Aerospace Physiology

• Lecture #14 – October 10, 2019
• Cardiopulmonary physiology
  – Respiratory
  – Cardiovascular
• Musculoskeletal
• Vestibular
• Neurological
• Environmental Effects
The Human Respiratory System
Lung Measurements

Respiratory Volume vs. Exertion

Notes:
1. All values 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 atm, dry gas). For oxygen cylinder endurance calculations, these numbers should be multiplied by 1.08 to yield working STPD.
3. BTPS means body temperature, pressure, saturated with water vapor, actual body temperature. For men's sea-level endurance calculations, this value should be multiplied by 0.96 to give corresponding values for dry gases at 77°F. The 0.95 factor ignores difference in the water vapor content between dry and saturated gas, but this is very small at most working depths.

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Oxygen Consumption (liters/min, STPD) (Note 2)

Respiratory Volume (liters/min, BTPS) (Note 3)

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Severe Work
- Running, 8 mph (2.0, 50)
- Swimming, 1.2 knots (2.5, 60) (Note 2)

Heavy Work
- Max Walking Speed, Mud Bottom (1.8, 40)
- Swimming, 1.0 knot
- Walking, 4 mph (1.2, 27)
- Slow Walking on Mud Bottom (1.1, 23)
- Swimming, 0.8 km/h (0.05 knot) (avg. speed) (1.4, 30)
- Walking, 2 mph (0.7, 16)
- Slow Walking on Hard Bottom (0.6, 13)
- Standing Still (0.0, 0)
- Sitting Easily (0.30, 7)
- Bed Rest (Banai) (0.20, 6)
Metabolic Processes

• Respiratory Quotient (“RQ”)

\[ RQ = \frac{\text{Exhaled volume of } CO_2}{\text{Inhaled volume of } O_2} \]

• 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, \( RQ \sim 0.85 \)
The Human Circulatory System

Arterial Network:
- Aorta
- Pulmonary artery
- Thoracic aorta
- Abdominal aorta
- Femoral artery
- Popliteal artery
- Ascending aorta
- Descending aorta
- Aortic arch

Vein Network:
- Superior vena cava
- Inferior vena cava
- Pulmonary vein
- Left atrium
- Left ventricle
- Right atrium
- Right ventricle

Muscle contracts
Valve closed

Muscle relaxes
Valve open

Blood propelled forward by
contractions of muscles and,
possibly, by gravity

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

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

Hypoxia Effective Performance Time

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

Oxygen Toxicity

Effects of ppCO2

Acute Effects of Hyperventilation

Gravity Effects on Arterial Pressure

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

Muscle contracts
Valve closed

Muscle relaxes
Valve open

Valve open

Valve closed

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

Back pressure due to
contractions of atria,
contractions of muscles, and,
possibly, by 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 mmH₂O = 296 mmHg

25/— mmHg
120/80 mmHg
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

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

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:

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

- 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 \( Q = \text{fraction of dissolved gas in atmosphere} \)

\( \Delta P_{O2} = \text{change in ppO2 due to metabolism} \)
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:

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

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

• 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

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

NITROGEN SAT/DESAT CURVES

Percent Saturation vs. Time in Minutes

Tissue Half-Times

Nitrogen Saturation Curves for Different Tissue Half-Times
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 \( P_g = P_{\text{amb}} \) in equilibrium

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

• All bubbles will eventually diffuse and collapse
Critical Bubble Size

- Minimum bubble size is defined by point at which interior pressure $P_{\text{int}} = \text{gas pressure } P_g$
  \[ r_{\text{min}} = \frac{2\gamma}{P_g - p_{\text{ambient}}} \]
- $r < r_{\text{min}}$ - interior gas diffuses into solution and bubble collapses
- $r > r_{\text{min}}$ - bubble will grow
- $r = r_{\text{min}}$ - unstable equilibrium
## 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,$^1$ kPa (psia)</th>
<th>EVA $O_2$ 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>
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<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>
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<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>
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<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
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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
EVA Denitrogenation - 14.7 psi Cabin

Cabin Atmosphere 14.7 psi 21% O2

Tissue Nitrogen Pressure (psi) vs. Time (min)

- 5-min tissue
- 80-min tissue
- 240-min tissue

Suit Pressure 4.3 psi 100% O2

R Value = 1.4
EVA Denitrogenation - 8.3 psi Cabin

R Value = 1.4

Suit Pressure 4.3 psi 100% O2

Cabin Atmosphere 8.3 psi 32% O2

Tissue Nitrogen Pressure (psi)

Time (min)

5-min tissue
80-min tissue
240-min tissue
## Constellation Spacecraft Atmospheres

<table>
<thead>
<tr>
<th>Environment</th>
<th>$P_B$ (psia mmHg)</th>
<th>$F_{\text{O}_2}$ (%)</th>
<th>$P_{\text{O}_2}$ (mmHg)</th>
<th>$P_{\Delta\text{O}_2}$ (mmHg)</th>
<th>Actual Altitude (m feet)</th>
<th>Equivalent Air Altitude (m feet)</th>
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<tbody>
<tr>
<td><strong>CEV + LSAM</strong></td>
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<tr>
<td>normal</td>
<td>8.0</td>
<td>32.0</td>
<td>117</td>
<td>77</td>
<td>4,877 16,000</td>
<td>1,828 6,000</td>
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<tr>
<td>best case</td>
<td>8.2</td>
<td>34.0</td>
<td>128</td>
<td>86</td>
<td>4,816 15,800</td>
<td>1,158 3,800</td>
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<tr>
<td>worse case</td>
<td>7.8</td>
<td>30.0</td>
<td>107</td>
<td>68</td>
<td>5,029 16,500</td>
<td>2,438 8,000</td>
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<tr>
<td><strong>HABITAT</strong></td>
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<tr>
<td>normal</td>
<td>7.6</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</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</td>
<td>30.0</td>
<td>101</td>
<td>63</td>
<td>5,364 17,600</td>
<td>2,395 9,500</td>
</tr>
</tbody>
</table>

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

Thresholds of Rotational Perception

- Rotational accelerations
  - Yaw: $0.14 \text{ deg/sec}^2$
  - Roll and Pitch: $0.5 \text{ deg/sec}^2$

- Mulder’s Constant
  - Acceleration $\times$ excitation time $= 2 \text{ deg/sec}$
  - $5 \text{ deg/sec}^2 \times 0.5 \text{ sec}$ -> sensed
  - $10 \text{ deg/sec}^2 \times 0.1 \text{ sec}$ -> not sensed

- Rotational velocities - minimum perceived rotation rates 1-2 deg/sec (all axes)
Otolith Responses

Thresholds of Translational Perception

- $a_x$: 0.006 g
- $a_y$: 0.006 g
- $a_z$: 0.01 g
- Apparent change in direction of $g$ vector = 1.5°
Space Motion Sickness

• “Space Adaptation Syndrome”
• 2/3 of astronauts report some effects
• Symptoms
  – Primary: stomach discomfort, nausea, vomiting
  – Secondary: pallor, cold sweats, salivation, depressed appetite, fatigue
• No correlation to susceptibility to motion sickness
• Primary hypothesis: sensory conflict (Treisman’s Theory)
Progression of Space Motion Sickness

SAS Experience of First 34 Shuttle Flights

- First Flight
  - None: 24
  - Mild: 72
  - Moderate: 96
  - Severe: 50

- Subsequent Flight
  - None: 48
  - Mild: 48
  - Moderate: 96
  - Severe: 50
SAS Experience of First 34 Shuttle Flights

First Flight %

Subsequent Flight %

<table>
<thead>
<tr>
<th>None</th>
<th>Mild</th>
<th>Moderate</th>
<th>Severe</th>
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</thead>
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<tr>
<td>0.50</td>
<td>0.25</td>
<td>0.25</td>
<td>0.00</td>
</tr>
</tbody>
</table>
Space Motion Sickness Countermeasures

- Preflight training
  - Desensitization
  - Autogenic feedback training (AFT)

- Pharmaceuticals
  - Oral - scopolamine/dex-amphetamine (Scopdex)
  - Transdermal - scopolamine
  - Intramuscular - promethazine

- Mechanical systems
  - Pressurized insoles
  - Load suits
  - Neck restraints
Artificial Gravity

\[ g_{rotation} = \omega^2 r \]

- Lunar gravity
- Mars gravity
- 0.5*Earth gravity
- 0.75*Earth gravity
- Earth gravity
Allowable Rotation Rates

- Select groups (highly trained, physically fit) can become acclimated to 7 rpm
- 95% of population can tolerate 3 rpm
- Sensitive groups (elderly, young, pregnant women) may have tolerance levels as low as 1 rpm
References