M1 - Cardiovascular / Respiratory, Fall 2007

Abrams, G.; Sisson, T.; Jacobson, P.
Unless otherwise noted, the content of this course material is licensed under a Creative Commons Attribution 3.0 License.

Copyright 2008, Thomas Sisson

The following information is intended to inform and educate and is not a tool for self-diagnosis or a replacement for medical evaluation, advice, diagnosis or treatment by a healthcare professional. You should speak to your physician or make an appointment to be seen if you have questions or concerns about this information or your medical condition. You assume all responsibility for use and potential liability associated with any use of the material.

Material contains copyrighted content, used in accordance with U.S. law. Copyright holders of content included in this material should contact open.michigan@umich.edu with any questions, corrections, or clarifications regarding the use of content. The Regents of the University of Michigan do not license the use of third party content posted to this site unless such a license is specifically granted in connection with particular content objects. Users of content are responsible for their compliance with applicable law. Mention of specific products in this recording solely represents the opinion of the speaker and does not represent an endorsement by the University of Michigan.

Viewer discretion advised: Material may contain medical images that may be disturbing to some viewers.
Objectives

• To recognize the importance of matching ventilation and perfusion
  – To explain the consequences of mismatched ventilation and perfusion
  – To define shunt and dead space physiology
  – To be able to determine the alveolar $\text{pO}_2$
  – To be able to determine the A-a $\text{O}_2$ gradient and understand the implications of an increased gradient
  – To explain and understand the consequences of regional differences in ventilation and perfusion due to effects of gravity
Ventilation and Perfusion at the Level of the Whole Lung

- Tidal Volume: 500 mL
- Anatomic Dead Space: 150 mL
- Alveolar Gas Volume: 3000 mL
- Volume of Blood in Pulmonary Capillaries: 70 mL
- Respiratory Rate: 15/min
- Total Ventilation: 7500 mL/min
- Alveolar Ventilation: 5250 mL/min
- Ventilation : Perfusion = $\frac{V}{Q} = 1$
- Pulmonary Blood Flow: 5000 mL/min

BY: University of Michigan Medical School
http://creativecommons.org/licenses/by/3.0/deed.en
Gas Composition in the Alveolar Space

Trachea: partial pressure of CO2 is approximately 0

\[ \text{PiO}_2 = (\text{barometric pressure}-\text{H}_2\text{O vapor pressure}) \times \text{FiO}_2 \]
\[ = (760 - 47) \times 0.21 = 150 \text{ mmHg} \]

In the alveolar space, oxygen diffuses into the blood and CO2 diffuses into the alveolus from the blood.
Alveolar Gas Equation

\[
PAO_2 = (PiO_2) - (PaCO_2/R).
\]

\(PaCO_2\) approximates \(PACO_2\) due to the rapid diffusion of \(CO_2\)

\(R = \text{Respiratory Quotient (VCO2/V02)} = 0.8\)

In a normal individual breathing room air:

\[
PAO_2 = 150 - 40/0.8 = 100 \text{ mmHg}
\]
Gas Composition in the Normal Alveolar Space

Trachea: partial pressure of CO2 is approximately 0

\[
PiO_2 = (\text{barometric pressure}-\text{H}_2\text{O vapor pressure}) \times FiO_2
= (760 - 47) \times 0.21 = 150 \text{ mmHg}
\]

In the alveolar space, oxygen diffuses into the blood and CO2 diffuses into the alveolus from the blood.
Consequences of Inadequate Ventilation

- **Apnea:**
  - PACO2 rises
  - PAO2 falls until there is no gradient for diffusion into the blood

- **Hypoventilation:**
  - Inadequate ventilation for perfusion
  - PACO2 rises
  - PAO2 falls, but diffusion continues
How Can We Tell if Alveolar Ventilation is Adequate?
PaCO2 and Alveolar Ventilation

• PaCO2 is:
  – directly related to CO2 production (tissue metabolism).
  – Inversely related to alveolar ventilation.

• Increased PaCO2 (hypercarbia) is always a reflection of inadequate alveolar ventilation (VA).

\[ \text{PaCO2} \approx \frac{V_{CO2}}{VA} \]
Suppose a patient hypoventilates, so that the PCO2 rises to 80 mmHg. We can estimate the PAO2 based on the alveolar gas equation.

\[
PAO2 = 150 - \frac{80}{0.8} = 50 \text{ mmHg}
\]

Thus even with perfectly efficient lungs, the PaO2 would be 50, and the patient would be severely hypoxemic. Therefore, hypoventilation results in hypoxemia.
V/Q Matching

- 300 million alveoli.

- Different alveoli may have widely differing amounts of ventilation and of perfusion.

- Key for normal gas exchange is to have matching of ventilation and perfusion for each alveolar unit
  - Alveoli with increased perfusion also have increased ventilation
  - Alveoli with decreased perfusion also have decreased ventilation
  - V/Q ratio = 1.0
Two Lungs, Not One

- Suppose the left lung is ventilated but not perfused (dead space).
- Suppose the right lung is perfused but not ventilated (shunt).
- Total $V/Q = 1$, but there is no gas exchange ($V/Q$ must be matched at level of alveolar unit).
Low V/Q Effect on Oxygenation

One lung unit has normal ventilation and perfusion, while the other has inadequate ventilation.

- Normal: PO2 114
- Low V/Q: PO2 50, PCO2 ↑, PO2 ↓
- PO2 ?

PO2 114, PO2 50
Mixing Blood

• What is the PO2 of a mixture of two volumes of blood with different initial PO2?
• Determined by interaction of oxygen with hemoglobin.
  – the partition of oxygen between plasma (and thus the pO2) and bound to hemoglobin is determined by the oxyhemoglobin dissociation curve.
Oxyhemoglobin Dissociation Curve

\[ \text{CO}_2 = (1.3 \times \text{HGB} \times \text{Sat}) + (.003 \times \text{PO}_2) \]

- Oxygen Combined With Hemoglobin
- Dissolved Oxygen

\% Hemoglobin Saturation

\( \text{PO}_2 \) mmHg

Oxygen Content (ml/100 ml)
Low V/Q Effect on Oxygenation

One lung unit has normal ventilation and perfusion, while the other has inadequate ventilation.

- Normal lung unit: PO2 114
- Low V/Q lung unit: PO2 50
- Increased PCO2
- Decreased PO2

PO2 question mark
Oxyhemoglobin Dissociation Curve and O2 Content

- Total Oxygen
- Oxygen Combined With Hemoglobin

**Graph:**
- Y-axis: % Hemoglobin Saturation
- X-axis: PO₂ mmHg
- Oxygen Content (ml/100 ml)

**Equations:**
- P₅₀ (PO₂ at 50% saturation)
- DO₂ = CO₂ × 1.34 × 10⁻³ × PO₂
- CO₂ = DO₂ × 0.24 × 10⁻³ × PO₂

**Notations:**
- PO₂: Partial Pressure of Oxygen
- DO₂: Dissolved Oxygen
- CO₂: Carbon Dioxide
- % Hemoglobin Saturation
- Oxygen Content (ml/100 ml)
Low V/Q Effect on Oxygenation

One lung unit has normal ventilation and perfusion, while the other has inadequate ventilation.

- Normal:
  - PO2 114 mmHg
  - O2sat 100%
  - O2 content 20ml/dl

- Low V/Q:
  - PO2 50 mmHg
  - O2sat 80%
  - O2 content 16ml/dl
Oxyhemoglobin Dissociation Curve and O2 Content

% Hemoglobin Saturation

P_{O_2} mmHg

Total Oxygen

Oxygen Combined With Hemoglobin

Oxygen Content (ml/100 ml)

20

16

12

8

4

0

600

400

200

0

20

40

60

80

100
One lung unit has normal ventilation and perfusion, while the other has inadequate ventilation.

**Normal**
- PO2 114 mmHg
- O2sat 100%
- O2 content 20 ml/dl

**Low V/Q**
- PO2 50 mmHg
- O2sat 80%
- O2 content 16 ml/dl

**PO2 60 mmHg**
PCO2 in V/Q Mismatch

- Increased ventilation can compensate for low V/Q units.
  - Shape of CO2 curve
- Total ventilation (VE) must increase for this compensation.
Extremes of V/Q Inequality

• Shunt
  – Perfusion of lung units without ventilation
    • Unoxygenated blood enters the systemic circulation
    • V/Q = 0

• Dead space
  – Ventilation of lung units without perfusion
    • Gas enters and leaves lung units without contacting blood
    • Wasted ventilation
    • V/Q is infinite
Effect of Changing V/Q Ratio on Alveolar PO2 and PCO2

Shunt

Gas Composition
- Mixed Venous Blood
- Normal
- Inspired Air

V/Q
- 0
- 1
- ∞

Dead Space

$P_{O_2} = 150\text{mmHg}$
$P_{CO_2} = 0\text{mmHg}$

$P_{O_2} = 40\text{mmHg}$
$P_{CO_2} = 45\text{mmHg}$

$P_{O_2} = 100\text{mmHg}$
$P_{CO_2} = 40\text{mmHg}$

$P_{O_2} = 40\text{mmHg}$
$P_{CO_2} = 45\text{mmHg}$

$P_{O_2} = 150\text{mmHg}$
$P_{CO_2} = 0\text{mmHg}$
Effects of V/Q Relationships on Alveolar PO2 and PCO2

BY: University of Michigan Medical School
http://creativecommons.org/licenses/by/3.0/deed.en
One lung unit has normal ventilation and perfusion, while the other has no ventilation.

- Normal unit:
  - PO2 114 mmHg
  - O2sat 100%

- Shunt unit:
  - PO2 40 mmHg
  - O2sat 50%
Response to Breathing 100% Oxygen

- Alveolar hypoventilation or V/Q mismatch responds to 100% oxygen breathing.

- Nitrogen will be washed out of low ventilation lung units over time.

- PaO2 will rise to > 550 mmHg.

- Limited response to oxygen in shunt.

- Use this characteristic to diagnose shunt.
Shunt Calculation

- \( Qt \times CaO2 = \) total volume of oxygen per time entering systemic arteries
  - \( Qt = \) total perfusion
  - \( Qs = \) shunt perfusion
  - \( CaO2, Cc’O2, CvO2 \) are oxygen contents of arterial, capillary and venous blood

- \( (Qt-Qs) \times Cc’O2 = \) oxygen coming from normally functioning lung units

- \( Qs \times CvO2 = \) oxygen coming from shunt blood flow
Shunt Equation

\[ Qt \times CaO2 = [(Qt - Qs) \times CcO2] + [Qs \times CvO2] \]

\[
\frac{Qs}{Qt} = \frac{Cc'O2 - CaO2}{Cc'O2 - CvO2}
\]
Causes of Shunt

- Physiologic shunts:
  - Bronchial veins, pleural veins

- Pathologic shunts:
  - Intracardiac
  - Intrapulmonary
    - Vascular malformations
    - Unventilated or collapsed alveoli
Detecting V/Q Mismatching and Shunt

- Radiotracer assessments of regional ventilation and perfusion.

- Multiple inert gas elimination.
  - Takes advantage of the fact that rate of elimination of a gas at any given V/Q ratio varies with its solubility.

- A-aO2 Gradient.
V/Q Relationships

• In a totally efficient lung unit with matched V/Q, alveolar and capillary PO2 would be equal.

• Admixture of venous blood (or of blood from low V/Q lung units) will decrease the arterial PaO2, without effecting alveolar O2 (PAO2).

• Calculate the PAO2 using the alveolar gas equation, then subtract the arterial PaO2: 
\[ (P_iO_2) - (PaCO_2/R) - PaO2 \]

• The A-a O2 gradient (or difference) is < 10-15 mmHg in normal subjects
  – Why is it not 0?
Apical and Basilar Alveoli in the Upright Posture

- Elastic recoil of the individual alveoli is similar throughout the normal lung.

- At end expiration (FRC) apical alveoli see more negative pressure and are larger than basilar alveoli.

- During inspiration, basilar alveoli undergo larger volume increase than apical alveoli.

- Thus at rest there is more ventilation at the base than the apex.

- Also More Perfusion to Lung Bases Due to Gravity.
Effects of Gravity on Ventilation and Perfusion

Effects of Gravity on Ventilation and Perfusion Matching

BY: University of Michigan Medical School
http://creativecommons.org/licenses/by/3.0/deed.en
Causes of Abnormal Oxygenation

- Hypoventilation
- V/Q mismatch
- Shunt
- Diffusion block
Key Concepts:

- Ventilation and Perfusion must be matched at the alveolar capillary level.

- V/Q ratios close to 1.0 result in alveolar PO2 close to 100 mmHg and PCO2 close to 40 mmHg.

- V/Q greater than 1.0 increase PO2 and Decrease PCO2. V/Q less than 1.0 decrease PO2 and Increase PCO2.

- Shunt and Dead Space are Extremes of V/Q mismatching.

- A-a Gradient of 10-15 Results from gravitational effects on V/Q and Physiologic Shunt.