CHAPTER 3

The Diffusion of Pulmonary Gases
• Ideal Gas Law

\[ PV = nRT \]
Ideal Gas Law

- Where $P$ is pressure, $V$ is volume, and $T$ is temperature on the Kelvin scale
- $N$ is the number of moles of gas molecules present
- $R$ is the gas constant
  - Fixed value of 0.02821
Ideal Gas Law

- If \( nR \) remains constant, then:

\[
\frac{P_1 \times V_1}{T_1} = \frac{P_2 \times V_2}{T_2}
\]
Boyle’s Law: $P_1 \times V_1 = P_2 \times V_2$

$$P_2 = \frac{P_1 \times V_1}{V_2}$$
Boyle’s Law: \( P_1 \times V_1 = P_2 \times V_2 \)

- If an air-tight container with a volume of 200 mL and a pressure of 10 cm H\(_2\)O, has its volume reduced by 100 mL, the new pressure will be:

\[
P_2 = \frac{P_1 \times V_1}{V_2}
\]

\[
= \frac{10 \text{ cm H}_2\text{O} \times 200 \text{ mL}}{100}
\]

\[
= 20 \text{ cm H}_2\text{O}
\]
Charles’ Law

\[ V_2 = \frac{V_1 \times T_2}{T_1} \]
Charles’ Law

• If the temperature of the gas in a 3-liter balloon is increased from 250 K° to 300 K°, the resulting volume of the balloon would be:

\[ V_2 = \frac{V_1 \times T_2}{T_1} \]

\[ = \frac{3 \text{ L} \times 300 \text{ K}}{275 \text{ K}} \]

\[ = 68 \text{ cm H}_2\text{O} \]
Gay Lussac’s Law

\[ P_2 = \frac{P_1 \times T_2}{T_1} \]
Gay Lussac’s Law

• If the temperature of the gas in a closed container, having a pressure of 50 cm $H_2O$, is increased from 275 K° to 375 K°, the resulting pressure would be:

$$P_2 = \frac{P_1 \times T_2}{T_1}$$

$$= \frac{50 \text{ cm } H_2O \times 375 \text{ K}}{275}$$

$$= 68 \text{ cm } H_2O$$
Dalton’s Law

Figure 3-1. Dalton’s law.
• Barometric pressure
  – The force of atmospheric gases surrounding the earth exert this force on the earth’s surface
<table>
<thead>
<tr>
<th>Gas</th>
<th>% of Atm</th>
<th>mm Hg</th>
</tr>
</thead>
<tbody>
<tr>
<td>N\textsubscript{2}</td>
<td>78.08</td>
<td>593</td>
</tr>
<tr>
<td>O\textsubscript{2}</td>
<td>20.95</td>
<td>159</td>
</tr>
<tr>
<td>Ar</td>
<td>0.93</td>
<td>7</td>
</tr>
<tr>
<td>CO\textsubscript{2}</td>
<td>0.03</td>
<td>0.2</td>
</tr>
</tbody>
</table>
EXAMPLE:  \( PO_2 \) ?

\( PO_2 = \text{Barometric Pressure} \times \% \text{ of Oxygen} \)

\( PO_2 = 760 \times 0.2095 \)

= 159
Partial Pressure of Oxygen and Carbon Dioxide

- Partial pressure (mm Hg) of gases in the air, alveoli, and blood

<table>
<thead>
<tr>
<th>Gas</th>
<th>Dry Air</th>
<th>Alveolar Gas</th>
<th>Arterial Blood</th>
<th>Venous Blood</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{PO}_2$</td>
<td>159</td>
<td>100</td>
<td>95</td>
<td>40</td>
</tr>
<tr>
<td>$\text{PCO}_2$</td>
<td>0.2</td>
<td>40</td>
<td>40</td>
<td>46</td>
</tr>
<tr>
<td>$\text{PH}_2\text{O}^+$</td>
<td>0.0</td>
<td>47</td>
<td>47</td>
<td>47</td>
</tr>
<tr>
<td>$\text{PN}_2*$</td>
<td>600</td>
<td>573</td>
<td>573</td>
<td>573</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>760</td>
<td>760</td>
<td>755</td>
<td>706</td>
</tr>
</tbody>
</table>

$^+$ water vapor

* and other gases in minute quantities
Partial Pressure of Oxygen and Carbon Dioxide

• In Table 3-2, why is $PO_2$ in the atmosphere (159) so much higher than the $PO_2$ in the alveoli (100)?

Answer:

$$PCO_2 = 40 \text{ mm Hg}$$

$$PH_2O = 47 \text{ mm Hg}$$
Water Vapor Pressure

- Water can exist as a liquid, gas, or solid
- Water in gaseous form is called water vapor, or molecular water
- Alveolar gas is assumed to have an absolute humidity of 44 mg/L, and a water vapor pressure of 47 mm Hg
## Relationship Between Temperature, Absolute Humidity, and Water Vapor Pressure

<table>
<thead>
<tr>
<th>Temperature (Celsius)</th>
<th>Absolute Humidity (mg/L)</th>
<th>Water Vapor Pressure (mm Hg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>370</td>
<td>44.0</td>
<td>47.0</td>
</tr>
<tr>
<td>350</td>
<td>39.6</td>
<td>42.2</td>
</tr>
<tr>
<td>300</td>
<td>30.4</td>
<td>31.8</td>
</tr>
<tr>
<td>270</td>
<td>25.8</td>
<td>26.7</td>
</tr>
<tr>
<td>250</td>
<td>23.0</td>
<td>23.8</td>
</tr>
<tr>
<td>200</td>
<td>17.3</td>
<td>17.5</td>
</tr>
</tbody>
</table>

Table 3-3
Ideal Alveolar Gas Equation

\[ PAO_2 = \left[ P_B - PH_2O \right] FIO_2 - PaCO_2 \ (1.25) \]
Ideal Alveolar Gas Equation

• If a patient is receiving an FIO$_2$ of 0.40 on a day when the barometric pressure is 755 mm Hg
• And if the PaCO$_2$ is 55
  – Then the patient’s alveolar oxygen tension is: (next slide)
Ideal Alveolar Gas Equation

\[ PAO_2 = [P_B - PH_2O] \times FIO_2 - PaCO_2 \ (1.25) \]

\[ = [755 - 47] \times 0.40 - 55 \ (1.25) \]

\[ = [708] \times 0.40 - 68.75 \]

\[ = 214.45 \]
Ideal Alveolar Gas Equation

• Clinically, when the PaCO$_2$ is less than 60 mm Hg
• And when the patient is receiving oxygen
  – The following simplified equation may be used:

  \[ \text{PAO}_2 = [P_B - PH_2O] \times FIO_2 - \text{PaCO}_2 \]
Figure 3-2. The major barriers of the alveolar-capillary membrane through which a gas molecule must diffuse.
Figure 3-3. Normal gas pressure for $O_2$ and $CO_2$ as blood moves through the alveolar capillary membrane.

$P_{O_2} = 100$ mm Hg

$P_{CO_2} = 40$ mm Hg

Nonoxygenated Blood

$P^\nu_{O_2} = 40$ mm Hg

$P^\nu_{CO_2} = 46$ mm Hg

Alveolus

Reoxygenated Blood

$PaO_2 = 100$ mm Hg

$PaCO_2 = 40$ mm Hg

Blood Flow
Diffusion Across Alveolar-Capillary Membrane Under Normal Conditions

Figure 3-4. Under normal resting conditions, blood moves through the alveolar capillary membrane in about 0.75 seconds.
Figure 3-5. During exercise or stress, the total transit time for blood through the alveolar capillary membrane is less than normal.
Diffusion Across Alveolar-Capillary Membrane with Alveolar Thickening

Figure 3-6. When the rate of diffusion is decreased because of alveolar thickening, oxygen equilibrium will likely not occur.
Gas Diffusion

- Fick’s Law

\[ V_{\text{gas}} = \frac{A \cdot D \cdot (P_1 - P_2)}{T} \]
Fick’s Law

Figure 3-7. Fick’s law.

\[ \dot{V}_{\text{gas}} \propto \frac{A.D. \cdot (P_1 - P_2)}{T} \]
Henry’s Law

• Amount of a gas that dissolves in a liquid at a given temperature is proportional to the partial pressure of the gas.

• Amount that can be dissolved is known as the gas’s:
  – Solubility coefficient
Henry’s Law

\[
\frac{\text{Solubility CO}_2}{\text{Solubility O}_2} = \frac{0.592}{0.0244} = 24
\]
Graham’s Law

• Rate of diffusion of a gas through a liquid is:
  – Directly proportional to the solubility coefficient of the gas, and
  – Inversely proportional to the square root of the gram-molecular weight (GMW) of the gas
In Comparing Rates of Diffusion of Oxygen (GMW: 32) and Carbon Dioxide (GMW: 44)

\[
\frac{\text{Diffusion rate for CO}_2}{\text{Diffusion rate for O}_2} = \frac{\sqrt{gmw O_2}}{\sqrt{gmw CO_2}} = \frac{\sqrt{32}}{\sqrt{44}}
\]

\[
= \frac{5.6}{6.6}
\]
Graham’s and Henry’s Laws

• By combining Graham’s and Henry’s laws, the rates of diffusion of two gases are:
  – Directly proportional to the ratio of their solubility coefficients, and
  – Inversely proportional to the ratio of their gram-molecular weights
Graham’s and Henry’s Laws

When the two laws are used to determine the relative rates of diffusion of $O_2$ and $CO_2$

\[
\frac{\text{Diffusion rate for } CO_2}{\text{Diffusion rate for } O_2} = \frac{5.6 \times 0.0592}{6.6 \times 0.0244} = 20
\]

$CO_2$ diffuses about 20 times faster than $O_2$
Clinical Application of Fick’s Law

\[ V_{\text{gas}} = \frac{A \times D \times (P_1 - P_2)}{T} \]
Clinical Application of Fick’s Law

• Area (A) component of the law verified when:
  – Decreased alveolar surface area
    • Caused by alveolar collapse or alveolar fluid, which decreases ability of oxygen to enter the pulmonary capillary blood
Clinical Application of Fick’s Law

• $P_1 - P_2$ portion of the law is confirmed when:
  – Decreased alveolar oxygen pressure ($PAO_2$ or $P_1$)
    • Caused by high altitudes or alveolar hypoventilation, which reduces diffusion of oxygen into pulmonary capillary blood
Clinical Application of Fick’s Law

• Thickness (T) factor is confirmed when:
  – Increased alveolar tissue thickness caused by alveolar fibrosis or alveolar edema reduces movement of oxygen across alveolar-capillary membranes
Perfusion-Limited Gas Flow

- Perfusion limited
  - Transfer of gas across the alveolar wall is a function of the amount of blood that flows past the alveoli.
Figure 3-8. Nitrous oxide ($\text{N}_2\text{O}$) quickly equilibrates with pulmonary blood. When equilibrium occurs, the diffusion of $\text{N}_2\text{O}$ stops.
Diffusion-Limited Gas Flow

• Diffusion limited
  – Movement of gas across the alveolar wall is a function of the integrity of the alveolar-capillary membrane itself
Carbon monoxide (CO) rapidly bonds to hemoglobin and, thus, does not generate an appreciable partial pressure in the plasma.
Clinical Conditions that Cause Diffusion Problems

Figure 3-10. Clinical conditions that decrease the rate of gas diffusion – diffusion-limited problems.

- Alveolar Collapse (Atelectasis)
- Alveolar-Capillary Destruction (Emphysema)
- Interstitial Edema
- Thickenig of Alveolar Wall (Alveolar Fibrosis)
- Alveolar Consolidation (Pneumonia)
- Frothy Secretions (Pulmonary Edema)
## Factors that Affect Measured DL\textsubscript{CO}

<table>
<thead>
<tr>
<th>Factor</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>Increases with age</td>
</tr>
<tr>
<td>Lung Volume</td>
<td>Increases with lung size</td>
</tr>
<tr>
<td>Body size</td>
<td>Increases with body size</td>
</tr>
<tr>
<td>Body position</td>
<td>Greater in supine position</td>
</tr>
<tr>
<td>Exercise</td>
<td>Increases with exercise</td>
</tr>
<tr>
<td>Alveolar PO\textsubscript{2} (PA\textsubscript{O2})</td>
<td>Decreases with high PA\textsubscript{O2}</td>
</tr>
<tr>
<td>Hemoglobin (Hb)</td>
<td>Decreases with low Hb</td>
</tr>
<tr>
<td>Carboxyhemoglobin</td>
<td>Decreases when CO in blood</td>
</tr>
</tbody>
</table>
HOW OXYGEN CAN BE EITHER PERFUSION OR DIFFUSION LIMITED
Figure 3-11. Under normal resting conditions, the diffusion of oxygen is perfusion limited.
Clinical Application 1 Discussion

• How did this case illustrate …

• Both the adverse and therapeutic effects of factors presented in Fick’s law?
Clinical Application of Fick’s Law

\[ V_{\text{gas}} = A \cdot D \cdot \frac{(P_1 - P_2)}{T} \]
Alveoli with Pulmonary Edema

Figure 3-12. Cross-sectional view of alveoli with pulmonary edema. Pathology includes (1) interstitial edema, (2) fluid engorgement throughout the alveolar wall interstitium, and (3) frothy white secretions in the alveoli.
Clinical Application 2 Discussion

• How did this case illustrate …
• Both the acute and chronic effects of an increased alveolar-capillary membrane?