Learning Objectives
- Explain the physiological requirements for adequate tissue oxygenation.
- Relate measured physiological parameters to specific sources of hypoxia.

Requirements for oxygen
- Body tissues require variable amounts of O2 for cellular metabolism
- Hypoxia- inadequate cellular O2 ==> anaerobic metabolism ==> lactic acidosis ==> death

Oxygen deficiency
- Normoxia- normal tissue O2
- Hypoxia- deficient tissue O2
- Hypoxemia- deficient arterial PO2
- Hypoxia may exist in the absence of hypoxemia

Requirements for tissue normoxia
- O2 in inspired air- PIO2
- O2 transport to alveoli- PAO2
- O2 transport to arterial blood
- Transportation vehicle- hemoglobin
- Circulation of arterial blood to tissues
  - cardiac output
  - local perfusion

Requirements for tissue normoxia
- Uptake and utilization of O2 by tissues
- Circulation of mixed venous blood to lung
Blood Gas Tensions

PaO2 = 95
SaO2 = 98%
CaO2 = 20 ml/dl

PvO2 = 40
SvO2 = 75%
CvO2 = 15 ml/dl

Hb cells

 PIO2 = 160 mm Hg

P02 40 mm Hg

P02 40 mm Hg

H+, CO2

Normal partial pressure relationships

- Dalton's law- the partial pressure of a gas in a mixture is proportional to its concentration.
- Normal barometric pressure (PB) at sea level = 760 mm Hg
- Concentration of O2 (FO2) = 0.21
- Sea level PO2 = (.21)(760) = 160

Normal partial pressure relationships

- Air entering alveoli is diluted with:
  - Water vapor- PH2O = 47 mm Hg
  - CO2- normal = 40 mm Hg
- Alveolar air equation
  - PAO2 = FIO2 (PB - 47) - (PaCO2 * 1.25)
  - PAO2 = .21(713) - (40 * 1.25) = 100

Normal partial pressure relationships

- There is a normal gradient between alveolar and arterial tensions-
  - P(A-a)O2 = 2-5, due to anatomic shunts ==>
  - normal PaO2 = 95
- Given PaO2 = 95; PAO2 = 100 ==>
  - Pa/PAO2 = 0.95

FYI - click for alveolar gas equation simulator
http://vam.anest.ufl.edu/simulations/alveolargasequation_simple.html
Hemoglobin saturation
- Saturation (SO2) - degree to which hemoglobin is saturated with O2
- Each gram Hb can carry 1.34 mL O2
- Hemoglobin with SO2 = 50% carries (.5)(1.34) = .67 mL O2

HbO2 Dissociation Curve
- Relationship between PO2 and SO2

HbO2 Dissociation Curve
- Rightward shift ==> lower SO2 for given PO2

Hemoglobin saturation
- Rightward shift ==> lower SO2 for given PO2
  - Hb releases O2 more readily
  - increased temperature
  - increased PCO2 (Bohr shift)
  - increased H+ (decreased pH)

HbO2 Dissociation Curve
- Leftward shift ==> greater SO2 for given PO2

Hemoglobin saturation
- Leftward shift ==> higher SO2 for given PO2
  - decreased temperature
  - decreased PCO2
  - decreased H+ (increased pH)
  - decreased 2,3 diphosphoglycerate (DPG)- associated with stored blood
  - interferes with release of O2 to tissues
Hemoglobin saturation

- Calculation vs. direct measurement
  - calculations are based on HbO2 curve
  - direct measurement with oximeter or co-oximeter is more accurate
- Calculated SO2 does not account for hemoglobinopathies, like:
  - HbCO (carbon monoxide)
  - methemoglobin
  - sulfhemoglobin

Hypoxemic Hypoxia

Abnormal Gas Tensions

- Hypoxemic hypoxia- subnormal PaO2
- Causes:
  - decreased PIO2
  - hypoventilation
  - ventilation-perfusion (VQ) mismatch
  - anatomic shunt
  - diffusion defect

Decreased PIO2

- Causes
  - altitude- decreased barometric pressure (PB)
  - suffocation
  - abnormal gas mixture
- Effects on oxygenation
  - decreased PAO2, PaO2, SaO2, CaO2
  - PvO2
  - normal P(A-a)O2, Pa/A O2

PIO2 = \(0.21(650) = 137\) torr

\[\text{PAO2} = 0.21(650 - 47) - (40 \times 1.25) = 77\]

\[77 \text{ torr} - 72 \text{ torr} = \text{Given } P(A-a)O2 = 5 \text{ torr} \]

\[\Rightarrow \text{ PaO2} = 72 \text{ torr}\]

Hypoventilation

- Defined by increased PaCO2
- Causes:
  - neuromuscular dx
  - ventilatory depressant drugs, toxins
  - deadspace-producing disease-
- Effects on oxygenation
  - decreased PAO2, PaO2, SaO2,
PIO2 = 160
PaCO2 = 60 (hypoventilation)

\[
\begin{align*}
PAO2 &= 0.21(713) - (60 \times 1.25) = 75 \\
70 \\
\text{Given } P(A-a)O2 &= 5 \\ 
\text{PaO2} &= 70 \text{ mm Hg}
\end{align*}
\]

Ventilation-Perfusion Mismatch

- Unequal distribution of ventilation and blood flow among alveoli
- Types:
  - low V/Q ==> venous admixture, physiologic shunt (QSP)
  - high V/Q ==> alveolar deadspace (VD_A)

Click for illustration of VQ mismatch
http://alpe-essential.com/files/billeder/tekst-billeder/fig_2.gif

Ventilation-Perfusion Mismatch

- Causes
  - airway obstruction
  - atelectasis
  - consolidation
  - emphysema
  - pulmonary vascular dx

Ventilation-Perfusion Mismatch

- Effects on oxygenation
  - Decreased PaO2, SaO2, CaO2, PvO2, Pa/AO2
  - Increased P(A-a)O2
  - Usually correctable with supplemental O2

V/Q mismatch

\[
\begin{align*}
\text{PaO2} &= 70 \text{ torr} \\
\text{P(A-a)O2} &= 100 - 70 = 30 \\
\text{Pa/AO2} &= 70/100 = 0.7
\end{align*}
\]

Anatomic shunt

- Circulation of venous blood into the arterial circulation.

Shunted venous blood bypasses the lung.
Anatomic shunt

- Causes
  - anomalous arteriovenous connections
  - intracardiac defect, like VSD
  - patent foramen ovale - common in adults (20% est.)
  - pulmonary hypertension MUST be present, to make blood flow from right-to-left.

- Effects on oxygenation
  - Decreased PaO2, SaO2, CaO2, PvO2, Pa/AO2
  - Increased P(A-a)O2
  - MINIMAL response to supplemental O2

Click to see shunt calculator and equation
http://www.studentconsult.com/spleen/calculator.cfm?calculator=QsQt.htm

Diffusion defect

- Defined - disruption of the diffusion of O2 from alveoli to capillaries.

- Causes
  - thickened alveolar membrane
  - inflammation
  - edema
  - fibrosis
  - loss of alveolar surface area - emphysema

- Effects on oxygenation
  - Does NOT affect CO2 diffusion
  - Decreased PaO2, SaO2, CaO2, PvO2, Pa/AO2
  - P(A-a)O2 increases with exercise
  - Usually correctable with supplemental O2

Using Pa/AO2 in calculations

- Predicting PaO2 for changed FIO2

A patient has these ABGs: FIO2 = 0.6, PaO2 = 50, PaCO2 = 30. Increasing FIO2 to 0.7 will produce what PaO2?

Use alveolar air equation to find Pa/AO2

PAO2 = .6(713) - (30 * 1.25) = 390

PaO2/PAO2 = 50/390 = 0.13
Using Pa/AO2 in calculations

- Predicting PaO2 for changed FIO2

Increasing FIO2 to 0.7 will produce what PaO2?

\[
FIO2 = 0.7; \quad PAO2 = 0.7(713) - (30 * 1.25) = 462
\]

\[
PaO2/PAO2 = 0.13 \Rightarrow 0.13 \times 462 = 60
\]

PaO2/FIO2 ratio

- common index for clinical setting & research

- values

  - normal = 95/.21 = 452
  - acute lung injury - PaO2/FIO2 < 300
  - ARDS - PaO2/FIO2 < 200

- disadvantages

  - index changes with FIO2
  - does not consider lung mechanics

Oxygenation index (OI)

- has been common index in pediatric clinical setting & research

- calculation:

\[
OI = \frac{FiO2 \times MAP \times 100}{PaO2}
\]

- values

  - very good < 5
  - medium 10 - 20
  - poor > 25

Click to access and use OI calculator
http://www.medcalc.com/oxygen.html

Oxygenation index (OI)

- Advantages

  - considers lung mechanics (mean airway pressure)
  - prognostic value - Greater peak OI \Rightarrow risk for mortality

FYI - click to download article about oxygenation indices
http://ceaccp.oxfordjournals.org/content/7/4/131.full.pdf

Non-Hypoxemic Hypoxia

Circulatory (stagnant) hypoxia

- \( O2 \) extraction}

- constant \( O2 \)

- decreased blood flow

- right heart

- left heart

- \( \text{cells} \)

- \( H2, CO2 \)

- \( P_{O2} = 30 \)

- \( CvO2 = 10 \)
Circulatory (stagnant) hypoxia

**Causes**
- decreased cardiac output
- shock from other origins - pooling of blood
- local hypoxia - vascular occlusion, constriction; e.g., vasopressors

**Effects on oxygenation**
- normal PaO2, P(A-a)O2, SaO2
- decreased PvO2, SvO2
- increased C(a-v)O2

Anemic Hypoxia

**Decreased CaO2, due to inadequate or dysfunctional Hb**

\[
\text{CaO}_2 = (\text{Hb g/dL})(\text{SaO}_2)(1.34) + (\text{PaO}_2 * 0.003)
\]

\[
\text{CaO}_2 = (15)(0.98)(1.34) + (95)(.003) = 19.7 \text{ ml} + 0.29 \text{ ml} = 20 \text{ ml}
\]

**Causes**
- anemia, due to decreased RBC production
- hemorrhage
- porphyria; e.g., vampires
- sickle-cell anemia
- Carbon monoxide poisoning - Hb\textsubscript{CO}
- Methemoglobinemia - Hb\textsubscript{MET}
- Sulfhemoglobinemia - Hb\textsubscript{SULF}

**Effects on oxygenation**
- Normal PaO2, P(A-a)O2
- Normal calculated SO2
- Decreased SaO2, CaO2 (measured)

**Elevated HbCO**
- CO binds to hemoglobin and cardiac myoglobin
  - normal < 1%
  - symptoms > 10%
  - fatal > 50%
  - fatal (fetus) > 30%
Anemic Hypoxia

- Elevated Hb_{MET}
  - Hb oxidized - does not carry O2
  - Causes
    - Hereditary
    - Nitrates, nitrites - beets, spinach, well water, medications
    - Local anesthetics; e.g., benzocaine
  - Values
    - Normal < 1%
    - Symptomatic > 40%

Histotoxic Hypoxia

- Failure of tissues to utilize O2

- Causes
  - Cyanide poisoning
  - Sepsis
  - Nucleoside analogue agents (antiretrovirals)

- Effects on oxygenation
  - Normal PaO2, SaO2, CaO2
  - Elevated FvO2, SvO2, CvO2
  - Decreased C(a-v)O2

Lactate

- Produced by hypoxic cells
- Useful in detecting tissue hypoxia, due to non-hypoxemic causes:
  - Septic shock
  - Histotoxicity
- Values
  - Normal < 2 mmol/L
  - Shock > 5 mmol/L

FYI - Link to article on HIV and lactic acidemia

FYI - Link to article on lactic acidosis
http://www.emedicine.com/med/topic1253.htm

Pulse Oximetry
Principles of operation

LEDs
Red Ired
Photodetector

FYI - Click for information and illustrations of pulse oximetry
http://www.oximetry.org/pulseox/principles.htm

Principles of operation

- Ratio of red:Ired used to compute SpO2
- Measurement at pulse to identify arterial blood
- Measurements of different light wave lengths for additional parameters

Measurement sites

- Adults
  - finger
  - toe
  - ear - most rapid response
  - forehead
    - reflective sensor, only
    - venous pulse may cause error

Measurement sites

- Infants
  - foot
  - finger
  - toe

Measurement sites

- Adults
  - finger
  - toe
  - ear - most rapid response
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    - reflective sensor, only
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Measurement sites

- Infants
  - foot
  - finger
  - toe

Limitations

- Perfusion - pulse
- Motion - false alarms, decreased by Masimo SET™
- SpO2 < 83%
- Skin pigmentation??
- Intravenous dyes; e.g., methylene blue - yield false low values
Limitations

- Abnormal hemoglobin; e.g., HbCO - depends on device
- Nail polish, nail decorations - must be a thick layer to impair measurement in mild hypoxemia
- Hyperoxemia - PO2 = 98 or 498??
- Sensor must be used for intended site
- Knowledge of user

FYI - click to see AARC pulse oximetry CPG
http://www.rcjournal.com/cpgs/pulsecpg.html

Masimo Rainbow Radical - 7™

Masimo Rainbow SET™

Monitored oxygenation parameters

- SpO2
- HbCO - carboxyhemoglobin
- HbMET - methemoglobin
- Hb - hemoglobin
- Oxygen content

FYI - Click for more information on Masimo Rainbow SET™
http://www.masimo.com/Rainbow/about.htm

Masimo Rainbow SET™

Monitored perfusion parameters

- Pulse
- Pleth wave form
  - pulsus paradoxus - change in pleth amplitude with respiration
  - perfusion Index (PI) - neonatal and adult surgical perfusion monitoring
  - pleth variability index (PVI) - fluid responsiveness

FYI - click for more information on PVI
http://www.masimo.com/pvi/index.htm

Summary & Review

Requirements for tissue oxygenation
- Blood gas tensions - Dalton’s law & alveolar air equation
- Hemoglobin saturation
- Hypoxemic hypoxia
  - decreased P,O2
  - hypoventilation
  - VQ mismatch
  - shunt
  - diffusion defect

Non-hypoxemic hypoxia
  - circulatory
  - anemic
  - histotoxic
- Lactate - detect non-hypoxemic hypoxia
- Pulse oximetry
  - limitations
  - parameters in addition to SpO2
References

