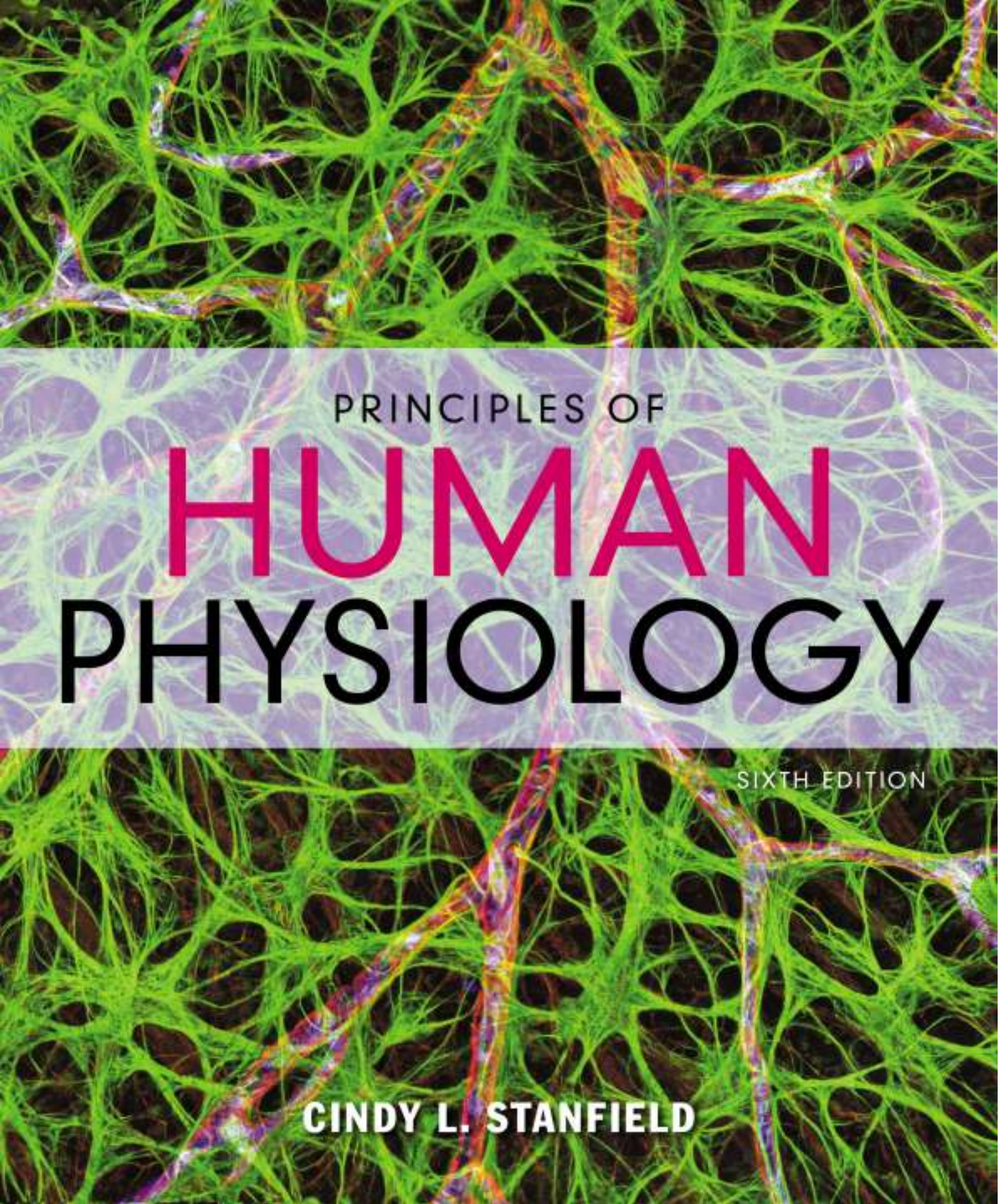


PowerPoint® Lecture Presentation

CHAPTER *16*

The Respiratory System: Pulmonary Ventilation

Chapter Outline

16.1 Overview of Respiratory Function

16.2 Anatomy of the Respiratory System

16.3 Forces for Pulmonary Ventilation

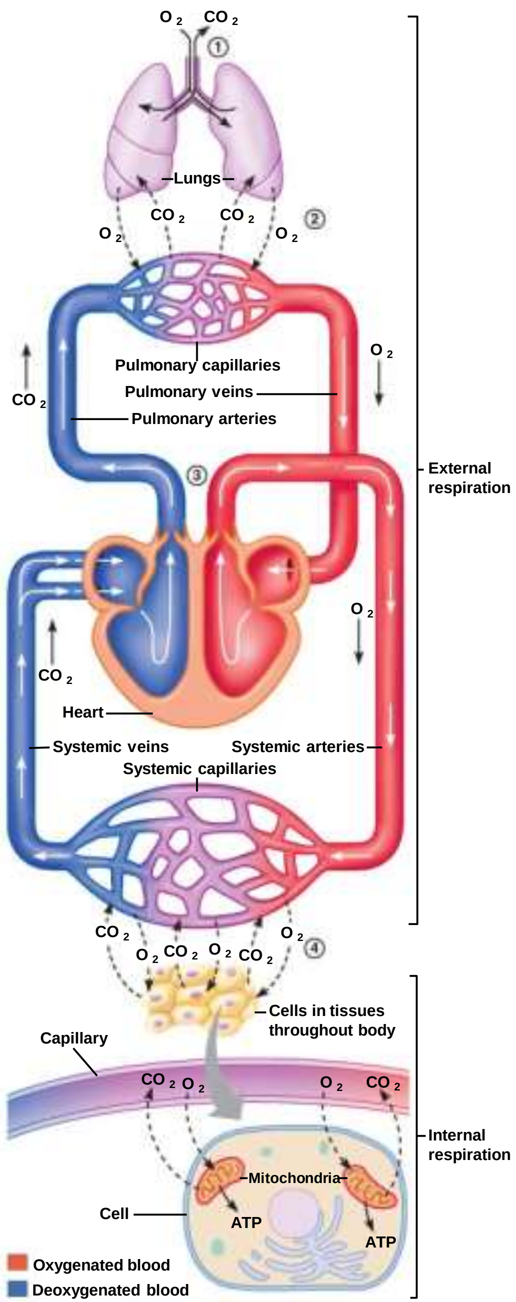
16.4 Factors Affecting Pulmonary Ventilation

16.5 Clinical Significance of Respiratory Volumes and Air Flows

16.1 Overview of Respiration

- Internal respiration
  - Oxidative phosphorylation
- External respiration
  - Pulmonary ventilation
  - Exchange between lungs and blood
  - Transportation in blood
  - Exchange between blood and body tissues

Figure 16.1 Relationship between external respiration and internal respiration.



16.2 Anatomy of the Respiratory System

- Upper airways
- Respiratory tract
- Structures of the thoracic cavity

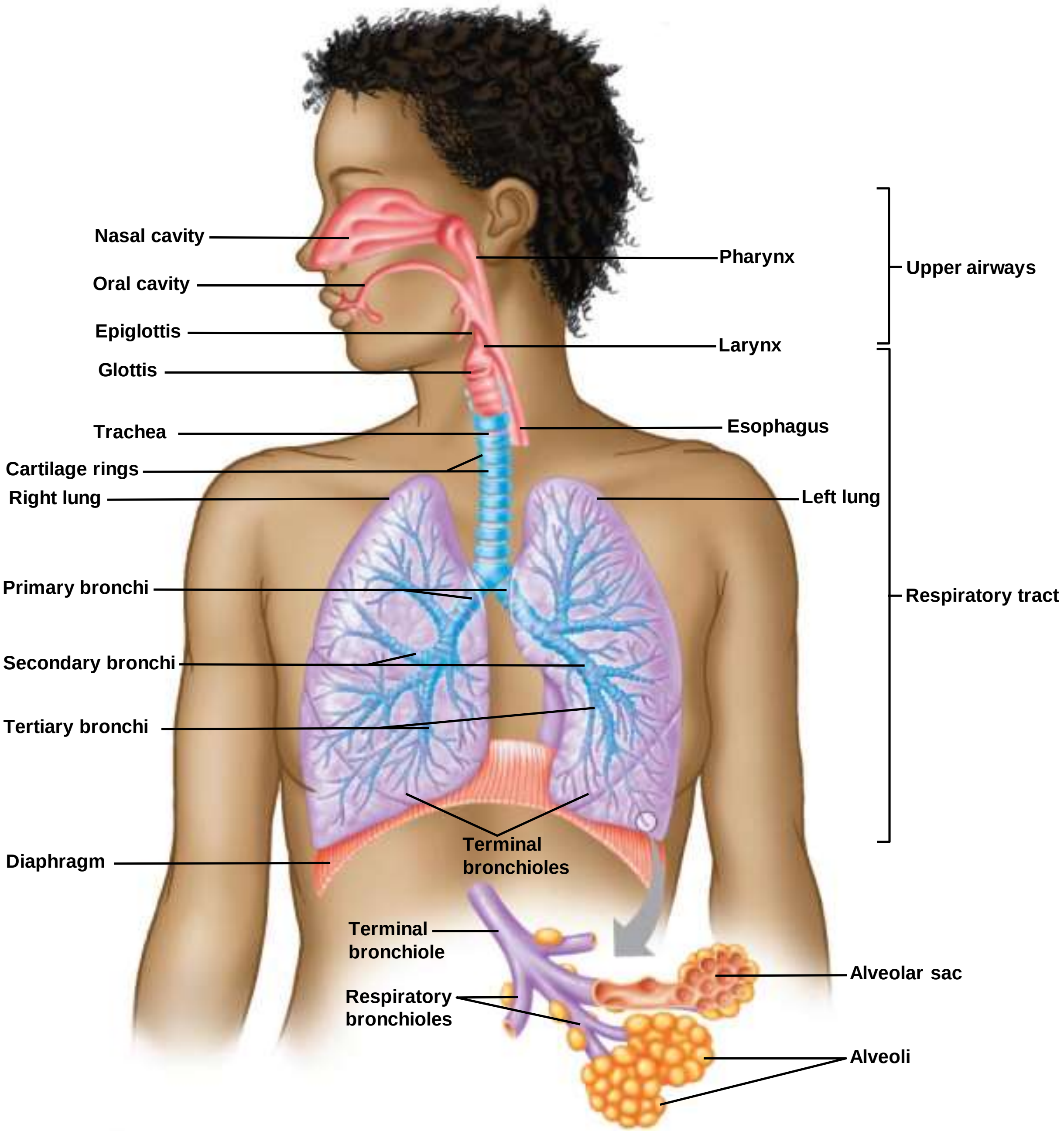
Upper Airways

- Air passages of the head and neck
  - Nasal cavities
  - Oral cavity
  - Pharynx

The Respiratory Tract

- Airways from pharynx to lungs
  - Larynx
  - Conducting zone
  - Respiratory zone

Figure 16.2 Anatomy of the upper airways and the respiratory tract.



The Respiratory Tract

- Conducting zone
  - Larynx
    - Glottis
    - Epiglottis
  - Trachea
    - 2.5 cm diameter
    - 10 cm long
    - 15–20 C-shaped bands of cartilage

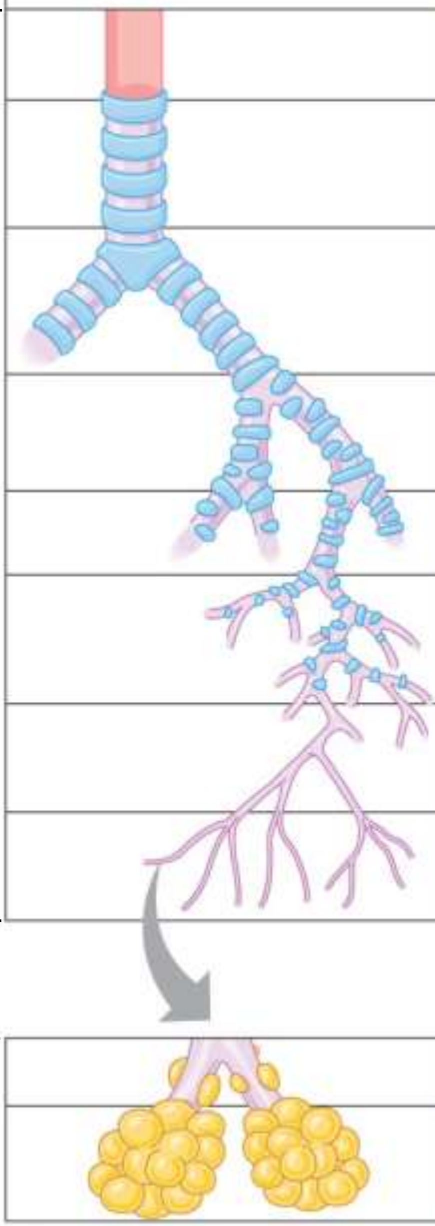
The Respiratory Tract

- Conducting zone
  - Bronchi
  - Secondary bronchi
    - Three on right side to three lobes of right lung
    - Two on left side to two lobes of left lung
  - Tertiary bronchi
    - 20–23 orders of branching
  - Bronchioles
    - Less than 1 mm in diameter
  - Terminal bronchioles

The Respiratory Tract

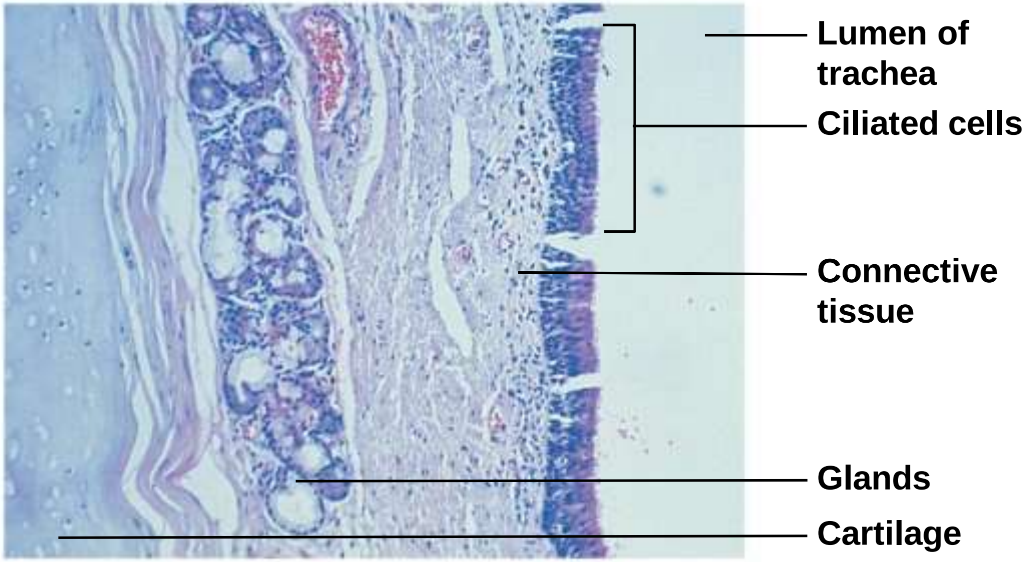
- Functions of the conducting zone
  - Air passageway: 150 mL in volume (dead space)
  - Increases air temperature to body temperature
  - Humidifies air
- Epithelium of the conducting zone
  - Goblet cells
    - Secrete mucus
  - Ciliated cells
    - Cilia move particles toward mouth
  - Mucus escalator

Figure 16.3 Anatomical features of the conducting and respiratory zones of the respiratory tract.



Zone	Structure	Inner diameter (mm)	Cilia	Goblet cells	Cartilage	Smooth muscle
Conducting zone	Larynx	35–45	+++	+++	+++	0
Conducting zone	Trachea	20–25	+++	+++	+++ (C-shaped)	+
Conducting zone	Primary bronchi	12–16	+++	++	+++ (rings)	++
Conducting zone	Secondary bronchi	10–12	+++	++	+++ (plates)	++
Conducting zone	Tertiary bronchi	8–10	+++	++	++ (plates)	++
Conducting zone	Smaller bronchi	1–8	+++	+	+ (plates)	++
Conducting zone	Bronchioles	0.5–1	++	+	0	+++
Conducting zone	Terminal bronchioles	<0.5	++	0	0	+++
Respiratory zone	Respiratory bronchioles	<0.5	+	0	0	+
Respiratory zone	Alveolar sacs	0.3	0	0	0	0

Figure 16.4 Respiratory tract epithelia.



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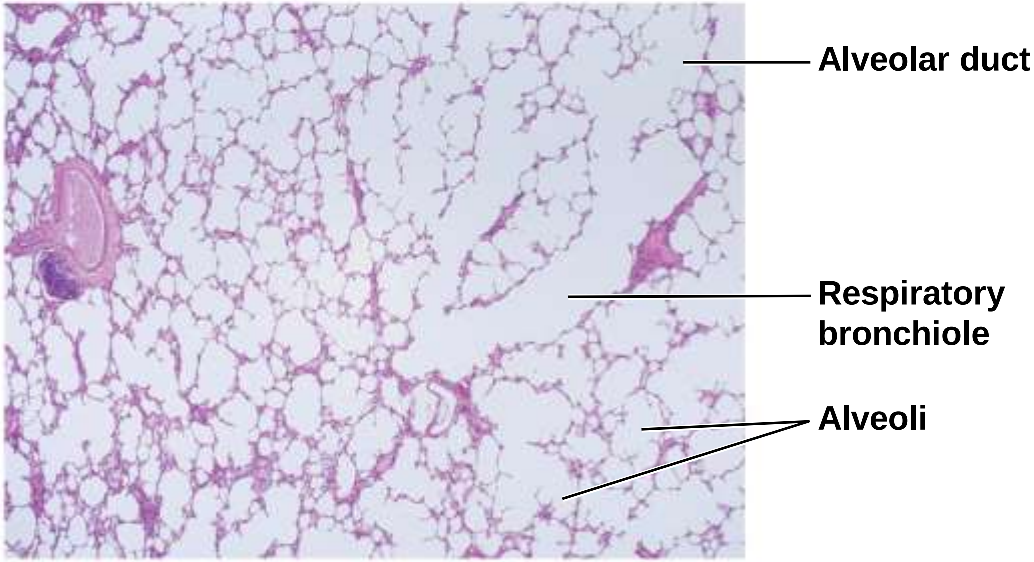


(b)

The Respiratory Tract

- Function of the respiratory zone
  - Exchange of gases between air and blood
  - Mechanism of action: diffusion
- Structures of the respiratory zone
  - Respiratory bronchioles
  - Alveolar ducts
  - Alveoli
  - Alveolar sacs

The Respiratory Tract

- Epithelium of the respiratory zone
  - Respiratory membrane
    - Epithelial cell layer of alveoli
    - Endothelial cell layer of capillaries

The Respiratory Tract

- Alveoli
  - Site of gas exchange
  - 300 million alveoli in the lungs (size of tennis court)
  - Rich blood supply: capillaries form sheet over alveoli
  - Alveolar pores
  - Type I alveolar cells: make up wall of alveoli
    - Single layer of epithelial cells
  - Type II alveolar cells: secrete surfactant
  - Alveolar macrophages

The Respiratory Tract

- Respiratory membrane
  - Barrier for diffusion
    - Type I cells + basement membrane
    - Capillary endothelial cells + basement membrane
  - 0.2 μm thick

Figure 16.5a Anatomy of the respiratory zone.

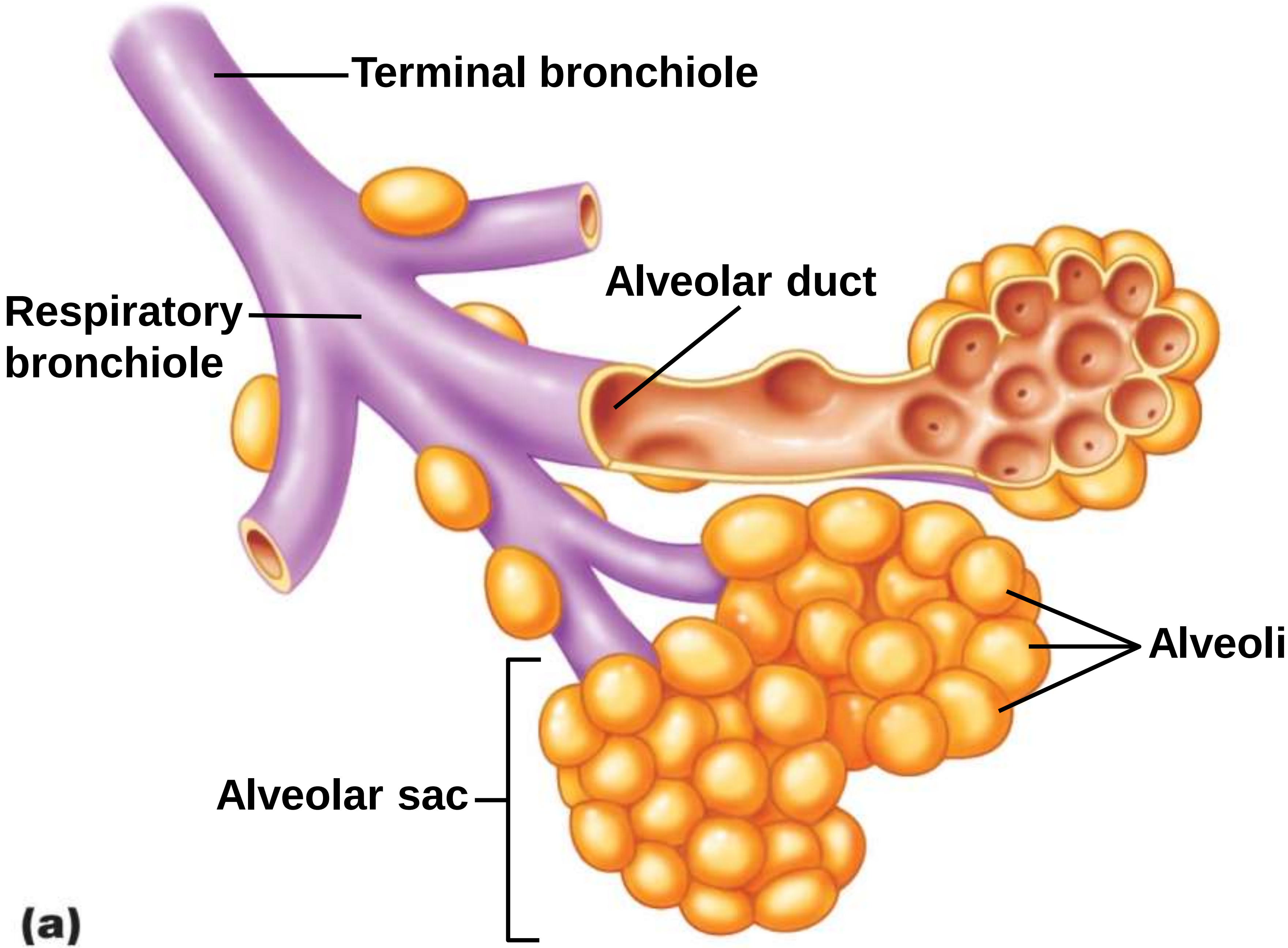


Figure 16.5b Anatomy of the respiratory zone.

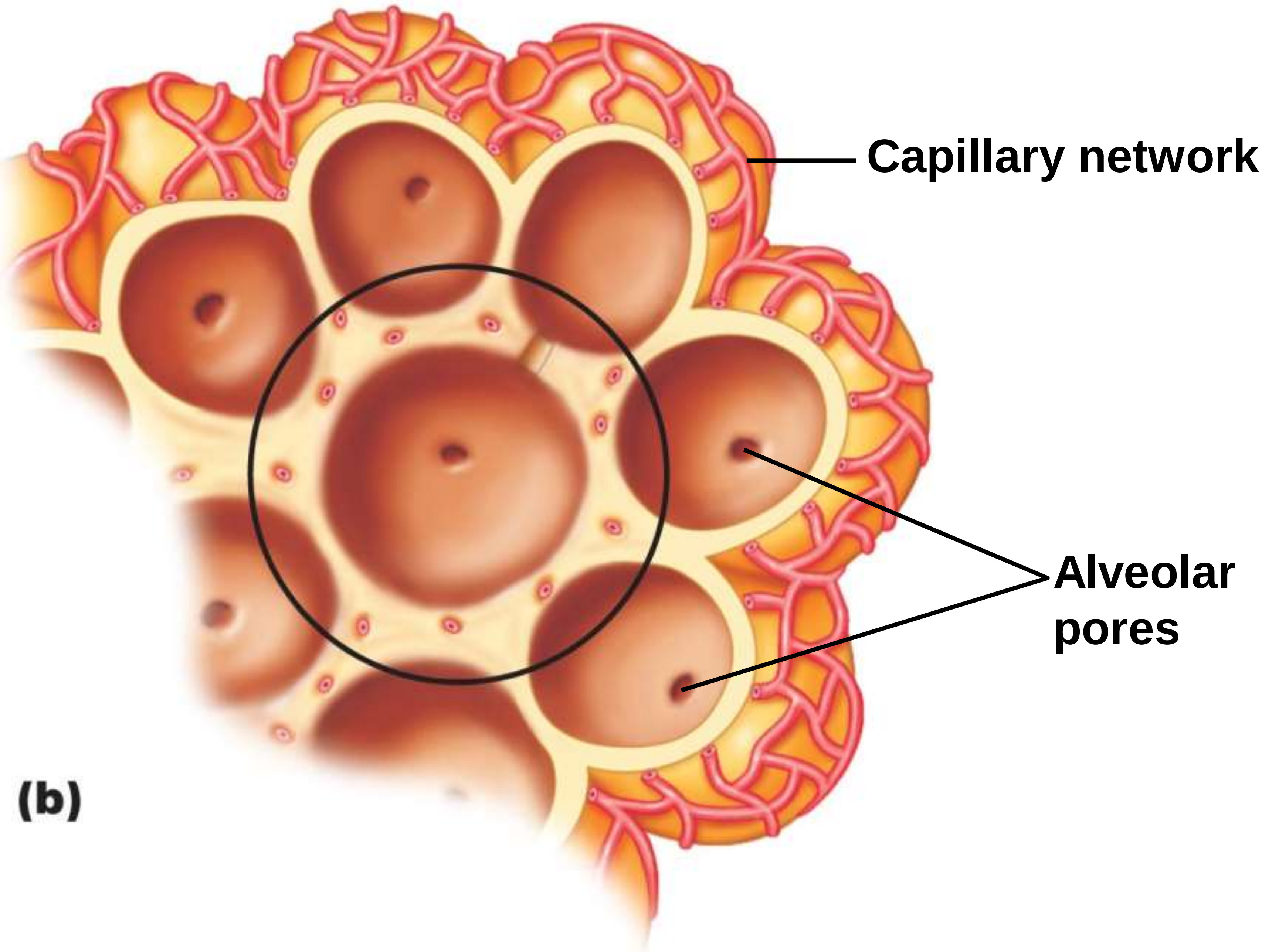


Figure 16.5c Anatomy of the respiratory zone.

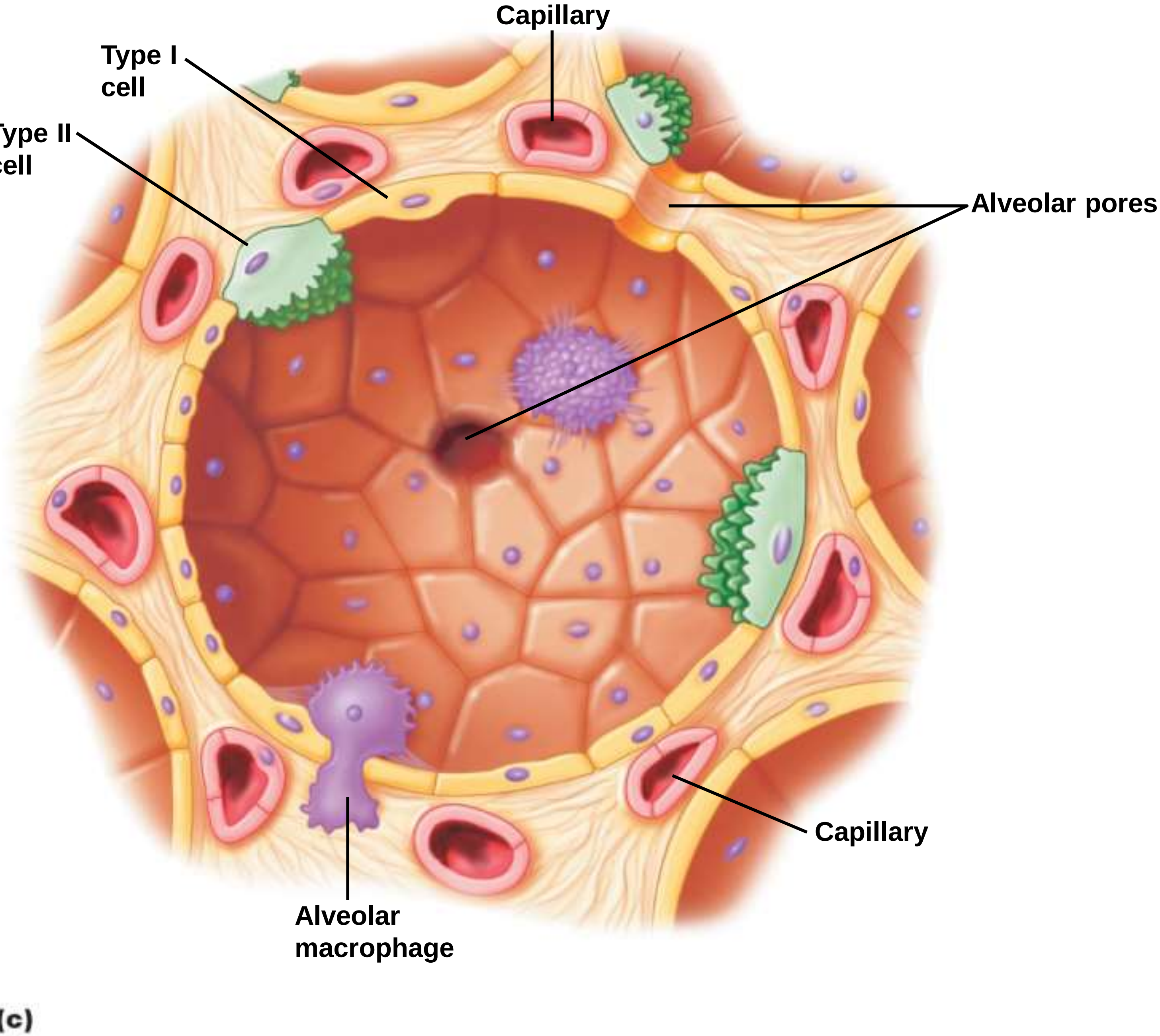


Figure 16.5d Anatomy of the respiratory zone.

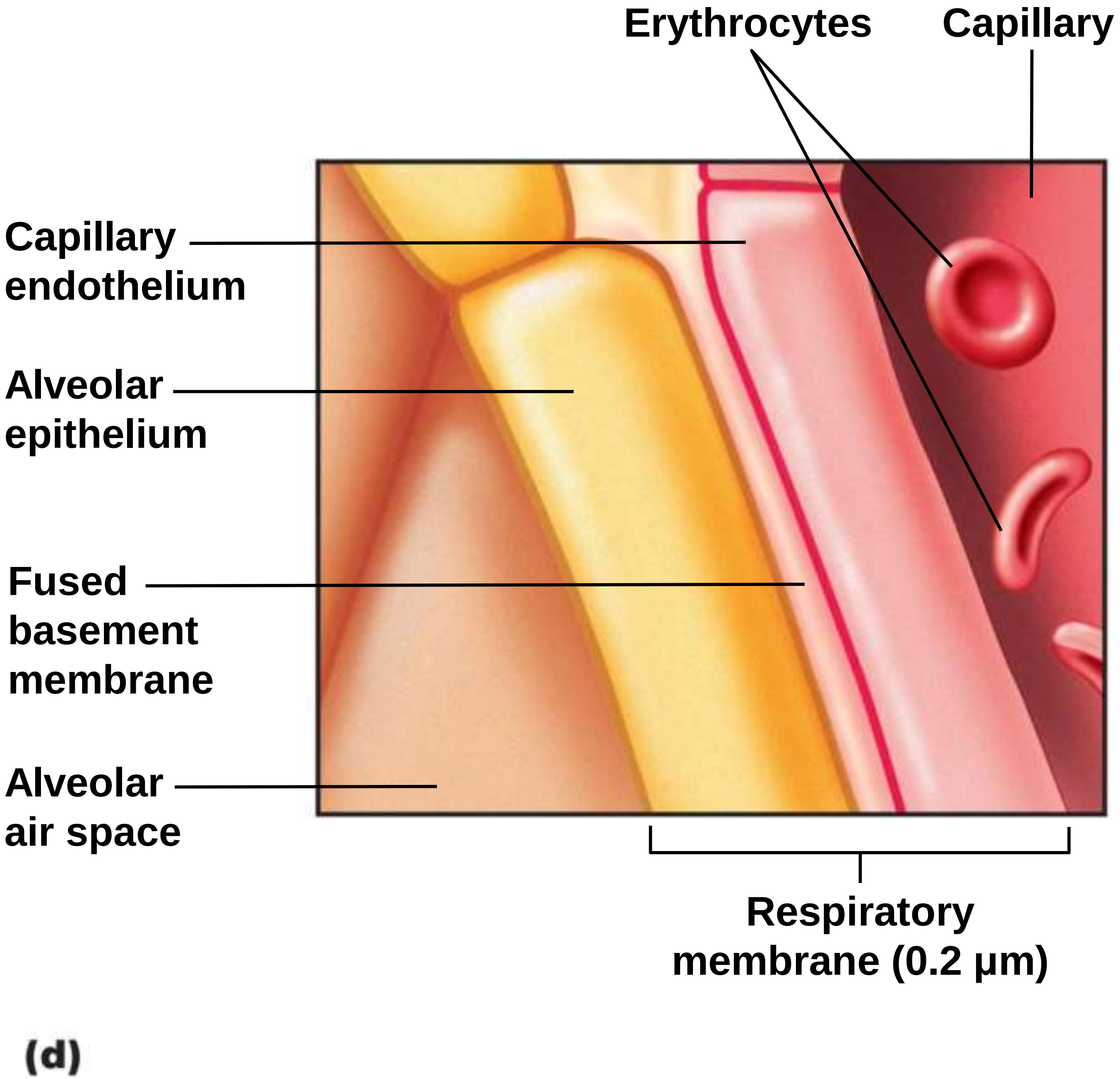


Figure 16.5e Anatomy of the respiratory zone.

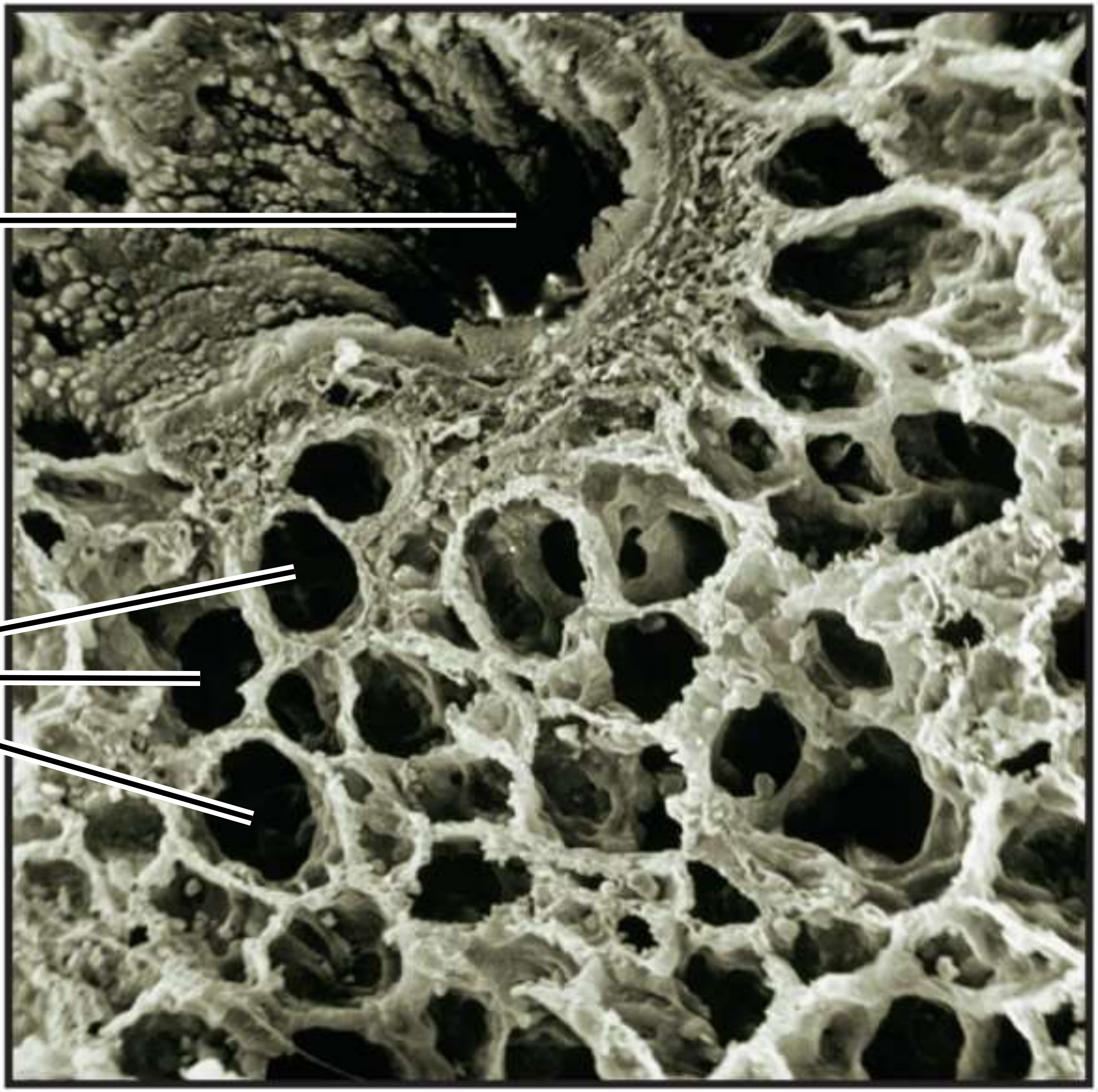
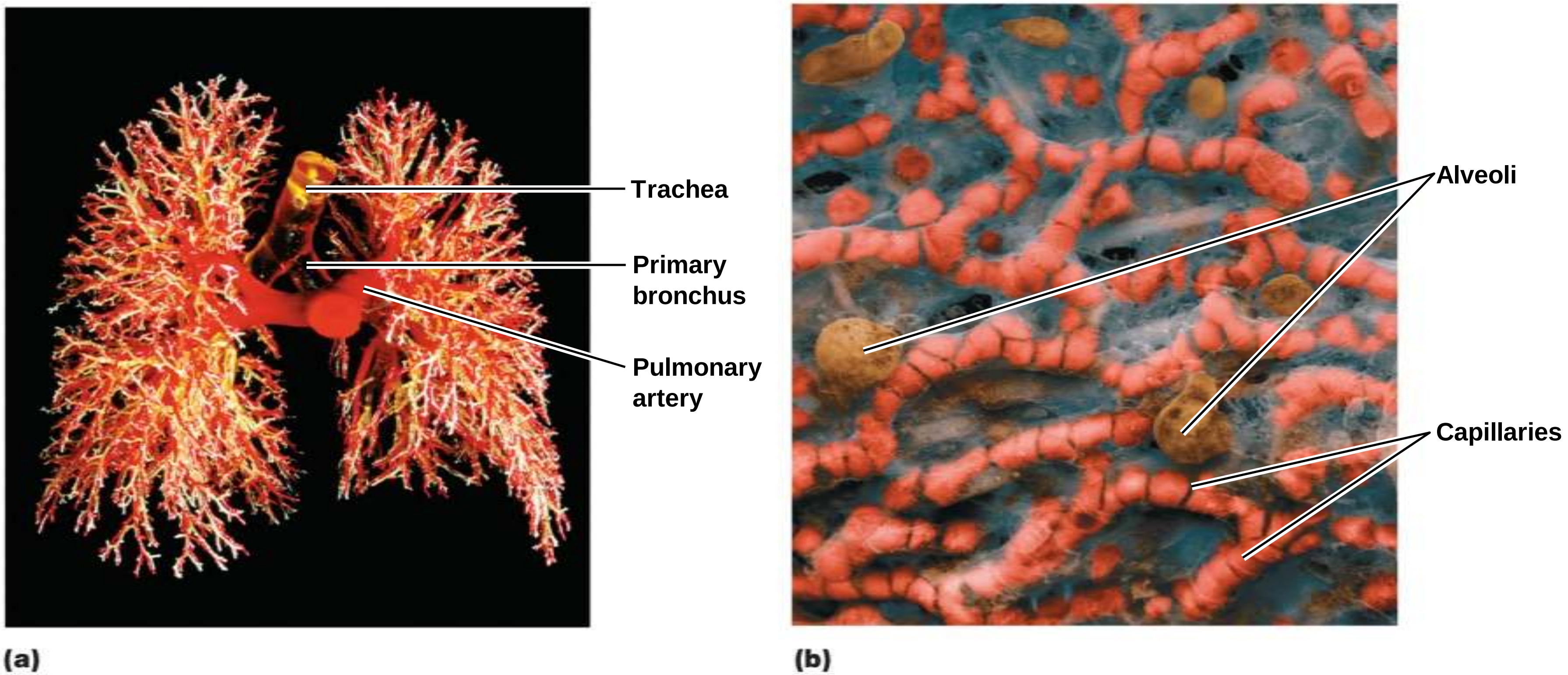


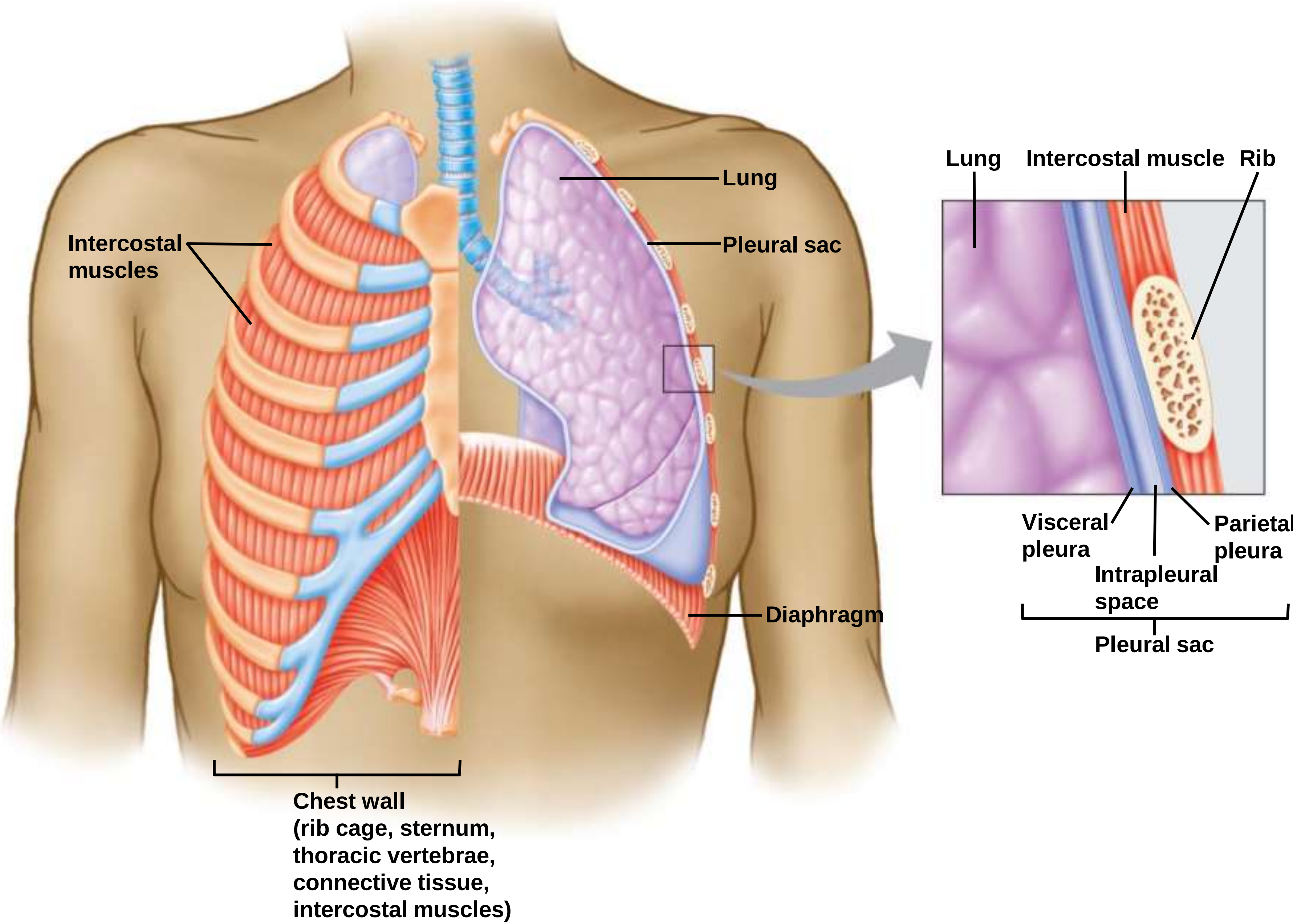
Figure 16.6 Blood supply to the lungs.



Structures of the Thoracic Cavity

- Chest wall: airtight, protects lungs
  - Rib cage
  - Sternum
  - Thoracic vertebrae
  - Muscles: internal and external intercostals, diaphragm
- Pleura: membrane lining of lungs and chest wall
  - Pleural sac around each lung
  - Intrapleural space is filled with intrapleural fluid
    - Volume = 15 mL

Figure 16.7 Chest wall and pleural sac.



16.3 Forces for Pulmonary Ventilation

- Air moves in and out of lungs by bulk flow
- Pressure gradient drives flow
  - Air moves from high to low pressure
  - Inspiration: pressure in lungs less than atmospheric pressure
  - Expiration: pressure in lungs greater than atmospheric pressure

Pulmonary Pressures

- Atmospheric pressure = P_{atm}
- Intra-alveolar pressure = P_{alv}
  - Pressure of air in alveoli
- Intrapleural pressure = P_{ip}
  - Pressure inside pleural sac
- Transpulmonary pressure = $P_{alv} - P_{ip}$
  - Distending pressure across the lung wall

Pulmonary Pressures

- Atmospheric pressure
  - 760 mm Hg at sea level
  - Decreases as altitude increases
  - Increases under water
  - Other lung pressures are given relative to atmospheric pressure (set P_{atm} = 0 mm Hg)

Pulmonary Pressures

- Intra-alveolar pressure
  - Pressure of air in alveoli
  - Given relative to atmospheric pressure
  - Varies with phase of respiration
  - During inspiration = negative (less than atmospheric)
  - During expiration = positive (more than atmospheric)
  - Difference between P_{alv} and P_{atm} drives ventilation

Pulmonary Pressures

- Intrapleural pressure
  - Pressure inside pleural sac
    - Always negative under normal conditions
    - Always less than P_{alv}
  - Varies with phase of respiration
    - At rest, –4 mm Hg
  - Negative due to elasticity in lungs and chest wall
    - Lungs recoil inward as chest wall recoils outward
    - Opposing forces pull on intrapleural space
    - Surface tension of intrapleural fluid prevents wall and lungs from pulling apart

Pulmonary Pressures

- Transpulmonary pressure
  - Transpulmonary pressure = $P_{alv} - P_{ip}$
  - Distending pressure across the lung wall
  - Increase in transpulmonary pressure
    - Increases distending pressure across lungs
    - Causes lungs (alveoli) to expand, increasing volume

Figure 16.8 Pleural pressures at rest.

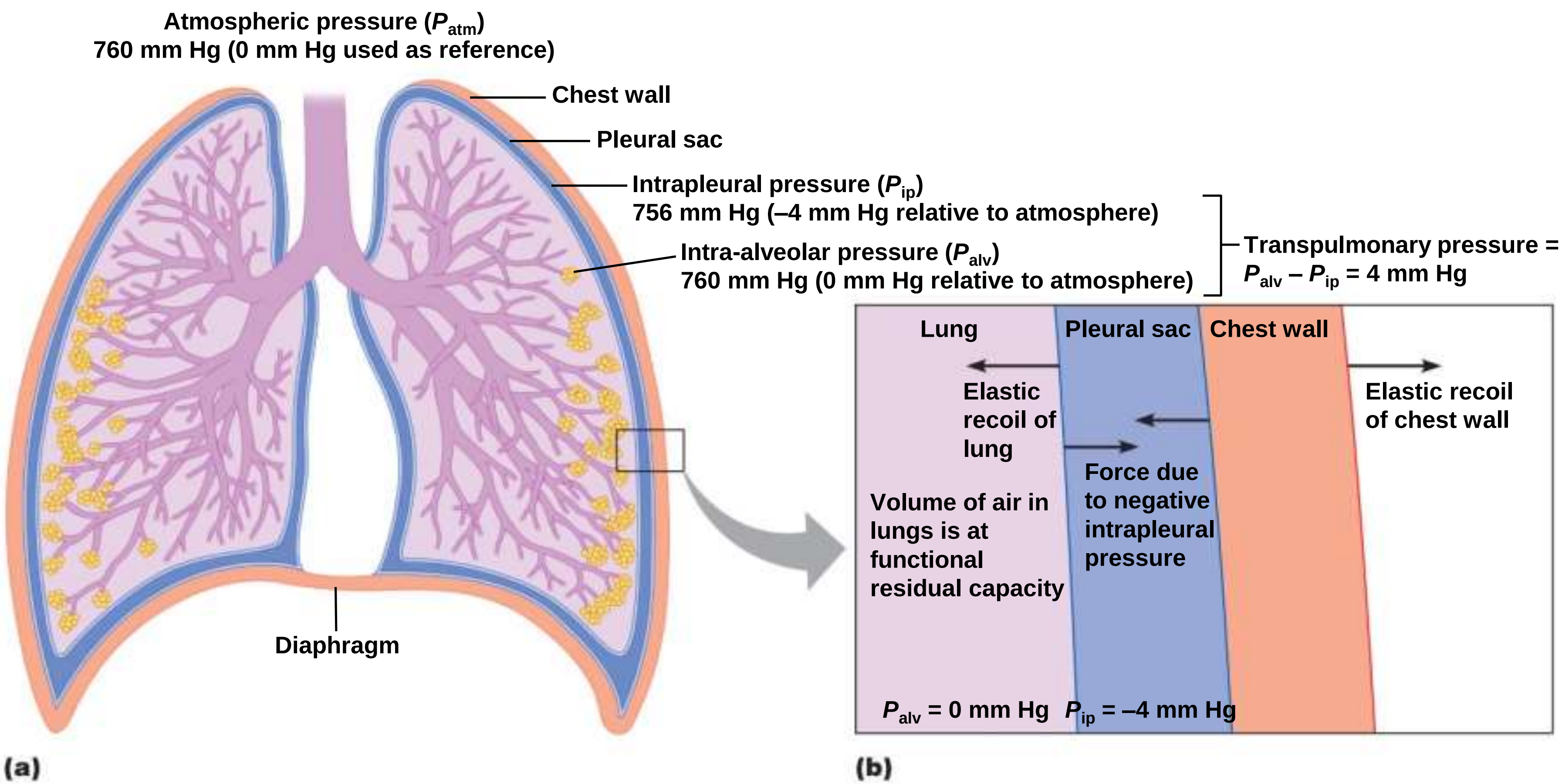
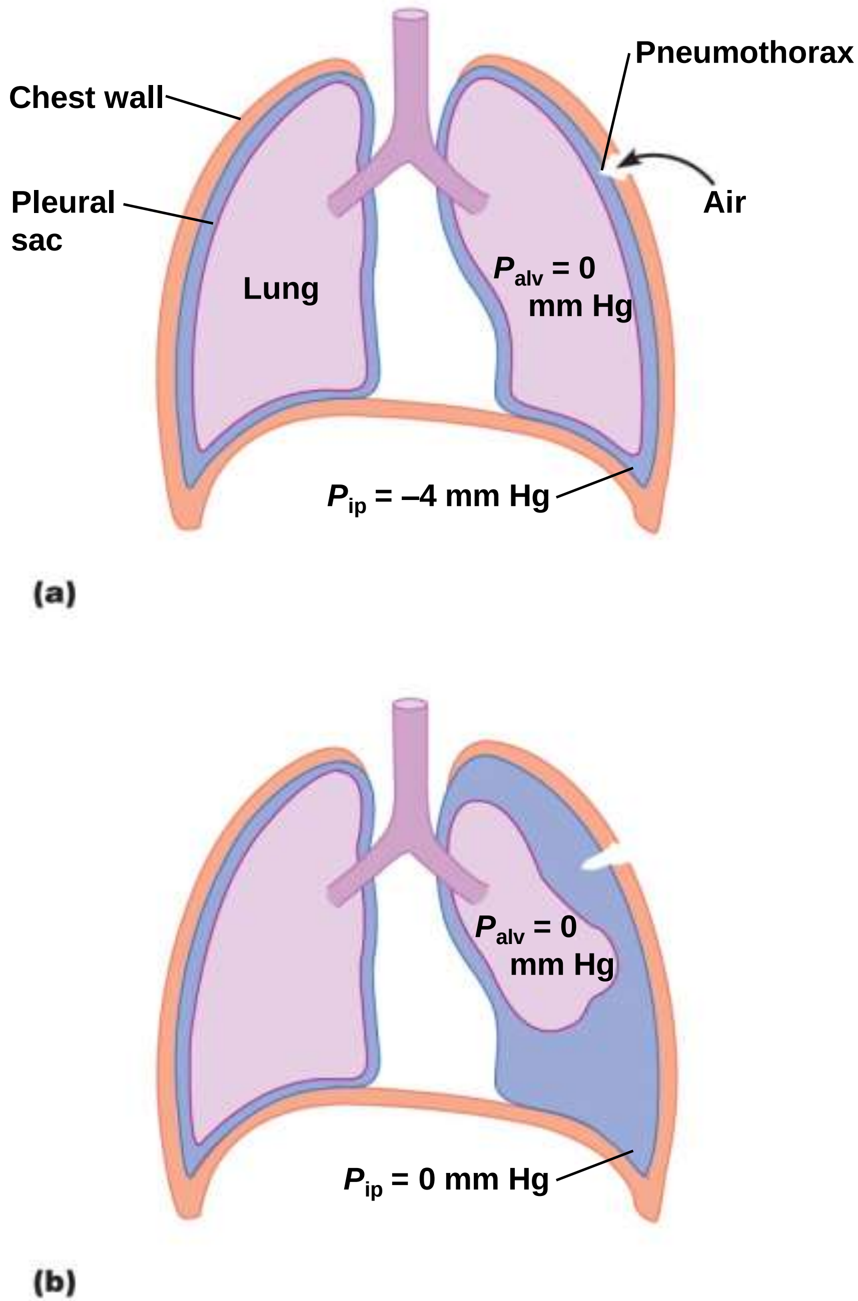


Figure 16.9 Pneumothorax.



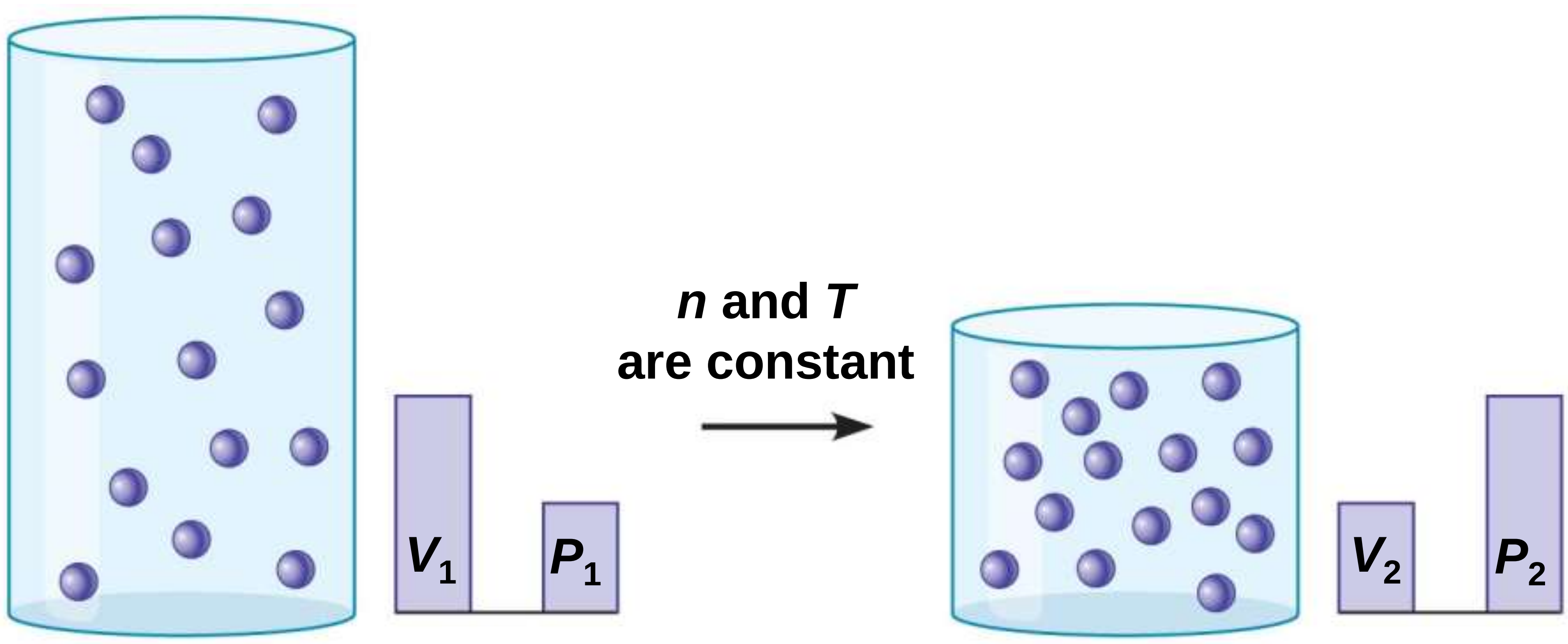
Mechanics of Breathing

- Movement of air in and out of lungs occurs due to pressure gradients
- Mechanics of breathing describes mechanisms for creating pressure gradients

Mechanics of Breathing

- Forces for air flow
  - Force for flow = pressure gradient
  - Atmospheric pressure remains constant (during breathing cycle)
  - Thus alveolar pressure changes affect gradients
  - *Boyle's law*: pressure is inversely related to volume
  - Can change alveolar pressure by changing its volume
  - Resistance to air flow (*R*) is related to airway radius and mucus

$$\text{Flow} = \frac{P_{\text{atm}} - P_{\text{alv}}}{R}$$



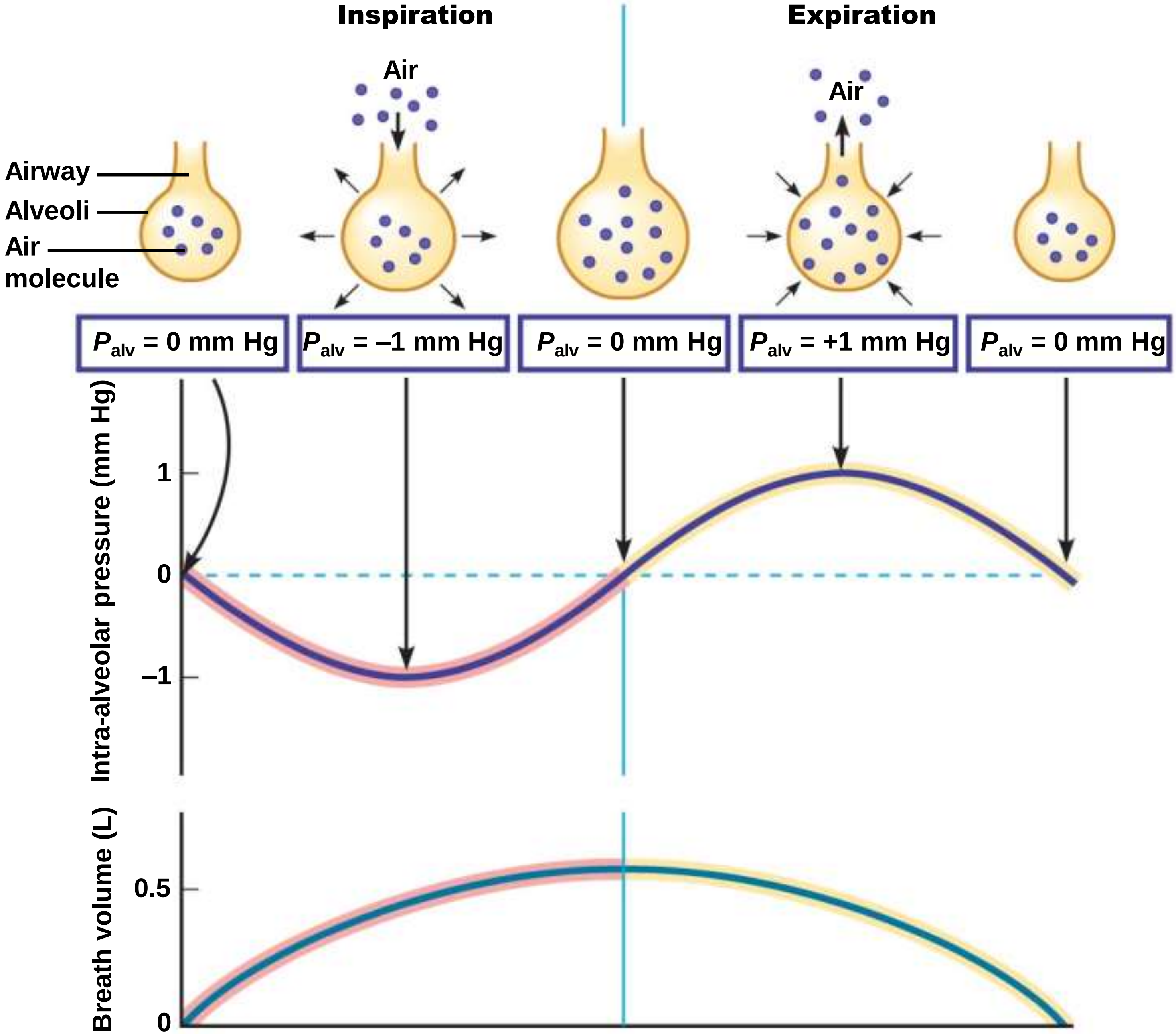
Container 1: $V_1 = 2 \quad P_1 = 1$

Container 2: $V_2 = 1 \quad P_2 = 2$

Mechanics of Breathing

- Determinants of intra-alveolar pressure
  - Factors determining intra-alveolar pressure
    - Quantity of air in alveoli
    - Volume of alveoli
  - Lungs expand—alveolar volume increases
    - P_{alv} decreases
    - Pressure gradient drives air into lungs
  - Lungs recoil—alveolar volume decreases
    - P_{alv} increases
    - Pressure gradient drives air out of lungs

Figure 16.10 Changes in alveolar pressure and breath volume during inspiration and expiration.



Mechanics of Breathing

- Inspiratory muscles increase volume of thoracic cavity
  - Diaphragm
  - External intercostals
- Expiratory muscles decrease volume of thoracic cavity
  - Internal intercostals
  - Abdominal muscles

Figure 16.11a Respiratory muscles.

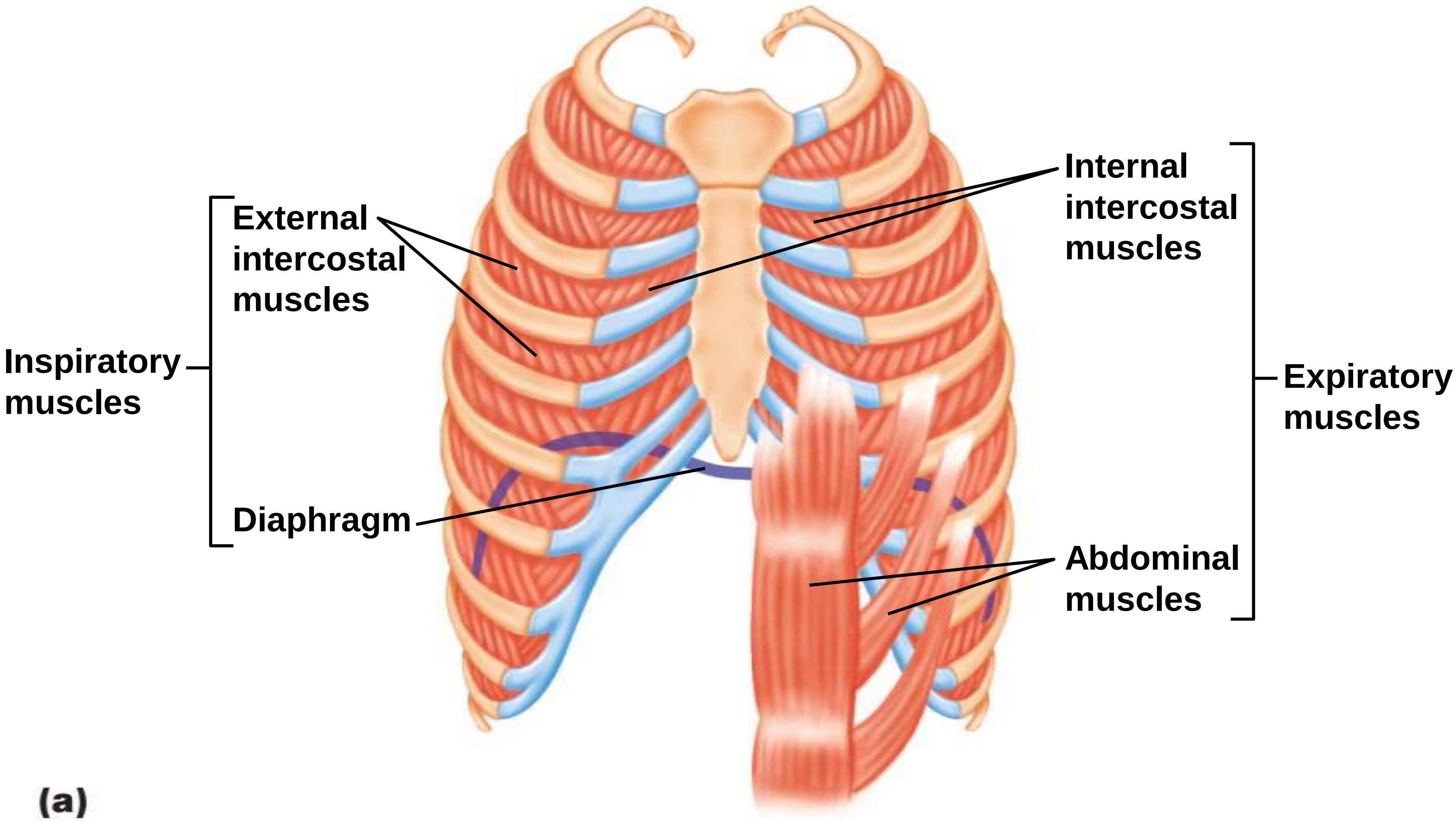
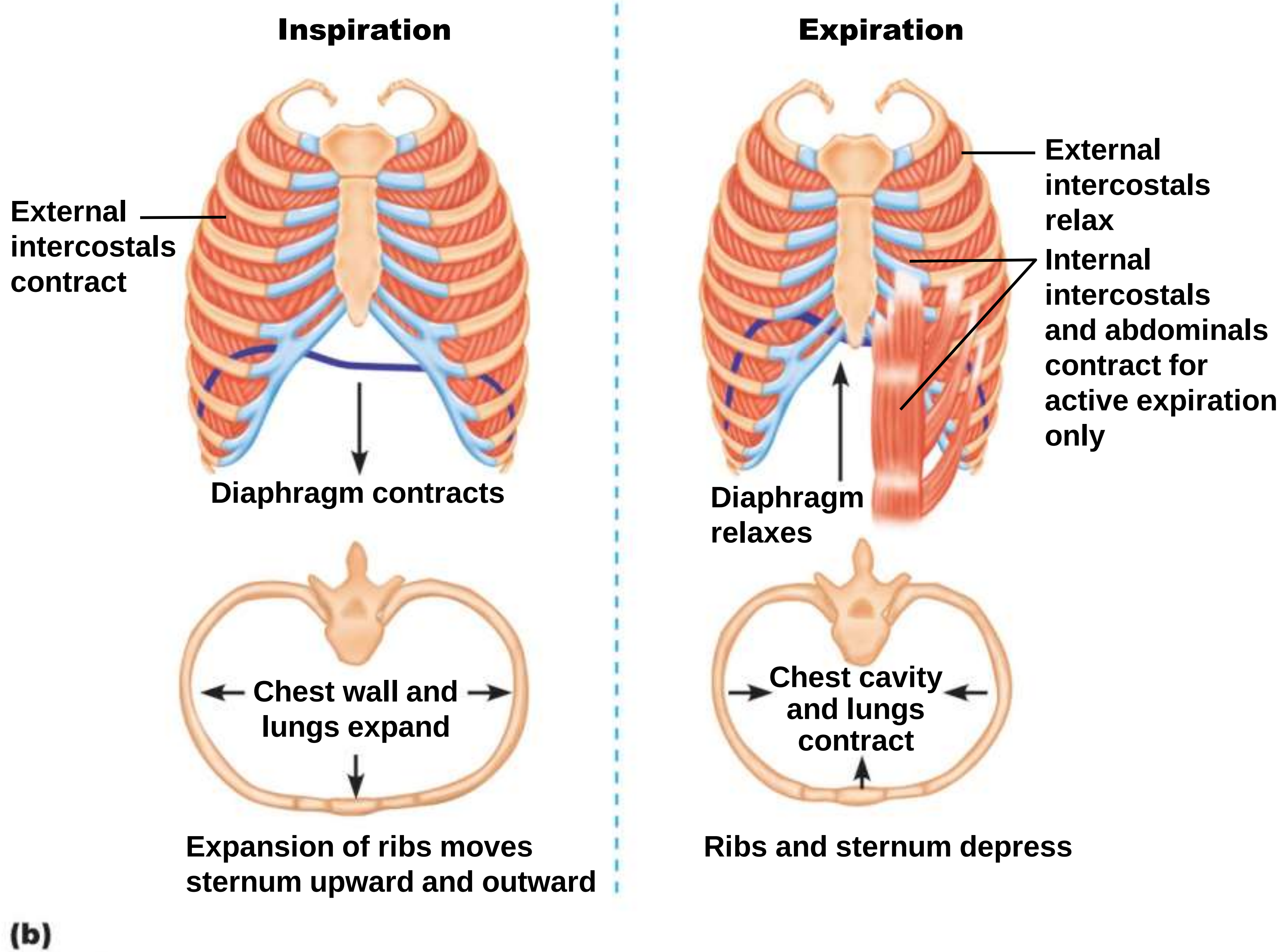


Figure 16.11b Respiratory muscles.



Mechanics of Breathing

- Inspiration
  - Neural stimulation of inspiratory muscles
  - Diaphragm contraction causes it to flatten and move downward
  - Contraction of external intercostals makes ribs pivot upward and outward, expanding the chest wall
  - Collectively, thoracic cavity volume increases
  - Outward pull on pleura decreases intrapleural pressure, which results in an increase in transpulmonary pressure
  - Alveoli expand, decreasing alveolar pressure
  - Air flows into alveoli by bulk flow

Figure 16.12 Events in the process of inspiration.

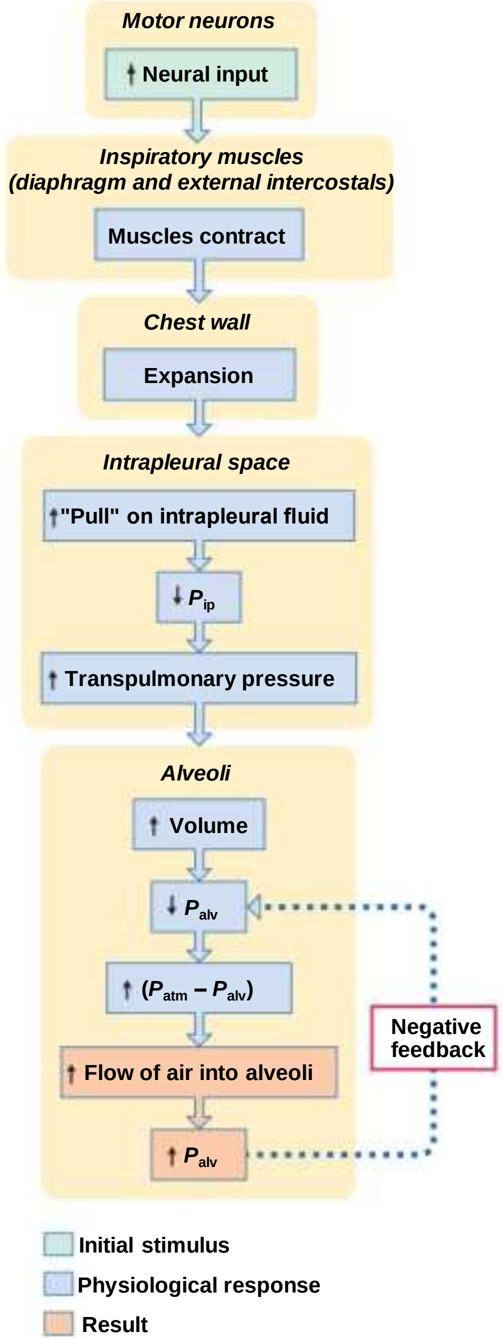


Figure 16.12 Events in the process of inspiration.

Motor neurons

↑ Neural input

Initial stimulus

Physiological response

Result

Figure 16.12 Events in the process of inspiration.

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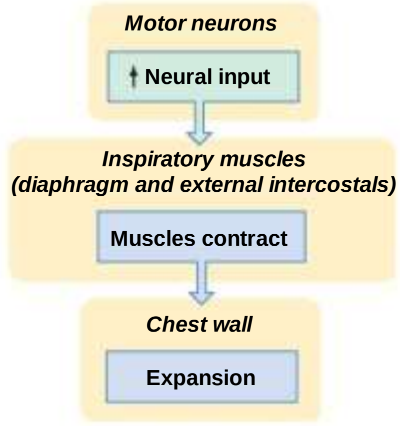
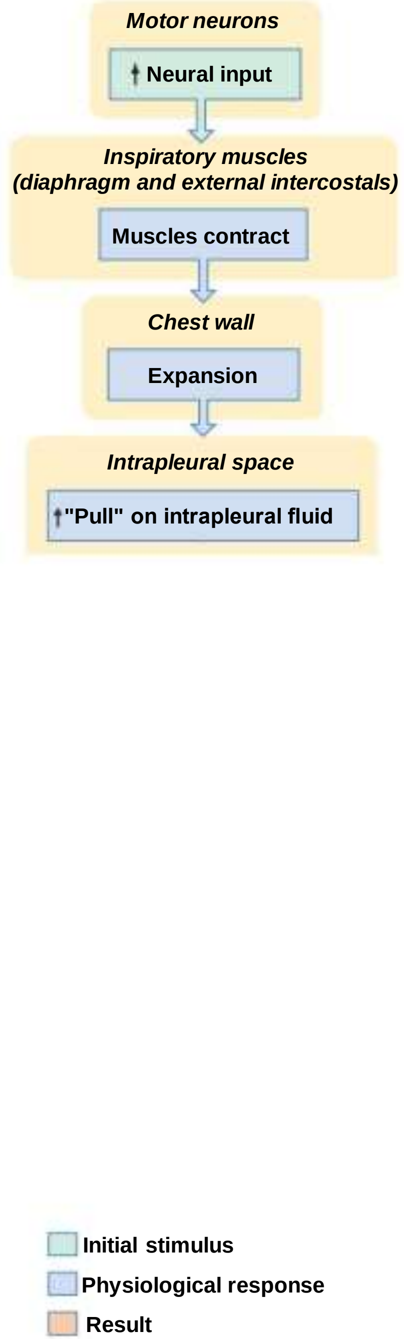


Initial stimulus
Physiological response
Result

Figure 16.12 Events in the process of inspiration.



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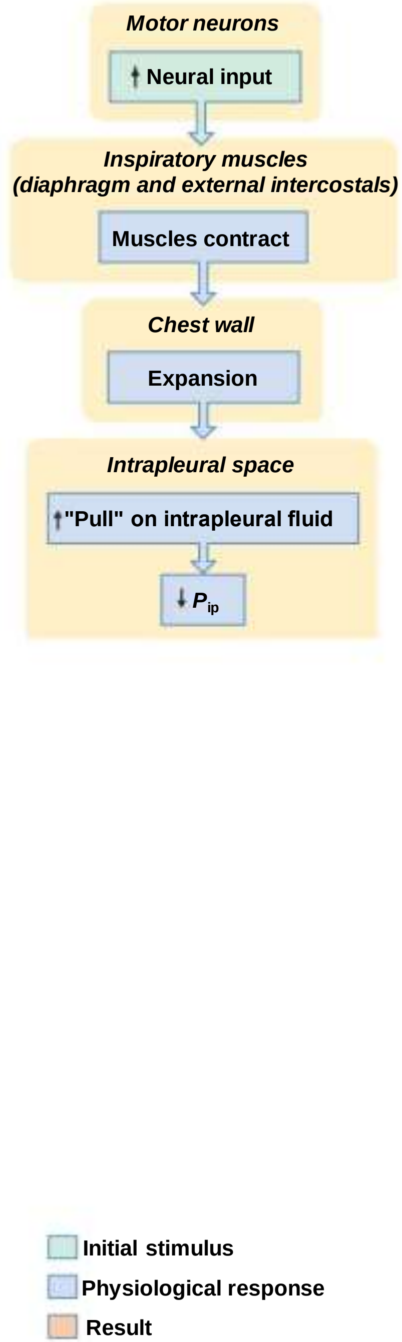

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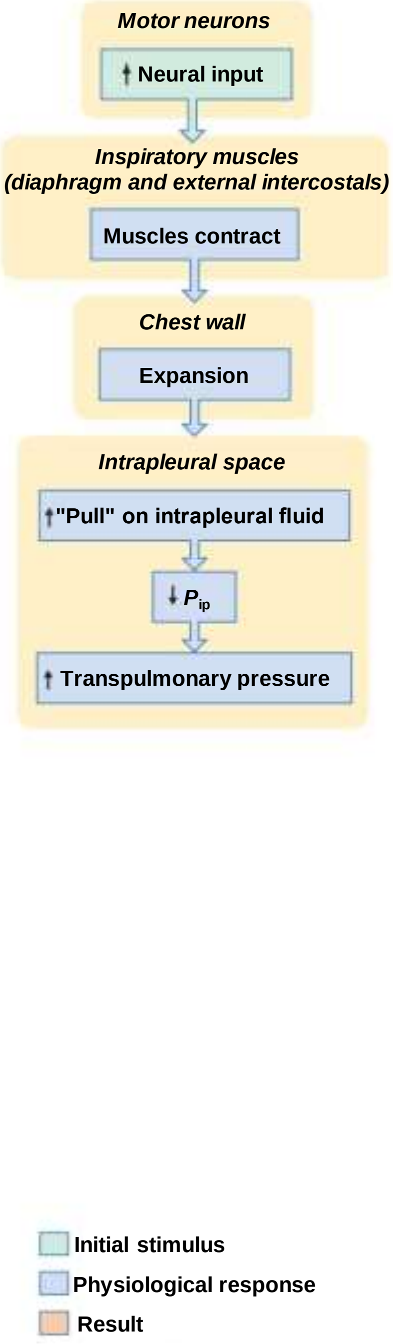


Figure 16.12 Events in the process of inspiration.

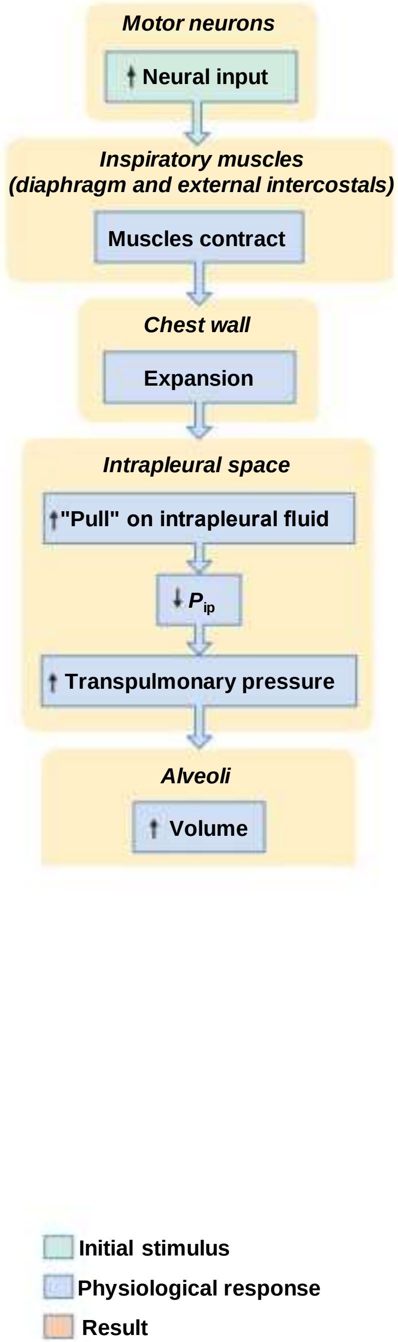


Figure 16.12 Events in the process of inspiration.

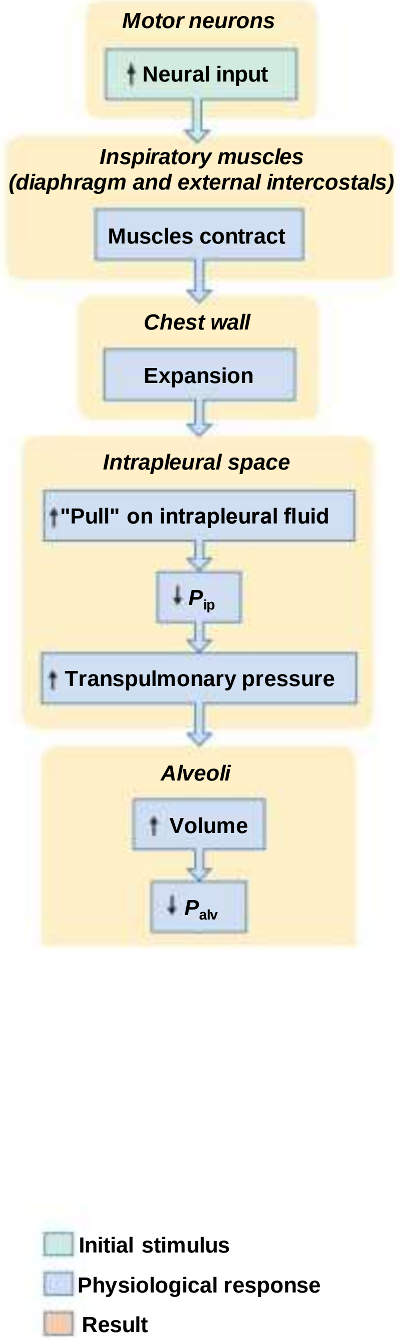


Figure 16.12 Events in the process of inspiration.

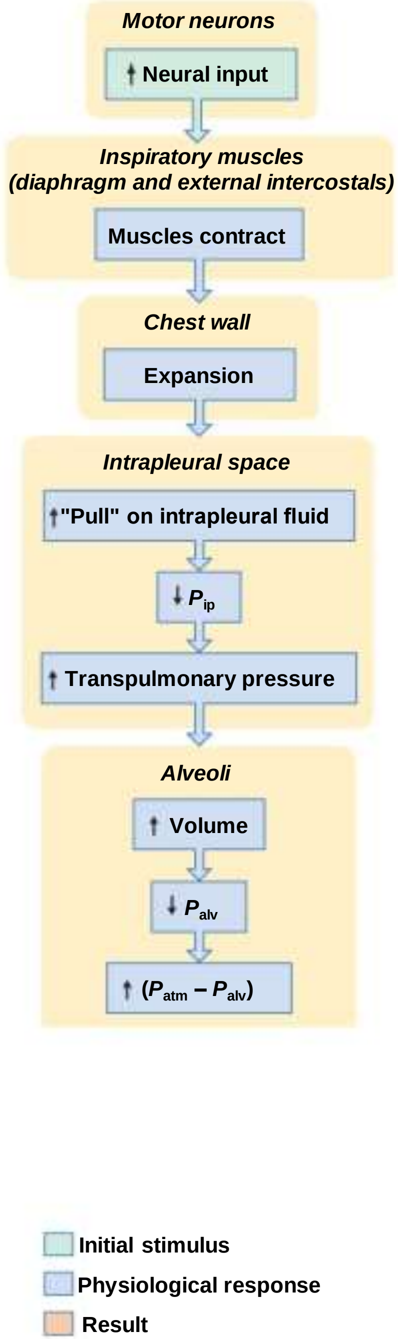


Figure 16.12 Events in the process of inspiration.

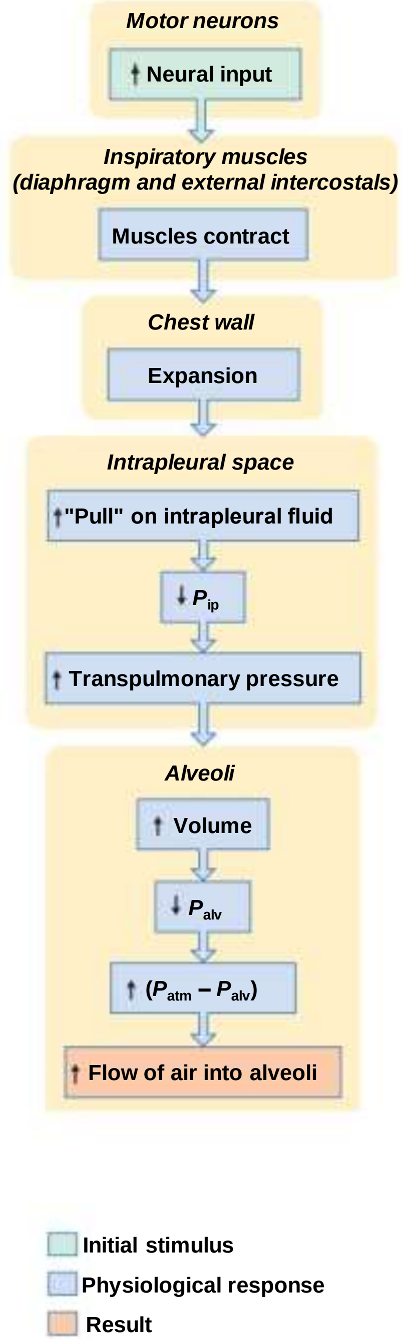


Figure 16.12 Events in the process of inspiration.

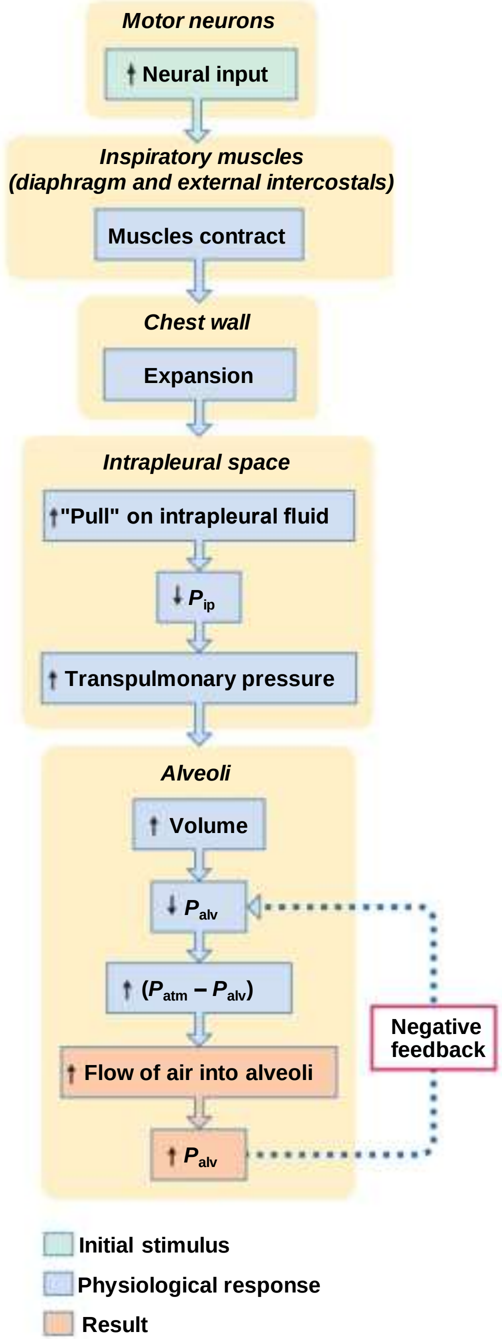
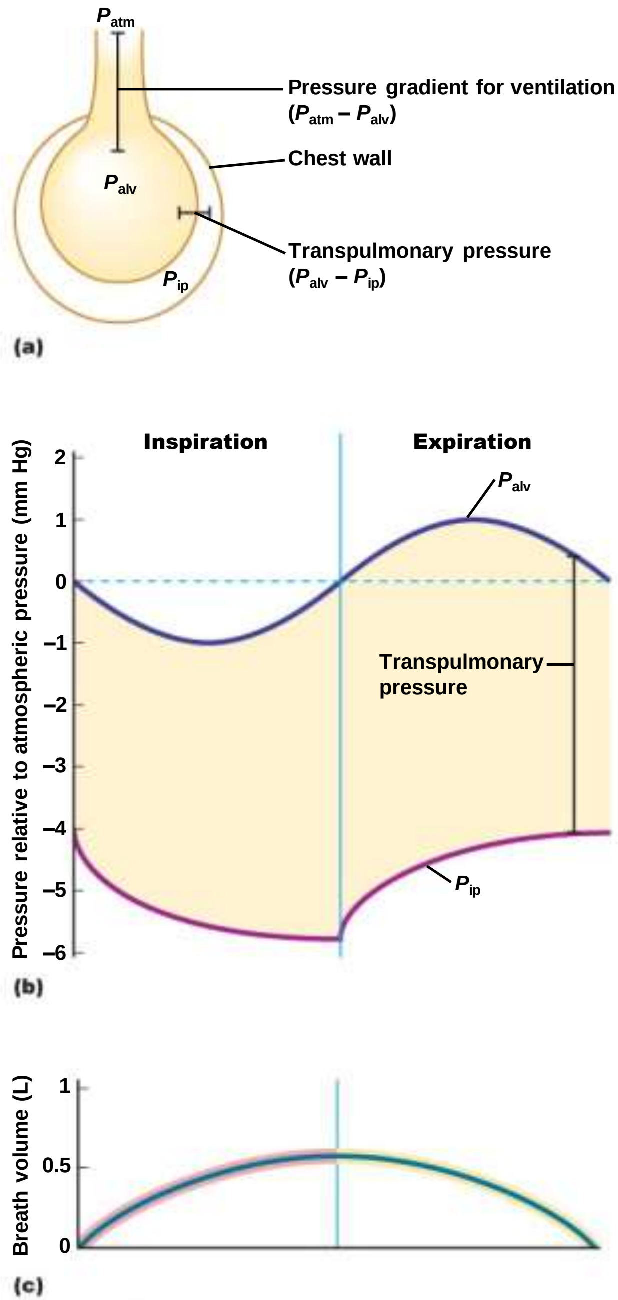


Figure 16.13 Volume and pressure changes during inspiration and expiration.



Mechanics of Breathing

- Expiration
  - Normally a passive process
    - When inspiratory muscles stop contracting, recoil of the lungs and chest wall to their original positions decreases the volume of the thoracic cavity
  - Active expiration requires expiratory muscles
    - Contraction of expiratory muscles creates a greater and faster decrease in the volume of the thoracic cavity

16.4 Factors Affecting Pulmonary Ventilation

- Lung compliance
- Airway resistance

Lung Compliance

- Ease with which lungs can be stretched

$$\text{Lung compliance} = \frac{\Delta V}{\Delta(P_{\text{alv}} - P_{\text{ip}})}$$

- Larger lung compliance
  - Easier to inspire
  - Smaller change in transpulmonary pressure needed to bring in a given volume of air

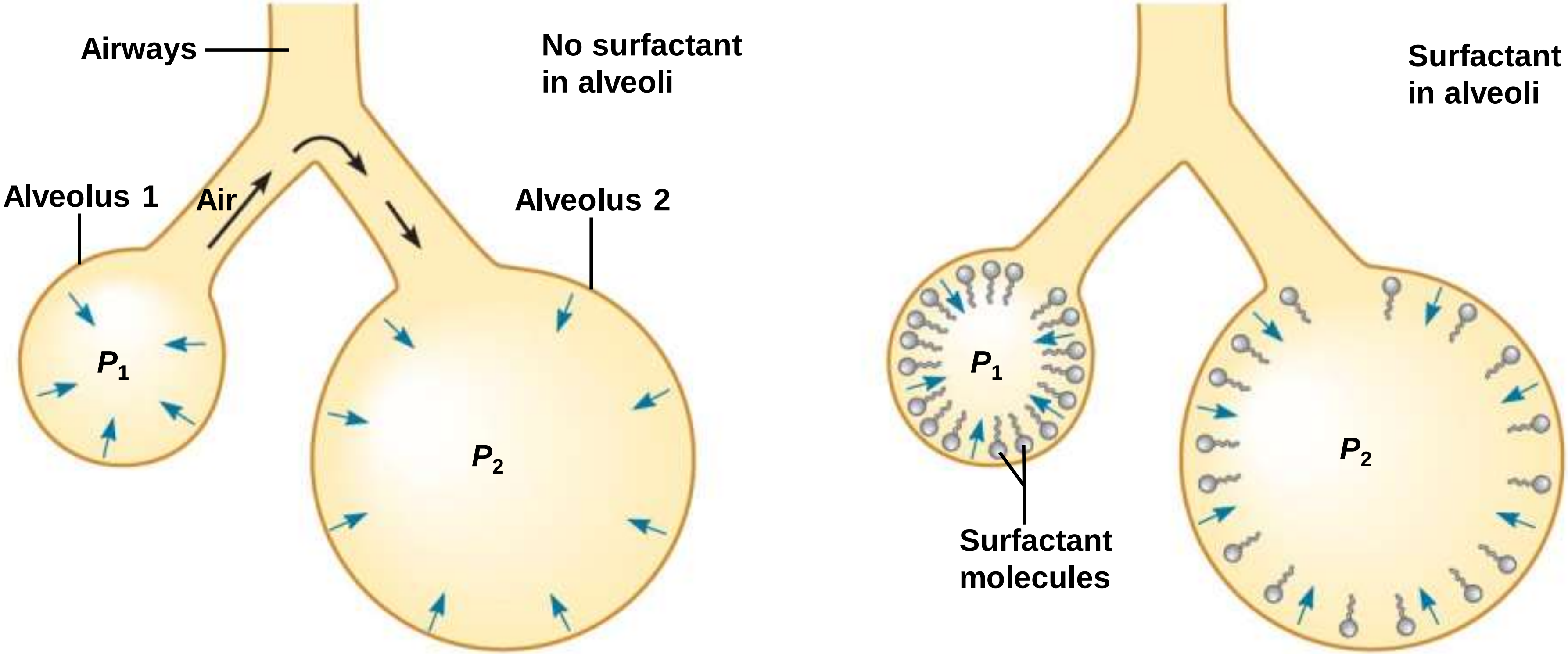
Lung Compliance

- Factors affecting lung compliance
  - Elasticity
    - More elastic → less compliant
  - Surface tension of lungs
    - Surface tension: force for alveoli to collapse or resist expansion
    - Thin layer of fluid lines alveoli
    - Surface tension arises due to attractions between water molecules
    - Greater tension → less compliant

Lung Compliance

- To overcome surface tension
  - Surfactant secreted from type II cells
    - Surfactant: detergent that decreases surface tension
  - Surfactant increases lung compliance
    - Makes inspiration easier

Toolbox 16.5



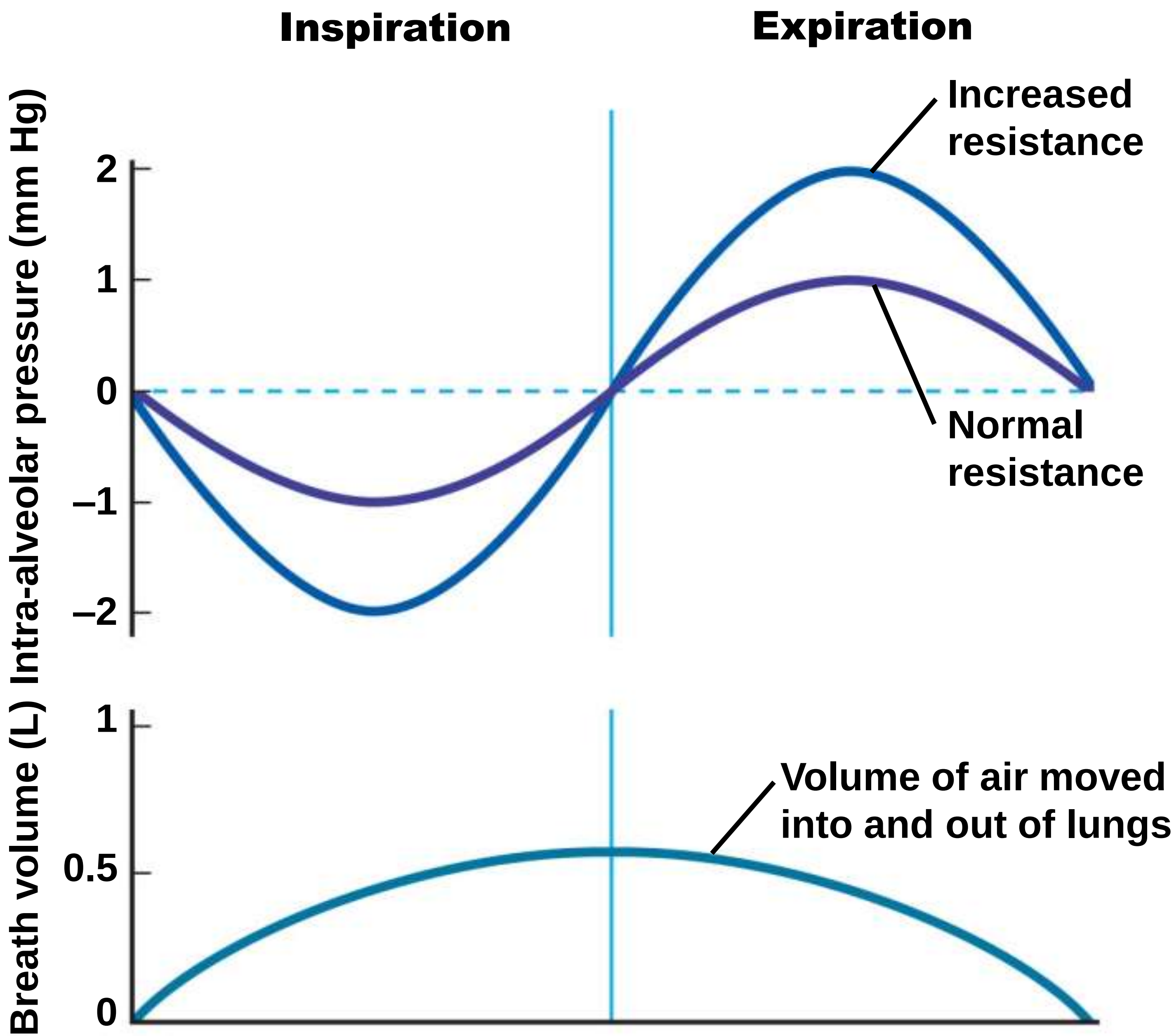
$r_1 < r_2$, $P_1 > P_2$
Smaller alveolus collapses into larger

$r_1 < r_2$, $P_1 = P_2$
Alveoli do not collapse

Airway Resistance

- As airways get smaller in diameter, they increase in number, keeping overall resistance low
- Pressure gradient is needed for air flow, so resistance is normally low
  - ~1 mm Hg
- Increase in resistance makes it harder to breathe
  - Pressure gradient needed for air flow: > 1 mm Hg

Figure 16.14 Effects of increasing airway resistance on the pressure changes required to move a fixed volume of air.



Airway Resistance

- Factors affecting airway resistance
  - Passive forces
    - Changes in transpulmonary pressure during respiratory cycle
      - Inspiration: transpulmonary pressure increases, causing airways to expand
    - Tractive forces
      - Inspiration: as tissues move away from airways, they pull the airways open
  - Contractile activity of smooth muscle
  - Mucus secretion

Airway Resistance

- Role of bronchiolar smooth muscle in airway resistance
  - Bronchoconstriction: smooth muscle contracts, causing radius to decrease
  - Bronchodilation: smooth muscle relaxes, causing radius to increase
  - Contractile state of bronchiolar smooth muscle under extrinsic and intrinsic controls

Airway Resistance

- Extrinsic control of bronchiole radius
  - Autonomic nervous system
    - Sympathetic
      - Relaxation of smooth muscle
      - Bronchodilation
    - Parasympathetic
      - Contraction of smooth muscle
      - Bronchoconstriction

Airway Resistance

- Extrinsic control of bronchiole radius
  - Hormonal control
  - Epinephrine
  - Relaxation of smooth muscle
  - Bronchodilation
- Intrinsic control of bronchiole radius
  - Histamine: bronchoconstriction
    - Released during asthma and allergies
    - Also increases mucus secretion
  - CO_2: bronchodilation

Airway Resistance

- Pathological states that increase airway resistance
  - Asthma
    - Caused by spastic contractions of bronchiolar smooth muscle
  - Chronic obstructive pulmonary diseases
    - COPD

16.5 Clinical Significance of Respiratory Volumes and Air Flows

- Lung volumes and capacities
- Pulmonary function tests
- Alveolar ventilation

Figure 16.15 Spirometry.

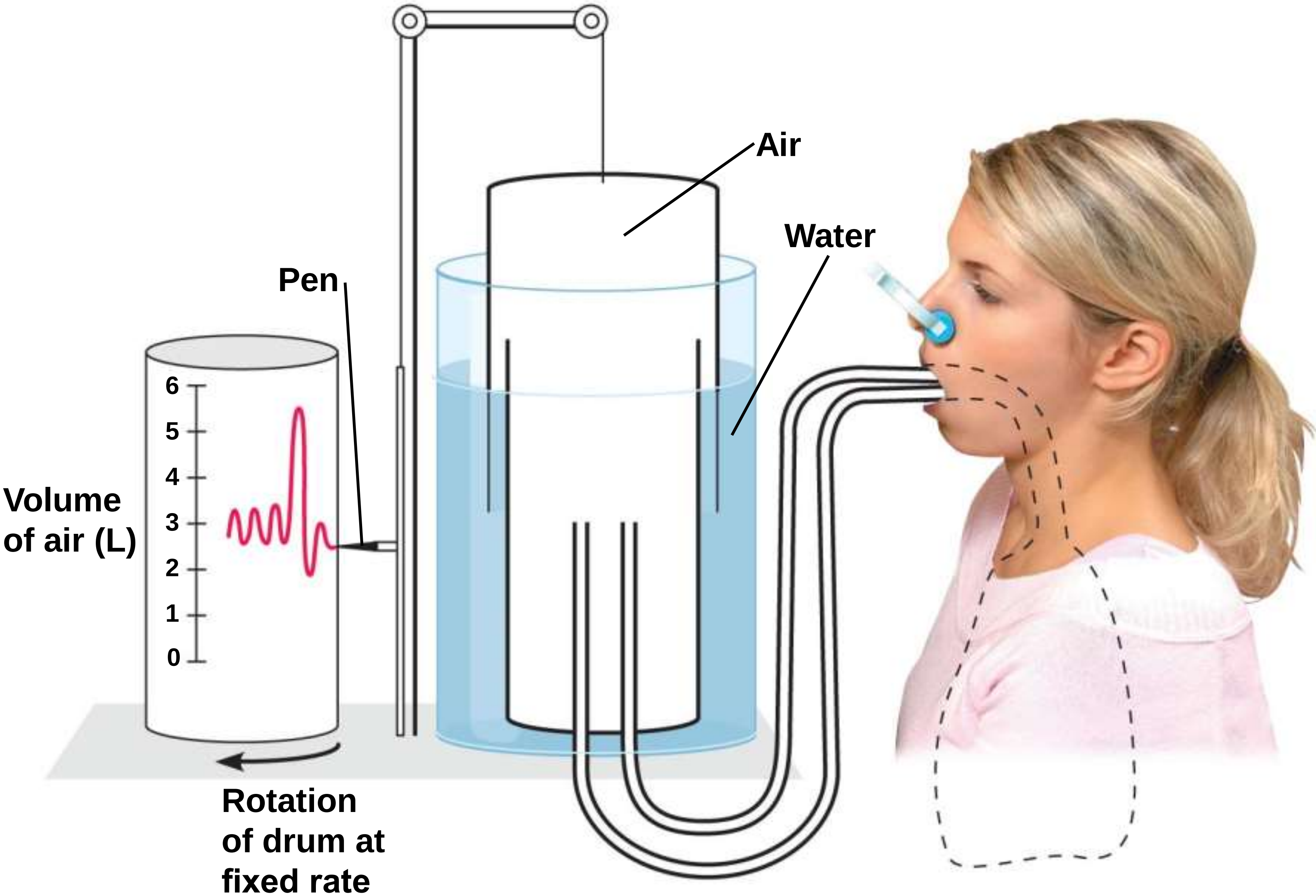
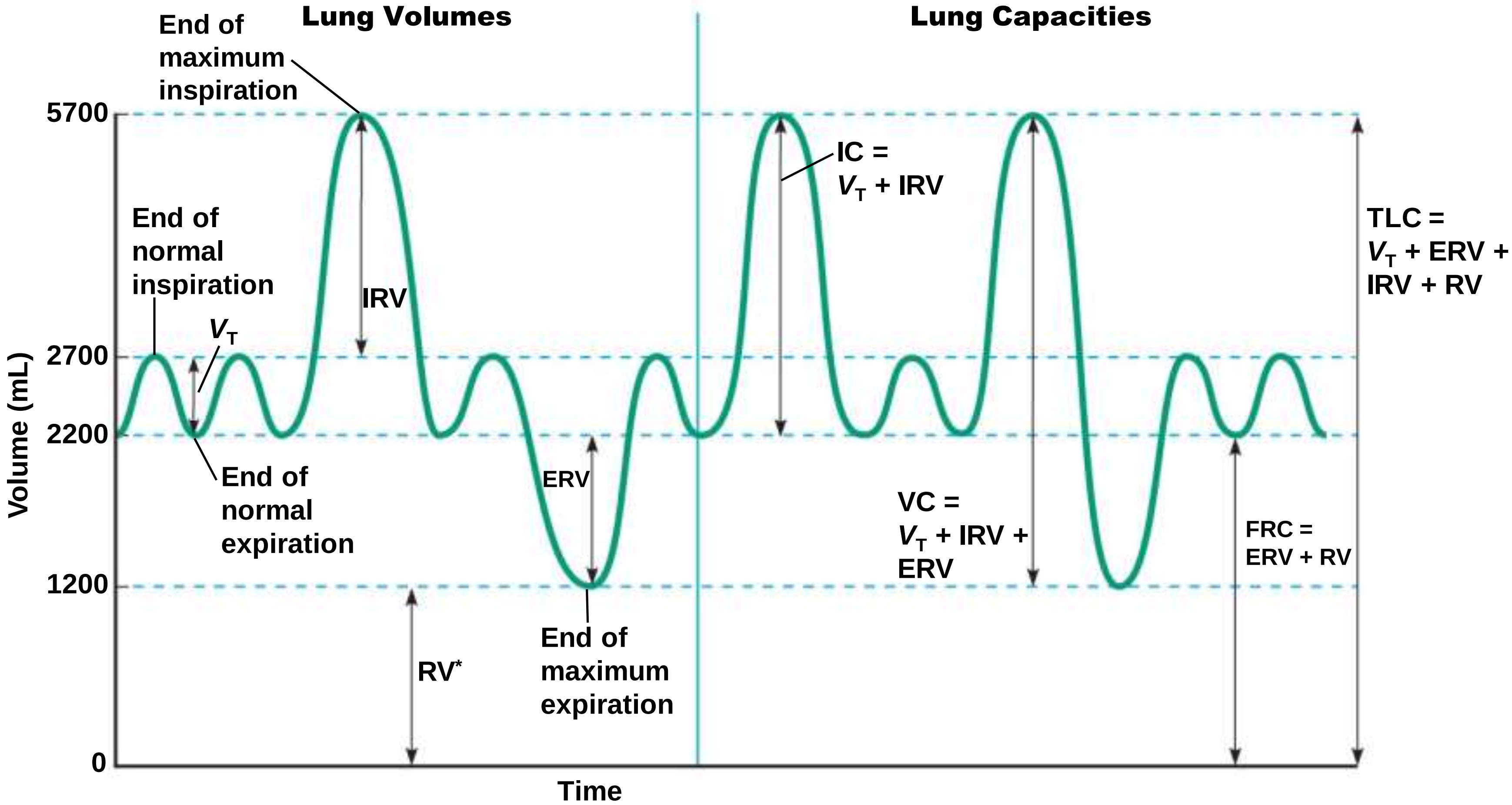


Figure 16.16 Lung volumes and capacities measured using spirometry.



Normal lung volumes and capacities for a healthy, approximately 154-lb. male

Lung Volumes

V_T = Tidal volume = 500 mL
IRV = Inspiratory reserve volume = 3000 mL
ERV = Expiratory reserve volume = 1000 mL
RV = Residual volume* = 1200 mL

*Cannot be measured by spirometry

Lung Capacities

IC = Inspiratory capacity = V_T + IRV = 3500 mL
VC = Vital capacity = V_T + IRV + ERV = 4500 mL
FRC = Functional residual capacity = ERV + RV = 2200 mL
TLC = Total lung capacity = V_T + ERV + IRV + RV = 5700 mL

Lung Volumes and Capacities

- Total lung capacity
  - Tidal volume (V_T): 500 mL
    - Single, unforced breath
  - Inspiratory reserve volume (IRV): 3000 mL
    - After breathing in, volume you can still inspire
  - Expiratory reserve volume (ERV): 1000 mL
    - After breathing out, volume you can still expire
  - Residual volume (RV): 1200 mL
    - Volume left after ERV
    - Measurable by *helium dilution method*

Lung Volumes and Capacities

- Inspiratory capacity (IC) = V_T + IRV = 3500 mL
- Vital capacity (VC) = maximum volume expired after maximum inspiration
  - VC = V_T + IRV + ERV = 4500 mL
- Functional residual capacity (FRC) = volume remaining after resting tidal volume
  - FRC = ERV + RV = 2200 mL
- Total lung capacity (TLC) = volume air in lungs after maximum inspiration
  - TLC = V_T + IRV + ERV + RV = 5700 mL

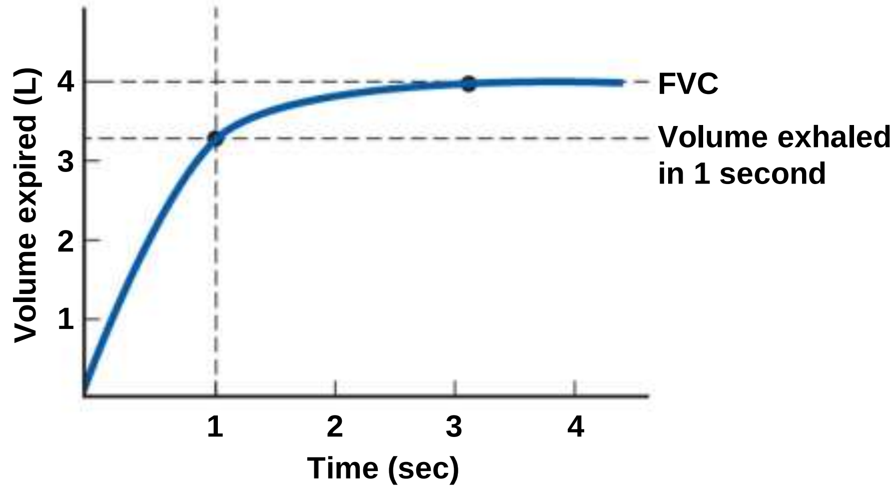
Pulmonary Function Tests

- Obstructive pulmonary diseases
  - Associated with increased airway resistance
  - Residual volume increases (making it more difficult to expire)
  - Functional residual capacity increases
  - Vital capacity decreases
  - Major obstructive pulmonary diseases
    - COPD (chronic bronchitis and emphysema)
    - Asthma

Pulmonary Function Tests

- Restrictive pulmonary diseases
  - More difficult for lungs to expand
  - Total lung capacity decreases
  - Vital capacity decreases

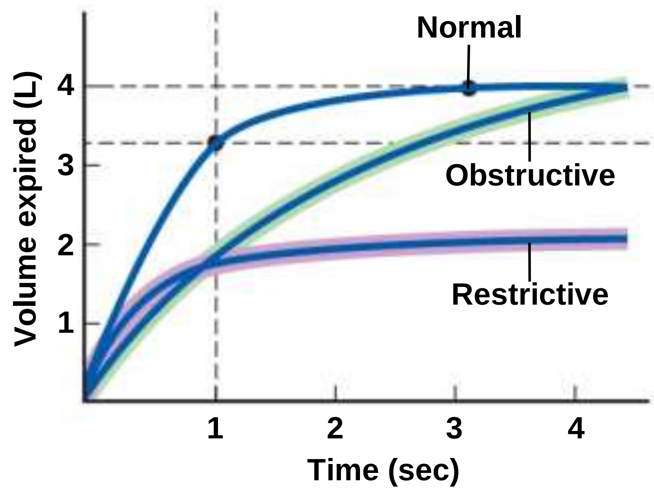
Figure 16.17 Pulmonary function test.



$$FEV_1 = \frac{\text{Volume exhaled in 1 sec}}{\text{FVC}} \times 100\% =$$

$$\frac{3200\text{ mL}}{4000\text{ mL}} \times 100\% = 80\%$$

(a)



(b)

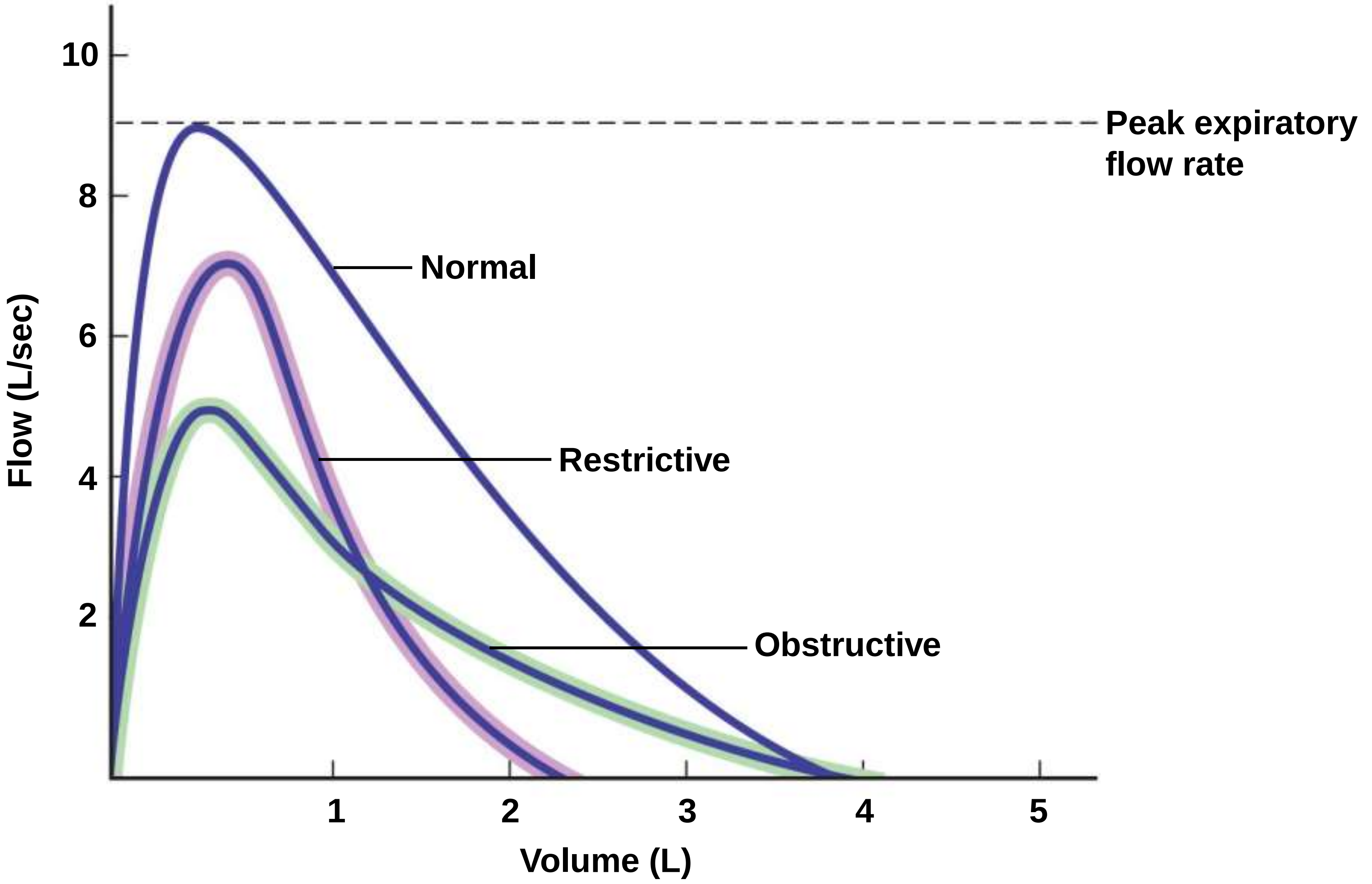
Pulmonary Function Tests

- Forced vital capacity (FVC) = maximum-volume inhalation followed by exhalation as fast as possible
  - Low FVC indicates restrictive pulmonary disease
- Forced expiratory volume (FEV) = percentage of FVC that can be exhaled within certain time frame
  - FEV_1 = percentage of FVC that can be exhaled within 1 second
  - Normal FEV_1 = 80%
    - If FVC = 4000 mL, should expire 3200 mL in 1 sec
    - FEV_1 < 80% indicates obstructive pulmonary disease

Pulmonary Function Tests

- Peak expiratory flow rate (PEFR) = maximum rate at which a person can exhale
- Men = 9 L/sec
- Women = 7 L/sec

Figure 16.18 Flow-volume curve for expiration.



Alveolar Ventilation

- Minute ventilation = total volume of air entering and leaving the respiratory system each minute
  - Minute ventilation = $V_T \times RR$
  - Normal respiration rate = 12 breaths/min
  - Normal V_T = 500 mL
  - Normal minute ventilation =
    500 mL × 12 breaths/min = 6000 mL/min

Alveolar Ventilation

- Anatomical dead space
  - Air in conducting zone does not participate in gas exchange
  - Conducting zone = anatomical dead space
  - Dead space = approximately 150 mL

Figure 16.19 The effects of anatomical dead space on alveolar ventilation.

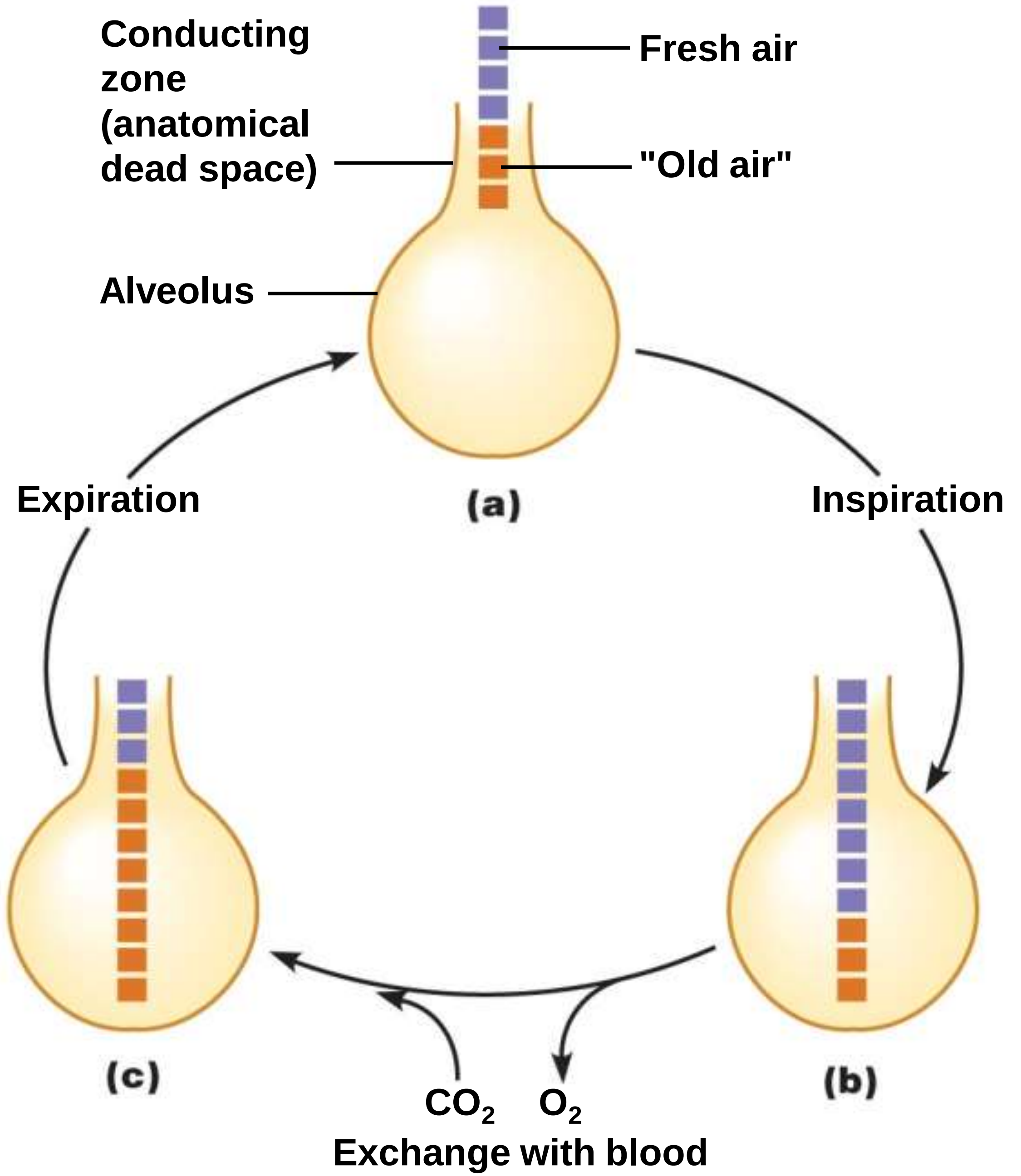
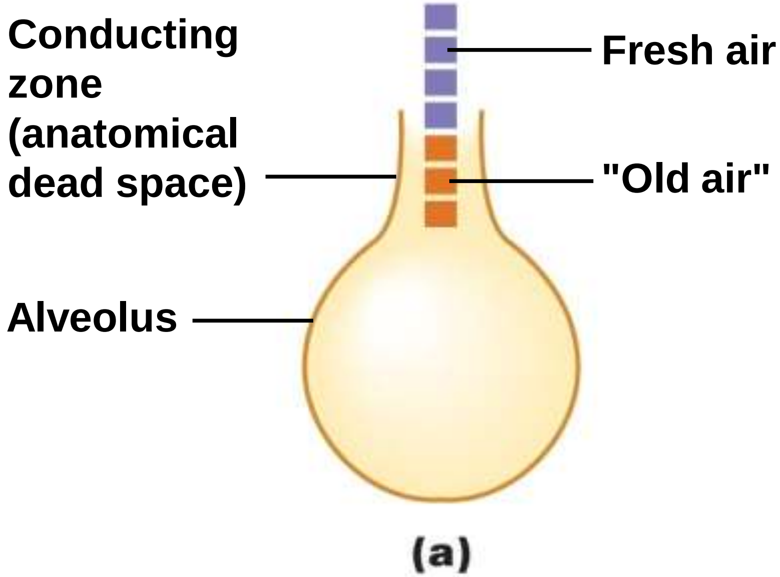


Figure 16.19 The effects of anatomical dead space on alveolar ventilation.



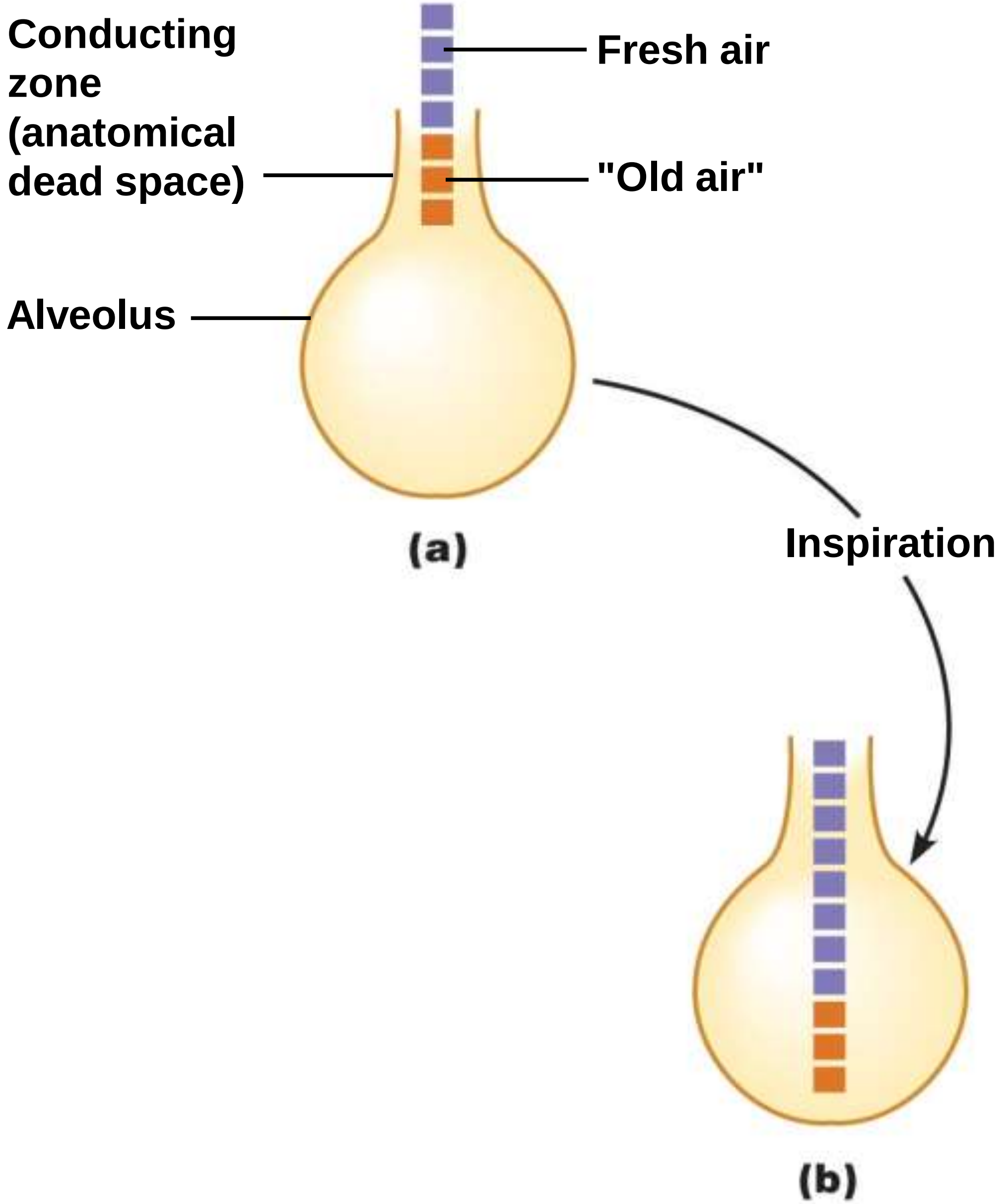

Conducting zone (anatomical dead space)
Fresh air
"Old air"
Alveolus
(a)
Inspiration
(b)

Figure 16.19 The effects of anatomical dead space on alveolar ventilation.

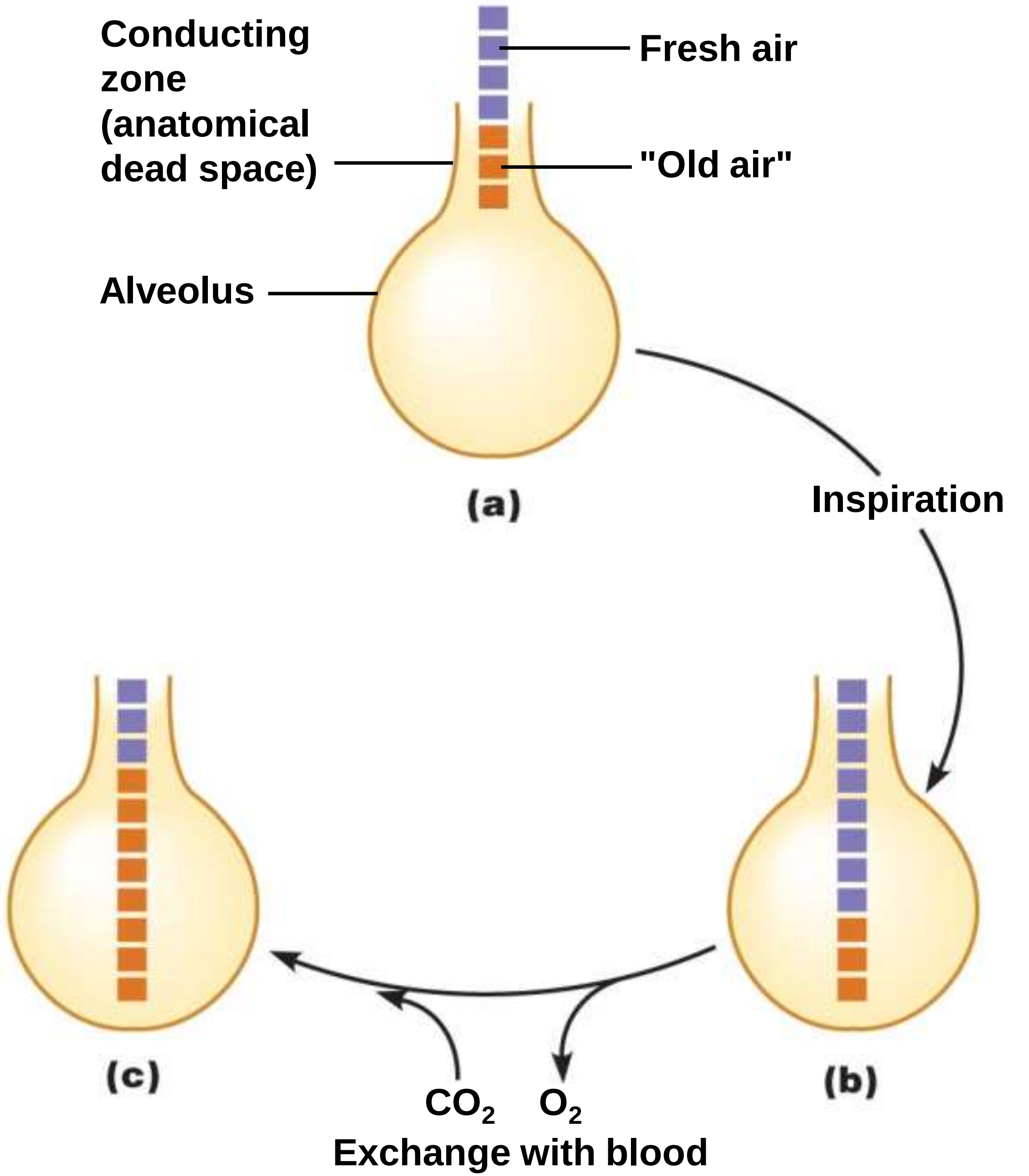
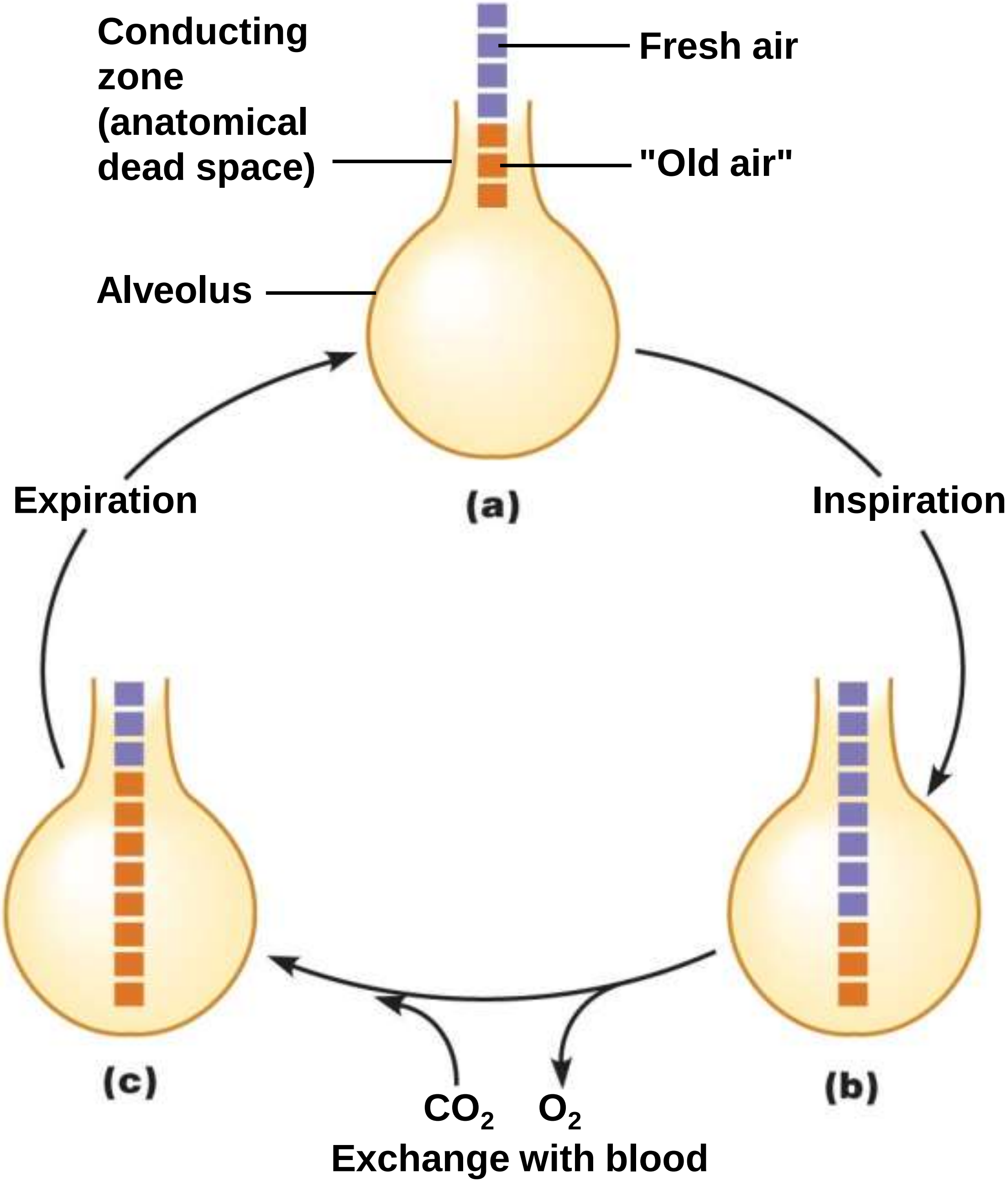


Figure 16.19 The effects of anatomical dead space on alveolar ventilation.



Alveolar Ventilation

- Volume of air reaching the gas exchange areas per minute
- Alveolar ventilation = (V_T × RR) – (DSV × RR)
- Normal = 4200 mL/min
  - (500 mL/breath × 12 breaths/min) – (150 mL/breath × 12 breaths/min)

TABLE 16.1 Effects of Respiration Rate and Tidal Volume on Minute Alveolar Ventilation

Tidal volume (mL)	Respiration rate (breaths/min)	Minute ventilation (mL/min)	Minute alveolar ventilation (mL/min)*
300	20	6000	3000
500	12	6000	4200
1000	6	6000	5100
500	24	12,000	8400
1000	12	12,000	10,200

*Assumes dead space volume = 150 mL.