Non-Invasive CO₂ Monitoring: The PICU and Beyond

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Sentec has supported my clinical research by providing me with a transcutaneous monitor and the disposable supplies for its use.

No honorarium or proprietary interests.

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Transcutaneous $CO_2$ Monitoring

- The need for continuous $CO_2$ monitoring
- Venous or capillary vs. arterial values
- Methods of continuous non-invasive $CO_2$ monitoring
- Applications of transcutaneous $CO_2$ monitoring
Continuous $P_{CO_2}$ Monitoring

- clinical assessment is inaccurate
  - gold standard for $P_{CO_2}$ monitoring is ABG analysis

- ABG analysis
  - instantaneous value for a continuously changing clinical picture
  - may not be immediately available
    - transport, remote locations, outlying ED’s
  - requires an invasive procedure
  - not immediately available without indwelling catheter
  - crying during procedure may alter results
  - cost: drawing sample + running test

- consequences of invasive procedure
  - pain and physiologic stress
  - risk of morbidity from indwelling catheter
  - does my patient really need an arterial line – will it last?
  - repeated phlebotomy
My Patient Needs Normocarbia

- **cardiovascular dysfunction**
  - hypercarbia & acidosis impair myocardial performance
- **closed head injury**
  - hyperventilation results in less favorable outcome
  - hypercarbia increases ICP
- **neonates**
  - alterations in PaCO₂ and CBF may → ICH
- **congenital heart disease**
  - infants with single ventricle physiology
  - pulmonary hypertension
Transcutaneous CO\textsubscript{2} Monitoring

- the need for continuous CO\textsubscript{2} monitoring
- *venous or capillary vs. arterial values*
- methods of continuous non-invasive CO\textsubscript{2} monitoring
- applications of transcutaneous CO\textsubscript{2} monitoring
CBG vs. ABG Values


- prospective trial in 75 pediatric patients
  - paired sample (CBG versus ABG)
  - perfusion, hemodynamics, blood pressure, temperature
- differences between the mean values
  - $P_{CO2} = 0.44 \text{ mmHg}$
  - $pH = 0$
  - $P_{O2} = 51 \text{ mmHg}$
- correlation for $P_{CO2}$
  - no hypotension $= 0.86$
  - hypotension $= 0.52$
### VBG vs. ABG Values

Inoue T et al, *Cardiology* 1993;82:383

- VBG vs. ABG values in adults
- 7 with CHF versus 10 without CHF

<table>
<thead>
<tr>
<th></th>
<th>CHF patients</th>
<th>controls</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CI (L/min/m²)</td>
<td>2.2 ± 0.2</td>
<td>3.1 ± 0.6</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>PCWP (mmHg)</td>
<td>24 ± 5</td>
<td>10 ± 4</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>SaO₂</td>
<td>97 ± 2</td>
<td>97 ± 1</td>
<td>NS</td>
</tr>
<tr>
<td>SvO₂</td>
<td>53 ± 12</td>
<td>75 ± 13</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>P(v-a)CO₂ (mmHg)</td>
<td><strong>7.8 ± 2.6</strong></td>
<td><strong>3.5 ± 2.2</strong></td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>PvCO₂ (mmHg)</td>
<td>50 ± 5</td>
<td>40 ± 5</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>PaCO₂ (mmHg)</td>
<td>41 ± 8</td>
<td>39 ± 5</td>
<td>NS</td>
</tr>
</tbody>
</table>
**VBG vs. ABG Values**


- 14 infants and children following cardiothoracic surgery
- 95 simultaneously obtained VBG vs. ABG values

<table>
<thead>
<tr>
<th>Central venous oxygen saturation (%)</th>
<th>Veno-arterial PCO(_2) difference (mmHg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>≥ 70</td>
<td>5.5 ± 3.1</td>
</tr>
<tr>
<td>60-69.9</td>
<td>9.0 ± 3.4*</td>
</tr>
<tr>
<td>50-59.9</td>
<td>9.9 ± 3.6*</td>
</tr>
<tr>
<td>&lt; 50</td>
<td>10.7 ± 4.1*</td>
</tr>
</tbody>
</table>

*p*<0.05 vs. ≥ 70% group
Arterial to Venous CO2 Gradient

A high arterial to venous CO$_2$ gradient at admission in the postoperative ICU was associated with increased postoperative complications in high-risk surgical patients.


269 samples from 139 infants. Patients with poor outcome had a venous to arterial CO$_2$ difference of 8.3 (5.6-14.9) versus 5.4 mmHg (3.0-8.4) in those without poor outcome.

Transcutaneous CO\textsubscript{2} Monitoring

- the need for continuous CO\textsubscript{2} monitoring
- venous or capillary vs. arterial values
- \textit{methods of continuous non-invasive CO}_{2} monitoring
- applications of transcutaneous CO\textsubscript{2} monitoring
End-tidal CO₂ Monitoring

- infrared absorption
  - most common method
  - CO₂ absorbs infrared light
  - light passed through gas sample
  - compared to gas with known CO₂ concentration

- Raman spectroscopy
  - gas sample illuminated with laser beam
  - gas sample scatters the light and shifts frequency

- mass spectroscopy
  - expensive and cumbersome
The Capnogram

A-B: Initial phase of expiration, no CO\textsubscript{2} only gas from anatomic dead space
B-C: Start of alveolar emptying, upstroke determined by distribution of ventilation
C-D: Alveolar or expiratory plateau, should be horizontal, point D is the highest CO\textsubscript{2} value (ETCO\textsubscript{2}), best reflection of alveolar CO\textsubscript{2} and therefore arterial CO\textsubscript{2}
D-E: Inspiration begins, baseline should approach zero unless there is rebreathing
End-tidal CO$_2$ Monitoring
**ETCO$_2$: Extubated - Nasal Cannula**


- prospective trial in 30 pediatric patients
  - 6 months to 16 years (average = 7.8 years)
  - extubated, spontaneous ventilation
  - postoperative, no intrinsic lung disease
  - ETCO$_2$ monitor from nasal cannula
  - 55 sample sets

- ETCO$_2$ to PaCO$_2$ difference
  - $2.2 \pm 0.9$ mmHg
  - $\leq 4$ mmHg in 54 of 55 samples
  - linear regression analysis
End-tidal CO$_2$ Monitoring

- easy to set-up and use, limited calibration time
- reflects PaCO$_2$ with normal pulmonary function
- documents intra-tracheal position of ETT
  - standard of care for intraoperative monitoring
  - standard of care for ET intubation anywhere
  - Standard of care for sedation monitoring???
- documents ongoing ETT placement
  - transport, ICU, OR (disconnect monitor)
- waveform provides → pulmonary function information
- demonstrates efficacy of CPR
Accuracy of ETCO$_2$ Monitoring

- normal ventilation-perfusion ratio
- alveolar CO$_2$ must correlate with arterial CO$_2$
  - patient positioning
  - decreased FRC
  - alveolar space disease $\rightarrow$ V/Q mismatch
  - decreased pulmonary blood flow
  - increased dead space
  - shunt (cyanotic congenital heart disease)
- sampling issues
  - small tidal volumes
  - rapid respiratory rates
  - sampling site
  - continuous gas flow ventilators
Accuracy of ETCO$_2$ Monitoring

ETCO$_2$ accuracy questionable during one-lung ventilation

ETCO$_2$ inaccurate in infants with CHD
Burrows FA, *Anesthesiology* 1989;70:219

Patient positioning affects accuracy of ETCO$_2$ monitoring

Site of sampling affects accuracy of ETCO$_2$ monitoring

Type of ventilator affects accuracy of ETCO$_2$ monitoring

ETCO$_2$ changes based on deadspace ventilation
Yamanaka MK et al, *Chest* 1987;92:832

ETCO$_2$ does not reflect PaCO$_2$ in critically ill adult ICU patients

ETCO$_2$ does not reflect PaCO$_2$ during intraoperative care
ETCO$_2$ is an essential monitoring device in the operating room and beyond.

It works well in patients with normal pulmonary function.

However, several factors may affect its accuracy or clinical scenarios may preclude its use.
Additionally, there may be situations in both the operating room and the ICU where ETCO$_2$ monitoring is not feasible.
Transcutaneous CO$_2$ Monitoring

- the need for continuous CO$_2$ monitoring
- venous or capillary vs. arterial values
- methods of continuous non-invasive CO$_2$ monitoring
- applications of transcutaneous CO$_2$ monitoring
Units for blood gas results:
1 kPa = 7.5 mmHg
TC-CO$_2$ Monitoring: Pediatric ICU
Tobias JD et al, Anesth Analg 1997;85:55

- prospective study, 35 infants & toddlers, respiratory failure
  - 1 to 40 months of age, 3.3 to 19.1 kgs, mechanical ventilation
  - TC and ET CO$_2$ compared to PaCO$_2$
  - 100 paired samples sets (TC, ET and PaCO$_2$)

<table>
<thead>
<tr>
<th>Difference from PaCO$_2$ (mmHg)</th>
<th>TC-CO$_2$</th>
<th>ET-CO$_2$</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.3 ± 1.3</td>
<td>6.8 ± 5.1</td>
<td>&lt;0.0001</td>
<td></td>
</tr>
<tr>
<td>≤ 4 mmHg from PaCO$_2$</td>
<td>96 of 100</td>
<td>38 of 100</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>
**TC-CO₂ Monitoring: Pediatric ICU**


- prospective study, 25 children, ≥ 4 years of age
  - mechanical ventilation
  - TC and ET CO₂ compared to PaCO₂
  - 82 paired samples sets (TC, ET and PaCO₂)

<table>
<thead>
<tr>
<th></th>
<th>TC-CO₂</th>
<th>ET-CO₂</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Difference from PaCO₂ (mmHg)</td>
<td>2.6 ± 2.0</td>
<td>6.4 ± 6.3</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>≤ 3 mmHg from PaCO₂</td>
<td>65 of 82</td>
<td>34 of 82</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>≤ 5 mmHg from PaCO₂</td>
<td>76 of 82</td>
<td>47 of 82</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Linear regression analysis, r value</td>
<td>0.9693</td>
<td>0.8745</td>
<td>&lt;0.05</td>
</tr>
</tbody>
</table>
TC-CO₂ Monitoring: Pediatric ICU


- prospective study, 14 patients
  - 1 day to 16 years of age
  - high frequency oscillatory ventilation
  - 100 paired samples sets (TC-CO₂ versus PaCO₂)

<table>
<thead>
<tr>
<th>Difference from PaCO₂ (mmHg)</th>
<th><strong>TC-CO₂</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>0-2 mmHg from PaCO₂</td>
<td>51 of 100</td>
</tr>
<tr>
<td>3-5 mmHg from PaCO₂</td>
<td>41 of 100</td>
</tr>
<tr>
<td>&gt; 5 mmHg from PaCO₂</td>
<td>8 of 100</td>
</tr>
<tr>
<td>Linear regression analysis, r value</td>
<td>0.960</td>
</tr>
<tr>
<td>Difference with PaCO₂ ≤ 50 mmHg (n=52)</td>
<td>1.9 ± 2.8</td>
</tr>
<tr>
<td>Difference with PaCO₂ &gt; 50 mmHg (n=48)</td>
<td>2.3 ± 2.6</td>
</tr>
</tbody>
</table>
TC-CO$_2$: Gastric Bypass Surgery

- prospective study, 30 adults, BMI $\geq 40$ kg/m$^2$
  - TC and ET-CO$_2$ compared to PaCO$_2$
  - 1 kPa = 7.5 mmHg

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**ORIGINAL RESEARCH**

Carbon dioxide monitoring during laparoscopic-assisted bariatric surgery in severely obese patients: transcutaneous versus end-tidal techniques

Joanna M. Dion • Chris McKee • Joseph D. Tobias •
Daniel Herz • Paul Sohner • Steven Teich •
Marc Michalsky
TC-CO$_2$: Following Cardiac Surgery

- prospective study, 30 infants & children, cardiac surgery
  - TC-CO$_2$ placed if initial Pa-ET CO$_2$ gradient ≥ 5 mmHg
  - 3 TC-CO$_2$ failures (cardiovascular instability)
    - dopamine 20 µg/kg/min + epinephrine 0.3-0.5 µg/kg/min
- study cohort (27 patients, 2 days to 9 years old)
  - 101 sample sets
- surgical procedure
  - thoracotomy, closed heart, open heart with bypass
- vasoactive medications
  - dopamine µg/kg/min: 0-5 (n=7), 6-10 (n=3), ≥ 11 (n=1)
  - dobutamine µg/kg/min: 0-5 (n=8), 6-10 (n=5), ≥ 11 (n=1)
  - milrinone µg/kg/min: 0.3-1 (n=6)
  - nicardipine (n=1), nitroglycerin (n=1)
<table>
<thead>
<tr>
<th></th>
<th>( TC-CO_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Difference from ( PaCO_2 ) (mmHg)</td>
<td>1.7 ( \pm ) 1.4</td>
</tr>
<tr>
<td>0-2 mmHg from ( PaCO_2 )</td>
<td>82 of 101</td>
</tr>
<tr>
<td>3-5 mmHg from ( PaCO_2 )</td>
<td>18 of 101</td>
</tr>
<tr>
<td>Linear regression analysis, r value</td>
<td>0.9410</td>
</tr>
</tbody>
</table>
• DKA results in hyperventilation
  – compensates for metabolic acidosis
• hyperventilation $\rightarrow$ ↓ PaCO$_2$
• may be correlation between PaCO$_2$ and acidosis
• prospective study in 28 pediatric patients with DKA
  – 1.6 to 21 years, 13 to 96 kgs
  – TC-CO$_2$ monitoring during therapy
  – calculated vs. actual serum bicarbonate values
    • PaCO$_2$ = (1.5 x HCO$_3$) + 8
Serum bicarbonate (HCO$_3^-$) 

\[ \text{Serum HCO}_3^-(\text{mmol}\cdot\text{L}^{-1}) = 0.61 \times (\text{TCCO}_2 - 3.9) \]
**TC-CO$_2$ Monitoring: Apnea Testing**


- brain death examination prior to organ donation
- apnea testing
  - no respiratory effort with PaCO$_2$ $\geq$ 60 mmHg
- TC-CO$_2$ monitoring during apnea test
  - used to guide timing of ABG analysis
  - 8 patients, 1 to 16 years of age
  - patients 1 & 2, ABG obtained with TC-CO$_2$ = 60 mmHg
    - PaCO$_2$ < 60 mmHg in both cases
  - ABG obtained with TC-CO$_2$ = 70 mmHg
    - 15 of 16, PaCO$_2$ > 60 mmHg
    - TC-PaCO$_2$ difference (2-11 mmHg, $5.8 \pm 2.7$ mmHg)
Results: In the first 20 patients, the mean Paco₂–Ptco₂ gradient was 0.7 ± 3.6 mmHg at baseline and 8.7 ± 7.1 mmHg after 20 min of apnea. Using receiver operating characteristic curve analysis (area under the curve: 0.983 ± 0.013), the best threshold value of Ptco₂ to predict that a Paco₂ of 60 mmHg had been reached was 60 mmHg (positive predictive value: 1.00 [0.93–1.00]). In the following 12 patients investigated with use of this Ptco₂ target value of 60 mmHg, the mean duration of the apnea test (11 ± 4 vs. 20 ± 0 min; P < 0.001), hypercapnia (74.0 ± 4.9 vs. 98.3 ± 20.0 mmHg; P < 0.001), acidosis (pH: 7.18 ± 0.06 vs. 7.11 ± 0.08; P < 0.001), and decrease in arterial oxygen partial pressure (−47 ± 44 vs. −95 ± 89; P < 0.05) at the end of the test were reduced as compared with the 20-min apnea test group.

Conclusion: During the apnea test in brain-dead patients, a Ptco₂ of 60 mmHg accurately predicts that a Paco₂ of 60 mmHg has been reached. This may allow a reduction in the duration of the apnea test and consequently limit occurrence of complications.
TC-CO$_2$ Monitoring & Transport


- TC-CO$_2$ monitoring during neonatal transport
  - 32 neonates with respiratory failure
  - control (no monitor) vs. monitored

- monitored patients
  - no hypercarbia on arrival vs. 2 in control group
  - more time in desired CO$_2$ range (35-45 mmHg), p<0.02
TC-CO$_2$ Monitoring & Transport

- prospective trial, infants transported more than 30 miles
- control (no monitor) vs. TC-CO2 monitoring
- monitored infants
  - PIP lowered during transport
    - -1.5 vs. +0.6 cmH$_2$O, p<0.04
  - more likely to arrive with normal pH & PaCO2
    - p=0.03 & 0.01
  - no difference in initial stabilization time at referring hospital
Transcutaneous versus blood carbon dioxide monitoring during acute noninvasive ventilation in the emergency department – a retrospective analysis

Christian M. Horvath*, Martin H. Brutsche*, Florent Baty*, Jochen J. Rüdiger*,b

a Pneumology and Sleep Medicine Kantonsspital St. Gallen, Switzerland
b Pneumology, University Hospital Basel, Switzerland
TC-CO$_2$ Monitoring

- **advantages**
  - more accurate than ETCO$_2$ in many clinical scenarios
  - easier to use in non-intubated patients
  - accuracy not affected by pulmonary disease, V/Q mismatch, etc.
  - accuracy not affected by small tidal volumes or rapid respiratory rates
  - can be used with high frequency ventilation

- **disadvantages**
  - more labor intensive
  - requires calibration and site changes
  - accuracy affected by low perfusion states
  - use of inotropic agents with vasoconstricting properties
    - lag time in CO$_2$ response
    - potential for superficial blister
    - less familiarity with its use when compared to ETCO$_2$

- Transcutaneous CO₂ monitoring provides an accurate continuous estimation of arterial CO₂ in most clinical scenarios.
- End-tidal CO₂ monitoring remains the standard of care to document the intratracheal position of the endotracheal tube.
- ET-CO₂ generally < PaCO₂ < TC-CO₂
- Consider using both monitors for critically ill patients.
- There is expanding use of TC-CO₂ monitoring outside of the PICU including postoperative monitoring of respiratory status in patients receiving opioids.

APSF believes that clinically significant drug-induced respiratory depression in the postoperative period remains a serious patient safety risk that continues to be associated with significant morbidity and mortality since it was first addressed by APSF in 2006.
thank you