The Respiratory System

Respiratory system functions as gas exchange system for oxygen and carbon dioxide → cellular respiration (energy production)

external vs internal respiration
closely tied to circulatory system

Physiology of Respiration

Pulmonary Ventilation

= External Respiration

we move ~500 ml of air in and out of lungs with each breath

breathing involves 2 processes:

  inspiration
  expiration

involves moving air down a pressure gradient

Inspiration

  an active process
  involves contraction of diaphragm
  → innervated by phrenic nerve
  may also involve external intercostals

  contraction of diaphragm lowers pressure in thoracic cavity:
  outside pressure > pressure in lungs → lungs inflate

  outside: 760 mmHg → inside: 754 mmHg

Expiration

  mainly a passive process
  → relaxation of diaphragm
  volume of chest decreases, forcing air out of lungs
  may also involve contraction of internal intercostals

  inside: 763 mmHg → outside: 760 mmHg
  (forced=up to 790 mmHg)
Factors that affect pulmonary ventilation:

1. **Resistance to airflow**
   - in respiratory passages
   - constriction increases resistance (=drag)
   - mainly in bronchi and bronchioles

2. **Compliance**
   - lungs are >100 x’s more distendable than a balloon
   - lungs increase in volume passively as chest cavity expands
   
   Pulmonary fibrosis reduces compliance

3. **Elasticity of lungs**
   - elasticity = tendency of organ to return to normal position or shape
   - lungs contain lots of elastin fibers
   
   Emphysema = less elastic and more collagen fibers
   - requires 3-4x’s more energy to breath
   - (15-20% vs 5% normal)

4. **Reduced Pressure in Thoracic Cavity**
   - pressure in thoracic cavity is kept lower than pressure in outside air
   - keeps lungs inflated
   - **pneumothorax**
     - opening in chest cavity
     - eliminates pressure differential
     - causes lungs to collapse

5. **Surface Tension**
   - outer surface of lungs and inner surface of alveoli are covered with thin
     - film of water
   - water has a high surface tension (very “sticky”)
   
   on outer surface of lungs:
   - visceral pleura tends to stick to parietal pleura
   - creates slight negative intrapleural pressure
   - helps to inflate lungs during inspiration
   
   on inside of alveoli:
   - tends to cause the alveoli to collapse upon themselves
counteracted by:

a. lungs never completely deflated;  
   always contain some air

b. secrete **surfactant**
   a lipoprotein
   reduces surface tension in alveoli
   not produced until 8\textsuperscript{th} month of pregnancy
   $\rightarrow$ respiratory distress syndrome

**Respiratory Volumes**

the volume of air exchanged in breathing is measured with a **spirometer**
\(\rightarrow\) provides information on pulmonary functions

**Tidal Volume (TV)**

- normal volume of air with each breath
- small part of total lung capacity (~10%)
- \(\sim 500\) ml

**Expiratory Reserve Volume (ERV)**

- additional air one can expire after releasing tidal volume
- use internal intercostals to forcibly expire additional air
- \(\sim 1000-1200\) ml

**Inspiratory Reserve Volume (IRV)**

- additional amount of air that can be inspired in addition to tidal volume
- use external intercostals to lift rib cage
- \(\sim 3100-3300\) ml

**Residual Volume**

- air that cannot be removed from lungs
- \(\sim 1200\) ml
- removed in pneumothorax

**Vital Capacity (VC)**

- largest volume of air that can be moved into or out of lungs
- \(VC = IRV + TV + ERV\)

vital capacity is affected by:

a. overall size of individual, gender $\rightarrow$ size of lungs

b. volume of blood in lungs $\rightarrow$ eg congestive heart failure

c. excess fluid in pleural or abdominal cavity

d. loss of lung elasticity $\rightarrow$ eg. emphysema

e. misc health related factors $\rightarrow$ eg. smoking, exercise, etc
% Forced Expiratory Volume (%FEV or FEV\textsubscript{1})
proportion of Vital Capacity one can exhale in 1 second
usually ~75-85% in healthy individuals

Total Lung Capacity (TLC)
maximum amount of air the lungs can hold
TLC = VC + RV
~5700-6200 ml

Minute Respiratory Volume (MRV)
amount of air that ventilates lungs each minute
is an index of respiratory efficiency
= TV x Breathing rate = ~500 ml x 12
= ~6000 ml/min [6 l/min vs exercise = ~100-200 liters/min]

But of the Tidal Volume (~500 ml)
about 150 ml never gets to alveoli
remains in air passages

Alveolar Ventilation Rate
= ~350 ml x 12
= ~4200 ml/min (~70% of MRV)
= 63 gallons/hr
= 1512 gallons/day
a better index of effective ventilation eliminates “dead space”
deeper breaths more effective than more frequent breaths

Disorders indicated with pulmonary functions tests:

Restrictive Disorders
diseases that reduce total lung capacity
→ lowers VC
eg. pulmonary fibrosis
eg. polio, TB, etc

Obstructive Disorders
diseases that increase airway resistance
→ lowers %FEV
eg. asthma (bronchiole constriction)
→ normal VC
→ but lower forced expiratory volume
eg. chronic bronchitis, asthma
Alveolar Gas Exchange

composition of air:

<table>
<thead>
<tr>
<th>air entering lungs</th>
<th>air exiting lungs</th>
</tr>
</thead>
<tbody>
<tr>
<td>[78% N₂]</td>
<td></td>
</tr>
<tr>
<td>21% O₂</td>
<td>14% O₂</td>
</tr>
<tr>
<td>0.04% CO₂</td>
<td>5.6% CO₂</td>
</tr>
</tbody>
</table>

the exchange of gasses in the lungs takes place between alveolar air and venous blood

gas exchange occurs across the lining of the alveoli and capillaries
(2 cell layers thick)

= respiratory membrane

total surface area ~ 70 (60-80)M² (=760 ft² ~20’x38’)

Gas exchange is the result of simple diffusion down oxygen and carbon dioxide concentration gradients:

concentrations of gasses usually measured in partial pressures

<table>
<thead>
<tr>
<th>PO₂</th>
<th>PCO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>21% of 760 mmHg = 160 mmHg</td>
<td>0.04% of 760 mmHg = 0.3 mmHg</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Alveoli</th>
<th>Blood Entering Lungs</th>
</tr>
</thead>
<tbody>
<tr>
<td>PO₂ 105mmHg</td>
<td>40mmHg</td>
</tr>
<tr>
<td>PCO₂ 39mmHg</td>
<td>46mmHg</td>
</tr>
</tbody>
</table>

Amount of O₂ diffusing into blood depends on:

1. oxygen pressure gradient
   alveolar airflow – blood flow coupling
   if low O₂/high CO₂ get
   → arterial constriction
   → bronchial dilation
   improves gas exchange in alveoli

2. surface area of lungs
3. respiratory rate

Oxygen binds to hemoglobin inside RBC’s = oxyhemoglobin

The exchange of gasses in tissues is also by simple diffusion:
Blood leaving lungs | Tissues
---|---
PO2 | 104mmHg | ≤40mmHg
PCO2 | 40mmHg | ≥45mmHg

The amount of oxygen delivered to tissue cells is affected by:
1. **rate of oxygen utilization**
   - regulates the rate of delivery by controlling size of gradient
   - as conc of O₂ in tissues decreases;
   - the bonds between O₂ and Hb weaken
2. **Carbon Dioxide concentration**
   - more CO₂ → more O₂ released
3. **pH**
   - lower pH → more O₂ released
4. **temperature**
   - higher temp → more O₂ released

**Dissociation Curve for Hemoglobin** (how easily Hb gives up oxygen):
- 1ˢᵗ O₂ on and off is hardest
- other 3 are easier to bind or remove
  - creates differential release of oxygen to cells needing it most
  - More oxygen is released to active muscle cells

**Myoglobin** → has 1 heme group
- accepts O₂ from Hemoglobin
- holds onto O₂ longer
  - “middleman”

**Transport of Gasses in Blood**

**A. Oxygen [O₂]**

hemoglobin has a very **high affinity** for O₂

almost all hemoglobin in blood going through lungs manages to pick up oxygen
  - 97-99% saturation
  - versus ~70% saturation in venous blood

only ~1-1.5% of O₂ is carried dissolved in plasma

  - eg. Hyperventilation doesn’t increase PO₂ of blood
    - only slightly increases dissolved O₂ concentrations
    - may deliver a little more O₂ to tissues but not much

Anatomy and Physiology: Respiratory System, Ziser, 2003
the amount of oxygen carried in the blood then is mainly dependent on the amount of hemoglobin in blood

\[ 4 \text{O}_2/\text{hemoglobin} \rightarrow 250 \text{ Million Hb/RBC} \rightarrow 1 \text{ Billion O}_2/\text{RBC} \]

anemia decreases oxygen transport

Only 20-25% of oxygen is unloaded per circuit of bloodflow

\[ \rightarrow \text{venous reserve} \]

eg. this is why you can “hold breath”

ie. don’t need oxygen continuously

CO binds to Hemoglobin even more strongly than does oxygen

\[ \rightarrow \text{CO poisoning (takes very little, but continuous exposure)} \]

B. Carbon Dioxide [CO$_2$]

transported in blood three major ways:

1. **7% dissolved in plasma**

\[ \rightarrow >20x’s \text{ more soluble than O}_2 \]

2. **20-23% bound to hemoglobin**

   CO$_2$ binds to amino group of hemoglobin

   \[ (\text{O}_2 \text{ binds to heme portion}) \]

   =carboxyhemoglobin

3. **70% converted to bicarbonate ions**

\[
\text{CO}_2 + \text{H}_2\text{O} \xrightarrow{\text{carbonic anhydrase}} \text{H}_2\text{CO}_3 \xrightarrow{\text{carbonic acid}} \text{H}^+ + \text{HCO}_3^- \\
\]

this reaction occurs mainly inside RBC’s

bicarbonate ions are then released into the plasma

oxygen release is enhanced by CO$_2$ loading
Regulation of Respiration

normal breathing is automatic, rhythmic

Skeletal muscles of diaphragm and intercostals are innervated by somatic motor neurons

controlled by respiratory reflex centers in brainstem

Three reflex centers in brain that regulate breathing:

1. respiratory center: medulla

   (medullary rhythmicity area)
   
establishes basic rhythm of breathing
   
maintains automatic breathing rate
   \[ \rightarrow \text{12-15 breaths/min} \]

   a. contain chemoreceptors that are sensitive to changes in CO$_2$

   b. chemoreceptors in aorta and carotid sinus also monitor CO$_2$ levels in arterial blood

      \[ \text{high blood CO}_2 \rightarrow \text{faster breathing} \]

   c. other chemoreceptors in aorta and carotid sinus also monitor pH

      \[ \text{more acidic} \rightarrow \text{faster breathing} \]

   d. O$_2$ sensors in aorta and carotid sinus detect slight reductions in O$_2$ and cause reflex stimulation of respiratory center

      \[ \rightarrow \text{rarely is the most important control} \]

       if cells in respiratory become hypoxic they may fail

       Hypoxic drive: people with respiratory disease
       \[ \rightarrow \text{these O}_2\text{ receptors become more important} \]

2. apneustic: pons

   promotes inspiration, breath holding
forceful, prolonged inspiration

3. pneumotaxic center: pons

antagonist to apneustic
inhibits inspiration
fine tunes, prevents overinflation

the two centers in pons insure a smooth transition between inspiration and expiration
→ helps maintains rhythmicity of breathing

when connection between medulla and pons are cut breathing becomes abnormal
→ gasps

“inflation & deflation reflexes” alternate activity

helps regulate depth of breathing

occurs when stretch receptors in pleura, bronchioles and alveoli are stimulated during inspiration
→ prevents overinflation

when stretch receptors are no longer stimulated
→ prevents further expiration

Hypothalamus
irritant receptors trigger bronchiole constriction, coughing etc

Cerebrum
emotional state, eg fear, pain, can speed up breathing

can voluntarily speed up or slow down breathing
→ but can’t overpower reflex controls
Diseases of Respiratory System

A. Diseases of inadequate ventilation

1. **Pneumothorax**
   collapsed lung or lungs

2. **paralysis of diaphragm muscle**
   due to injury to respiratory center of brainstem
   eg. caused by polio which damages respiratory center
damage to nerves supplying diaphragm (phrenic nerve)

3. **bronchial asthma**
   allergic reaction
   excessive mucous secretions and constrictions of bronchioles

4. **emphysema**
   progressive degenerative disease causing destruction of alveolar walls
   may be due to chronic irritation (eg smoking)
   loss of tissue elasticity

5. **lung cancer**
   uncontrolled growth of cells
   crowd out normal cells

B. Diseases of Poor Gas Exchange

1. **emphysema**

2. **infections**
   viral or bacterial
   eg. hay fever, bronchitis
   cause lining of tubes to swell and become inflamed

2. **pneumonia**
   more severe result of respiratory infection
   bacterial or viral
   alveoli fill with fluids

3. **tuberculosis**
   tubercles formed to wall off bacterial infection
   if infection is not controlled may invade more lung tissue causing fibrosis
causes extensive destruction of lung tissue

4. **Respiratory Distress Syndrome**
collapse of lungs in baby due to lack of surfactants