Pulmonary Adaptations

The Respiratory System

1 Larynx; 2 Pulmonary arteriole; 3 Pulmonary venule; 4 Respiratory bronchiole; 5 Alveoli; 6 Lnugs; 7 Tertiary bronchiole; 8 Secondary bronchiole; 9 Primary bronchi; 10 Right bronchi; 11 Trachea

Items 1, 10, 9, 8, 7 = conducting zone
Items 4 and 5 = respiratory zone
This is a cast of the airways that conduct air to the lungs.

Why is this morphology potentially detrimental to air conductance into and from the lungs?

Note;
The respiratory zone has the greatest surface area and a dense capillary network.
Note the density of the alveoli and their thin walls.

Note the dense capillary network that surrounds alveoli.

**Surfactant**
A phospholipoprotein molecule, secreted by specialized cells of the lung, that *lines the surface of alveoli and respiratory bronchioles*. Surfactant *lowers the surface tension* of the alveoli membranes, *preventing the collapse* of alveoli during exhalation and *increasing compliance* during inspiration.

**Respiration**
The process of gas exchange, which for the human body involves oxygen ($O_2$) and carbon dioxide ($CO_2$).

- **Internal respiration** - at the cellular level
- **External respiration** - at the lung
The distribution of surfactant is aided by holes that connect alveoli called Pores of Kohn.

**Ventilation**

The movement of air into and from the lung by the process of bulk flow.

Ventilation \((V_E)\) (L/min) = frequency (br/min) \(\times\) tidal volume (L)

For rest conditions,

\[
V_E (L/min) = 12 \text{ (br/min)} \times 0.5 \text{ (L)} = 6 \text{ L/min}
\]

For exercise at VO2max,

\[
V_E (L/min) = 60 \text{ (br/min)} \times 3.0 \text{ (L)} = 180 \text{ L/min}
\]

**Compliance** - the property of being able to increase size or volume with only small changes in pressure.
Ventilation During Rest

**Inspiration** is controlled by a repetitive discharge of action potentials from the *inspiratory center*.

**Expiration** involves the *passive recoil* of the diaphragm.

Minimal regulation from chemoreceptors occurs during normal acid-base conditions.

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**Alveolar Ventilation**

The volume of “fresh” air that reaches the respiratory zone of the lung.

Alveolar Ventilation ($V_A$) (L/min)

$$V_A = \text{frequency (br/min)} \times (\text{tidal volume} - 0.15) \text{ (L)}$$

For normal breathing conditions,

$$V_A = 12 \text{ (br/min)} \times (1.0 - 0.15) \text{ (L)}$$

$$= 12 \times 0.85 = 10.2 \text{ L/min}$$

For rapid shallow breathing conditions,

$$V_A = 60 \text{ (br/min)} \times (0.2 - 0.15) \text{ (L)} \quad (8.2b)$$

$$= 60 \times 0.05 = 3.0 \text{ L/min}$$
Lung Volumes and Capacities

- Maximal inspiratory level
- Maximal expiratory level
- Resting end-expiratory level

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tidal volume</td>
<td>V_t</td>
<td>Volume of air inhaled and exhaled each breath</td>
</tr>
<tr>
<td>Inspiratory reserve volume</td>
<td>IRV</td>
<td>Maximum volume of air that can be inhaled after a normal resting end tidal inspiration</td>
</tr>
<tr>
<td>Expiratory reserve volume</td>
<td>ERV</td>
<td>Maximum volume of air that can be exhaled after a normal resting end tidal expiration</td>
</tr>
<tr>
<td>Inspiratory capacity</td>
<td>IC</td>
<td>Sum of IRV + V_t</td>
</tr>
<tr>
<td>Expiratory capacity</td>
<td>EC</td>
<td>Sum of ERV + V_t</td>
</tr>
<tr>
<td>Vital capacity</td>
<td>VC</td>
<td>Maximum volume of air exhaled after reaching IC = IC + ERV</td>
</tr>
<tr>
<td>Forced vital capacity</td>
<td>FVC</td>
<td>Same as for VC, but with forced rapid exhalation</td>
</tr>
<tr>
<td>Forced expiratory volume in 1 s</td>
<td>FEV1</td>
<td>Maximum volume of air that can be expired in 1 s when starting at IC</td>
</tr>
<tr>
<td>Maximal voluntary ventilation</td>
<td>MVV</td>
<td>Maximum rate of ventilation that can be attained with voluntary effort</td>
</tr>
<tr>
<td>Residual volume</td>
<td>RV</td>
<td>Volume of air remaining in the lungs at ERV</td>
</tr>
<tr>
<td>Functional residual capacity</td>
<td>FRC</td>
<td>Sum of RV + ERV</td>
</tr>
<tr>
<td>Total lung capacity</td>
<td>TLC</td>
<td>Sum of V_t + IRV + ERV + RV</td>
</tr>
</tbody>
</table>

*Not determined by spirometry*
Control of Ventilation During Exercise

Diffusion of Gases
The gases of respiration (O$_2$ and CO$_2$) diffuse down pressure gradients that exist between,

a. pulmonary blood and the alveoli

b. systemic capillary blood and cells

The factors that govern the directionality and magnitude of gas diffusion are?
What Determines Gas Exchange?

The factors that govern the directionality and magnitude of gas diffusion are,

• the gas diffusion capacity

• the gas partial pressure gradient

• characteristics of the medium through which diffusion occurs (hydration, thickness, cross sectional area)

The fact that alveolar and blood gas partial pressures approximately reach equilibrium within the lung enables researchers to estimate arterial blood gas partial pressures from alveolar partial pressures!

Gas Partial Pressures in Atmospheric and Alveolar Air

<table>
<thead>
<tr>
<th>Gas</th>
<th>Air* Fraction</th>
<th>Air* Partial Pressure</th>
<th>Alveolar Fraction(^\wedge)</th>
<th>Alveolar Partial Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>H(_2)O</td>
<td>0</td>
<td>0</td>
<td>----</td>
<td>47</td>
</tr>
<tr>
<td>O(_2)</td>
<td>0.2095</td>
<td>159.0</td>
<td>0.1459</td>
<td>104</td>
</tr>
<tr>
<td>CO(_2)</td>
<td>0.0003</td>
<td>0.3</td>
<td>0.0561</td>
<td>40</td>
</tr>
<tr>
<td>N(_2)</td>
<td>0.7808</td>
<td>600.6</td>
<td>0.7980</td>
<td>569</td>
</tr>
</tbody>
</table>

* assumes dry air at sea level, P\(_B\)=760 mmHg

\(^\wedge\) note that the water vapor pressure is removed to calculate alveolar gas fractions
\[ P_{H_2O} = 47 \text{ mmHg} \]
\[ P_{gases} = 760 - 47 \text{ mmHg} = 713 \text{ mmHg} \]
\[ P_{O_2} = 104 \text{ mmHg} \]
\[ F_{O_2} = \frac{104}{713} = 0.146 \text{ mmHg} \]
\[ P_{CO_2} = 40 \text{ mmHg} \]
\[ F_{CO_2} = \frac{40}{713} = 0.0561 \]

Note the decreases in alveolar \(O_2\) fractions from atmospheric air to alveolar air. Note that estimating \(F_{A}\) as 0.146 enables you to estimate \(P_{A}O_2\) for any given barometric pressure condition.

**Oxy-hemoglobin Dissociation Curve**

Note the relatively flat region of the curve between 80-100 mmHg. Note the small range of \(PO_2\) in muscle during exercise when intramuscular \(PO_2\) may decrease to less than 5 mmHg.
Exchange of gas at the cellular level
(i.e., systemic capillary blood and muscle cells)

In addition to the Bohr and Haldane effects, unloading of oxygen is also aided by the molecule myoglobin.

Myoglobin is found within skeletal muscle fibers and is similar to hemoglobin in that it contains a heme prosthetic group that can bind oxygen.

When PaO2 drops below 60 mmHg, myoglobin has a higher affinity for oxygen than does hemoglobin.

This allows for a unidirectional transfer of O2 from hemoglobin (blood) to the myoglobin (muscle fiber).

Transport of Oxygen in the Blood
Oxygen is transported in blood bound to hemoglobin (Hb). 1 gram of Hb can maximally bind 1.34 mL of oxygen (1.34 mL O₂/g Hb @ 100% saturation).

Table 8.1: Examples of hemoglobin (Hb) and oxygen carrying capacity conditions (98% saturation and pH = 7.4)

<table>
<thead>
<tr>
<th>Population/Condition</th>
<th>[Hb]</th>
<th>mL O₂/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Males</td>
<td>14.0</td>
<td>183.8</td>
</tr>
<tr>
<td>Females</td>
<td>12.0</td>
<td>157.6</td>
</tr>
<tr>
<td>Blood Doping</td>
<td>18.0</td>
<td>236.4</td>
</tr>
<tr>
<td>Anemia</td>
<td>&lt; 10.0</td>
<td>&lt; 131.3</td>
</tr>
</tbody>
</table>

[Hb] = g/100 mL
The oxygen content (CaO$_2$) of blood can be calculated;

\[
CaO_2 = [Hb] \times \text{O}_2/\text{g Hb} \times \text{Hb-O}_2 \text{ saturation} \\
= 150 \, \text{g/L} \times 1.34 \, \text{mL O}_2/\text{g} \times 0.98 \\
= 197 \, \text{mL O}_2/\text{L}
\]

Another small source of oxygen in blood is the volume of *oxygen dissolved in plasma*. However, due to the low solubility of oxygen, this value is small and approximates,

\[
\text{dissolved O}_2 = 0.003 \, \text{mL} / 100 \, \text{mL blood} / \text{mmHg PO}_2 \\
\sim 0.3 \, \text{mL} / 100 \, \text{mL} \text{ at sea level \ (PaO}_2 \sim 100 \, \text{mmHg)}
\]
When acid is produced from metabolism, the liberated proton can bind with bicarbonate, eventually forming CO$_2$, which is then expired by the lung.

Buffering

The bicarbonate-carbon dioxide system relies on ventilation for proper function as a buffer system.

It is this increased production of carbon dioxide from the bicarbonate buffering of acid that accounts for the increase in RER above 1.0 during intense exercise.

Remember, the respiratory exchange ratio (RER) is calculated by;

\[
\frac{\text{VCO}_2}{\text{VO}_2}
\]
**Transport of Carbon Dioxide in the Blood**

The volume of CO₂ in the blood is approximately 10-fold greater than O₂.

<table>
<thead>
<tr>
<th>Transport Location</th>
<th>Form</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma</td>
<td>Dissolved</td>
<td>5</td>
</tr>
<tr>
<td>(&lt;10%)</td>
<td>CO₂ + H₂O → H₂CO₃ → H⁺ + HCO₃⁻</td>
<td>&lt;1</td>
</tr>
<tr>
<td></td>
<td>Bound to proteins</td>
<td>5</td>
</tr>
<tr>
<td><strong>Red Blood Cell</strong></td>
<td>CO₂ + H₂O → H₂CO₃ → H⁺ + HCO₃⁻</td>
<td>65</td>
</tr>
<tr>
<td>(90%)</td>
<td>Dissolved</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Bound to hemoglobin</td>
<td>20</td>
</tr>
</tbody>
</table>

Note, this is typical of intense exercise.

Note, this is typical of acute altitude exposure.
Acidosis

Quantified by the pH scale, where pH equals the negative logarithm of the hydrogen ion concentration ([H⁺])

\[ \text{pH} = -\log([\text{H}^+]) \quad \text{or} \quad [\text{H}^+] = 10^{-\text{pH}} \]

Normal blood pH is ~7.4 = [H⁺] = 0.0000004 M

The main determinants of blood pH are;
- Balance of proton release/consumption
- PaCO₂
- Ventilation
- Renal excretion of electrolyes, protons and bases
- Buffer capacity
- Concentration of HCO₃⁻ and other bases or acids

Acute Adaptations of Pulmonary Function During Exercise

After the onset of exercise there is;
- a rapid ↑ in ventilation (proportional to intensity)
- a similar rapid ↑ in pulmonary blood flow
- an improved \( V_E \) vs Q relationship in the lung (both ventilation & perfusion become more evenly distributed)
- ↑ lung compliance
- airway dilation and ↓ resistance to air flow (enlargement of trachea, dilation of bronchi & bronchioles)
**Ventilatory Threshold**

Exercise intensity at which there is a deviation from linearity in ventilation and an increase in $VE/VO_2$.

The abrupt increase in acidosis and subsequent increase in PaCO2, disproportionately increases ventilation above that of oxygen use.

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**Mechanics of Ventilation**

As ventilation increases, both tidal volume and breathing frequency increase, with an eventual plateau seen in tidal volume.

As ventilation and intensity increase;

- ↑ air remaining in lung after expiration
- ↑ inspiratory pleural pressure
- ↑ work of breathing
Exercise-Induced Hypoxemia

A lowering of partial pressure of oxygen (PaO\textsubscript{2}) (hypoxia) resulting in a reduced CaO\textsubscript{2} (hypoxemia) during exhausting exercise in highly endurance-trained individuals, even at sea level.

- decreased pulmonary transit time
- decreased / uneven diffusion capacities in lung
- venoarterial shunts
- ventilation-perfusion inequalities
- inadequate hyperventilation

Note, the decrement in SaO\textsubscript{2} is not totally dependent on the magnitude of VO\textsubscript{2}-max