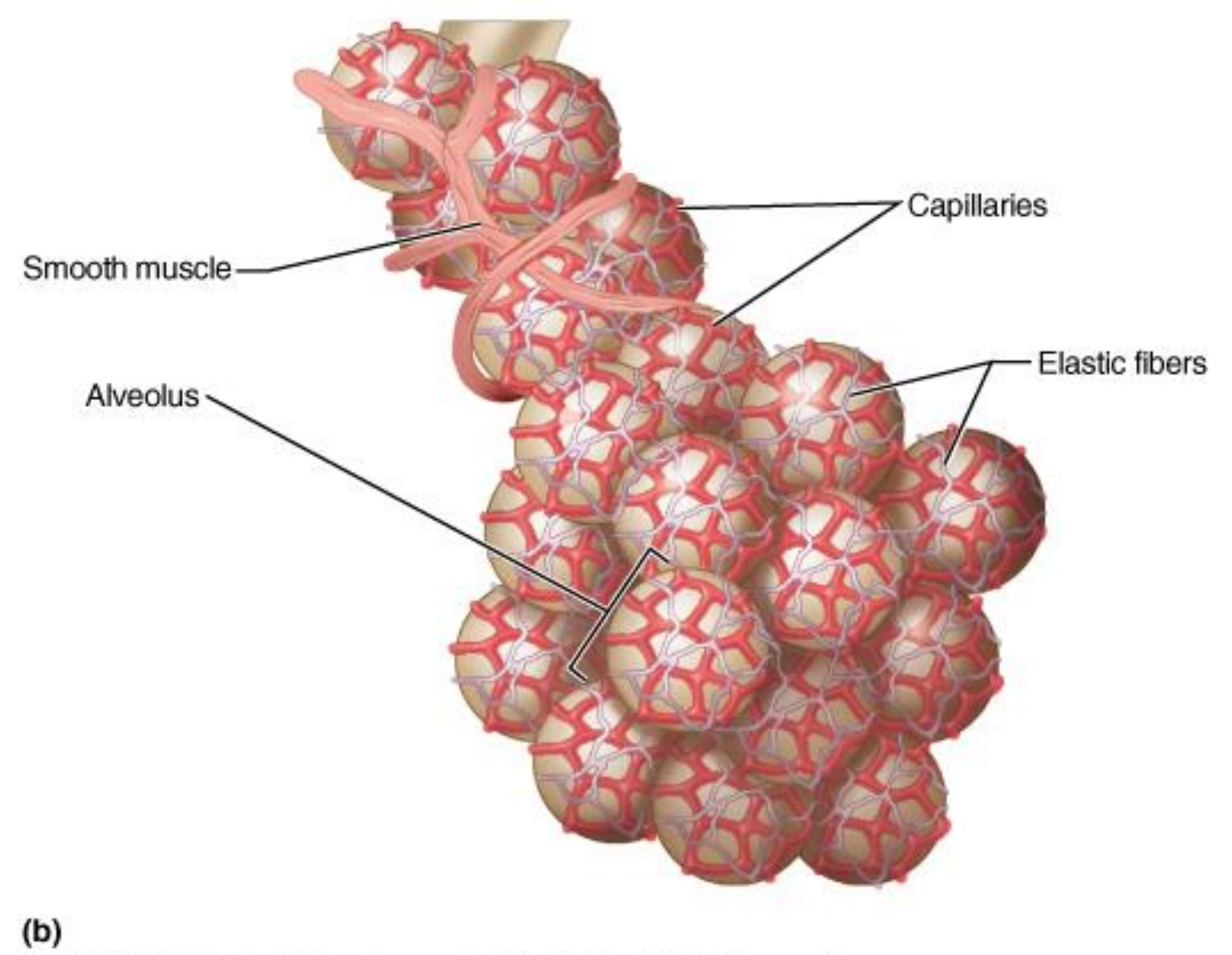
Vital capacity (4600 mL)
Total lung capacity (5800 mL)

- RR X (TV-DAV) = Alveolar Ventilation = 4200 mls/min
- If double RR: AV = 8400 mls/min
- If double TV: AV = 10200 mls/min

Alveolar Ventilation Efficiency

- Pulmonary vessels
  - Vessels can constrict in areas where oxygen flow is low
- Respiratory passageways
  - Airways can dilate where carbon dioxide levels are high

Matching Alveolar air flow with blood flow


Capillaries
Smooth muscle
Elastic fibers
Alveolus
(b)