Ventilation/Perfusion Matching

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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 $pO_2$
  – To be able to determine the A-a $O_2$ 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
- Pulmonary Blood Flow: 5000 mL/min

Ventilation / Perfusion = \( \frac{V}{Q} = 1 \)
Gas Composition in the Alveolar Space

Trachea: partial pressure of CO2 is approximately 0

\[ \text{PiO}_2 = (\text{barometric pressure-H2O vapor pressure}) \times \text{FiO2} \]
\[ = (760 - 47) \times 0.21 = 150 \text{ mmHg} \]

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

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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

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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).

\[ \text{PaCO2} \approx \frac{VCO2}{VA} \]
Alveolar Hypoventilation

Suppose a patient hypoventilates, so that the PCO2 rises to 80 mmHg. We can estimate the PAO2 based on the alveolar gas equation.

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

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
- PO2 ?
- PO2 114

PCO2 ↑
PO2 ↓
• 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

\[ \text{CO}_2 = (1.3 \times \text{HGB} \times \text{Sat}) + (0.003 \times \text{PO}_2) \]

% Hemoglobin Saturation

\( P_{O_2} \) mmHg

Oxygen Combined With Hemoglobin

Dissolved Oxygen

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.

PO2 114

PO2 50

PO2 ?

PO2 114

PO2 ?

↑ PCO2

↓ PO2

↓ PCO2

↑ PO2

Normal

Low V/Q
Oxyhemoglobin Dissociation Curve and O2 Content

- Total Oxygen
- Oxygen Combined With Hemoglobin

**Graph Details:**
- **X-axis:** PO₂ (mmHg)
- **Y-axis:** % Hemoglobin Saturation
- **Legend:**
  - Oxyhemoglobin
  - O2 Content (ml/100 ml)

**Key Points:**
- PO₂ at 0 mmHg corresponds to 0% Hemoglobin Saturation.
- PO₂ at 100 mmHg corresponds to approximately 100% Hemoglobin Saturation.
- The curve illustrates the relationship between PO₂ and % Hemoglobin Saturation.
Low V/Q Effect on Oxygenation

One lung unit has normal ventilation and perfusion, while the other has inadequate ventilation.
Oxyhemoglobin Dissociation Curve and O2 Content

- Total Oxygen
- Oxygen Combined With Hemoglobin

**Oxyhemoglobin Dissociation Curve and O2 Content**

- **% Hemoglobin Saturation**
- **PO₂ (mmHg)**
- **Oxygen Content (ml/100 ml)**

<table>
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<th>% Hemoglobin Saturation</th>
<th>PO₂ (mmHg)</th>
<th>Oxygen Content (ml/100 ml)</th>
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- Oxygen combined with hemoglobin:
  - At PO₂ = 40 mmHg, % Hemoglobin Saturation ≈ 40%.
  - At PO₂ = 60 mmHg, % Hemoglobin Saturation ≈ 80%.

- Total oxygen content:
  - At % Hemoglobin Saturation = 100%, PO₂ ≈ 100 mmHg.

- The curve shows the relationship between PO₂ and % Hemoglobin Saturation, indicating the oxygen capacity of hemoglobin.
Low V/Q Effect on Oxygenation

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

- Normal V/Q:
  - 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**
  - $P_{O_2} = 40\text{ mmHg}$
  - $P_{CO_2} = 45\text{ mmHg}$

- **Normal**
  - $P_{O_2} = 100\text{ mmHg}$
  - $P_{CO_2} = 45\text{ mmHg}$

- **Inspired Air**
  - $P_{O_2} = 150\text{ mmHg}$
  - $P_{CO_2} = 0\text{ mmHg}$

- **Dead Space**
  - $P_{O_2} = 150\text{ mmHg}$
  - $P_{CO_2} = 0\text{ mmHg}$

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Effects of V/Q Relationships on Alveolar PO2 and PCO2

Mixed Venous Blood

Normal

Inspired Air

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Shunt Physiology

One lung unit has normal ventilation and perfusion, while the other has no ventilation.
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 x 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) x Cc’O2 = oxygen coming from normally functioning lung units
• Qs x CvO2 = oxygen coming from shunt blood flow
Shunt
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

Multiple Inert Gas Elimination

A-a O2 gradient

• 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: 
  \[ (P_{iO_2}) - \frac{(P_{CO_2}/R)}{\text{PaO2}} \]

• 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

![Diagram showing the effects of gravity on ventilation and perfusion. The graph illustrates the changes in blood flow, ventilation, and VA/Q with varying rib numbers. The x-axis represents rib number (Bottom to Top), and the y-axis represents VA or Q per unit lung volume.](image-url)

Effects of Gravity on Ventilation and Perfusion Matching

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Causes of Abnormal Oxygenation

- Hypoventilation
- V/Q mismatch
- Shunt
- Diffusion block
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.