Aerospace Physiology

- Lecture #11 – Oct. 7, 2014
- Cardiopulmonary physiology
  - Respiratory
  - Cardiovascular
- Musculoskeletal
- Vestibular
- Neurological
- Environmental Effects
The Human Respiratory System
Lung Measurements

Respiratory Volume vs. Exertion

Notes:
1. All figures are average values. There is considerable variation between individuals.
2. STPD means "standard temperature and pressure, dry gas." As given here, it is medical STPD (i.e., 32°F, 1 ata, dry gas). For oxygen cylinder endurance or helmet ventilation calculations, the values should be multiplied by 1.08 to yield engineering STPD.
3. BTPS means "body temperature (98.6°F), ambient barometric pressure, saturated with water vapor at body temperature." For open-circuit scuba endurance calculations, this value should be multiplied by 0.95 to give corresponding values for dry gas at 70°F. The 0.95 factor ignores difference in the water vapor content between dry and saturated gas, but this is very small at most diving depths.

- Uphill Running (4.0, 95)
- Severe Work
- Swimming, 1.2 knots (2.5, 60) (Note 2)
- Running, 8 mph (2.0, 50)
- Heavy Work
- Max Walking Speed, Mud Bottom Swimming, 1.0 knot
- Max Walking Speed, Hard Bottom Swimming, 0.85 knot (avg. speed) (1.8, 40)
- Moderate Work
- Walking, 4 mph (1.2, 27)
- Slow Walking on Mud Bottom (1.1, 23)
- Walking, 2 mph (0.7, 16)
- Light Work
- Slow Walking on Hard Bottom (0.6, 12)
- Standing Still (0.40, 9)
- Sitting Quietly (0.30, 7)
- Rest (0.25, 6)
Metabolic Processes

• Respiratory Quotient ("RQ")

\[
RQ = \frac{\text{Exhaled volume of } \text{CO}_2}{\text{Inhaled volume of } \text{O}_2}
\]

• Function of activity and dietary balance
  – Sugar: \( C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O \) \((RQ = 1.0)\)
  – Protein: \( 2C_3H_7O_2N + 6O_2 \rightarrow 5CO_2 + 5H_2O \) \((RQ = 0.83)\)
  – Fat: \( C_{57}H_{104}O_6 + 80O_2 \rightarrow 57CO_2 + 52H_2O \) \((RQ = 0.71)\)

• For well-balanced diet, RQ~0.85
The Human Circulatory System

Arterial Network:

Vein Network:

Muscle contracts
Valve closed

Muscle relaxes
Valve open

Blood propelled forward by
muscle contractions and,
possibly, by gravity

Back pressure due to
contractions of atria,
contractions of muscles, and,
possibly, gravity
Blood Pressure in Circulatory System

- Artery
- Arterioles
- Capillaries
- Venules
- Vein

Blood pressure (mm Hg)

Velocity (cm/sec)

Total area (cm²)

Large arteries
Small arteries
Arterioles
Capillaries
Venules
Veins
Gas Exchange in the Lungs

Gas Exchange in the Tissues

Respiratory Problems

• Hypoxia
  – Hypoxic
  – Hypemic
  – Stagnant
  – Histotoxic
• Hyperoxia
• Hypocapnia
• Hypercapnia
Types of Hypoxia

- **Hypoxic** (insufficient O₂ present)
  - Decompression
  - Pneumonia

- **Hypemic** (insufficient blood capacity)
  - Hemorrhage
  - Anemia

- **Stagnant** (insufficient blood transport)
  - Excessive acceleration
  - Heart failure

- **Histotoxic** (insufficient tissue absorption)
  - Poisoning
Pressure Effects on Blood Oxygenation

Pressure Effects on Blood Oxygenation

Effects of Supplemental Oxygen

From Roy DeHart, Fundamentals of Aerospace Medicine, Lea & Febiger, 1985
Hypoxia Effective Performance Time

From Roy DeHart, Fundamentals of Aerospace Medicine, Lea & Febiger, 1985
Lung Overpressure Following Decompression

Oxygen Toxicity

Effects of \( \text{ppCO}_2 \)

Acute Effects of Hyperventilation

Gravity Effects on Arterial Pressure

- Doppler sound (cholesterol plaque)
- Carotid Artery
- Jugular Vein
- Cephalic Vein
- Axillary Artery and Vein
- Superior Vena Cava
- Ascending Aorta
- Pulmonary Trunk
- Celiac Artery
- Renal Artery and Vein
- Superior Mesenteric Artery
- Portal Vein
- Radial Artery and Vein
- Ulnar Artery and Vein
- Inferior Vena Cava
- Abdominal Aorta
- Ultrasound image (aneurysm)
- Peroneal Artery
- Tibial Vein
- Subclavian Artery and Vein
- Pulmonary Arteries and Veins
- Coronary Angiogram (atherosclerotic plaque)
- Coronary Arteries
- Common Iliac Artery and Vein
- Internal Iliac Artery and Vein
- External Iliac Artery and Vein
- Great Saphenous Vein
- Femoral Artery and Vein
- Popliteal Artery and Vein
- Anterior Tibial Artery
- Posterior Tibial Artery

**Pressures**
- 95/55 mmHg
- 120/80 mmHg
- 1200 mm
- 210/170 mmHg
- 1000 mmH₂O = 74.1 mmHg
The Human Circulatory System, Revisited

**Muscle contracts**
- Valve closed
- Blood propelled forward by muscle contractions and, possibly, by gravity

**Muscle relaxes**
- Valve open
- Back pressure due to contractions of atria, contractions of muscles, and, possibly, gravity
Cardiovascular Effects of Microgravity

- Cardiovascular deconditioning
- Upper body blood pooling
- Changes in blood volume
- Increased calcium content
Acceleration Effects on Arterial Pressure

At 4 g’s longitudinal:
1000 mm$H_2O = 296$ mmHg

25/-- mmHg

320 mm

120/80 mmHg

1200 mm

475/435 mmHg
Supersaturation of Blood Gases

- Early observation that “factor of two” (50% drop in pressure) tended to be safe
- Definition of tissue ratio $R$ as ratio between saturated pressure of gas compared to ambient pressure

$$ R = \frac{P_{N2}}{P_{ambient}} = 0.79 \text{ (nominal Earth value)} $$

- 50% drop in pressure corresponds to $R=1.58$ ($R$ values of $\sim1.6$ considered to be “safe”)}
Tissue Models of Dissolved Gases

- Issue is dissolved inert gases (not involved in metabolic processes, like N2 or He)
- Diffusion rate is driven by the gradient of the partial pressure for the dissolved gas

\[
\frac{dP_{tissue}(t)}{dt} = k \left[ P_{alveoli}(t) - P_{tissue}(t) \right]
\]

where \( k \) = time constant for specific tissue (min\(^{-1}\))

\( P \) refers to partial pressure of dissolved gas
Solution of Dissolved Gas Differential Eqn.

• Assume ambient pressure is piecewise constant (response to step input of ambient pressure)
• Result is the Haldane equation:

\[ P_{tissue}(t) = P_{tissue}(0) + [P_{alveoli}(0) - P_{tissue}(0)] (1 - e^{-kt}) \]

• Need to consider value of \( P_{alveoli} \)

\[ P_{alveoli} = (P_{ambient} - P_{H2O} - P_{CO2} + \Delta P_{O2}) Q \]

\[ P_{alveoli} = \left( P_{ambient} - P_{H2O} + \frac{1 - RQ}{RQ} P_{CO2} \right) Q \]

where \( Q \)=fraction of dissolved gas in atmosphere
\( \Delta P_{O2} \)=change in ppO2 due to metabolism
Linearly Varying Pressure Solution

- Assume R is the (constant) rate of change of pressure - solution of dissolved gases PDE is

\[ P_t(t) = P_{alv0} + R \left( t - \frac{1}{k} \right) - \left( P_{alv0} - P_{t0} - \frac{R}{k} \right) e^{-kt} \]

- This is known as the Schreiner equation
- For R=0 this simplifies to Haldane equation
- Produces better time-varying solutions than Haldane equation
- Easily implemented in computer models
Haldane Tissue Models

- Rate coefficient frequently given as time to evolve half of dissolved gases:

\[ T_{1/2} = \frac{\ln(2)}{k} \quad \text{and} \quad k = \frac{\ln(2)}{T_{1/2}} \]

- Example: for 5-min tissue, \( k = 0.1386 \) min\(^{-1}\)

- Haldane suggested five tissue “compartments”: 5, 10, 20, 40, and 75 minutes

- Basis of U. S. Navy tables used through 1960’s

- Three tissue model (5 and 10 min dropped)

- 1950’s: Six tissue model (5, 10, 20, 40, 75, 120)
Workman Tissue Models

• Dr./Capt. Robert D. Workman of Navy Experimental Diving Unit in 1960’s
• Added 160, 200, 240 min tissue groups
• Recognized that each type of tissue has a differing amount of overpressure it can tolerate, and this changes with depth
• Defined the overpressure limits as “M values”
Workman M Values

• Discovered linear relationship between partial pressure where DCS occurs and depth

\[ M = M_0 + \Delta M d \]

\( M \) = partial pressure limit (for each tissue compartment)
\( M_0 \) = tissue limit at sea level (zero depth)
\( \Delta M \) = change of limit with depth (constant)
\( d \) = depth of dive

• Can use to calculate decompression stop depth

\[ d_{\text{min}} = \frac{P_t - M_0}{\Delta M} \]
Effect of Multiple Tissue Times

Nitrogen Sat/Desat Curves

- Percent Saturation vs. Time in Minutes
- Different curves represent tissue half-times: 5, 10, 20, 40, 80, 120, 160, 200
Physics of Bubbles

• Pressure inside a bubble is balanced by exterior pressure and surface tension

\[ P_{\text{internal}} = P_{\text{ambient}} + P_{\text{surface}} = P_{\text{ambient}} + \frac{2\gamma}{r} \]

where \( \gamma \) = surface tension in J/m\(^2\) or N/m (=0.073 for water at 273°K)

• Dissolved gas partial pressure \( P_g = P_{amb} \) in equilibrium

• Gas pressure in bubble \( P_{int} > P_{amb} \) due to \( \gamma \)

• All bubbles will eventually diffuse and collapse
Bubble Formation and Growth

- In equilibrium, external pressure balanced by internal gas pressure and surface tension
- Surface tension forces inversely proportional to radius
## Historical Data on Cabin Atmospheres

<table>
<thead>
<tr>
<th>Program</th>
<th>Cabin Pressure, kPa (psia)</th>
<th>Cabin Oxygen Concentration, volume %</th>
<th>EVA Suit Pressure, kPa (psia)</th>
<th>EVA O₂ Pre-breathe Time, minutes</th>
<th>EVA Prebreathe Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>34.5 (5)</td>
<td>100</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Gemini/Apollo</td>
<td>34.5 (5)</td>
<td>100</td>
<td>25.8 (3.75)</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Skylab</td>
<td>34.5 (5)</td>
<td>70</td>
<td>25.8 (3.75)</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Shuttle</td>
<td>70.3 (10.2)</td>
<td>26.5</td>
<td>29.6 (4.3)</td>
<td>40</td>
<td>In-suit (after 36 hours at 70.3 kPa)</td>
</tr>
<tr>
<td></td>
<td>101.3 (14.7)</td>
<td>21</td>
<td>29.6 (4.3)</td>
<td>240(3)</td>
<td>In-suit</td>
</tr>
<tr>
<td>ISS/US</td>
<td>101.3 (14.7)</td>
<td>21</td>
<td>29.6 (4.3)</td>
<td>120-140</td>
<td>Mask and in-suit; staged w/exercise</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>240(3)</td>
<td>In-suit</td>
</tr>
<tr>
<td>Salyut, Mir, ISS/Russian</td>
<td>101.3 (14.7)</td>
<td>21</td>
<td>40.0 (5.8)(2)</td>
<td>30</td>
<td>In-suit</td>
</tr>
</tbody>
</table>


1. 100% oxygen.
2. In earlier versions of the Orlan suit, the pressure could be reduced to 26.5 kPa (3.8 psia) for short-duration work regime.
3. Under emergency conditions, a minimum of 150 minutes of unbroken prebreathe is recommended.

from Scheuring et. al., "Risk Assessment of Physiological Effects of Atmospheric Composition and Pressure in Constellation Vehicles" 16th Annual Humans in Space, Beijing, China, May 2007
Spacecraft Atmosphere Design Space

from Scheuring et. al., “Risk Assessment of Physiological Effects of Atmospheric Composition and Pressure in Constellation Vehicles” 16th Annual Humans in Space, Beijing, China, May 2007
Effect of Pressure and %O₂ on Flammability

Atmosphere Design Space with Constraints

from Scheuring et. al., “Risk Assessment of Physiological Effects of Atmospheric Composition and Pressure in Constellation Vehicles” 16th Annual Humans in Space, Beijing, China, May 2007
## Constellation Spacecraft Atmospheres

<table>
<thead>
<tr>
<th>Environment</th>
<th>$P_B$ (psia mmHg)</th>
<th>$F_{1O_2}$ (%)</th>
<th>$P_{O_2}$ (mmHg)</th>
<th>$P_{A\text{O}_2}$ (mmHg)</th>
<th>Actual Altitude (m/feet)</th>
<th>Equivalent Air Altitude (m/feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEV + LSAM</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>normal</td>
<td>8.0 414</td>
<td>32.0</td>
<td>117</td>
<td>77</td>
<td>4,877/16,000</td>
<td>1,829/6,000</td>
</tr>
<tr>
<td>best case</td>
<td>8.2 424</td>
<td>34.0</td>
<td>128</td>
<td>86</td>
<td>4,816/15,800</td>
<td>1,158/3,800</td>
</tr>
<tr>
<td>worse case</td>
<td>7.8 403</td>
<td>30.0</td>
<td>107</td>
<td>68</td>
<td>5,029/16,500</td>
<td>2,438/8,000</td>
</tr>
<tr>
<td>HABITAT</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>normal</td>
<td>7.6 393</td>
<td>32.0</td>
<td>111</td>
<td>71</td>
<td>5,182/17,000</td>
<td>2,286/7,500</td>
</tr>
<tr>
<td>best case</td>
<td>7.8 403</td>
<td>34.0</td>
<td>121</td>
<td>80</td>
<td>5,029/16,500</td>
<td>1,524/5,000</td>
</tr>
<tr>
<td>worse case</td>
<td>7.4 383</td>
<td>30.0</td>
<td>101</td>
<td>63</td>
<td>5,364/17,600</td>
<td>2,895/9,500</td>
</tr>
</tbody>
</table>

From Scheuring et. al., “Risk Assessment of Physiological Effects of Atmospheric Composition and Pressure in Constellation Vehicles” 16th Annual Humans in Space, Beijing, China, May 2007
Categories of Sensing

- Proprioception (internal to body)
  - “Self-Sensing”
  - Vestibular (inertial forces)
  - Muscle and tendon sensors (extension)
  - Joint sensors (angle)
- Exteroception (external to body)
  - Visual
  - Auditory
  - Cutaneous
Anatomy of the Ear

Vestibular System

Vestibular Sense Organs