Question 1
Response to Exercise

1. During exercise, which of the following increases:
   A. Arterial CO₂ content
   B. Arterial O₂ content
   C. Venous CO₂ content
   D. Arterial pH
   E. Physiologic Dead Space

Topic 1
Exercise Physiology

• Response to Exercise in Health:
  – Increase CO₂ Production [VCO₂] and O₂ Consumption [VO₂]
    • Normally 200 mL/min and 250 mL/min at rest respectively
    • \[ \text{RQ} = \frac{\text{VCO}_2}{\text{VO}_2} = 0.8 \]
    • Increases CvCO₂; Decreases CvO₂
  – TV/RR/MV all Increase
    • Normal values at rest 500cc, 10/min, 5 LPM
  – SV/HR/CO all Increase
    • Normal values at rest 75cc, 70/min, 5 LPM
    • Including pulmonary blood flow

RQ = Respiratory Quotient, CvCO₂ = Venous Content of CO₂, CvO₂ = Venous Content of O₂, TV = Tidal Volume, RR = Respiratory Rate, MV = Minute Ventilation, SV = Stroke Volume, HR = Heart Rate, CO = Cardiac Output
Topic 1
Response to Exercise

• Exercise in Health:
  – $\text{VO}_2$ increases until oxygen delivery fails to meet oxidative phosphorylation requirements at anaerobic threshold
    • After which lactic acidosis occurs

– Increases TV/RR/MV (3L, 40/min, 120 lpm)
– Increases SV/HR/CO (125cc, “220-age”, 25 lpm)
– NO CHANGE in arterial Oxygenation (PaO$_2$)
– Decreased Dead Space
Question 2
Respiratory System Compliance

2. The pressure-volume curve B describes which disease process:
A. Emphysema  
B. Pulmonary Fibrosis  
C. Cystic Fibrosis  
D. Bronchial Asthma

Topic 2
Respiratory System Compliance

- Compliance = ΔV/ΔP
  - Nl: 60 to 100 mL/cmH2O
- Increased Compliance:
  - Loss of elastic recoil
    - eg Emphysema
    - Hyperinflation
- Decreased Compliance:
  - Increased elastic recoil
    - eg Pulmonary Fibrosis
    - Small Lungs
Question 3
3. What accounts for the difference between minute ventilation and alveolar ventilation:
   A. Tidal Volume
   B. Respiratory Rate
   C. Functional Residual Capacity
   D. Residual Volume
   E. Dead Space

Topic 3
Dead Space
• Definition:
  – Volume of inspired gas that does not participate in gas exchange (ventilated but not perfused)
    • Anatomic: Major Trachea/Bronchi
    • Physiologic: Zone 1 of the Lung
**Topic 3: Dead Space**

**Definition:**
- Volume of inspired gas that does not partake in gas exchange (ventilated but not perfused)
  - Anatomic: Major Trachea/Bronchi
  - Physiologic: Zone 1 of the Lung

**Calculated:**
- \( \text{VD} = \text{VT} \left( \frac{\text{PaCO}_2 - \text{PeCO}_2}{\text{PaCO}_2} \right) \)
- \( \text{VD} / \text{VT} = \text{the fraction of each TV that is "wasted"} \)

**Normal Values:**
- TV 500cc
- Anatomic Dead Space ~ 1 cc/lb ~ 150 cc
- \( \text{VD} / \text{VT} = 150cc / 500cc = 30\% \)

\( \text{VD} \) = Dead Space Volume, \( \text{VT} \) = Tidal Volume (also abbreviated TV), \( \text{PaCO}_2 \) = partial pressure of CO₂ in the inspired gas

**VD/VT Decreases During Exercise (normally to < 15%)**
- Increased pulmonary blood flow to the apex resulting in reduced Zone 1
- And increased VT

**VD/VT Increases in Disease States including**
- Decreased Perfusion of Normally Ventilated Lung:
  - Pulmonary Emboli
  - Volume Depletion
  - Pulmonary Arterial Hypertension
- Increased Alveolar Pressures (Decreased Perfusion due to alveolar over-distension):
  - Mechanical Ventilation and intrinsic-PEEP in Emphysema

**Consequence of Increased VD/VT**
- Either reduced CO₂ elimination (hypercapnea)
- Or Increased Work of Breathing (dyspnea)

\( \text{PEEP} = \text{Positive End Expiratory Pressure} \)
Topic 3
Dead Space

<table>
<thead>
<tr>
<th>CO2 Production</th>
<th>Minute Ventilation</th>
<th>VD/VT</th>
<th>PaCO2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal At Rest</td>
<td>200 mL/min</td>
<td>SLM</td>
<td>Normal 40 mm Hg</td>
</tr>
</tbody>
</table>

Exercise Normal Normal
Panic Attack Normal Normal
Increased VD/VT with intact CNS Normal
Increased VD/VT without intact CNS Normal (inappropriately)
Pulmonary Embolism (due to pain, fever, anxiety, hypoxia) (Despite increased VD/VT due to an even greater increase in MV)

Question 4

4. A 65 yo M has these arterial blood gas findings:
   Normal PaO₂, Normal O₂ Saturation, Low O₂ Content
Which disease state best explains these results:
A. Anemia
B. Asthma
C. High Altitude
D. Emphysema
E. Cyanide Poisoning
Topic 4
O2 Pressure, Saturation, Content, and Delivery

- PaO2 = partial pressure of O2
- SaO2 = Saturation of Hgb
  - Each gram of Hgb can bind 1.34 mL O2
- CaO2 = Content of O2 in blood
  - CaO2 = (SaO2)(1.34)(Hgb) + (PaO2)(0.003)
- DaO2 = Delivery of O2
  - DaO2 = CaO2 * Cardiac Output

<table>
<thead>
<tr>
<th></th>
<th>PaO2</th>
<th>SaO2</th>
<th>CaO2</th>
<th>DaO2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>100 mm Hg</td>
<td>100%</td>
<td>20 mL O2/dL</td>
<td>1000 mL/min</td>
</tr>
<tr>
<td>&quot;Lung Disease&quot;</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Altitude</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Carbon Monoxide Poisoning</td>
<td>Normal</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Anemia</td>
<td>Normal</td>
<td>Normal</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Cardiomyopathy</td>
<td>Normal</td>
<td>Normal</td>
<td>Normal</td>
<td>Low</td>
</tr>
</tbody>
</table>
Question 5

5. A 25 yo living in Maywood reports dyspnea and has a PaO₂ of 70 and PaCO₂ of 32. Which of the following is increased:
A. Alveolar-Arterial Oxygen Gradient [150 – 32/(0.8) – 70 = 40]
B. Peripheral Oxygen Consumption
C. Left to Right Cardiac Shunting
D. Lung Diffusion Capacity

Topic 5
The Alveolar-Arterial Oxygen Gradient

• Definition:
  – The difference between the expected ALVEOLAR O₂ and the patient’s measured ARTERIAL O₂

• Conceptually:
  – What is the O₂ gradient between an ‘ideal’ alveolus and the pulmonary capillaries?
  – An elevated gradient implies disease

• Helps determine if your patient’s measured PaO₂ is what it “should” be:
  – i.e., A young person breathing room air at sea level should have a PaO₂ = 95 mmHg...
  – whereas a PaO₂ of 60 mmHg would be perfectly normal at altitude
  – and the PaO₂ should be over 500 if breathing 100% FIO₂
PB = PN2 + PH2O + PCO2 + PAlvO2

Mixed Venous Blood
PmvCO2 45 mmHg; PmvO2 40 mmHg

Arterial Blood
PaCO2 40 mmHg; PaO2 95 mmHg

Atmospheric Air
PatmO2 = PB x FIO2 = 760 x 0.21 = 160 mmHg

Air passing through the nasopharynx and tracheobronchial tree is humidified
PH2O = 47 mmHg

In the alveolus, O2 is removed as CO2 is added

\[ \text{A-a Gradient} = P_{AlvO2} - P_{aO2} \]

\[ = (PB - PH2O) \times FIO2 - (PaCO2/RQ) \]

\[ + 150 \text{ if sea level and room air} \]

PaO2 from ABG; RQ = 0.8

PaCO2 from ABG; FIO2

---

**Topic 5**
The Alveolar-Arterial Oxygen Gradient

- A-a Gradient varies with age:
  - Normal A-a Gradient = (age/4) + 4
- Increases with most lung diseases
  - But not with altitude, decreased FIO2, or hypercapnea

---
Question 6

6. In which organ would this graph be expected:
   A. Heart
   B. Lung
   C. Brain
   D. Kidney
   E. Skin

---

Topic 6
Hypoxic Pulmonary Vasoconstriction

- In other tissues:
  - Hypoxia results in dilation of arteries
- In the lungs:
  - Hypoxia results in pulmonary arterial vasoconstriction
- Why?
  - Redirects blood to better ventilated areas
  - Useful if localized pulmonary hypoxia (i.e. pneumonia)
  - But results in Pulmonary Hypertension & Cor Pulmonale if diffuse pulmonary hypoxia
Question 7

7. Your classmate spent her ISI in Peru where, after 1 week, she was evaluated for dyspnea. Which ABG findings would you expect to see?

<table>
<thead>
<tr>
<th></th>
<th>pH</th>
<th>pCO2</th>
<th>pO2</th>
<th>HCO3</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>7.40</td>
<td>40</td>
<td>100</td>
<td>24</td>
</tr>
<tr>
<td>B</td>
<td>7.48</td>
<td>20</td>
<td>60</td>
<td>15</td>
</tr>
<tr>
<td>C</td>
<td>7.32</td>
<td>55</td>
<td>80</td>
<td>31</td>
</tr>
<tr>
<td>D</td>
<td>7.50</td>
<td>30</td>
<td>96</td>
<td>17</td>
</tr>
<tr>
<td>E</td>
<td>7.57</td>
<td>50</td>
<td>75</td>
<td>32</td>
</tr>
</tbody>
</table>

Topic 7

Altitude

- At Altitude:
  - NORMAL FIO2 but a reduced Barometric Pressure
    - At 15,000 feet, BP = 450
    - Therefore, the expected ALVEOLAR O2 would be
      \[(450-47) \times 0.21 = \text{only } 35 \text{ mmHg}\]
- Hypoxia due to Decreased Barometric Pressure
- Compensatory Hyperventilation (immediate)
  - Results in respiratory alkalosis
- Renal Bicarbonate Wasting (after days)

Topic 7

Altitude

- Other Physiologic Consequences:
  - Increased EPO .... Increased Hct
  - Increased 2,3 DPG
    - Binds to Hgb releasing more \(O_2\)
    - Increased mitochondria
- Hypoxic pulmonary vasoconstriction
  - Acute: High Altitude Pulmonary Edema
  - Chronic: Pulmonary Hypertension
- High Altitude Cerebral Edema
Topic 8
Oxygen-Hemoglobin Dissociation Curve

- Shift to the right:
  - Decreased O₂ affinity
  - PCO₂, temp, H⁺, altitude, 2-3 DPG
- Bohr Effect:
  - peripheral acidosis shifts curve to the right, unloading O₂
- Haldane Effect:
  - in the lungs, oxygenation of Hgb results in CO₂ release from RBC’s
Topic 9
Pulmonary Hypertension

• Definition:
  – Normal PASP: < 25 mm Hg
  – PHTN: anything greater than normal

• Symptoms:
  – Dyspnea, Chest Pain, Syncope

• Physiology:
  – Increased VD/VT (so increased WOB)
  – RV Strain / Cor Pulmonale / Reduced Cardiac Output

Pulmonary Hypertension: Etiologies (WHO Classification)

1. Pulmonary Arterial Hypertension
   – Heritable, Drug-associated, CTD, HIV, Portal Hypertension, Congenital Heart Disease, Schistosomiasis, PVOD

2. PHTN due to Left Heart Disease

3. PHTN due to Lung Diseases and/or Hypoxia
   – COPD, ILD, SDB, Altitude

4. CTEPH (Chronic Thromboembolic PHTN)

5. Unclear/Multifactorial
   – Sarcoid, Vasculitis, Fibrosing Mediastinitis, etc
Topic 10
Mechanisms of Hypoxia

• Increased A-a Gradient
  – Common:
    • VQ Mismatch
    • Shunt
  – Other:
    • Diffusion Impairment
    • Diffusion-Perfusion Impairment

• Normal A-a Gradient:
  – Common:
    • Hypoventilation
  – Other:
    • Altitude
    • Decreased FIO₂ (rarely encountered clinically)

VQ Mismatch

• Decreased V relative to Q
• O₂ exits alveolus more quickly than enters via bronchi
• Hypoxia is MILD
• Hypoxia improves with supplemental O₂
• Causes:
  – Asthma, COPD
  – Pulmonary Emboli
  – ILD
Shunt

- No O₂ reaches some set of pulmonary capillaries
- Hypoxia is SEVERE
- Hypoxia does NOT improve with supplemental O₂
- Causes:
  - Pulmonary Shunt:
    - No ventilation to alveoli that are still perfused
  - Blood
  - Pus
  - Water
    ▶ Pulmonary Edema
    ▶ ARDS
  - Atelectasis
  - Pulmonary AVM
  - Cardiac Shunt
    ▶ PFO, ASD, VSD

Diffusion Impairment

- NOT a common problem
  - Blood is normally fully oxygenated within 25% of its transit through the alveolar capillaries.
  - Therefore, even if slowed by a diffusion barrier, blood usually reaches full saturation
Diffusion Impairment

- NOT a common problem
  - Blood is normally fully oxygenated within 25% of its transit through the alveolar capillaries.
  - Therefore, even if slowed by a diffusion barrier, blood usually reaches full saturation
- Hypoxia is MILD
- Hypoxia improves with supplemental O₂

Diffusion-Perfusion Impairment

- Seen occasionally in cirrhosis
- Dilated capillaries pose an impairment to full oxygenation

Topic 10
Mechanisms of Hypoxia

- Increased A-a Gradient
  - Common:
    - V/Q Mismatch
    - Shunt
  - Other:
    - Diffusion Impairment
    - Diffusion-Perfusion Impairment
- Normal A-a Gradient:
  - Common:
    - Hypoventilation
  - Other:
    - Altitude
    - Decreased FₐO₂ (rarely encountered clinically)
Pulmonary Top 10

1. Normal Response to Exercise
2. Pulmonary Compliance
3. Dead Space
4. Oxygen Pressure, Saturation, and Content
5. The Alveolar-Arterial Oxygen Gradient
6. Hypoxic Pulmonary Vasoconstriction
7. Altitude
8. Oxygen-Hemoglobin Dissociation Curve
9. Pulmonary Hypertension
10. Mechanisms of Hypoxia