Chapter 21: Respiratory System

For the body to survive, there must be a constant supply of O\textsubscript{2} and a constant disposal of CO\textsubscript{2}.

Respiratory System Functions:
1) Provides surface area for gas exchange (between air / blood)
2) Moves air to / from gas exchange surface
3) Protect system (dehydration / temp. change / pathogens)
4) Sound production
5) Assist in detection of olfactory cues
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Functional Anatomy:

Overview of Respiratory System:

- Upper Respiratory System
  - Filters / warms / humidifies incoming air
  - Conduction of air
  - Gas exchange

- Lower Respiratory System

1) External nares
2) Nasal cavity
   - Resonance chamber
3) Uvula
4) Pharynx
   - Nasopharynx
   - Oropharynx
   - Laryngopharynx
5) Larynx
   - Provide open airway
   - Channel air / food
   - Voice production

6) Trachea
7) Bronchial tree
8) Alveoli

Overview of Respiratory System:

- Epiglottis
- Pharynx
   - Nasopharynx
   - Oropharynx
   - Laryngopharynx

- Trachea

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Bronchiole
- Terminal Bronchiole
- Respiratory Bronchiole

Functional Anatomy:

- Trachea

Naming of pathways:
- > 1 mm diameter = bronchus
- < 1 mm diameter = bronchiole
- < 0.5 mm diameter = terminal bronchiole

Bronchi bifurcation
(23 orders)

Green = Conducting Zone
Purple = Respiratory Zone

- Bronchi
- Terminal Bronchiole
- Alveoli

Functional Anatomy:

Respiratory Mucosa / Submucosa (Variable):

- Location in Bronchial Tree
  - Near Trachea
  - Near Alveoli

- Epithelium:
  - Simple cuboidal
  - Pseudostratified columnar
  - No cilia

- Lamina Propria (areolar tissue layer):
  - Smooth muscle
  - No mucous glands

- Mucosa:
  - Mucous membranes

- Cartilage:
  - Rings
  - Plates / none
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Functional Anatomy:

How are inhaled debris / pathogens cleared from respiratory tract?

Nasal Cavity:
- Particles > 10 µm

Conducting Zone:
- Particles 5 – 10 µm

Respiratory Zone:
- Particles 1 – 5 µm

Mucus Escalator

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Functional Anatomy:

Trachea
- Tough, flexible tube (~ 1” diameter)
- 15 – 20 tracheal cartilages (hyaline)
  - Protect airway (prevent collapse)
  - Allow for food passage (C-shaped)

Bronchi (> 1 mm diameter)
- 1st = Extrapulmonary bronchi
- 2nd → Intrapulmonary bronchi
  - Smooth muscle layer
  - Cartilaginous plates

Bronchitis:
- Inflammation of airways

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Functional Anatomy:

Bronchioles (< 1 mm diameter)
- Loss of cartilage
- Mucous glands rare → Why?
- Thick smooth muscle layer
  - Sympathetic stimulation: Bronchodilation
  - Parasympathetic stimulation: Bronchoconstriction

Terminal Bronchioles
- Ciliated epithelium (columnar / cuboidal)
- No mucous glands

Respiratory Bronchioles
- Ciliated → non-ciliated epithelium
- Actively participates in respiration

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Pseudostratified ciliated columnar epithelium
Functional Anatomy:

**Alveoli** (~ 1.5 million / lung)
- Cup-shaped, thin-walled sacs
  - Type I cells: Simple squamous; forms wall of alveoli
  - Alveolar pores (~6 / alveoli)
  - Type II cells: Cuboidal / round
    - Surfactant: Secretion; reduces surface tension (prevents alveoli collapse)
    - Respiratory Distress Syndrome (e.g., pre-mature babies)
    - Dust cells: Macrophages; clear debris on alveolar surface

Respiratory Membrane:
1) Type I cells of the alveoli
2) Endothelial cells of capillaries
3) Fused basement membranes

0.1 – 0.5 \( \mu \)m thick

Pneumonia: Thickening of respiratory membrane

Respiration includes:

1) **Pulmonary ventilation** (pumping air in / out of lungs)
2) **External respiration** (gas exchange @ blood-gas barrier)
3) **Transport of respiratory gases** (blood)
4) **Internal respiration** (gas exchange @ tissues)
Pressure relationships in the thoracic cavity:

1) **Intrapulmonary Pressure** (w/in the alveoli):
   - Static conditions = 0 mm Hg
2) **Intrapleural pressure** (w/in pleural cavity):
   - Always relatively negative (~ -4 mm Hg)

Atmospheric pressure = ~ 760 mm Hg
(Consider $P_{\text{atm}} = 0$ mm Hg)

Why is the intrapleural pressure negative?

Answer: Interaction of opposing forces

Forces acting to collapse lung:
1) Elasticity of lungs
2) Alveolar surface tension

Forces resisting lung collapse:
1) Rigid chest wall
   - Surface tension of serous fluids keep lungs "stuck" to chest wall
   - Forces equilibrate at $P_{\text{ip}} = -4$ mm Hg

Pneumothorax:
- "sucking chest wound"
- Puncture of chest wall – results in inability to generate negative pressure and expand the lungs
Mechanisms of Ventilation:

- Process dependent on thoracic cavity volume changes

**Boyle’s Law**

\[ P_1 V_1 = P_2 V_2 \]

- \( P \) = pressure of gas (mm Hg)
- \( V \) = volume of gas (mm³)
- \( P_1 \) = initial pressure; \( V_1 \) = initial volume
- \( P_2 \) = resulting pressure; \( V_2 \) = resulting volume

**Example:**

4 mm Hg \( (2 \text{ mm}^3) = P_2 \) \( (4 \text{ mm}^3) \)

\[ P_2 = 2 \text{ mm Hg} \]

CHANGING THE VOLUME RESULTS IN INVERSE CHANGE OF PRESSURE!

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1) Pulmonary Ventilation:

Mechanisms of Ventilation:

1) **Inspiration:** Muscular expansion of thoracic cavity

A) Contraction of diaphragm
   - Lengthens thorax (pushes liver down)

B) Contraction of external intercostal muscles
   - Widens thorax

Results in:

- Reduced intrapleural pressure \( (P_{ip}) \)
- Reduced intrapulmonary pressure \( (P_{pul}) \)
1) **Pulmonary Ventilation:**

Mechanisms of Ventilation:

2) **Expiration:** Retraction of thoracic cavity

A) **Passive Expiration**
- Diaphragm relaxes
- External intercostals relax
- Elastic rebound (lungs rebound)

B) **Active (Forced) Expiration**
- Abdominal muscles contract
- Internal intercostals contract

**Eupnea:** Quiet breathing (active inspiration; passive expiration)

**Hyperpnea:** Forced breathing (active inspiration; active expiration)

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1) **Pulmonary Ventilation:**

Physical Factors Influencing Pulmonary Ventilation:

A) **Airway resistance**
- Flow of air = change in pressure / resistance (F = ΔP / R)
  - Asthma - allergic response to irritants
    - Constriction of bronchioles = ↓ radius = ↑ resistance

B) **Surface tension in alveoli**
- Moist alveolar surfaces attract to one another (H₂O polarity – collapses alveoli)
- Alveolar cells secrete surfactant (e.g., detergents)

C) **Lung compliance**
- “Stretchiness” of lung (↑ compliance = easier to expand lung)
- Determined by:
  a) Elasticity of lung
  b) Surface tension
- **Emphysema:** Lungs lose elasticity (too compliant)
1) Pulmonary Ventilation:

Respiratory Volumes:
- Tidal Volume: Amount of air moved in / out of lung during single respiratory cycle
- Inspiratory reserve volume (~ 3100 ml)
- Expiratory reserve volume (~ 1200 ml)
- Residual volume (~ 1200 ml)
- Vital capacity (~ 4800 ml)
- Total lung capacity (~ 6000 ml (Male) ~ 4200 ml (Female))

Marieb & Hoehn – Figure 21.16

\[ V_{M} = f \text{ (breaths / minute)} \times V_{T} \text{ (tidal volume)} \]
\[ = 12 \text{ breaths / minute} \times 500 \text{ ml} \]
\[ = 6000 \text{ ml / minute} \]
\[ = 6.0 \text{ liters / minute} \]

Alveolar Ventilation:
\[ V_{A} = f \text{ (breaths / minute)} \times (V_{T} \text{ (tidal volume)} - V_{D} \text{ (anatomic dead space)}) \]
\[ = 12 \text{ breaths / minute} \times (500 \text{ ml} - 150 \text{ ml}) \]
\[ = 4200 \text{ ml / minute} \]
\[ = 4.2 \text{ liters / minute} \]

Alveolar ventilation is available for gas transfer...

Respiration includes:
1) Pulmonary ventilation (pumping air in / out of lungs)
2) External respiration (gas exchange @ blood-gas barrier)
3) Transport of respiratory gases (blood)
4) Internal respiration (gas exchange @ tissues)
**Dalton’s Law of Partial Pressures**: The total pressure of a gas is equal to the sum of the pressure of its constituents.

\[
P_{\text{atmosphere}} = 760 \text{ mm Hg}
\]

\[
P_{\text{CO}_2} = 0.21 \times 760 \text{ mm Hg} = 159 \text{ mm Hg}
\]

\[
P_{\text{O}_2} = 0.79 \times 760 \text{ mm Hg} = 601 \text{ mm Hg}
\]

\[
P_{\text{CO}_2} = 0.0004 \times 760 \text{ mm Hg} = 0.30 \text{ mm Hg}
\]

Gases diffuse down pressure gradients.

Additional factors affecting gas / liquid interchange:

A) **Solubility of gas in water**
   - \( \text{CO}_2 \gg \text{O}_2 \gg \text{N}_2 \) (the "bends")

B) **Temperature**
   - Solubility inversely related to temperature

**Why is alveolar gas high in CO\(_2\) and water vapor?**

Lung air modified by gas exchange:

1) \( \text{O}_2 \) into blood; \( \text{CO}_2 \) out of blood
2) Humidification of air (conducting pathways)
3) Mixture of fresh and residual air / breath
Gas exchange at the respiratory membrane is efficient:

A) Differences in partial pressure across respiratory membrane substantial

- **Lung – Blood Interface**
  - $P_{O_2}$ in alveoli = ~100 mm Hg
  - $P_{O_2}$ in blood = ~40 mm Hg
  - Net movement into blood
- **Blood – Tissue Interface**
  - $P_{CO_2}$ in blood = ~40 mm Hg
  - $P_{CO_2}$ in tissue = ~45 mm Hg
  - Net movement into blood

B) Exchange area thin (thickness < 1.0 μm) and expansive (~ 50 - 70 m²)

C) Ventilation – Perfusion Coupling:

- $\uparrow$ $O_2$/ $\downarrow$ $CO_2$ in alveoli triggers:
  1) constriction of arterioles feeding area
  2) dilation of bronchioles feeding area
- $\downarrow$ $O_2$/ $\uparrow$ $CO_2$ in alveoli triggers:
  1) dilation of arterioles feeding area
  2) Constriction of bronchioles feeding area
Respiration includes:

1) Pulmonary ventilation (pumping air in/out of lungs)
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3) Gas Transport:
A) Oxygen Transport:
   • Most O₂ in blood bound to hemoglobin (Hb) (> 98.5%)
   • Hemoglobin saturation = % of heme units bound to O₂ in blood
   • O₂ solubility low in plasma (~ 1.5%)

\[
\text{Hb} + \text{O}_2 \rightleftharpoons \text{HbO}_2
\]

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3) Gas Transport:
A) Oxygen Transport:
   • Rate of O₂ binding to hemoglobin dependent on partial pressure of O₂

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Oxygen Dissociation Curve
Describes relationship between percent saturation of Hb and partial pressure of oxygen
Sub-unit Cooperativity (hemoglobin)
Oxygination of first heme group facilitates oxygination of other heme groups
Factors influencing O₂ binding to Hb:
1) \( P_{O2} \) + \( P_{CO2} \) = \( \uparrow \) release of O₂
2) Temperature (\( \uparrow \) temp. = \( \uparrow \) release of O₂)
3) pH (\( \downarrow \) pH = \( \uparrow \) release of O₂)
4) \( P_{CO2} \) (\( \uparrow \) \( P_{CO2} \) = \( \uparrow \) release of O₂)

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Marieb & Hoehn – Figure 21.20
3) Gas Transport:

A) Oxygen Transport:

• Oxygen transport impairments:
  1) Anemic Hypoxia (RBC deficiency – e.g., iron deficiency)
  2) Ischemic Hypoxia (Circulation deficiency – e.g., sickle-cell anemia)
  3) Histotoxic Hypoxia (Tissue uptake – e.g., cyanide)
  4) Hypoxemic Hypoxia (Reduced arterial P\textsubscript{O\textsubscript{2}} – e.g., CO poisoning)

B) Carbon Dioxide Transport:

3) Chloride Shift:

Mass influx of Cl\textsuperscript{-} into RBC to offset efflux of HCO\textsubscript{3}\textsuperscript{-}

Bohr Effect:

↓ pH due to HCO\textsubscript{3}\textsuperscript{-} production leads to ↑ in O\textsubscript{2} release from Hb

\[
\text{CO}_2 + \text{H}_2\text{O} \xrightleftharpoons[\text{CA}]{\text{H}_2\text{CO}_3} \xrightarrow{\text{H}^+ + \text{HCO}_3^-} \text{H}_2\text{O} + \text{CO}_2
\]
• CO₂ transport allows for blood buffering:
  • HCO₃⁻ acts as a proton acceptor (H⁺) in plasma
  • If blood [H⁺] rises, H⁺ combines with HCO₃⁻
  • If blood [H⁺] drops, H⁺ dissociates from H₂CO₃
• Mechanism maintains stable blood pH ~ 7.4
Control of Respiration:

2) Chemoreceptor Reflexes
   A) $P_{CO2}$
   B) $P_{O2}$
      • Minor respiratory stimulant ($\downarrow O_2 = \uparrow$ respiratory rate)
      • Mediated via peripheral chemoreceptors (e.g., carotid artery)
      • Stimulated by $P_{CO2} < 60$ mm Hg in arterial blood
   C) Arterial pH
      • Mediated via peripheral chemoreceptors ($\downarrow$ pH = $\uparrow$ respiratory rate)

3) Hering-Breuer Reflexes
   A) Inflation Reflex
      • Lung stretch inhibits inspiratory center (prevents lung over-inflation)
   B) Deflation Reflex
      • Lung deflation inhibits expiratory center (during active expiration)

4) Protective Reflexes:
   A) Pulmonary Irritant Reflexes:
      • Irritant stimulates sneezing (nasal cavity) or coughing (lower conduction system)
   B) Laryngeal Spasm
      • Irritant around glottis leads to closure of epiglottis (protect lung)

5) Voluntary Control:
   A) Emotion:
      • $\uparrow$ respiratory rate via hypothalamic input (limbic system)
   B) Anticipation of Strenuous Exercise:
      • $\uparrow$ respiratory rate via sympathetic input
   C) Conscious Control (bypass / block respiratory centers)

Increase in lung cancer rates correlated with rise in smoking among adult man and woman