Non-Invasive Respiratory Gas Monitoring

Bryan E. Bledsoe, DO, FACEP
The George Washington University Medical Center

Endorsements
This educational module has been endorsed by the following professional organizations:

- Roy Alson, MD, PhD, FACEP
- James Augustine, MD, FACEP
- Edward Dickinson, MD, FACEP
- Marc Eckstein, MD, FACEP
- Steven Katz, MD, FACEP
- Mike McEvoy, PhD, RN, EMT-P
- Joe A. Nelson, DO, MS, FACOEP, FACEP
- Ed Racht, MD
- Mike Richards, MD, FACEP
- Keith Wesley, MD, FACEP
- Paula Willoughby-DeJesus, DO, MHPE, FACOEP

Respiratory Gas Physiology

Respiratory Gasses

- Normal Atmospheric Gasses:
  - Oxygen (O₂)
  - Carbon Dioxide (CO₂)
  - Nitrogen (N₂)
  - Water Vapor (H₂O)
- Trace Gasses:
  - Argon (Ar)
  - Neon (Ne)
  - Helium (He)

Most important respiratory gasses:
- Oxygen (O₂)
- Carbon Dioxide (CO₂)
Respiratory Gasses

Respiratory gasses often represented based upon their partial pressures.

Dalton’s Law:
"The total pressure in a container is the sum of partial pressures of all gasses in the container."

Determining partial pressures:
\[ P_A = X_A \times P \]

Where:
- \( P_A \) = pressure of the gas
- \( X_A \) = mole fraction of the gas
- \( P \) = total pressure of the mixture

\[ PO_2 = 0.2095 \times 760 \text{ mm Hg} \]
\[ PO_2 = 159.22 \text{ mm Hg} \]

Partial pressure of oxygen in atmosphere at sea level = 159 mm Hg

Atmospheric Gasses

<table>
<thead>
<tr>
<th>GAS†</th>
<th>PRESSURE (mm Hg)</th>
<th>PERCENTAGE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen (N₂)</td>
<td>593.408</td>
<td>78.08</td>
</tr>
<tr>
<td>Oxygen (O₂)</td>
<td>159.220</td>
<td>20.95</td>
</tr>
<tr>
<td>Argon (Ar)</td>
<td>7.144</td>
<td>0.94</td>
</tr>
<tr>
<td>Carbon Dioxide (CO₂)</td>
<td>0.288</td>
<td>0.03</td>
</tr>
<tr>
<td>Neon (Ne)</td>
<td>0.013</td>
<td>0.0018</td>
</tr>
<tr>
<td>Helium (He)</td>
<td>0.003</td>
<td>0.0005</td>
</tr>
<tr>
<td>TOTAL</td>
<td>760</td>
<td>100</td>
</tr>
</tbody>
</table>

† = dry air at sea level.

Respiratory Gasses

Oxygen

- Odorless.
- Tasteless.
- Colorless.
- Supports combustion.
- Present in the atmosphere as a diatomic gas (O₂).
- Necessary for animal life.

Derived from plant photosynthesis:
- Algae (75%).
- Terrestrial Plants (25%).
- Oxygen atom must share electrons for stability.
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**Carbon Dioxide**
- Colorless.
- Sour taste at high concentrations.
- Found in very low concentrations in fresh air.
- Asphyxiating.

**Abnormal Respiratory Gasses**
- Carbon monoxide (CO)

**Carbon Monoxide**
- Colorless
- Odorless
- Tasteless
- Results from incomplete combustion of carbon-containing compounds.
- Heavier than air.

**Respiratory Gas Transport**
- Oxygen
  - 97% reversibly bound to hemoglobin.
  - 3% dissolved in plasma.
- Carbon Dioxide
  - 70% as bicarbonate ($\text{HCO}_3^-$).
  - 23% reversibly bound to hemoglobin.
  - 7% dissolved in plasma.

**Hemoglobin**
- Protein-Iron Complex.
- Transports oxygen to peripheral tissues.
- Removes a limited amount of carbon dioxide from the peripheral tissues.
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**Hemoglobin**
- Human hemoglobin is made of various sub-units:
  - 2 α sub-units
  - 2 β sub-units
  - 4 iron-containing heme structures.

**Hemoglobin Binding Sites**
- Deoxyhemoglobin: Heme is in Fe²⁺ state and domed. Can bind oxygen. Also called the "T" state.
- Oxyhemoglobin: Heme is in Fe³⁺ state and planar. Oxygen bound. Also called the "R" state.

**Abnormal Hemoglobin States**
- Carboxyhemoglobin
- Methemoglobin

**Hemoglobin**
- The binding of oxygen changes the conformation (shape) of the hemoglobin molecule.
- Deoxyhemoglobin is converted to oxyhemoglobin.

**Carboxyhemoglobin (COHb)**
- Results from the binding of CO to hemoglobin following CO exposure.
- Some always present in smokers.
Carboxyhemoglobin (COHb)
- CO has 250 times the affinity for hemoglobin as does O₂.
- CO displaces O₂ from hemoglobin.
- CO can be displaced by high-concentration O₂.
- Half-life is 4-6 hours.

Methemoglobin
- Heme must be in the ferrous (Fe²⁺) state to bind O₂.
- Methemoglobin is hemoglobin in the ferric (Fe³⁺) state and cannot bind O₂.
- Normally < 1% of hemoglobin is methemoglobin.
- High levels lead to hypoxemia.

Methemoglobin
- Hereditary:
  - Hemoglobin M
  - Enzyme deficiency
- Acquired:
  - Nitrates
  - Nitrites
  - Dyes
  - Sulfonamides
  - Lidocaine
  - Benzocaine

Oxygen Saturation
- Hemoglobin oxygen saturation is directly related to the partial pressure of oxygen in the blood (PO₂).
- Venous blood saturation.
- Arterial blood saturation.

Factors Affecting Saturation
- Decreased saturation.
  - Decreased pH (acidosis).
  - Increased CO₂.
  - Increased temperature.
  - Increased BPG (2,3-biphosphoglycerate)
- Increased saturation.
  - Increased pH (alkalosis)
  - Decreased CO₂.
  - Decreased temperature.
  - Decreased BPG (2,3-biphosphoglycerate)

2,3-biphosphoglycerate
- Aids in oxygen release in the peripheral tissues.
- Higher levels found in people who live at high altitudes.
- Helps mitigate the effects of hypoxia.
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**Carbon Dioxide Transport**
- Majority of CO₂ transported in the form of bicarbonate ion (HCO₃⁻).

\[ \text{CO}_2 + \text{H}_2\text{O} \rightarrow \text{H}_2\text{CO}_3 \rightarrow \text{H}^+ + \text{HCO}_3^- \]

Carbonic Anhydrase increases speed of reaction 5,000 fold.

**Bohr Effect**
- Increases in CO₂ levels in the blood cause oxygen to be displaced from hemoglobin.
- Increases oxygen transport.

**Haldane Effect**
- Binding of oxygen to hemoglobin tends to displace CO₂.
- Oxyhemoglobin is more acidic than deoxyhemoglobin:
  - Promotes removal of CO₂ in the alveoli.
  - Promotes release of hydrogen ions which combine with bicarbonate ions to form H₂O and CO₂ which are eliminated.

**Respiratory Gas Measurement**
- Arterial Blood Gas Sampling
- Pulse Oximetry
- Capnography
- Transcutaneous CO₂ Monitoring
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Arterial Blood Gasses
- Gold standard for respiratory gas monitoring.
- Invasive
- Expensive
- Painful
- Difficult

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Normal</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>7.35-7.45</td>
</tr>
<tr>
<td>PO$_2$</td>
<td>80-100 mm Hg</td>
</tr>
<tr>
<td>PCO$_2$</td>
<td>35-45 mm Hg</td>
</tr>
<tr>
<td>HCO$_3^-$</td>
<td>22-26 mmol/L</td>
</tr>
<tr>
<td>BE</td>
<td>-2 to +2</td>
</tr>
<tr>
<td>SaO$_2$</td>
<td>&gt; 95%</td>
</tr>
</tbody>
</table>

Arterial Blood Gasses
- Excellent diagnostic tool.
- Impractical in the prehospital setting.

OXYGEN

Pulse Oximetry
- Introduced in early 1980s.
- Non-invasive measurement of oxygen saturation.
- Safe
- Inexpensive

Pulse Oximetry
- How it works:
  - Probe is placed over a vascular bed (finger, earlobe).
  - Light-emitting diodes (LEDs) emit light of two different wavelengths:
    - Red = 660 nm
    - Infrared = 940 nm

Pulse Oximetry
- Some light is absorbed by:
  - Arterial blood
  - Venous blood
  - Tissues
- Light that passes through the tissues is detected by a photodetector.

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Pulse Oximetry
- Only inflow of blood is used to determine SpO₂.
- Hence the name “Pulse Oximetry”
- Hb and HbO₂ absorb light and different rates due to color and conformation.

Pulsatilie Flow
- This is the band used to measure SpO₂.

Oximetry Probe Placement
- Finger
- Earlobe
- Heel (neonates)

Oximetry Probe Placement
- Accuracy falls when LEDs and photoreceptors poorly aligned.
- Accuracy decreases with lower pulse oximetry readings.

Pulse Oximetry
- Some manufacturers use reflective oximetry for monitoring.
- LEDs and photodetectors in same electrode.
- Light reflected from the tissues and detected by photodetectors and findings interpreted by the software in the oximeter.
- Can be used on forehead or back.
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Pulse Oximetry
- HbO₂ absorbs more infrared light than Hb.
- Hb absorbs more red light than HbO₂.
- Difference in absorption is measured.
- Ratio of absorbance matched with SpO₂ levels stored in the microprocessor.

Perfusion Index
- Reflects the pulse strength at the monitoring site.
- Ranges from 0.02% (very weak pulse strength) to 20% (very strong pulse strength).
- Helps determine best site to place probe.

Pulse Oximetry
- SaO₂ used for oxygen saturation readings derived from arterial blood gas analysis.
- SpO₂ used for oxygen saturation readings from pulse oximetry.
- SpO₂ and SaO₂ are normally very close.

Pulse Oximetry
- Pulse oximetry tells you:
  - SpO₂
  - Pulse rate
- Pulse oximetry cannot tell you:
  - O₂ content of the blood
  - Amount of O₂ dissolved in blood
  - Respiratory rate or tidal volume (ventilation)
  - Cardiac output or blood pressure.

Who Should Use?
- Any level of prehospital care provider who administers O₂.
- First Responders
- EMTs
- EMT-Intermediates
- Paramedics

Prehospital Indications
1. Monitor the adequacy of arterial oxyhemoglobin saturation (SpO₂).
2. To quantify the SpO₂ response to an intervention.
3. To detect blood flow in endangered body regions (e.g., extremities).
Limitations

- Oximetry is NOT a measure of ventilation (EtCO₂ a better measure of ventilation).
- Oximetry may lag behind hypoxic events.
- Oximetry is not a substitute for physical examination.
- Very low saturation states may be inaccurate due to absence of measured SpO₂ levels in the database.

First-Generation Oximeter Problems

- False Readings:
  - Hypotension.
  - Hypothermia.
  - Vasoconstriction.
  - Dyes/pigments (e.g., nail polish).
  - Movement may cause false reading in absence of pulse.
- Abnormal hemoglobin:
  - COHb.
  - METHb.
- Oximeter can’t perform:
  - Bright ambient lighting.
  - Shivering.
  - Helicopter transport.

First-Generation Oximeter Problems

- Motion, noise, and low perfusion states can cause artifacts and false oximetry readings.
- These have been eliminated or minimized in second-generation oximeters.

Second-Generation Technology

- Newer technology uses signal processing to minimize artifacts and false readings:
  - Adaptive Filters
  - Signal Processing Algorithms
  - Improved Sensors

Second-Generation Technology

- Technology prevents:
  - Motion artifact.
  - False readings during low-flow states.
  - False bradycardias.
  - False hypoxemias.
  - Missed desaturations.
  - Missed bradycardias.
  - Data dropouts.
  - Effects of dyshemoglobins.

Myths

- Age affects SpO₂
- Gender affects SpO₂
- Anemia affects SpO₂
- SpO₂ inaccurate in dark-skinned individuals.
- Jaundice affects SpO₂.
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Prehospital Usage

- Assure scene safety.
- Initial assessment.
- ABCs
- Apply oxygen when appropriate (either with or after oximetry).
- Secondary Assessment
- Ongoing monitoring.

Always treat the patient and not the oximeter.

Reading the Oximeter

- SpO2 (%)
- PI (%)
- Pulse Rate (bpm)

What Does it Mean?

<table>
<thead>
<tr>
<th>SpO2 READING (%)</th>
<th>INTERPRETATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>95 – 100</td>
<td>Normal</td>
</tr>
<tr>
<td>91 – 94</td>
<td>Mild Hypoxemia</td>
</tr>
<tr>
<td>86 – 90</td>
<td>Moderate Hypoxemia</td>
</tr>
<tr>
<td>&lt; 85</td>
<td>Severe Hypoxemia</td>
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</tbody>
</table>

Interventions

<table>
<thead>
<tr>
<th>SpO2 READING (%)</th>
<th>INTERPRETATION</th>
<th>INTERVENTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>95 – 100</td>
<td>Normal</td>
<td>Change FiO2 to maintain saturation.</td>
</tr>
<tr>
<td>91 – 94</td>
<td>Mild Hypoxemia</td>
<td>Increase FiO2 to increase saturation.</td>
</tr>
<tr>
<td>86 – 90</td>
<td>Moderate Hypoxemia</td>
<td>Increase FiO2 to increase saturation. Assess and increase ventilation.</td>
</tr>
<tr>
<td>&lt; 85</td>
<td>Severe Hypoxemia</td>
<td>Increase FiO2 to increase saturation. Increase ventilation.</td>
</tr>
</tbody>
</table>

Oximetry to Assess Circulation

- Oximeter probe can be placed onto tissue distal to an injury to detect circulation.
- Oximeter can monitor distal circulation with fractures and crush injuries.
- Clinical correlation always needed.
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CARBON DIOXIDE

End-Tidal CO\(_2\) Monitoring
- CO\(_2\) cannot be measured with the same technology used in oximetry.
- CO\(_2\) binds to a different site on hemoglobin compared to O\(_2\).
- No hemoglobin color change.
- No hemoglobin conformation change.
- Carbaminohemoglobin cannot be distinguished from deoxyhemoglobin via oximetry.

End-Tidal CO\(_2\) Monitoring
- CO\(_2\) can be non-invasively monitored through measurement of exhaled air.
- Sensors available for endotracheal tubes and for non-intubated patients.

End-Tidal CO\(_2\) Monitoring
- Exhaled CO\(_2\) detected with pH sensitive paper or infrared spectography.
- Respiratory cycle results in a capnogram.
- End-tidal CO\(_2\) (EtCO\(_2\)) is the maximum amount of exhaled CO\(_2\) at the end of respiration.

End-Tidal CO\(_2\) Monitoring
- Capnography provides information about ventilation.
- Normal EtCO\(_2\):
  - ~ 5%
  - ~ 35-37 mm Hg
- Gradient (PaCO\(_2\) and EtCO\(_2\)): 5-6 mm Hg
- EtCO\(_2\) can be used to estimate PaCO\(_2\) in patients with normal lungs.

Indications:
- Endotracheal tube placement.
- To determine the adequacy of ventilation.
- Continuous monitoring of a critical patient where ABGs may not be available.
- To maintain a specific carbon dioxide level (e.g., brain injury).
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End-Tidal CO₂ Monitoring
- Elevated or continually rising:
  - Increased CO₂ production (e.g., fever, seizures).
  - Decreased alveolar ventilation (e.g., CNS depression, ↓ \( V_{\text{min}} \), muscular disorder).
  - Equipment malfunction (e.g., bad sensor).

End-Tidal CO₂ Monitoring
- Lowered of continually diminishing:
  - Decreased CO₂ production (e.g., hypothermia, cardiac arrest, pulmonary embolism).
  - Increased alveolar ventilation (e.g., tachypnea, hyperpnea, ↑ \( V_{\text{min}} \)).
  - Equipment malfunction (e.g., obstruction of ventilation system, misplaced ET tube, bad sampling head).

Transcutaneous CO₂ Monitoring
- Technology available for almost 30 years.
- Primarily used in neonates.
- Transcutaneous O₂ often available.
- Correlates to PCO₂.
- Probe is heated and must be moved often.
- Measurements based upon pH.

CARBON MONOXIDE

Carbon Monoxide
- Carbon monoxide (CO) is the leading cause of poisoning deaths in industrialized countries.
- ~ 3,800 people in the US die annually from CO poisoning.

Carbon Monoxide
- CO results from the incomplete combustion of carbon-based fuels.
- It is odorless, colorless and tasteless.
- CO is heavier than air and tends to accumulate in the lower aspect of structures.
Carbon Monoxide

- CO detection previously required hospital-based ABGs to measure COHb.
- Technology now available to detect COHb levels in the prehospital and ED setting.

CO-Oximetry

- CO evaluation should be routine at all levels of EMS and the fire service.
- All field personnel should be educated in use of the oximeter and CO-oximeter.

Cherry red skin color not always present and, when present, is often a late finding.

COHb levels do not always correlate with symptoms nor predict sequelae.

<table>
<thead>
<tr>
<th>Severe</th>
<th>41 - 59%</th>
<th>Palpitations, dysrhythmias, hypotension, myocardial ischemia, cardiac arrest, respiratory arrest, pulmonary edema, seizures, coma.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fatal</td>
<td>&gt; 60%</td>
<td>Death</td>
</tr>
</tbody>
</table>

CO binds 250 times stronger than O₂

Only very high concentration of O₂ can displace CO molecule

- Cherry red skin color not always present and, when present, is often a late finding.
- COHb levels do not always correlate with symptoms nor predict sequelae.

Missed CO poisoning is a significant legal risk for EMS and fire service personnel.
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CO-Hb Levels in Persons 3-74 Years

<table>
<thead>
<tr>
<th>Smoking Status</th>
<th>% COHb (mean ± σ)</th>
<th>% COHb (98th percentile)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nonsmokers</td>
<td>0.83 ± 0.67</td>
<td>&lt; 2.50</td>
</tr>
<tr>
<td>Current Smokers</td>
<td>4.30 ± 2.55</td>
<td>≤ 10.00</td>
</tr>
<tr>
<td>All persons combined</td>
<td>1.94 ± 2.24</td>
<td>≤ 9.00</td>
</tr>
</tbody>
</table>

Treatment

- Treatment is based on the severity of symptoms.
- Treatment generally indicated with SpCO > 12-15%.
- High-concentration O2 should be administered to displace CO from hemoglobin.
- Be prepared to treat complications (e.g., seizures, cardiac ischemia).

Treatment

- Prehospital CPAP can maximally saturate hemoglobin and increase oxygen solubility.
- Strongly suggested for moderate to severe poisonings.

Treatment

- Efficacy of hyperbaric oxygen therapy (HBO) is a matter of conjecture although still commonly practiced.
- Generally reserved for severe poisonings.
- May aid in alleviating tissue hypoxia.

Treatment Algorithm

CO Poisoning Considerations

- Significant and evolving body of literature now suggests that there are numerous long-term and permanent sequelae from CO poisoning.
CO Poisoning Considerations
- Fetal hemoglobin has a much greater affinity for CO than adult hemoglobin.
- Pregnant mothers may exhibit mild to moderate symptoms, yet the fetus may have devastating outcomes.

CO Poisoning
- Remember, CO poisoning is the great imitator.
- Missed CO exposure often leads to death and disability.
- CO is a particular risk for firefighters.

A simple COHb reading can save a life and prevent long-term problems.

Methemoglobin
- METb is hemoglobin with heme in the Fe³⁺ state.
- Cannot bind O₂.
- SpMET levels usually < 1% (Range 1-3%)
- Reflects hemoglobin at the end of its functional life.
- Results in dark reddish-brown blood.
- Most frequently seen in children < 4 months (blue baby).

Methemoglobinemia
- As SpMET levels increase, a functional anemia occurs (total Hb normal but significant percentage of Hb non-functional).
- Cyanosis begins (usually around lips) when SpMET >10 - 15%.
- Organs with high O₂ demands (e.g., CNS, cardiovascular system) manifest toxicity first.

Methemoglobinemia Causes
- Inherited:
  - Hemoglobin disorder (HgM).
  - Enzyme disorders (e.g., G6PD deficiency).
- Acquired:
  - Nitrites
  - Nitrates
  - Sulfonamides
  - Lidocaine
  - Benzocaine
  - Certain aromatic hydrocarbons
  - Dyes
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**Symptoms**

<table>
<thead>
<tr>
<th>SpMET</th>
<th>Symptom</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-3%</td>
<td>Normal, asymptomatic</td>
</tr>
<tr>
<td>3-15%</td>
<td>Slight grayish blue skin discoloration</td>
</tr>
<tr>
<td>15-20%</td>
<td>Asymptomatic, but cyanotic.</td>
</tr>
<tr>
<td>25-50%</td>
<td>Headache, dyspnea, confusion, weakness, chest pain.</td>
</tr>
<tr>
<td>50-70%</td>
<td>Altered mental status, delirium.</td>
</tr>
</tbody>
</table>

**Prehospital Treatment**

- High-concentration O₂.
- Remove offending agents.
- Methylene blue (accelerates the enzymatic degradation of METHb) is antidote.

**CO and Cyanide**

- Parts of cyanide antidote (amyl nitrite) induce methemoglobinemia.
- Cyanide antidotes and carbon monoxide (CO) can elevate COHb and METHb, reducing O₂ capacity of blood.
- Sodium nitrite should be avoided for combination cyanide/CO poisonings when SpCO >10%.
- Hydroxocobalamin converts cyanide to cyanocobalamin (Vitamin B₁₂) which is renally-cleared.

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