Application of Volumetric Capnography in Pediatric Patients

Objectives

- Describe the differences between capnography and volumetric capnography.
- Discuss the clinically relevant information that can be obtained from volumetric capnography.
- Review of different approaches of using volumetric capnography in regards to evaluation of metabolic rate and calculation of physiologic dead space fraction.

Physiologic Basis for Exhaled CO$_2$ Monitoring

- Cellular Metabolism
  - CO$_2$ Production
  - Metabolic Rate
- Transport of CO$_2$
  - Cardiac Output
  - Pulmonary Perfusion
- Ventilation
  - CO$_2$ Diffusion
  - Dead Space Fraction
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**Time Based Capnography**

- CO₂ Waveform Plotted Over Time
- Normal PaCO₂ - ETCO₂ Gradient = 2 – 5 mmHg

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**Clinical Application of Time Based Capnography**

- Monitoring Adequacy of Ventilation
- Confirmation of Endotracheal Intubation
- Monitoring Respiratory Status
- Monitoring During Cardiopulmonary Resuscitation

Monitoring Exhaled CO₂  Resp Care 2016

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**Volumetric Capnography**

- CO₂ Waveform Plotted Against Exhaled Tidal Volume
- Volumetric capnography allows more advanced physiologic monitoring than time based capnography
Clinical Application of Volumetric Capnography
- Estimating Metabolic Rate and Resting Energy Expenditure
- Measuring Physiologic Dead Space
  - Predicting Survival in Pediatric ARDS Patients
  - Assessing the Severity of Lung Pathology (BPD)
  - Indication of Lung Recruitment Versus Overdistension
- Predicting Successful Liberation from Mechanical Ventilation

Volumetric Capnography
- Measurement of tidal CO₂ volume / breath
- VCO₂ (minute CO₂ volume elimination)
- PECO₂ (mean expired CO₂)
- VD/VT (Physiologic Dead Space)
- Visual assessment (slope of phase III)

Visual assessment of capnography waveform
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Volumetric Capnography

- Requires mainstream CO2 sensor
- Cannot be done with side stream CO2 sampling

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Stand Alone Volumetric Capnography Monitors

Integrated Mainstream CO2 Sensor and Flow Sensor
NICO2                                NM3

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Ventilators with Volumetric Capnography

Separate CO2 Sensor and Flow
Technical Limitations in Pediatric Patients

- Leaks due to uncuffed ET tubes
- Minimizing the dead-space volume of main-stream sensors
- Minimizing sensor weight at the airway
- Faster response time of the CO2 analyzer because higher respiratory rates, especially in preterm neonates with stiff lungs
- Faster sample rate to provide sufficient numerical and graphic resolution of the capnogram
- Minimizing the phase shift between CO2 and flow signals to prevent errors in calculations.

Clinical Application of Volumetric CO2 Monitoring

- Estimating Metabolic Rate and Resting Energy Expenditure
- Measuring Physiologic Dead Space
  - Predicting Survival in Pediatric ARDS Patients
  - Assessing the Severity of Lung Pathology (BPD)
  - Indication of Lung Recruitment Versus Overdistension
  - Predicting successful liberation from Mechanical Ventilation

Estimating Metabolic Rate and Resting Energy Expenditure Using VCO2

- Caloric Equivalence of CO2
- Modification of the Wier Equation
Caloric Equivalence of CO2

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Respiratory Quotient</th>
<th>Carbon Dioxide Caloric Equivalent (KCAL/L)</th>
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</thead>
<tbody>
<tr>
<td>Carbohydrate</td>
<td>1.0</td>
<td>5.05</td>
</tr>
<tr>
<td>Mixed</td>
<td>0.90</td>
<td>5.52</td>
</tr>
<tr>
<td>Protein</td>
<td>0.80</td>
<td>5.57</td>
</tr>
<tr>
<td>Fat</td>
<td>0.71</td>
<td>6.67</td>
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</tbody>
</table>

REE-CO2 Equivalent = 5.52 x VCO2 x 1.44
Hess Resp Care 1986

Simplified Indirect Calorimetry
Modification of the Weir Equation

- RQ = VCO2 / VO2 = 0.85

REE = (3.9 x VO2) + (1.1 x VCO2) x 1.44
REE = (3.9 x VCO2 / 0.85) + (1.1 x VCO2) x 1.44
- Estimates REE based on VCO2 alone

Modification of the Weir Equation

REE-CO2 = 8.19 x VCO2
REE-CO2 Factor
REE-CO2 = 7.82 x VCO2
REE-CO2 = 8.19 x VCO2
Estimating Metabolic Rate and Resting Energy Expenditure Using VCO2

- Caloric Equivalence of CO2
  \[5.52 \times 236 \times 1.44 = 1876 \text{ kcal}\]
- Modification of the Wier Equation
  \[7.82 \times 236 = 1846 \text{ kcal}\]

Accuracy of a simplified equation for energy expenditure based on bedside volumetric carbon dioxide elimination measurement - a two-center study. Clin Nutr 2015

Modified Wier equation (RQ = 0.89) vs IC with Vmax and Delta Trac

CONCLUSIONS:
A simplified metabolic equation using VCO2 values was superior to the standard equation in estimating REE, and provided a reasonably accurate metabolic classification in mechanically ventilated children. In the absence of indirect calorimetry, bedside VCO2 monitoring could provide valuable continuous metabolic information to guide optimal nutrient intake.
Validation of ventilator-derived VCO2 measurements to determine energy expenditure in ventilated critically ill children. Clin Nutr 2017

Caloric equivalence factor of 5.5 vs IC-DT vs pred equation

CONCLUSIONS:
In children ≥15 kg, VCO2 measurements of the Servo-300 seem sufficiently accurate for use in clinical practice. Technical performance of the CO2 sensor limited accuracy at smaller VT and higher respiratory frequencies.

A Comparison of Carbon Dioxide Elimination Measurements Between a Portable Indirect Calorimeter and Volumetric Capnography Monitor: An In Vitro Simulation. Resp Care 2016

Compared NM3 to IC using CCM Express

CONCLUSIONS:
Currently available portable gas exchange monitors demonstrated acceptable agreement with reference VCO2 values in an in vitro simulation.
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<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
<th>Device</th>
<th>Mean Bias (%)</th>
<th>95% CI (%)</th>
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<tbody>
<tr>
<td>$VCO_2$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adult</td>
<td>-1.6</td>
<td>OCM Express</td>
<td>-0.8 to -0.2</td>
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<tr>
<td>Pediat.</td>
<td>-0.9</td>
<td>OCM Express</td>
<td>-0.1 to -0.5</td>
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</tr>
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</table>

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Estimating Metabolic Rate and Resting Energy Expenditure Using VCO2

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Simplified Indirect Calorimetry Using VCO2

- Reasonable alternative as an initial screening method or when a metabolic analyzer is not available
- Not affected by errors or stability of $\text{FiO}_2$ measurement
- Can be performed on any $\text{FiO}_2$
- Accurate to approximately $\pm 5\%$ to $10\%$ of standard REE measurements
- $\text{VCO}_2$ is increasingly more available on ventilators.
- Accuracy of measurements needs to be validated to determine bias and precision of REE-CO2 calculations.
Clinical Application of Volumetric CO2 Monitoring

- Estimating Metabolic Rate and Resting Energy Expenditure
- Measuring Physiologic Dead Space
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Physiologic Dead Space ($V_D/V_T$) is the Percent of Wasted Ventilation

$V_D/V_T = \frac{V_D \text{ Anatomic} + V_D \text{ Alveolar}}{V_T}$

Ventilation with No Perfusion

Ventilation to Perfusion Relationships

- Pure Shunt
  - Perfusion with No Ventilation
- Pure Dead Space
  - Ventilation with No Perfusion
- Shunt Like Units
- Dead Space Like Units

Arterial Obstruction
- Low V/Q
- High V/Q

Overdistension
- High V/Q
Physiologic dead space is traditionally calculated by the Enghoff modification (1938) to the Bohr equation (1891) which substitutes \( \text{PaCO}_2 \) for \( \text{PACO}_2 \).

\[
\frac{V_D}{V_T} = \frac{\text{PaCO}_2 - \text{PeCO}_2}{\text{PaCO}_2}
\]

\( \text{PaCO}_2 \) has been difficult to measure in the clinical setting.

Normal \( \frac{V_D}{V_T} \) is ~33% (range ~20 – 40%)

\[\text{PaCO}_2\text{can be measured by:}\]

- Exhaled gas collection (Douglas bag method)
- Metabolic analyzer (measurement of \( \text{FeCO}_2 \) and calculation of \( \text{PeCO}_2 \))
- Volumetric capnography (stand alone monitor, incorporated into ventilators)

Dead Space Fraction Measurements Using Ventilator Volumetric Capnography

Validated compared to metabolic analyzers and NICO2 monitor

Resp Care 2013
Clinical Application of Volumetric CO2 Monitoring

- Estimating Metabolic Rate and Resting Energy Expenditure
- Measuring Physiologic Dead Space
  - Predicting Survival in Pediatric ARDS Patients
  - Assessing the Severity of Lung Pathology (SIP)
  - Indication of Lung Recruitment Versus Overdistension
  - Predicting Successful Liberation from Mechanical Ventilation


CONCLUSIONS:
- Alveolar dead space fraction at pediatric ARDS onset discriminates mortality and is independently associated with non-survival.
- Alveolar dead space fraction represents a single, useful, readily obtained clinical biomarker reflective of pulmonary and non-pulmonary variables associated with mortality.

End tidal alveolar dead space fraction
\( \frac{\text{PaCO}_2 - \text{PETCO}_2}{\text{PaCO}_2} \)

Higher Dead Space Is Associated With Increased Mortality in Critically Ill Children. Crit Care Med 2015

CONCLUSIONS:
- Increased dead space is associated with higher mortality in critically ill children. End-tidal alveolar dead space fraction is easy to calculate at the bedside, it may be useful for risk stratification and severity-of-illness scores.

End tidal alveolar dead space fraction
\( \frac{\text{PaCO}_2 - \text{PETCO}_2}{\text{PaCO}_2} \)
Clinical Application of Volumetric CO2 Monitoring

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Capnography in spontaneously breathing preterm infants with bronchopulmonary dysplasia. *Pediatr Pulmonol* 2011

CONCLUSIONS:
Compared with healthy infants, a higher PaCO2 – EtCO2 gradient was observed in infants with BPD, suggesting that ventilation-perfusion mismatch may be present in these infants.


CONCLUSIONS:
The ability of Slope of phase III to discriminate between BPD and controls was significantly higher. Volumetric capnography may provide valuable information regarding functional lung alterations related to BPD and might be considered as an alternative to more involved lung function techniques for monitoring chronic lung disease during early infancy.
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Clinical Application of Volumetric CO2 Monitoring

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Optimum End Expiratory Airway Pressure in Patients with Acute Pulmonary Failure. Suter PM, Fairley HB, Isenberg MD. NEJM 1975

- Best PEEP corresponds to the lowest dead space fraction and the highest compliance

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Clinical Application of Volumetric CO2 Monitoring

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Dead space to tidal volume ratio predicts successful extubation in infants and children.

- Dead Space Fraction ≤ 0.50 reliably predicted successful extubation, whereas a VD/VT > 0.65 identified patients at risk for respiratory failure following extubation.

Understanding Volumetric Capnography

- Phases I, II, and III of capnogram analysis.
Fowler Dead Space
Am J Physiol 1948
• Midpoint of the slope of Phase II
• Transition point between airway and alveolar emptying
• Equal to the anatomic dead space

Fowler Dead Space
equals
Anatomic Dead Space
VD anat

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Single Breath CO2 Analysis
Fletcher Br J Anesth 1981
Allows partitioning of the components of dead space for further study and analysis.

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PaCO2 to ETCO2 difference increases as VD_{alv} increases.
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**Bohr vs Enghoff Dead Space Calculation**
- Recent data shows that the midpoint of Phase III is equal to the mean alveolar CO\(_2\) (PACO\(_2\))
  - Resp Care 2017

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**Bohr vs Enghoff Dead Space Comparison**

**Why is this Important?**
- Bohr dead space calculations more accurately reflects true V\(_D\)/V\(_T\)
- Enghoff dead space calculations are elevated in the presence of shunt and low V\(_Q\)/V\(_A\)

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**Ventilation - Perfusion Relationships and VD/VT**

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Use of PACO\textsubscript{2} and PetCO\textsubscript{2} to calculate V\textsubscript{D}/V\textsubscript{T} more closely reflects true Bohr dead space in the presence of increased shunt and low V/Q.

\[
\text{ADSF}_{ET} = \frac{(60-43)}{60} = 0.28
\]
\[
\text{VD}_{ANAT} = \frac{168}{517} = 0.33
\]
\[
\text{VD}/V_{ET} = 0.61
\]
Bohr vs Enghoff Dead Space Comparison

Use of PetCO₂ to calculated V₆/V₉ more closely reflects true Bohr dead space in the presence of increased shunt and low V/Q.

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Bohr vs Enghoff dead space comparison in the presence of increased shunt and low V/Q in a porcine model

Suarez-Sipmann et al, (Tusman Group), Resp Phys NeuroBiol 2013

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Assessment of Bohr and Enghoff Dead Space Equations in Mechanically Ventilated Children Resp Care 2017
• Volumetric capnography is increasingly more prevalent in patient monitoring and will be incorporated into future ventilator designs.

• REE based on VCO₂ is a reasonable alternative as an initial screening method or when a metabolic analyzer is not available.

• Bohr dead space calculations more accurately reflect true Vd/Vt, because Enghoff dead space calculations are elevated in the presence of shunt and low V/Q.

• Continuous Bohr dead space measurements using PACO₂ or PetCO₂ and volumetric capnography is technically feasible. Does not require ABG analysis.

• Further evaluation is needed to determine the best methods for these important physiologic measurements in pediatric patients.

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**Summary and Conclusions**

- Volumetric capnography is increasingly more prevalent in patient monitoring and will be incorporated into future ventilator designs.
- REE based on VCO₂ is a reasonable alternative as an initial screening method or when a metabolic analyzer is not available.
- Bohr dead space calculations more accurately reflect true Vd/Vt, because Enghoff dead space calculations are elevated in the presence of shunt and low V/Q.
- Continuous Bohr dead space measurements using PACO₂ or PetCO₂ and volumetric capnography is technically feasible. Does not require ABG analysis.
- Further evaluation is needed to determine the best methods for these important physiologic measurements in pediatric patients.