

Assessment of Oxygenation

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This Presentation is AARC Approved
for 1.5 CRCE Credit Hours

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Learning Objectives

- Explain the physiological requirements for adequate tissue oxygenation
- Interpret values for all parameters pertaining to tissue oxygenation
- Discriminate between hypoxemic & non-hypoxemic hypoxia
- Given clinical data, evaluate status of oxygenation
- Explain the rationale, compensatory mechanisms, & precautions associated with permissive hypoxemia

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Requirements for Oxygen

- Body tissues require variable amounts of O₂ for cellular metabolism
- Hypoxia - inadequate cellular O₂ → anaerobic metabolism → lactic acidosis → death

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Oxygen Deficiency

- Normoxia: normal tissue O₂
- Hypoxia: deficient tissue O₂
- Hypoxemia: deficient arterial PO₂
- Hypoxia may exist in the absence of hypoxemia (non-hypoxemic hypoxia)

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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

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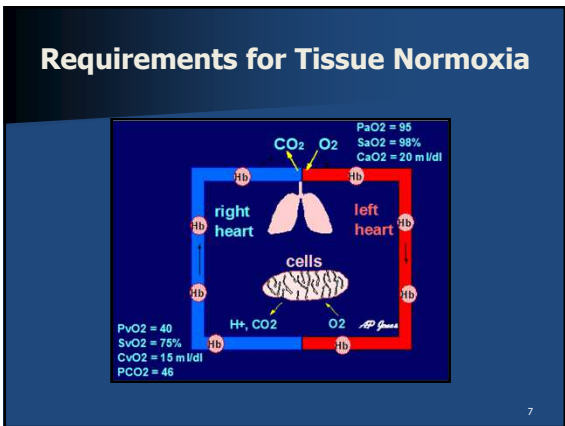
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Requirements for Tissue Normoxia

- Uptake & utilization of O₂ by tissues
- Circulation of mixed venous blood to lung

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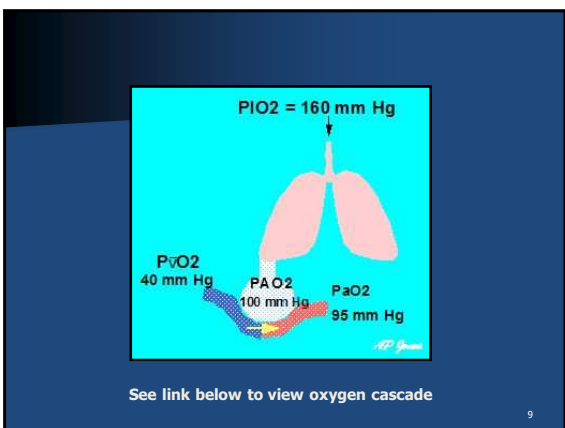
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Blood Gas Tensions

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Normal Partial Pressure Relationships

- > Dalton's Law: the partial pressure of a gas in a mixture is proportional to its concentration
 - ❖ Normal barometric pressure at sea level: 760 mm Hg
 - ❖ Concentration of O_2 (FiO_2) = 0.21
 - ❖ Sea level $PO_2 = (0.21)(760) = 160 \text{ mm Hg}$

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Normal Partial Pressure Relationships

- > Air entering the alveoli is diluted with
 - ❖ Water vapor (P_{H_2O}) = 47 mm Hg
 - ❖ CO_2 - normal = 40 mm Hg
- > Alveoli air equation
 - ❖ $PAO_2 = FiO_2 (PB - 47) - (PaCO_2 * 1.25)$
 - ❖ $PAO_2 = 0.21 (713) - (40 * 1.25) = 100$
- > Clinical pearl: multiply the FiO_2 by 5 for a Q&D estimate for PAO_2
- > Clinical pearl: $(7 \times FiO_2) - (CO_2 + 10)$

Up next: Alveolar air equation practice

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Alveolar Air Equation Practice

Barometric pressure: 750
 FiO_2 : .28
 pCO_2 : 45

$.28(750-47) - (45 \times 1.25)$
 $.28(703) - 56.25$
 $197 - 56$
 140

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Alveolar Air Equation Practice

Barometric pressure: 760
 FiO₂: .21
 pCO₂: 60

$$.21(760-47) - (60 \times 1.25)$$

$$.21(713) - 75$$

$$150 - 75$$

$$75$$

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Alveolar Air Equation Practice

Barometric pressure: 680
 FiO₂: .35
 pCO₂: 55

$$.35(680-47) - (55 \times 1.25)$$

$$.35(633) - 69$$

$$222 - 69$$

$$153$$

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Normal Partial Pressure Relationships

- > There is a normal gradient between alveolar & arterial tensions (A = alveolar, a = arterial)
- > P(A-a)O₂ = 2 - 5 mm, due to anatomic shunts & A-C membrane diffusion → normal PaO₂ = 95
- > Pa/A O₂ - given PaO₂ = 95; PAO₂ = 100 → Pa/PA O₂ = 0.95

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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 (0.5) (1.34) = 0.67 mL O₂

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HbO₂ Dissociation Curve

> Relationship between PO₂ & SO₂

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HbO₂ Dissociation Curve

> Right shift → Lower SO₂ for a given PO₂

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Hemoglobin Saturation

- > Right shift → Lower SO_2 for a given PO_2
- > Hb releases O_2 more readily
- > Causes
 - ❖ Increased temperature
 - ❖ Increased PCO_2 (Bohr shift)
 - ❖ Increased H^+ (decreased pH)

Memorize: Hot Acid is Right

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HbO₂ Dissociation Curve

- > Left shift → Greater SO_2 for a given PO_2

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Hemoglobin Saturation

- > Left shift → Greater SO_2 for a given PO_2
 - ❖ Decreased temperature
 - ❖ Decreased PCO_2
 - ❖ Decreased H^+ (increased pH)
 - ❖ Decreased 2,3 diphosphoglycerate (DPG) - associated with stored blood
 - ❖ Interferes with release of O_2 to the tissues

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Hemoglobin Saturation

- > Calculation vs. direct measurement
 - ❖ Calculations are based on Hb curve
 - ❖ Direct measurement with oximeter or co-oximeter is more accurate
- > Calculated SO_2 doesn't account for hemoglobinopathies, such as
 - ❖ HbCO (carbon monoxide)
 - ❖ Methemoglobin
 - ❖ Sulfhemoglobin

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Hypoxemic Hypoxia

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Abnormal Gas Tensions

- > Hypoxemic hypoxia: subnormal PaO_2
 - > Causes
 - ❖ Decreased PiO_2
 - ❖ Hypoventilation
 - ❖ Ventilation-perfusion (VQ) mismatch
 - ❖ Anatomic shunt
 - ❖ Diffusion defect

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Decreased PiO_2

- > Causes
 - ❖ Altitude - decreased barometric pressure (PB)
 - ❖ Suffocation
 - ❖ Abnormal gas mixture
- > Effects on oxygenation
 - ❖ Decreased PAO_2 , PaO_2 , SaO_2 , CaO_2 , $\bar{V}O_2$
 - ❖ Normal $P(A-a)O_2$, $Pa/A O_2$

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$PIO_2 = .21(650) = 137 \text{ torr}$

$PAO_2 = .21(650 - 47) - (40 \times 1.25) = 77$

77 torr 72 torr

Given $P(A-a)O_2 = 5 \text{ torr} \implies$
 $PaO_2 = 72 \text{ torr}$

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Hypoventilation

- > Defined by increased PCO_2
- > Causes
 - ❖ Neuromuscular Dx
 - ❖ Ventilatory depressant drugs, toxins
 - ❖ Dead-space-producing disease
- > Effects on oxygenation
 - ❖ Decreased PAO_2 , PaO_2 , SaO_2 , CaO_2 , $\bar{V}O_2$
 - ❖ Normal $P(A-a)O_2$, $Pa/A O_2$

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$PIO_2 = 160$

$PaCO_2 = 60$
(hypoventilation)

$PAO_2 = .21(713) - (60 \times 1.25) = 75$

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Given $P(A-a)O_2 = 5 \implies$
 $PaO_2 = 70 \text{ mm Hg}$

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Ventilation-Perfusion Mismatch

- > Unequal distribution of ventilation & blood flow among alveoli
- > Types
 - ❖ Zero ventilation: $V/Q = 0$ - physiologic shunt (Q_{sp})
 - ❖ Zero perfusion: $VQ = \text{Infinity}$ (V_{DA})
 - ❖ Zero perfusion & ventilation (dead unit)

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VQ Relationship

- > $VQ = 0.8$ - normal

$PVO_2 = 40$ $PaO_2 = 95$
 $PVCO_2 = 46$ $PaCO_2 = 40$

$PAO_2 = 100$
 $PACO_2 = 40$

Up Next: Video of VQ Mismatch

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VQ Relationships

- > **VQ = 0**
 - ❖ Physiologic shunt unit
 - ❖ Contributes venous blood to the system
 - ❖ Other units compensate for CO₂ excretion

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VQ Relationships

- > **VQ = low**
 - ❖ Venous admixture unit
 - ❖ Contributes subnormal PaO₂
 - ❖ PaCO₂ normal

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VQ Relationships

- > **VQ = infinity**
 - ❖ Deadspace unit
 - ❖ No contribution to systemic circulation
 - ❖ Accumulation of VD units increase PaCO₂
 - ❖ Decrease surface for gas exchange

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VQ Relationships

- > **Dead Unit: no ventilation or perfusion**
 - ❖ No contribution to ventilation or perfusion
 - ❖ Increase FRC & WOB
 - ❖ Decrease surface for gas exchange
 - ❖ Bullae, blebs

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Ventilation-Perfusion Mismatch

- > **Causes**
 - ❖ Airway obstruction
 - ❖ Atelectasis
 - ❖ Consolidation
 - ❖ Emphysema
 - ❖ Pulmonary vascular disease

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Ventilation-Perfusion Mismatch

- > **Effects on oxygenation**
 - ❖ Decreased PaO₂, SaO₂, CaO₂, \bar{v} , Pa/A O₂
 - ❖ Increased P(A-a) O₂
 - ❖ Usually correctable with supplemental oxygen

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Diagram illustrating a V/Q mismatch. The partial pressure of inspired oxygen (PIO₂) is 160. The arterial partial pressure of oxygen (PaO₂) is 70 torr. The alveolar-arterial oxygen gradient (P(A-a)O₂) is calculated as 100 - 70 = 30. The ratio of arterial to alveolar oxygen (Pa/AO₂) is 70/100 = 0.7.

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Anatomic Shunt

> Circulation of venous blood into the arterial circulation

Shunted venous blood bypasses the lung.

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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 right-to-left

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Anatomic Shunt

> Effects on oxygenation

- ❖ Decreased PaO₂, SaO₂, CaO₂, \bar{v} , Pa/A O₂
- ❖ Increased P(A-a) O₂
- ❖ Minimal response to supplemental oxygen

See link below to view shunt equation

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Diffusion Defect

> Defined: disruption of the diffusion of O₂ from the alveoli to capillaries

Diagram illustrating a diffusion defect. A block is shown in the capillary bed, preventing O₂ diffusion from the alveoli to the capillaries.

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Diffusion Defect

> Causes

- ❖ Thickened alveolar membrane
 - Inflammation
 - Edema
 - Fibrosis
- ❖ Loss of alveolar surface area - emphysema

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Diffusion Defect

- > Diagnosis
 - ❖ Single-breath D_1CO
 - ❖ Exercise ABG or SPO_2

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Diffusion Defect

- > Effects on oxygenation
 - ❖ Does NOT affect CO_2 diffusion
 - ❖ Decreased PaO_2 , SaO_2 , CaO_2 , \bar{V} , $Pa/A O_2$
 - ❖ $P(A-a) O_2$ increases with exercise
 - ❖ Usually correctable with supplemental oxygen

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Using $Pa/A O_2$ in calculations

- > Predicting PaO_2 for changed FiO_2
- ABGs: $FiO_2 = 0.6$, $PaO_2 = 50$, $PaCO_2 = 30$
 Increasing FiO_2 to 0.7 will produce what PaO_2 ?
- Use alveolar air equation to find $Pa/A O_2$
- $$PAO_2 = 0.6 (713) - (30 * 1.25) = 390$$
- $$PaO_2/PAO_2 = 50/390 = 0.13$$

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Using $Pa/A O_2$ in calculations

- > Predicting PaO_2 for changed FiO_2
- Increasing FiO_2 to 0.7 will produce what PaO_2 ?
- $$FiO_2 = 0.7$$
- $$PAO_2 = 0.7 (713) - (30 * 1.25) = 462$$
- $$PaO_2/PAO_2 = 50/390 = 0.13 \text{ (original)}$$
- $$0.13 * 462 = 60$$

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Pa/FiO_2 Ratio

- > Common index for clinical settings & research
- > Values
 - ❖ Normal $95 / 0.21 = 452$
 - ❖ Acute lung injury: $PaO_2 / FiO_2 = < 300$
 - ❖ ARDS: $PaO_2 / FiO_2 = < 200$
- > Disadvantages
 - ❖ Index changes with FiO_2
 - ❖ Does not consider lung mechanics

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Oxygen Index (OI)

- > For patients on CMV
- > Pediatric clinical settings & research
- > Calculation

$$OI = \frac{FiO_2 \times MAP \times 100}{PaO_2}$$
- > Values
 - ❖ Very good < 5
 - ❖ Medium $10 - 20$
 - ❖ Poor > 25

See link below to use OI calculator

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Oxygen Index (OI)

- > Advantages
 - ❖ Considers lung mechanics (mean airway pressure)
 - ❖ Prognostic value: Greater OI → risk for mortality

See link below for abstract on OI applied to adults

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Permissive Hypoxemia

- > Rationale: to avert VILI, and/or pulmonary oxygen toxicity
- > Considerations
 - ❖ Fetal PO₂: UA 12 - 18 mm Hg, UV 26 - 32 mm Hg
 - ❖ Lowest PaO₂ in adult human 19 mm Hg
 - ❖ Hyperoxia is associated with increased mortality

FYI see link below to download an article about permissive hypoxemia

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Permissive Hypoxemia

- > Compensations
 - ❖ Cardiac output augmentation
 - ❖ Hypercapnia: increases tissue release to the tissues
 - ❖ Erythrocytosis: increases content
 - ❖ Decreased muscular activity decreases O₂ requirements - hibernation?

FYI see link below to download another article about permissive hypoxemia

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Permissive Hypoxemia

- > Monitoring
 - ❖ PaO₂ , SpO₂
 - ❖ Noninvasive cardiac output
 - ❖ Blood lactate
 - ❖ Acid-base status
- > Inappropriate for
 - ❖ Brain-injured patients
 - ❖ Patients with limited cardiac output
 - ❖ Anemic patients, Jehovah's Witnesses
 - ❖ Patients with pulmonary hypertension

Up next: Predicted PaO₂ practice

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Practice Predicting PaO₂

Given the following data, predict the future PO₂ if the FiO₂ is changed to 40%.

PB = 760
 FiO₂ = .28
 PO₂ = 60
 PCO₂ = 50

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Practice Predicting PaO₂

$$.28(760-47) - (50 \times 1.25)$$

$$199 - 62.5 = 136.5$$

$$a/A = .44$$

$$.40(760-47) - (50 \times 1.25)$$

$$285 - 62.5 = 222.5$$

$$222.5 \times .44 = 98$$

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Practice OI

Given the following data, calculate the Oxygen Index.

PB = 760
 FiO2 = 0.28
 PO2 = 60
 PCO2 = 50
 MAP = 17

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Practice OI

$$\frac{FiO_2 \times MAP \times 100}{PaO_2}$$

$$= \frac{.28 \times 17 \times 100}{60}$$

Answer = 8

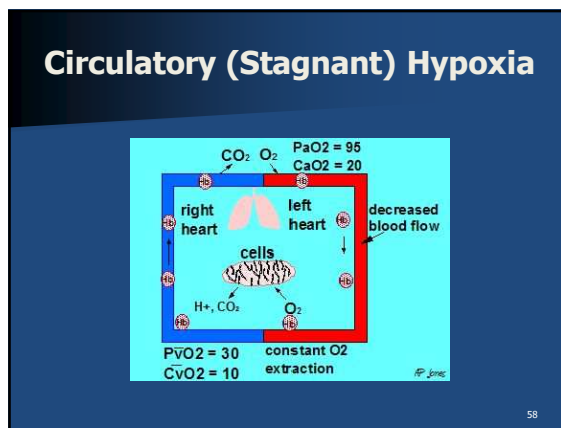
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Non-Hypoxemic Hypoxia

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Circulatory (Stagnant) Hypoxia

> Causes

- ❖ Decreased cardiac output
- ❖ Shock from other origins - pooling of blood
- ❖ Local hypoxia - vascular occlusion, constriction, e.g. vasopressors

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Circulatory (Stagnant) Hypoxia

> Effects on oxygenation

- > Normal PaO₂, P(A-a) O₂, SaO₂
- > Decreased $\bar{v}O_2$, $\bar{v}O_2$
- > Increased $\bar{v}O_2$

See link below to article on lack of benefit for PA catheters

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Anemic Hypoxia

- > Decreased CaO_2 due to inadequate or dysfunctional Hb

$$CaO_2 = (Hb \text{ g/dL}) (SaO_2) (1.34) + (PaO_2 * 0.003)$$

$$CaO_2 = (15 * 0.98 * 1.34) + (95 * 0.003)$$

<u>on Hb</u>	+	<u>dissolved</u>	=	<u>total</u>
19.7 ml		0.29 ml		20 ml

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Anemic Hypoxia

- > Causes
 - ❖ Anemia, due to decreased RBC production
 - ❖ Hemorrhage
 - ❖ Porphyria, e.g. vampires
 - ❖ Sickle-cell anemia
 - ❖ Carbon monoxide poisoning: Hb_{CO}
 - ❖ Methemoglobinemia: Hb_{MET}
 - ❖ Sulfhemoglobinemia: Hb_{SULF}

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Anemic Hypoxia

- > Effects on oxygenation
 - > Normal PaO_2 , $P(A-a) O_2$
 - > Normal calculated SO_2
 - > Decreased SaO_2 , CO_2 (measured)

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Anemic Hypoxia

- > Elevated $HbCO$
 - ❖ CO binds to hemoglobin & cardiac myoglobin
 - ❖ Normal < 1%
 - ❖ Symptoms > 10%
 - ❖ Fatal > 50%
 - ❖ Fatal (fetus) > 30%

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Anemic Hypoxia

- > Elevated Hb_{MET}
 - ❖ Hb oxidizes - does not carry O_2
 - ❖ Causes
 - Hereditary
 - Nitrates, nitrites - beets, spinach, well water, medications
 - Local anesthetics, e.g. benzocaine
 - ❖ Values
 - Normal < 1%
 - Symptomatic > 40%

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Histotoxic Hypoxia

- > Failure of tissues to utilize O_2

The diagram illustrates a circulatory loop. At the top, a blue box represents the lungs with $CaO_2 = 20$. A red line (arterial blood) carries oxygenated blood to the right heart, then to the left heart, and finally to the cells. The venous blood returning to the right heart has $CvO_2 = 18$. The cells are shown with $SvO_2 = 85\%$. However, the diagram indicates a failure of cellular O_2 uptake, with H^+ and CO_2 being released from the cells and O_2 not being fully utilized. The text 'decreased cellular O_2 uptake' is written at the bottom of the diagram.

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Histotoxic Hypoxia

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

FYI see link below to article on HIV & lactic acidemia

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Histotoxic Hypoxia

- > Effects on oxygenation
 - ❖ Normal PaO₂, SaO₂, CaO₂
 - ❖ Elevated $\bar{v}O_2$, $\bar{v}O_{2i}$
 - ❖ Decreased $\bar{v}O_{2t}$

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Lactate

- > Produced by hypoxic cells
- > Indications for testing
 - ❖ Detecting tissue hypoxia, due to non-hypoxemic causes, such as histotoxicity, septic shock
 - ❖ Predicting mortality from septic shock
 - ❖ Evaluating safety of vasopressors
 - ❖ Sports medicine - endurance (portable analyzers)

FYI see link below to an article on blood lactate in critical illness

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Lactate

- > Sampling sites - arterial, venous, capillary (venous values higher)
- > Sample requires icing, if analysis is delayed
- > Infusion of Ringer's lactate does not interfere with measurement
- > Values
 - ❖ Normal < 1.2 mmol/L (arterial)
 - ❖ Critical > 5.5 mmol/L (arterial)

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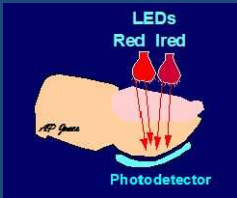
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Pulse Oximetry

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Principles of Operation



FYI see link below for more information and illustrations of pulse oximetry

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Principles of Operation

- Ratio of red:Infrared used to compute SpO₂
- Measurement at pulse to identify arterial blood
- Measurements of different light wave lengths for additional parameters, e.g. HbCO

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Measurement Sites



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Measurement Sites

- Adults
 - ❖ Finger
 - ❖ Toe
 - ❖ Ear: most rapid response
 - ❖ Forehead
 - Reflective sensor
 - Venous pulse may cause error

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Measurement Sites

- Infants
 - ❖ Foot
 - ❖ Finger
 - ❖ Toe



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Limitations

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

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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?
- User knowledge
- Sensor must be used for intended site

FYI see link below to AARC pulse oximetry CPG

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Masimo Rainbow Radical - 7



Image courtesy of Masimo

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Masimo Rainbow SET™

- > Monitored oxygenation parameters
 - ❖ SpO₂
 - ❖ Hb_{CO} - carboxyhemoglobin
 - ❖ Hb_{MET} - methemoglobin
 - ❖ Hb - hemoglobin
 - ❖ Oxygen content

FYI see link below for more information on Masimo Rainbow SET

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Masimo Rainbow SET™

- > Monitored perfusion parameters
 - ❖ Pulse
 - ❖ Pleth wave form
 - Pulses paradoxus: change in pleth amplitude with respiration
 - Perfusion Index (PI): neonatal & adult surgical perfusion monitoring
 - Pleth Variability Index (PVI): fluid responsiveness

FYI see link below for more information on PVI

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Oxygenation Algorithm

Etiology	PaO ₂	P(A-a)O ₂	CaO ₂	C(a-v)O ₂
Low PIO ₂	Low	Norm	Low	Norm
Hypoventilation	Low	Norm	Low	Norm
V/Q mismatch	Low	High	Low	Norm
QSP, QSAN	Low	High	Low	Norm
Diffusion block	Low	High	Low	Norm
Stagnant	Norm	Norm	Norm	High
Anemic	Norm	Norm	Low	Norm
Histotoxic	Norm	Norm	Norm	Low

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Summary & Review

- > Requirements for tissue oxygenation
- > Blood gas tensions: Dalton's Law & alveolar gas equation
- > Hemoglobin saturation
- > Hypoxemic hypoxia
 - ❖ Decreased PIO₂
 - ❖ Hypoventilation
 - ❖ VQ mismatch
 - ❖ Shunt
 - ❖ Diffusion defect
- > Hypoxemia Indexes

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Summary & Review

- > Non-hypoxemic hypoxia
 - ❖ Circulatory
 - ❖ Anemic
 - ❖ Histotoxic
- > Lactate - detect non-hypoxemic hypoxia
- > Pulse oximetry
 - ❖ Limitations
 - ❖ Parameters in addition to SpO₂

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