Transcutaneous carbon dioxide monitoring in the Pediatric Intensive Care Unit

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Joseph D. Tobias
Department of Anesthesiology
Pediatric Critical Care/Pediatric Anesthesiology
University of Missouri
Department of Anesthesiology, 3W40H
One Hospital Drive
Columbia, Missouri 65212
USA

Arterial blood gas analysis with the measurement of the partial pressure of carbon dioxide in arterial blood may be performed in the Pediatric ICU to evaluate the efficacy of ventilation or evaluate acid-base status.

Although the direct measurement of $PaCO_2$ remains the gold standard, it provides only a single measurement of what is often an ever-changing clinical picture. Additional concerns include its cost, requirement for either arterial puncture or placement of an arterial cannula, potential for iatrogenic anemia, and the exposure of healthcare providers to the patient's blood.

Given these concerns, there remains a significant clinical interest in the development of a means by which to continuously monitor $PaCO_2$ without the need for repeated blood gas analysis. Commonly used non-invasive means to monitor $PaCO_2$ include end-tidal and transcutaneous devices.

However, in the critically ill Pediatric ICU patient, alterations in cardiorespiratory function may interfere with the accuracy of end-tidal CO_2 monitoring. The following article reviews the potential applications of transcutaneous CO_2 monitoring in the Pediatric ICU setting in various clinical scenarios.

Introduction

Arterial blood gas analysis with the measurement of the partial pressure of carbon dioxide in arterial blood ($PaCO_2$) may be performed in the Pediatric ICU setting to evaluate the efficacy of ventilation.

Although the direct measurement of $PaCO_2$ remains the gold standard, ABG analysis provides only a single measurement of what is often an ever-changing clinical picture. Additional concerns include its cost (approximately USD 75 per test), requirement for an

invasive procedure (either arterial puncture or placement of an arterial cannula), potential for iatrogenic anemia with repeated blood drawing, and the exposure of healthcare providers to the patient's blood.

Given these concerns, there remains a significant clinical interest in the development of a means by which to continuously measure $PaCO_2$ without the need for repeated blood gas analysis. Commonly used non-invasive means of continuously monitoring $PaCO_2$ include end-tidal and transcutaneous devices.

Monitoring of end-tidal CO_2 ($ETCO_2$) is considered the standard of care in the operating room and anywhere that endotracheal intubation takes place.

Although there are concerns regarding the accuracy of the $ETCO_2$, especially in patients with ventilation-perfusion mismatch and other cardiorespiratory pathologies, $ETCO_2$ monitoring demonstrating the presence of CO_2 in exhaled gases documents the correct intratracheal location of the endotracheal tube (ETT) following endotracheal intubation and also serves as a continuous disconnect monitor so that should the ETT become dislodged or disconnected from the anesthetic circuit, there will be cessation of CO_2 exhalation, thereby alerting the anesthesiologist of the problem [1, 2].

Similar efficacy has been demonstrated with the use of $ETCO_2$ monitoring in the arena of procedural sedation [3]. During such procedures, sedative and analgesic medications are administered to alleviate the pain and discomfort of an invasive procedure while monitoring the patient's cardiorespiratory function.

Although pulse oximetry is the most commonly used monitor during procedural sedation, $ETCO_2$ may also be advantageous in that it will immediately identify apnea (cessation of air flow and cessation of CO_2 exhalation due either to apnea or upper airway obstruction) while pulse oximetry may not change for up to 30-90 seconds following apnea [3].

Despite these applications, the correlation of $ETCO_2$ with $PaCO_2$ may be affected by several patient factors

such as patient positioning and alterations in ventilation-perfusion ratios [4-7].

Other factors which may affect the accuracy of $ETCO_2$ monitoring include the smaller tidal volumes routinely used in infants and children, the site of $ETCO_2$ sampling, and variability in the type of mechanical ventilation (intermittent versus continuous gas flow) [8, 9].

As such, in many critically ill patients, there may be a variable gradient between the $ETCO_2$ and the $PaCO_2$, thereby necessitating frequent arterial blood gas analysis to assess respiratory function or the use of a different non-invasive PCO_2 monitor.

The following article reviews the potential applications of transcutaneous CO_2 monitoring in the Pediatric ICU setting during mechanical ventilation (including high frequency oscillatory ventilation), in spontaneously breathing patients and in other clinical scenarios including apnea testing during brain death examination and in the assessment of patients with diabetic ketoacidosis (DKA).

Transcutaneous carbon dioxide monitoring

Since its introduction into clinical practice, the largest use of transcutaneous CO_2 monitoring has been in the neonatal ICU population. The currently available transcutaneous CO_2 devices heat the skin to 43-45 °C leading to capillary vasodilatation decreasing the transit time of blood through the capillary, resulting in a close approximation of capillary and arterial $PaCO_2$.

The vasodilatation of the capillary bed also allows for the diffusion of CO_2 from the arterial capillary lumen to the membrane of the transcutaneous monitor, resulting in the transcutaneous CO_2 readout.

The externally applied heat leads to an increase in the temperature of the tissue, which without temperature correction would result in an erroneous PCO_2 value.

Alterations in temperature affect the solubility of CO_2 in blood such that an increase in the temperature increases

the partial pressure of CO_2 with a larger gradient between the actual $PaCO_2$ and the transcutaneous CO_2.

Additionally, the higher temperature increases the metabolic rate of the tissues, thereby further increasing the PCO_2. These factors are considered in modern transcutaneous CO_2 devices in that a correction factor is used to calculate the actual $PaCO_2$ based on the measured transcutaneous CO_2 and the working temperature of the electrode.

The importance of temperature correction is illustrated by the study of Tremper *et al* [10]. The authors, without correcting the transcutaneous CO_2 value for temperature differences, compared the transcutaneous and arterial values of CO_2 in 435 data pairs from 44 patients in a mixed operating room and ICU setting.

Despite a wide mean difference between the actual transcutaneous CO_2 and $PaCO_2$ values (23 ± 11 mmHg), linear regression analysis yielded a correlation coefficient of 0.80.

The authors also noted that, with a low cardiac output state (cardiac index less than 1.5 L/min/m2), there was a further increase in the transcutaneous-to-arterial CO_2 gradient with the transcutaneous CO_2 value trending inversely with the cardiac index rather than PCO_2.

A similar effect of cardiovascular performance and the gradient between arterial and TC carbon dioxide has been reported by other investigators (see below).

Transcutaneous carbon dioxide monitoring in the Pediatric ICU setting

Given its successful use in various patient populations and clinical scenarios, there remains a definite role for transcutaneous CO_2 monitoring in the Pediatric ICU population.

Various reports (summarized in **table I** and **II**) exist regarding its use during mechanical ventilation (including high frequency oscillatory ventilation), in spontaneously breathing patients, and in other clinical scenarios including apnea testing during brain death examination and in the assessment of patients with diabetic ketoacidosis (DKA).

Mechanical ventilation

Tobias and Meyer evaluated the efficacy of transcutaneous and end-tidal CO_2 monitoring in a cohort of Pediatric ICU patients with respiratory failure [11]. The patients ranged in age from 1 to 40 months and in weight from 3.3 to 19.1 kilograms.

A total of 100 simultaneously obtained sets of arterial, transcutaneous, and end-tidal CO_2 values were analyzed. The end-tidal-to-arterial CO_2 difference was 6.8 + 5.1 mmHg while the transcutaneous-to-arterial CO_2 difference was 2.3 ± 1.3 mmHg, p<0.0001.

The absolute difference between the end-tidal and arterial CO_2 was 4 mmHg or less in 38 of 100 values, while the absolute difference between the transcutaneous and arterial CO_2 value was 4 mmHg or less in 96 of 100 values, p<0.0001.

The authors concluded that in neonates and infants with respiratory failure, transcutaneous CO_2 monitoring provided a more accurate estimate of arterial CO_2 than $ETCO_2$ monitoring.

As a follow-up study, the same group of investigators evaluated the technique in an older cohort of patients with respiratory failure who ranged in age from 4 to 16 years of age [12].

As in the previous study, the authors noted that transcutaneous CO_2 monitoring provided a more accurate estimate of arterial CO_2 than did $ETCO_2$ monitoring. In the 82 sample sets, the end-tidal-to-arterial CO_2 difference was 6.4 ± 6.3 mmHg, while the transcutaneous-to-arterial CO_2 difference was 2.6 ± 2.0 mmHg, p<0.0001.

The absolute difference between the end-tidal and arterial CO_2 was 5 mmHg or less in 47 of 82 values, while the absolute difference between the transcutaneous

and arterial CO_2 value was 5 mmHg or less in 76 of 82 values, p<0.00001.

Regression analysis revealed a slope of 0.5418 and an r value of 0.8745 when comparing end-tidal versus arterial CO_2 and a slope of 1.0160 and an r value of 0.9693 when comparing transcutaneous versus arterial $PaCO_2$ values.

An additional study from Tobias et al evaluated the accuracy of transcutaneous CO_2 monitoring following cardiothoracic surgery in infants and children [13].

Given the potential for various physiologic factors including residual shunt and ventilation-perfusion mismatch, which may exist following cardiopulmonary bypass (CPB) and surgery for infants with congenital heart disease [6, 7, 14], the authors speculated that $ETCO_2$ would be significantly inaccurate in this patient population and of limited benefit for continuous monitoring in the Pediatric ICU setting.

The study population included 33 consecutive patients following surgery for congenital heart disease. Transcutaneous CO_2 monitoring was initiated if the initial ABG following CPB demonstrated an arterial-to-end-tidal gradient of 5 mmHg or more.

In 3 of the patients, the arterial-to-end-tidal CO_2 gradient was less than 5 mmHg and therefore transcutaneous CO_2 monitoring was not initiated. In the remaining 30 patients, the arterial-to-end-tidal CO_2 gradient was 5 mmHg or greater, and the transcutaneous monitor was used.

Of these 30 patients, there were 3 patients in whom, despite recalibrating the device and its placement at several different sites, the transcutaneous value was not reflective of the arterial CO_2 level.

These 3 patients all demonstrated cardiovascular instability and were requiring dopamine at 20 mcg/kg/min and epinephrine at 0.3-0.5 mcg/kg/min. In the remaining 27 patients, the transcutaneous-to-arterial CO_2 difference was 1.7 ± 1.4 mmHg in the 101 sample sets that were analyzed.

The absolute difference between the transcutaneous and arterial CO_2 was 2 mmHg or less in 82 of 101 values, 3 to 5 mmHg in 18 of 101 values, and greater than 6 mmHg in 1 of 101 values. Linear regression analysis revealed a slope of 0.90 and an r value of 0.9410 when comparing transcutaneous versus arterial CO_2.

Sivan et al compared end-tidal and transcutaneous CO_2 values with arterial CO_2 values during mechanical ventilation in a cohort of 134 infants and children, ranging in age from 2 days to 16 years [15].

Their findings suggested that both techniques were effective; however, using a Bland-Altman analysis they noted that the difference (bias ± precision) between the end-tidal and arterial CO_2 was 7.8 ± 7.3 mmHg when the arterial-to-alveolar ratio was less than 0.3 (indicative of significant pulmonary pathology with poor oxygenation) versus 0.0 ± 3.4 mmHg in patients with an arterial-to-alveolar oxygen ratio greater than 0.3.

They also noted variability in the accuracy of transcutaneous CO_2 monitoring based on the skin perfusion, which they evaluated using capillary refill. When the capillary refill was less than 3 seconds, the bias ± precision of the transcutaneous versus the arterial CO_2 was –0.2 ± 5.4 mmHg versus –4.1 ± 9.9 mmHg when the skin perfusion was decreased (capillary refill greater than 3 seconds).

Rauch et al used intermittent instead of continuous transcutaneous CO_2 monitoring as a means of avoiding the cost associated with having a transcutaneous monitor dedicated to each bedside [16].

There were 49 simultaneous readings (arterial and transcutaneous CO_2 values) from 19 patients ranging in age from 5 days to 16 years. The $PaCO_2$ value varied from 19 to 86 mmHg. Prior to the reading, the monitor was left in place for approximately 5 minutes at which time an arterial blood gas value was obtained.

The mean difference between the transcutaneous and arterial CO_2 value was 1.94 mmHg with a 95 % confidence interval of –0.12 to 4.07 mmHg. Scatter plot

revealed a regression line characterized by the equation: $PaCO_2 = (TC\text{-}CO_2 \times 1.05) - 4.08$.

Although the previous studies have demonstrated either equal or improved efficacy of transcutaneous versus end-tidal CO_2 monitoring techniques, there are other certain situations in which end-tidal CO_2 monitoring is not feasible.

One such situation is during high frequency oscillatory ventilation (HFOV). HFOV is used in patients with severe respiratory failure in whom conventional ventilation fails to provide adequate oxygenation and ventilation.

Given that high rates (greater than 300 breaths/minute) are used in conjunction with minimal tidal volumes (less than deadspace), end-tidal CO_2 monitoring is not feasible. In this setting, we have found that transcutaneous CO_2 can be effectively used [17].

The study included 100 sample sets from 14 patients ranging in age from 1 day to 16 years. The absolute difference between the transcutaneous and arterial CO_2 was 2.8 ± 1.9 mmHg.

Linear regression analysis of transcutaneous versus arterial CO_2 revealed a slope of 1.09 and an r value of 0.96.

Author	Setting	End-tidal versus $PaCO_2$	Transcutaneous versus $PaCO_2$
Tobias & Meyer [11]	PICU, respiratory failure, mechanical ventilation, patients < 4 years of age	6.8 ± 5.1 mmHg*	2.3 ± 1.3 mmHg*
Berkenbosch et al [12]	PICU, respiratory failure, mechanical ventilation, patients > 4 years of age	6.4 ± 6.3 mmHg*	2.6 ± 2.0 mmHg*
Tobias et al [13]	PICU, infants and children following CPB, mechanical ventilation	> 5 mmHg difference in 30 of 33 patients	1.7 ± 1.4 mmHg*; excluded 3 patients since there was a wide gradient between the $PaCO_2$ and the transcutaneous value. These 3 patients were all receiving dopamine > 10 mcg/kg/min and epinephrine
Sivan et al [15]	PICU, mechanical ventilation, patients ranged in age from 2 days to 16 years	0.0 ± 3.4 mmHg+ when a-A gradient was > 0.3 7.8 ± 7.3 mmHg+ when a-A gradient was < 0.3	−0.2 ± 5.4 mmHg+ when capillary refill was < 3 seconds −4.1 ± 9.9 mmHg+ when capillary refill was > 3 seconds
Rauch [16]	PICU, mechanical ventilation, intermittent transcutaneous CO_2 monitoring	-	1.94 mmHg; −0.12 to 4.07 mmHg#
Berkenbosch & Tobias [17]	PICU, high frequency oscillatory ventilation, patients ranged in age from 1 day to 16 years	-	2.8 ± 1.9 mmHg*

PICU = Pediatric ICU, CPB = cardiopulmonary bypass, a-A = arterial-to-alveolar gradient

*mean ± SD of difference, +bias ± precision by Bland-Altman analysis, #mean with 95 % confidence intervals

TABLE I. Transcutaneous carbon dioxide monitoring during mechanical ventilation

To determine if there were any difference in the accuracy of transcutaneous CO_2 monitoring during hypercarbia, the bias and precision were compared when the arterial CO_2 was < 50 mmHg versus when it was more than 50 mmHg (bias/precision: 1.9/2.8 mmHg versus 2.3/2.6 mmHg, p=NS).

Spontaneous ventilation

Continuous monitoring of ventilatory function is equally important during spontaneous ventilation. In fact, non-invasive devices may be even more useful since these patients are often awake as opposed to sedated during mechanical ventilation and therefore invasive procedures may be more traumatic and more difficult.

In this setting, end-tidal CO_2 monitoring has been used and found to be accurate; however, it requires the use of specialized nasal cannula so that oxygen can be delivered via one limb and end-tidal CO_2 sampled from the other [18, 19].

The utility of transcutaneous CO_2 monitoring has been demonstrated in this clinical scenario and in fact, a significant incidence of previously unrecognized hypercarbia has been reported [20].

We have found transcutaneous CO_2 monitoring to be invaluable in the spontaneously breathing pediatric patient with various etiologies of respiratory insufficiency including bronchiolitis, asthma as well as during the perioperative period. Confidence in this non-invasive modality has virtually eliminated the need for direct arterial or capillary blood gas analysis and its associated pain and cost.

Apnea testing

The demonstration of brain death following traumatic or hypoxic-ischemic events requires the documentation of the irreversible cessation of all brain function [21]. A key component of such examinations is the absence of ventilatory function despite a $PaCO_2$ > 60 mmHg.

This is demonstrated by the performance of an apnea test during which time an arterial blood gas analysis is drawn to demonstrate a $PaCO_2$ > 60 mmHg. As the rate of increase of $PaCO_2$ is variable, it may be difficult to demonstrate when this threshold has been achieved, necessitating frequent blood gas analysis or waiting too long with the resultant hemodynamic compromise from hypercarbia or the development of hypoxemia.

We have found that transcutaneous $PaCO_2$ monitoring can be used to predict the timing of blood gas analysis and thereby avoid the risks of excessive hypercarbia and hypoxemia [22]. In a cohort 8 pediatric patients, transcutaneous CO_2 monitoring was used during apnea testing.

In the first 2 patients, an ABG was obtained when the transcutaneous CO_2 was 60 mmHg and the arterial CO_2 was less than 60 mmHg in all 4 instances. For the subsequent patients, an ABG was drawn when the transcutaneous CO_2 was greater than 70 mmHg and in 16 of 17 instances, the arterial CO_2 was greater than 60 mmHg.

Despite the potential for lag time or delay in the equilibration between the arterial and the transcutaneous CO_2, we found transcutaneous CO_2 monitoring useful to help predict the timing of ABG analysis during brain death evaluation.

Monitoring of acid-base status

Although the majority of reports regarding transcutaneous CO_2 monitoring describe its use as a means of non-invasively monitoring respiratory function, given the relationship of arterial CO_2 to pH and serum bicarbonate, it is possible that changes in PCO_2 could be used to reflect changes in pH.

During diabetic ketoacidosis (DKA), acidosis is partially compensated by an increase in minute ventilation and a lowering of the $PaCO_2$ to induce respiratory alkalosis. As the DKA is treated and the acidosis resolves, there is a gradual return of the $PaCO_2$ to normal values.

We postulated that transcutaneous CO_2 values could be

used to follow the response to therapy during DKA [23]. We studied this hypothesis in a cohort of 30 patients with DKA. In 2 patients, transcutaneous CO_2 monitoring was not feasible due to poor tissue perfusion.

In 28 patients, we found that there was a gradual increase in transcutaneous CO_2 values during correction of metabolic acidosis and using the equation: $PaCO_2 = (1.5 \times$ serum bicarbonate$) + 8$, a calculated bicarbonate value was determined and compared with simultaneously obtained serum bicarbonate values.

The difference between the calculated and actual serum bicarbonate values was 1.5 + 1.2 mmol/L. The difference was < 2 mmol/L in 74.4 % of the sample sets and < 5 mmol/L in 99.2 % of the sample sets.

Linear regression analysis of calculated versus actual serum bicarbonate revealed a slope of 0.95 and an r^2 value of 0.88. From this linear regression analysis, we determined that serum bicarbonate could be calculated from the transcutaneous CO_2 using the equation: $0.61 \times (TCCO_2 - 3.9)$.

Technical aspects of transcutaneous carbon dioxide monitoring

As with any non-invasive monitor, attention to detail regarding specific aspects of transcutaneous CO2 monitoring is required to ensure the accuracy of the technique.

When compared with ET-CO_2 monitoring, TC-CO_2 monitoring requires a longer preparation time including a 5-minute calibration period prior to placement and then an additional 5- to 10-minute equilibration period after placement on the patient to allow for an equilibration between the transcutaneous and arterial CO_2 values.

Although our practice has been to allow for 10 minutes for equilibration, the study of Rauch et al [16] suggests that 5 minutes or less may be adequate. The electrode should be recalibrated and placed at another site every 4 hours to avoid burns or blistering of the skin.

These requirements make the device slightly more labor intensive than end-tidal CO_2 monitoring.

Author	Setting	Findings
Tobias [22]	Transcutaneous CO_2 monitoring used to time drawing of ABGs during apnea testing in brain death examination.	With a transcutaneous CO_2 > 70 mmHg, the $PaCO_2$ value was > 60 mmHg (the required value) in 16 of 17 cases.
McBride et al [23]	Transcutaneous CO_2 monitoring used to evaluate resolution of metabolic acidosis during therapy for DKA. TC-CO_2 value used to derive calculated serum bicarbonate value using the formula: $PaCO_2 = (1.5 \times$ serum bicarbonate$) \pm 8$	The difference between the calculated and actual serum bicarbonate was 1.5 ± 1.2 mmol/L*. The difference was < 2 mmol/L in 74.4 % of the sample sets and < 5 mmol/L in 99.2 % of the sample sets. Linear regression analysis of calculated versus actual serum bicarbonate revealeda slope of 0.95 and an r^2 value of 0.88. Serum bicarbonate can be calculated from the transcutaneous CO_2 value using the equation: serum bicarbonate = $0.61 \times (TCCO_2 - 3.9)$.

DKA = diabetic ketoacidosis

*mean ± SD of difference

TABLE II. Additional applications of transcutaneous carbon dioxide monitoring

Although we have found that transcutaneous CO_2 monitoring provides a more accurate reflection of $PaCO_2$ in most patients and in most clinical scenarios, several factors related to the monitor itself may affect this accuracy including technical variables such as trapped air bubbles, improper placement technique, damaged membranes, and inappropriate calibration techniques.

In addition to technical problems, patient problems may affect the accuracy of transcutaneous CO_2 monitoring. These may include variations in skin thickness, the presence of edema, tissue hypoperfusion, or the administration of vasoconstricting drugs [13, 15, 23].

Following our clinical experience, we would recommend keeping the working temperature of the probe at 44-45 °C to improve the accuracy of the device. The higher temperatures may increase the risk of blistering, and therefore it may be prudent to change the site every 2 to 3 hours if problems are noted.

Our clinical experience also suggests that more accurate readings are provided when the probe is placed over specific areas of the body such as the ventral (volar) aspect of the forearm.

Summary

Clinical studies have demonstrated the utility of transcutaneous monitoring in the Pediatric ICU setting and beyond.

When compared with end-tidal techniques, transcutaneous CO_2 monitoring has been shown to be equally as accurate in patients with normal respiratory function and more accurate in patients with shunt or ventilation-perfusion inequalities [11-13, 15, 16, 18].

Additionally, transcutaneous monitoring is also effective in situations that preclude end-tidal monitoring such as HFOV [17], during non-invasive positive pressure ventilation (BiPAP), and in spontaneously breathing

	Transcutaneous	End-tidal
Advantages	• More accurate than end-tidal. • Easy to use in both intubated and non-intubated patients. • Accuracy not affected by pulmonary parenchymal disease, shunt, ventilation-perfusion inequalities, type of ventilator, and low tidal volumes. • Can be used with high frequency types of mechanical ventilation.	• Rapid to set up. • Technically easy to use. • Confirms intratracheal position of ET tube. • Provides ventilator disconnect alarm. • Capnogram provides information regarding pulmonary function.
Disadvantages	• More labor intensive than end-tidal. • Requires calibration and placement. • Must be repositioned every 3-4 hours. • Potential for superficial skin blistering. • Accuracy affected by decreased perfusion or use of vasoconstricting agents.	• Less accurate than transcutaneous devices. • Accuracy affected by pulmonary parenchymal disease, shunt, ventilation-perfusion inequalities, type of ventilator, low tidal volumes, and site of sampling. • Use in non-intubated patients requires specialized sampling device (nasal cannula).

TABLE III. Advantages and disadvantages of transcutaneous and end-tidal devices

patients without the need for the specialized nasal cannula which is required for end-tidal monitoring [18].

Transcutaneous CO_2 monitoring may also be useful in other clinical scenarios including the timing of ABG analysis during brain death examination [22] and to monitor therapy during DKA [23].

Despite its efficacy, transcutaneous CO_2 monitoring does not necessarily replace end-tidal CO_2 monitoring. End-tidal CO_2 monitoring is still necessary to demonstrate the intratracheal location of the ETT following endotracheal intubation and as a disconnect alarm in the operating room.

Other potential uses of end-tidal CO_2 monitoring include a means to judge the efficacy of cardiopulmonary resuscitation, to identify intraoperative air embolism, and to evaluate pulmonary function by analysis of the capnogram [1, 2].

Given the complimentary nature of these two non-invasive monitors, their joint use should be considered in many of our critically ill pediatric patients.

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