Today, we will:

- Continue discussing The Respiratory System
- Describe spirometry, the Bohr model, and the extended Bohr model
- Discuss carbon monoxide (CO) and why CO is hazardous

Figure 2.10 Compliance of the lung during inspiration and expiration (adapted from Guyton, 1986).

Figure 2.11 Lung volumes and elements of spirometry. A pen records changes in the air volume on graph paper that moves to the left. The residual volume and functional residual volume cannot be measured with the spirometer (from Heinsohn & Kabel, 1999).
\( V_r = \text{residual volume} = \text{vol. left over in lungs after max. exhalation} \)
\( V_r = 1500 \text{ mL} \)

\( V_{fr} = \text{functional residual volume} = \text{same thing except for normal breathing} \)
\( V_{fr} = 3000 \text{ mL} \)

\[ \text{The Bohr Model} \rightarrow \text{unsteady model} \]
models lung as a big balloon with a rigid pipe to model the bronchial tree

\[ V_d = \text{anatomic dead space} \]
\[ < 150 \text{ mL} \]

\[ V_a(t) = \text{alveolar volume} \]

Actual breathing: 
- unsteady
- variable volume
- nonuniform concentration (of \( O_2, CO_2, + \text{contaminants} \))

The extended Bohr Model – Alveole
- steady
- fixed volume
- well-mixed

Well mixed means the concentrations are uniform everywhere in space (inside lung)
The Extended Bohr Model:

**Inspiration:**
- $Q_a$: air flow rate
- $C_{molar, air}$
- Inhale, $C_{molar} = C_{molar, air}$
- Alveolar region (well mixed)
- $V_{alveolar}$, $C_{molar, alveolar}$

**Expiration:**
- $Q_o$: air flow rate
- $C_{molar} = C_{molar, alveolar}$

Alveolar capillary barrier
- $Q_b$, $k_b$, $P_{venous}$
- $dP_y$
- $dy$
- $P_y$ and $P_y + dP_y$
- $y$
- $L$
- Blood
- $Q_b$, $k_b$

$P_y$ and $dP_y$

**Figure 2.24** Extended Bohr model illustrating mass transfer of a nonreacting gas through the alveolar capillary barrier.

(From Heinsohn and Cimbala, Indoor Air Quality Engineering, 2003.)

- $Q_b$: blood flow rate (liquid), L/min or mL/min
- $V_{alveolar} \sim 3000$ mL
- $C_{alveolar}$ = molar conc. of $O_2$, $CO_2$, or some species
- $C_{molar, alveolar}$ = molar conc. $C_{molar} = C_{molar, alveolar}$
- $k_b$: solubility coefficient

**Volume of gas that can be absorbed by the blood**

**Volume of blood**

- e.g., $k_b$ for Oxygen
- $k_b = 10.7 \frac{\text{mL} O_2}{\text{mL} \text{ blood}}$

**How can $k_b$ be > 1?**
- $O_2$ & a gas, blood is a liquid
Hemoglobin molecule — attach O\textsubscript{2} in the molecule

Define \( Q_t \) = tidal ventilation rate

\( = \text{avg. volume flow rate of air breathed in at rest} \)

\[ Q_t = V_t \times f \]

\( f = \text{breathing frequency} \)

Typ. 10 to 15 breaths per minute

d' take \( f = 12 \) on average

\[ Q_t = (500 \ \text{mL/breath})(12 \ \text{breath/min}) = 6000 \ \text{mL/min} = 6 \ \text{L/min} \]

Not all of this is useful due to the anatomic dead space

Define \( Q_a \) = alveolar ventilation rate = avg. volume flow rate of fresh air that actually reaches the alveoli for gas exchange

\[ Q_a = (V_t - V_d) \times f \]

\[ Q_a = (500 - 150) \ \text{mL/breath} \times (12 \ \text{breath/min}) = 4200 \ \text{mL/min} = 4.2 \ \text{L/min} \]
\[ Q_a = (1 - \frac{V_d}{V_t}) Q_t \]

At rest, you use only about \( V_a = V_t - V_d \)

\[ = 800 - 158 = 642 \text{ mL of fresh air per breath} \]

\( V = \text{total lung capacity} = 6580 \text{ mL} \)

\[ \frac{V_a}{V} = \frac{350}{6580} = 5\% \]

\( R_{vp} = \text{ventilation perfusion ratio} = \frac{Q_a}{Q_b} \)

\[ \begin{align*}
\text{Table 2.4 in H\&C lists } & Q_t, V_t, R_{vp}, \text{ etc. for } \\
4 \text{ standard levels of exercise:} & \\
R &= \text{rest} \\
LE &= \text{light exercise} \\
ME &= \text{moderate} \\
HE &= \text{heavy} \\
\text{As exercise level } \uparrow & \text{ } Q_t \uparrow \text{ } Q_a \uparrow \text{ } Q_b \uparrow \\
\text{Exerc. level is limited by heart, not lungs} & \\
\text{But, } Q_a \text{ increases faster than } Q_b \text{ increases} \\
\therefore R_{vp} &= \frac{Q_a}{Q_b} \text{ grows } \uparrow \\
\text{With exercise at ME (by a factor of } \approx 2.6) &
\end{align*} \]
Table 2.4  Ventilation, blood flow, and the ventilation perfusion ratio \((R_{vp})\) during various activity levels (abstracted from Ultman, 1988 and 1989).

<table>
<thead>
<tr>
<th>parameter</th>
<th>exercise or activity level</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>rest</td>
</tr>
<tr>
<td>ventilation rate, (Q_t) (L/min)</td>
<td>11.6</td>
</tr>
<tr>
<td>frequency, min(^{-1}) = (\dot{f})</td>
<td>13.6</td>
</tr>
<tr>
<td>tidal volume, (V_t) (L)</td>
<td>0.85</td>
</tr>
<tr>
<td>(V_d/V_t)</td>
<td>0.34</td>
</tr>
<tr>
<td>blood flow, (Q_b) (L/min)</td>
<td>6.5</td>
</tr>
<tr>
<td>(Q_a = Q_t(1 - V_d/V_t)) (L/min)</td>
<td>7.66</td>
</tr>
<tr>
<td>(R_{vp} = Q_a/Q_b)</td>
<td>1.18</td>
</tr>
</tbody>
</table>

\(\text{Also, oxygen uptake efficiency goes down as exercise level goes up}\)

(see footnote on next table)
**Figure 2.26** Absorption efficiency versus modified ventilation-perfusion ratio for different values of the diffusion parameter corresponding to rest (R), light exercise (LE), moderate exercise (ME) and heavy exercise (HE) (adapted from Ultman, 1988).

<table>
<thead>
<tr>
<th>activity level</th>
<th>$N_D$</th>
<th>$R_{vpm}$</th>
<th>$\eta_u$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>rest state</em> (R)</td>
<td>1.0</td>
<td>0.11</td>
<td>85.</td>
</tr>
<tr>
<td><em>light exercise state</em> (LE)</td>
<td>0.49</td>
<td>0.18</td>
<td>69.</td>
</tr>
<tr>
<td><em>moderate exercise state</em> (ME)</td>
<td>0.37</td>
<td>0.21</td>
<td>59.</td>
</tr>
<tr>
<td><em>heavy exercise state</em> (HE)</td>
<td>0.31</td>
<td>0.29</td>
<td>48.</td>
</tr>
</tbody>
</table>

**Reduction in Oxygen Uptake Efficiency**

- $\eta_u$: Oxygen uptake efficiency
- $\eta_u \downarrow$: as exercise level ↑

**Carbon Monoxide (CO)**

- Hemoglobin absorbs CO more readily than O₂
- $\eta_u_{CO} > \eta_u_{O₂}$
- CO is toxic because it causes your blood to absorb less oxygen than your body needs. CO itself does not harm your body.
Figure 2.41 Response to carbon monoxide as a function of concentration (PPM) and exposure time (hr). The OSHA 8-hr PEL is 35 PPM and the EPA Primary Air Quality Standard is 9 PPM (redrawn from Seinfeld, 1986).

Comment: • Amount of CO in your bloodstream depends on both CO concentration and exposure time.

• E.g., 600 PPM → 1 hr exposure causes headache
  → 10 hr → death