

# Effect of Transcutaneous Electrode Temperature on Accuracy and Precision of Carbon Dioxide and Oxygen Measurements in the Preterm Infants

Jessica F Jakubowicz MD, Shasha Bai PhD, David N Matlock MD, Michelle L Jones DO, Zhuopei Hu MSc, Betty Proffitt RRT, and Sherry E Courtney MD

**BACKGROUND:** High electrode temperature during transcutaneous monitoring is associated with skin burns in extremely premature infants. We evaluated the accuracy and precision of CO<sub>2</sub> and O<sub>2</sub> measurements using lower transcutaneous electrode temperatures below 42°C. **METHODS:** We enrolled 20 neonates. Two transcutaneous monitors were placed simultaneously on each neonate, with one electrode maintained at 42°C and the other randomized to temperatures of 38, 39, 40, 41, and 42°C. Arterial blood was collected twice at each temperature. **RESULTS:** At the time of arterial blood sampling, values for transcutaneously measured partial pressure of CO<sub>2</sub> (P<sub>tcCO<sub>2</sub></sub>) were not significantly different among test temperatures. There was no evidence of skin burning at any temperature. For P<sub>tcCO<sub>2</sub></sub>, Bland-Altman analyses of all test temperatures versus 42°C showed good precision and low bias. Transcutaneously measured partial pressure of O<sub>2</sub> (P<sub>tcO<sub>2</sub></sub>) values trended arterial values but had large negative bias. **CONCLUSION:** Transcutaneous electrode temperatures as low as 38°C allow an assessment of P<sub>tcCO<sub>2</sub></sub> as accurate as that with electrodes at 42°C. *Key words:* transcutaneous monitoring; carbon dioxide monitoring; oxygen monitoring; electrode temperature; blood gas monitoring. [Respir Care 0;0(0):1–. © 0 Daedalus Enterprises]

## Introduction

Extremes and fluctuations of arterial CO<sub>2</sub> and O<sub>2</sub> tension pose well-documented risks to the neonate, including periventricular leukomalacia,<sup>1-3</sup> intraventricular hemorrhage,<sup>3-6</sup> retinopathy of prematurity,<sup>7</sup> bronchopulmonary dysplasia, and mortality.<sup>8-10</sup>

Therefore, these levels must be closely monitored. Arterial blood sampling is the accepted standard, but this provides only a single measurement of what is often a constantly changing clinical picture. It is also invasive by nature, requiring either an indwelling catheter or multiple needle sticks and can lead to anemia, which is an already prevalent issue in premature infants.

Transcutaneous monitors can provide continuous CO<sub>2</sub> and O<sub>2</sub> monitoring. One limitation to the widespread use of transcutaneous monitors in neonatal ICUs is the previously reported association of skin burning in extremely low birth-weight infants due to the elevated electrode temperature required to achieve arterialization of the capillary bed, particularly in the measurement of P<sub>tcCO<sub>2</sub></sub>.<sup>11-13</sup> High electrode temperature may not be needed for P<sub>tcCO<sub>2</sub></sub> assessment.

Drs Jakubowicz, Bai, Matlock, and Courtney, and Mr Hu and Ms Proffitt, are affiliated with the Department of Pediatrics, University of Arkansas for Medical Sciences, Little Rock, AR. Dr Jones is affiliated with St. John Medical Center and Hillcrest Medical Center, Tulsa, OK. At the time of this study, Dr Jones was affiliated with the Department of Pediatrics, University of Arkansas for Medical Sciences, Little Rock, AR.

The authors report partial funding for this project by an intramural grant from the UAMS College of Medicine Children's University Medical Group Grant Program, grant #2822-3. Transcutaneous monitors were provided for this study by Radiometer, which did not have any participation in study design, data collection or statistical analysis.

Dr Jakubowicz presented a version of this article at the Pediatric Academic Societies Meeting held May 6, 2017, in San Francisco, California.

Correspondence: Jessica F Jakubowicz MD, University of Arkansas for Medical Sciences, 4301 W Markham St, Slot 512-5B, Little Rock, AR 72205. E-mail: [jmjakubowicz@uams.edu](mailto:jmjakubowicz@uams.edu).

DOI: 10.4187/respcare.05887

## TRANSCUTANEOUS ELECTRODE TEMPERATURES IN PRETERM INFANTS

We hypothesized that a transcutaneous electrode temperature as low as 38°C would be accurate and precise in the measurement of CO<sub>2</sub> levels. We sought (1) to assess the accuracy and precision of 4 lower electrode temperatures (38, 39, 40, 41°C) compared to the recommended temperature of 42°C in the measurement of CO<sub>2</sub> levels in preterm infants between 1–2 kg; (2) to assess the accuracy and precision of all measured electrode temperatures (38–42°C) in the measurement of CO<sub>2</sub> compared to the accepted standard, arterial blood gas P<sub>CO<sub>2</sub></sub>; (3) to reassess the accuracy and precision of P<sub>tcCO<sub>2</sub></sub> compared to P<sub>aO<sub>2</sub></sub> and assess P<sub>tcO<sub>2</sub></sub> at the 4 lower electrode temperatures (38, 39, 40, 41°C).

## Methods

### Subjects

This study was approved by the Institutional Review Board of the University of Arkansas for Medical Sciences. A total of 20 neonates were enrolled after written parental consent was obtained. Inclusion criteria included birthweight 1–2 kg, umbilical arterial access, and hematocrit levels > 35%. Exclusion criteria included pressor support, hematocrit levels < 35%, congenital anomalies, nitric oxide use, persistent pulmonary hypertension, and cyanotic heart disease.

### Methods

The precision and accuracy of P<sub>tcCO<sub>2</sub></sub> and P<sub>tcO<sub>2</sub></sub> were examined at 5 different electrode temperatures (38, 39, 40, 41, and 42°C) in each infant. All newborns were monitored using 2 transcutaneous monitors applied simultaneously (TCM CombiM, Radiometer, Copenhagen, Denmark). This allowed for one electrode to remain unchanged at 42°C (ie, control) while the temperature of the other electrode was randomized to 38, 39, 40, 41, or 42°C (to assure accuracy of the control monitor). The transcutaneous electrodes were applied to the skin of the trunk as recommended by the manufacturer. The accepted standard to which the transcutaneous values were compared was the P<sub>aCO<sub>2</sub></sub> and P<sub>aO<sub>2</sub></sub>. After stabilization of both monitors, 2 arterial blood gases were collected at each temperature, approximately 15 min apart from an indwelling umbilical arterial catheter (for a total of 10 blood gases). For the purposes of this project, stabilization was defined as a change of ≤ 2 mm Hg P<sub>tcCO<sub>2</sub></sub> over 5 min. Approximately 0.2 mL of arterial blood was collected with each sample, which totaled 2 mL of blood per subject. Total blood collected per subject was recorded during the study. Arterial blood gas sampling and readings of the P<sub>tcCO<sub>2</sub></sub> and P<sub>tcO<sub>2</sub></sub> levels were performed simultaneously and recorded. After changing the electrode temperature, an appropriate amount of time was allowed for calibration (usually

## QUICK LOOK

### Current knowledge

Transcutaneous monitoring provides continuous CO<sub>2</sub> and O<sub>2</sub> measurements without the need for blood sampling. Premature infants are at higher risk for complications secondary to abnormal CO<sub>2</sub> and O<sub>2</sub> levels, therefore continuous monitoring is vital. However, transcutaneous monitoring requires warming of the skin, which has been associated with skin injury in extremely low birthweight infants.

### What this paper contributes to our knowledge

Transcutaneous temperatures as low as 38°C provide an accurate assessment of CO<sub>2</sub> compared to the previously recommended temperature of 42°C. Use of lower transcutaneous temperatures to track CO<sub>2</sub> trends should allow this technology to be applied in even the smallest preterm infants. Transcutaneous monitoring may be useful for tracking O<sub>2</sub> levels as well.

5–10 min) and stabilization of the new electrode temperature (usually 10–15 min). Transcutaneous data were continuously recorded and downloaded from the monitor after the study. The collection of data, per subject, took approximately 4 hours.

### Statistical Analysis

For a sample size estimate, with the design of 5 repeated measurements at each pair of temperatures, a compound symmetry structure was used, and we assumed every pair had the same correlation for within-subject covariance. A sample size of 20 neonates achieved 80% power to detect a minimum difference of 0.67, 0.97, and 1.2 per standard deviation, respectively, when the correlation between observations on the same subject was 0.1, 0.5, and 0.9. We used a repeated-measures design for this study, thereby requiring substantially fewer subjects and increasing trial feasibility compared to a 2-group or *n*-group comparison study.

Summary statistics such as mean and standard deviations were reported. Several comparisons were carried out for the main analysis. Comparison of average P<sub>tcCO<sub>2</sub></sub> or P<sub>tcO<sub>2</sub></sub> between each of the 5 test temperatures and the control temperature were analyzed using repeated-measures analysis of variance followed by Dunnett's method adjusting for multiple comparisons. Comparison of average P<sub>tcCO<sub>2</sub></sub> or P<sub>tcO<sub>2</sub></sub> levels between test temperatures and blood gas measurements, and average warm-up times for stabilization between test temperatures and the con-

## TRANSCUTANEOUS ELECTRODE TEMPERATURES IN PRETERM INFANTS

Table 1. Transcutaneous Test Temperatures

	Temperature	$P_{tcCO_2}$			$P_{tcO_2}$		
		Mean (SD)	95% CI vs 42°C	<i>P</i>	Mean (SD)	95% CI vs 42°C	<i>P</i>
Control	42°C	46 (5.4)	NA	NA	48 (18)	NA	NA
Test	38°C	47 (4.1)	(−3.1, 5.0)	.94	31 (8.2)	(−26.4, −6.0)	.01
	39°C	47 (4.2)	(−3.0, 5.0)	.93	32 (7.7)	(−25.9, −5.5)	.01
	40°C	49 (6.1)	(−1.1, 6.9)	.22	37 (17)	(−20.8, −0.4)	.039
	41°C	47 (5.5)	(−2.4, 5.7)	.70	36 (11)	(−21.5, −1.1)	.030

Comparisons were based on the average values of 2 repeated measurements for each subject.  
NA = not applicable

Table 2. Comparison of Transcutaneous Test Temperatures vs Arterial Value

Test Temperature	$CO_2$			$O_2$		
	Transcutaneous Mean (SD)	Arterial Mean (SD)	<i>P</i>	Transcutaneous Mean (SD)	Arterial Mean (SD)	<i>P</i>
38°C	47 (4.1)	43 (4.4)	.01	31 (8.2)	64 (13)	.01
39°C	47 (4.2)	42 (3.6)	< .001	32 (7.7)	63 (13)	< .001
40°C	49 (6.1)	41 (3.4)	< .001	37 (17)	63 (12)	< .001
41°C	47 (5.5)	43 (4.4)	< .001	36 (11)	67 (11)	< .001
42°C	46 (5.4)	43 (4.7)	< .001	48 (18)	64 (13)	< .001

Comparisons were based on the average values of 2 repeated measurements for each subject.

trol temperature were analyzed by testing whether the difference was something other than zero, using the Wilcoxon signed-rank test due to the small sample size. For continuous data, the differences between test and control temperatures were assessed using generalized linear mixed-effect models.

For each neonate, measurements of  $P_{tcCO_2}$  and  $P_{tcO_2}$  between the 2 blood gas draws were used for analysis of agreement. Agreement between test and control temperatures, as well as test temperatures versus arterial measurements of  $P_{tcCO_2}$  and  $P_{tcO_2}$  was assessed using Bland-Altman plots. Limits of agreements and mean difference were reported. *P* values < .05 indicate statistical significance. All statistical analysis was performed using STATA 14.2 (StataCorp, College Station, Texas) or R v.3.3.2 (R Foundation for Statistical Computing, Vienna, Austria).

## Results

Twenty infants were enrolled. Subject characteristics were (mean ± SD) gestational age  $30 \pm 2$  wk, birth-weight  $1,449 \pm 304$  g, weight at study  $1,378 \pm 323$  g, and age at study  $2 \pm 1$  d.  $P_{tcCO_2}$  levels of the control and test sites at 42°C were not different ( $45.5 \pm 1.0$  vs  $45.7 \pm 1.2$  mm Hg, *P* = .87). However,  $P_{tcO_2}$  levels of the control and test sites were different ( $57.9 \pm 3.2$  vs  $47.6 \pm 4.0$ , *P* = .02). At the time of blood gas analyses,

the mean  $P_{tcCO_2}$  among all test temperatures versus control (42°C) were not different, while for  $P_{tcO_2}$  there were significant differences between test and control sites for all temperatures (Table 1). The differences between  $P_{tcCO_2}$  and  $P_{aCO_2}$  values were similar at all temperatures, while  $P_{tcO_2}$  values varied markedly with large mean differences compared to blood gas values (Table 2).

Figure 1 shows continuous data for both  $P_{tcCO_2}$  and  $P_{tcO_2}$  at the lowest test temperature of 38°C versus control (42°C). For  $P_{tcCO_2}$ , while differences were statistically significant (longitudinal analysis, test of fixed effects, *P* = .005), they are not clinically important. For  $P_{tcO_2}$ , the difference between 42°C versus 38°C is quite large. For both  $P_{tcCO_2}$  and  $P_{tcO_2}$ , results at 38°C aligned well with results at 42°C. Bland-Altman analysis of 38°C versus the control of 42°C showed an average bias of 2.2 for  $P_{tcCO_2}$  at 38°C. Bias is defined as the tendency of a statistic to overestimate or underestimate a parameter. The 95% limit of agreement is between −7.04 and 11.44, which indicates poor precision (Fig. 2A). Precision refers to how close measurements from different samples are to each other. Results of other test temperatures versus control for  $P_{tcCO_2}$  were similar (not shown). Analysis of  $P_{tcCO_2}$  versus  $P_{aCO_2}$  at 38°C showed a positive bias of 4.85 and poor precision with a 95% limit of agreement between −2.69 and 13.39 (Fig. 2B). For  $P_{tcO_2}$ , 38°C versus 42°C (Fig. 3A), Bland-Altman analysis showed poor precision and a strong negative bias of −26.1

## TRANSCUTANEOUS ELECTRODE TEMPERATURES IN PRETERM INFANTS

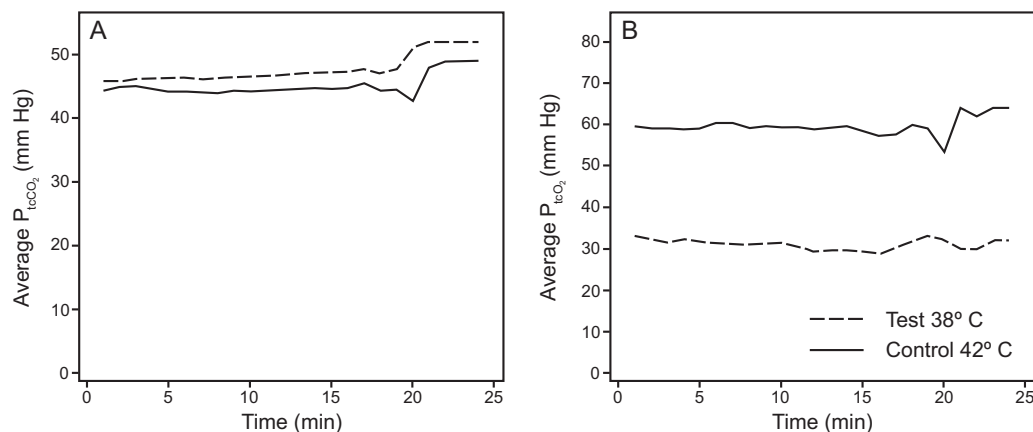


Fig. 1. Continuous data comparing the average  $P_{tcCO_2}$  at the lowest test temperature of 38°C versus the recommended temperature of 42°C. The time period shown is between the 2 blood gas draws for each subject at the represented temperatures. Subjects varied in time between blood gas draws. Higher  $P_{tcCO_2}$  noted between approximately 20–25 min reflect a smaller  $n$ .  $P = .005$ .

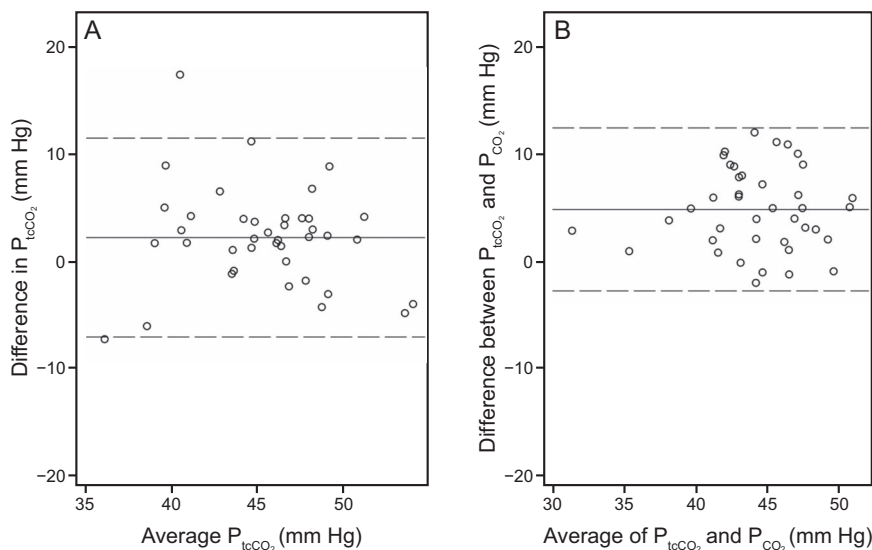


Fig. 2. A: Bland-Altman analysis of  $P_{tcCO_2}$  at 38°C versus the control of 42°C. The center horizontal line denotes an average bias of  $P_{tcCO_2}$  at 38°C of 2.2. The 95% limit of agreement is between -7.04 and 11.44, which indicates poor precision (indicated by dotted lines showing  $\pm 1.96$  SD). B: Bland-Altman analysis of  $P_{tcCO_2}$  at 38°C versus  $P_{aCO_2}$ . For  $P_{tcCO_2}$ , there was an average bias of 4.85 (center horizontal line) and poor precision (95% limit of agreement between -2.69 and 13.39, indicated by dotted lines showing  $\pm 1.96$  SD).

(95% limit of agreement between -48.51 and -3.61). Analysis of  $P_{O_2}$  versus  $P_{tcCO_2}$  (Fig. 3B) showed a strongly negative bias of -31.85 and poor precision (95% limit of agreement between -64.05 and 0.35). Bland-Altman analysis was done for all test temperatures versus control as well as all temperatures versus  $P_{CO_2}$  and  $P_{O_2}$ . Electrode temperature had minimal effect on bias and precision of  $P_{tcCO_2}$  measurement. However, results of  $P_{tcCO_2}$  measurements were similar with strong negative biases and poor precision at all test temperatures except for 42°C. At 42°C, there was a significantly lower bias and poor precision (Table 3). Time to warm-up for each temperature was not different, ranging from 10.5 to 12.3 min.

## Discussion

Extremes and fluctuations in levels of  $CO_2$  and  $O_2$  are known to be dangerous and can result in morbidity and mortality for premature infants. The effects of hypercapnia (both permissive and incidental) have been associated with worse neurodevelopmental outcome.<sup>4,8-10</sup> Hypercapnia is also associated with impaired cerebral autoregulation, leading to an increased incidence of intraventricular hemorrhage.<sup>5</sup> In fact, extremes and fluctuations in both hypercapnia and hypocapnia are associated with severe intraventricular hemorrhage, especially in the first few days of life.<sup>6</sup> Not only can over-ventilation damage the

## TRANSCUTANEOUS ELECTRODE TEMPERATURES IN PRETERM INFANTS

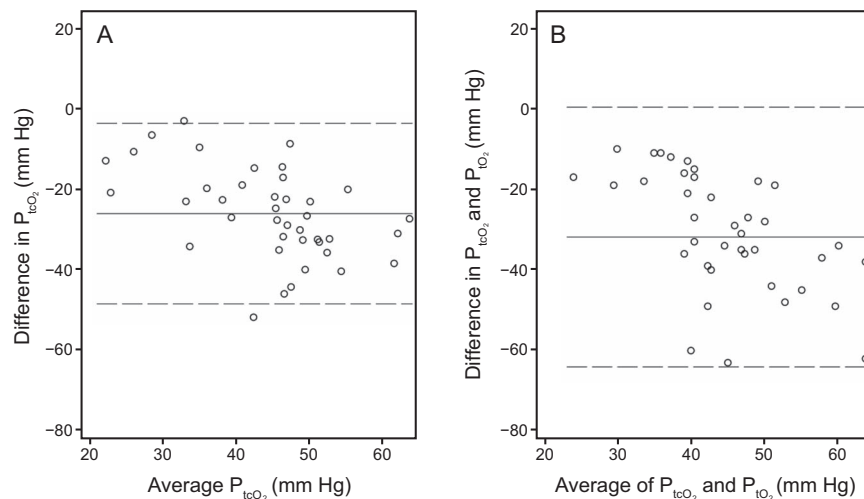


Fig. 3. A: Bland-Altman analysis of  $P_{tcO_2}$  at 38°C versus the control of 42°C. Analysis shows poor precision and strong negative bias of  $-26.1$ , shown by the center horizontal line (95% limit of agreement between  $-48.51$  and  $-3.69$ , indicated by dotted lines showing  $\pm 1.96$  SD). B: Bland-Altman analysis of  $P_{tcO_2}$  at 38°C versus  $P_{aCO_2}$ . For  $P_{tcO_2}$ , there was a strongly negative bias of  $-31.85$  (center horizontal line) and poor precision (95% limit of agreement between  $-64.05$  and  $0.35$ , indicated by dotted lines showing  $\pm 1.96$  SD).

Table 3. Bias and Precision for  $P_{tcCO_2}$  and  $P_{tcO_2}$

	P <sub>tcCO<sub>2</sub></sub>			P <sub>tcO<sub>2</sub></sub>		
	Bias	95% Limit of Agreement		Bias	95% Limit of Agreement	
		Low	High		Low	High
Test vs control						
38°C vs 42°C	2.20	−7.04	11.44	−26.10	−48.51	−3.69
39°C vs 42°C	1.72	−8.29	11.74	−27.17	−48.37	−5.98
40°C vs 42°C	2.35	−6.78	11.48	−23.45	−56.37	9.47
41°C vs 42°C	1.47	−8.93	11.88	−24.37	−49.15	0.40
42°C vs 42°C	0.20	−10.63	11.03	−10.30	−48.69	28.09
Test vs arterial						
38°C vs arterial	4.85	−2.69	13.39	−31.85	−64.05	0.35
39°C vs arterial	5.50	−1.76	12.76	−31.13	−57.77	−4.48
40°C vs arterial	6.03	−3.16	15.21	−30.23	−70.90	10.45
41°C vs arterial	4.63	−3.94	13.19	−27.55	−67.04	11.94
42°C vs arterial	2.93	−8.16	14.01	−16.53	−59.69	26.64

lung, but hypocapnia has also been found to cause or worsen cerebral ischemia<sup>1</sup> and is known to be associated with periventricular leukomalacia.<sup>2,3</sup> Extremes in  $O_2$  levels also have negative effects on the neonate. Hyperoxia is associated with periventricular leukomalacia and retinopathy of prematurity, while hypoxia has been shown to cause ischemia and is related to a higher chance of mortality.<sup>7</sup>

Transcutaneous monitoring provides a method to continuously monitor  $CO_2$  and  $O_2$ , and in a recent Cochrane review, Bruschetti et al<sup>14</sup> called for additional studies demonstrating safety and efficacy in transcutaneous monitoring. More studies are needed to evaluate long-term outcomes of the use of transcutaneous monitoring. There

is evidence of earlier diagnosis of pneumothorax prior to decompensation as well as assessment for clinical disease severity in infants with bronchiolitis using continuous transcutaneous monitoring.<sup>15,16</sup> Transcutaneous monitoring is not the only option for continuous monitoring of  $CO_2$  and  $O_2$ , but at this time it is the most useful. End-tidal  $CO_2$  monitoring has been used, but there are documented disadvantages to end-tidal monitoring that make it less feasible in the neonate. In infants with lung disease, who comprise a large proportion of neonatal subjects, ventilation-perfusion mismatch can lead to inaccurate results. Most neonates have a high breathing frequency requiring a faster response time than end-tidal sensors can deliver. This population also has a lower tidal volume resulting in proportionally increased dead



## TRANSCUTANEOUS ELECTRODE TEMPERATURES IN PRETERM INFANTS

space of the sensors. In addition, end-tidal monitoring can underestimate  $\text{CO}_2$  levels.<sup>17-19</sup> Monitoring end-tidal  $\text{CO}_2$  at the distal end of a double-lumen endotracheal tube may be useful, but these tubes are not always used for neonates.<sup>20</sup> Given these issues, transcutaneous monitoring is the best option at this time for continuous  $\text{CO}_2$  monitoring.

To measure  $\text{O}_2$  saturation, the modality used most frequently is pulse oximetry ( $\text{S}_{\text{pO}_2}$ ).  $\text{S}_{\text{pO}_2}$  is widely available and easy to use, but it has weaknesses as well. Due to the  $\text{O}_2$ -dissociation curve,  $\text{S}_{\text{pO}_2}$  is unable to provide accurate estimates of  $\text{P}_{\text{O}_2}$  levels at higher  $\text{O}_2$  saturation levels, which may be associated with very high  $\text{P}_{\text{O}_2}$ , which is harmful to the infant.<sup>21,22</sup> Continuous accurate monitoring of  $\text{P}_{\text{O}_2}$  could be useful to avoid hyperoxia and hypoxia. Infants with pulmonary hypertension and infants of extremely low birthweight are examples of subjects in whom very close monitoring of  $\text{P}_{\text{aO}_2}$  levels could be especially useful. It may be of more limited use in extremely premature infants, given their lower oxygenation targets. In our study, wide differences in  $\text{P}_{\text{tcO}_2}$  and  $\text{P}_{\text{aO}_2}$  occurred, even at  $42^\circ\text{C}$ . As noted above, there were also electrode-site differences for  $\text{P}_{\text{tcO}_2}$ . Because arterialization of the capillary bed is so important for  $\text{P}_{\text{tcO}_2}$  monitoring, perhaps a higher electrode temperature is required to accurately assess  $\text{P}_{\text{tcO}_2}$  trends. Transcutaneous monitoring may have an important role in continuous  $\text{P}_{\text{O}_2}$  assessment in larger infants who can tolerate higher electrode temperatures, and its use should perhaps be re-evaluated, particularly in the setting of pulmonary hypertension.

In our study, we assessed both  $\text{P}_{\text{tcCO}_2}$  and  $\text{P}_{\text{tcO}_2}$  at the recommended electrode temperature of  $42^\circ\text{C}$  and at several lower temperatures. We found that electrode temperatures as low as  $38^\circ\text{C}$  provide an accurate assessment of  $\text{P}_{\text{CO}_2}$  and similar trends compared to the recommended electrode temperature of  $42^\circ\text{C}$ . In comparison to the accepted standard of arterial blood gas measurement, transcutaneous electrode temperatures were accurate at every test temperature ( $38$ ,  $39$ ,  $40$ ,  $41$ , and  $42^\circ\text{C}$ ), with mean differences from arterial values ranging from 2 to 8 mm Hg.

Using an older transcutaneous monitor, Sorensen et al<sup>13</sup> found that electrode temperatures of  $40$  and  $41^\circ\text{C}$  could be used to track  $\text{P}_{\text{tcCO}_2}$ ; they recommend, however, using a correction factor of 12–15%. More recently, Hirata et al<sup>23</sup> found results similar to ours with electrode temperatures of  $38$ ,  $39$ , and  $40^\circ\text{C}$  in comparison to a control of  $42^\circ\text{C}$ , but they recommended a correction factor of 6 mm Hg. Hirata et al,<sup>23</sup> however, did not use 2 monitors simultaneously, which is a major strength of our study. Given our average difference of 2.2 mm Hg between  $38^\circ\text{C}$  and  $42^\circ\text{C}$ , we do not feel a correction factor is needed, although occasional correlation with an arterial gas must be done. It is important to note that the limit of agreement in the neonate between arterial and transcutaneous values may be more dependent on skin perfusion due to blood flow

changes in the neonatal skin. The trend in any one infant is more important than the absolute difference between the transcutaneous reading and the arterial value, therefore it may be more important to be aware of trends than to use a correction factor.

For  $\text{P}_{\text{tcO}_2}$ , transcutaneous monitoring has been associated with skin burns as well as measurement inaccuracies at lower electrode temperatures. For accurate measurement of  $\text{P}_{\text{O}_2}$  trends, transcutaneous monitoring requires an electrode temperature sufficient for arterialization of the capillary bed.<sup>13,24</sup> In our study we reassessed  $\text{P}_{\text{tcO}_2}$  using newer electrode technology recently developed by Radiometer (Copenhagen, Denmark). We tested this technology to assess any improvements in  $\text{P}_{\text{tcO}_2}$  measurements. The new sensors reportedly have a very small surface and a site time-heat function monitor that ensures that the heating of the sensor is automatically switched off after a monitoring session, theoretically decreasing the risk of skin damage. We found that while  $\text{P}_{\text{tcO}_2}$  values were much lower than arterial values, especially at low electrode temperatures,  $\text{P}_{\text{tcO}_2}$  appeared to track the higher electrode temperature results relatively well. Thus, following both  $\text{P}_{\text{tcO}_2}$  and  $\text{P}_{\text{tcCO}_2}$  may be clinically useful, even when low electrode temperatures are employed.

## Limitations

This was a small study with an enrollment of 20 subjects. We did not include babies with birthweight of  $< 1$  kg due to the potential of skin burns in this population at the higher electrode temperatures. The majority of our infants required only minimal respiratory support, and the study was short in duration, lasting approximately 4–5 h. It is also worth noting that, in general, the monitor performed with limited precision, likely due to changes in perfusion. For this reason, we recommend occasional correlation with an arterial blood gas.

## Conclusions

Continuous  $\text{CO}_2$  and  $\text{O}_2$  monitoring are of utmost importance in extremely premature infants. Our results support and expand current literature. Use of transcutaneous monitor temperatures as low as  $38^\circ\text{C}$  allow accurate monitoring and tracking of  $\text{P}_{\text{CO}_2}$  and therefore can be used instead of the recommended  $42^\circ\text{C}$ . For  $\text{P}_{\text{O}_2}$ , transcutaneous monitoring may be useful for trending, although caution must be used in the interpretation of  $\text{P}_{\text{tcO}_2}$  values. Use of lower transcutaneous temperatures to track  $\text{P}_{\text{CO}_2}$  values should allow this technology to be applied in even the smallest preterm infants.

## REFERENCES

1. Curley G, Kavanagh BP, Laffey JG. Hypocapnia and the injured brain: Evidence for harm. *Crit Care Med* 2011;39(1):229-230.

## TRANSCUTANEOUS ELECTRODE TEMPERATURES IN PRETERM INFANTS

2. Wiswell TE, Graziani LJ, Kornhauser MS, Stanley C, Merton DA, McKee L, et al. Effects of hypocarbia on the development of cystic periventricular leukomalacia in premature infants treated with high-frequency jet ventilation. *Pediatrics* 1996;98(5):918-924.
3. Zhou W, Liu W. Hypercapnia and hypocapnia in neonates. *World J Pediatr* 2008;4(3):192-196.
4. Altaany D, Natarajan G, Gupta D, Zidan M, Chawla S. Severe intraventricular hemorrhage in extremely premature infants: Are high carbon dioxide pressure or fluctuations the culprit? *Am J Perinatol* 2015;32(9):839-844.
5. Kaiser JR, Gauss CH, Pont MM, Williams DK. Hypercapnia during the first 3 days of life is associated with severe intraventricular hemorrhage in very low birth weight infants. *J Perinatol* 2006;26(5):279-285.
6. Fabres J, Carlo WA, Phillips V, Howard G, Ambalavanan N. Both extremes of arterial carbon dioxide pressure and the magnitude of fluctuations in arterial carbon dioxide pressure are associated with severe intraventricular hemorrhage in preterm infants. *Pediatrics* 2007;119(2):299-305.
7. Askie LM, Darlow BA, Davis PG, Finer N, Stenson B, Vento M, Whyte R. Effects of targeting lower versus higher arterial oxygen saturations on death or disability in preterm infants. *Cochrane Database Syst Rev* 2017;4:CD011190.
8. Thome UH, Carroll W, Wu TJ, Johnson RB, Roane C, Young D, et al. Outcome of extremely preterm infants randomized at birth to different PaCO<sub>2</sub> targets during the first seven days of life. *Biol Neonate* 2006;90(4):218-225.
9. Ambalavanan N, Carlo WA, Wrage LA, Das A, Laughon M, Cotten CM, et al. PaCO<sub>2</sub> in surfactant, positive pressure, and oxygenation randomised trial (SUPPORT). *Arch Dis Child Fetal Neonatal Ed* 2015;100(2):F145-F149.
10. McKee LA, Fabres J, Howard G, Peralta-Carcelen M, Carlo WA, Ambalavanan N. PaCO<sub>2</sub> and neurodevelopment in extremely low birth weight infants. *J Pediatr* 2009;155(2):217-221.
11. Aliwalas LL, Noble L, Nesbitt K, Fallah S, Shah V, Shah PS. Agreement of carbon dioxide levels measured by arterial, transcutaneous and end tidal methods in preterm infants < or = 28 weeks gestation. *J Perinatol* 2005;25(1):26-29.
12. Thomas PE. What's the latest on carbon dioxide monitoring? *Neonatal Netw* 2004;23(4):70-72.
13. Sorensen LC, Brage-Andersen L, Greisen G. Effects of the transcutaneous electrode temperature on the accuracy of transcutaneous carbon dioxide tension. *Scand J Clin Lab Invest* 2011;71(7):548-552.
14. Bruschetti M, Romantsik O, Zappettini S, Ramenghi LA, Calevo MG. Transcutaneous carbon dioxide monitoring for the prevention of neonatal morbidity and mortality. *Cochrane Database Syst Rev* 2016;2:CD011494.
15. McIntosh N, Becher JC, Cunningham S, Stenson B, Laing IA, Lyon AJ, et al. Clinical diagnosis of pneumothorax is late: use of trend data and decision support might allow preclinical detection. *Pediatr Res* 2000;48(3):408-415.
16. Gal S, Riskin A, Chistyakov I, Shifman N, Srugo I, Kugelman A. Transcutaneous PCO<sub>2</sub> monitoring in infants hospitalized with viral bronchiolitis. *Eur J Pediatr* 2015;174(3):319-324.
17. Tingay DG, Mun KS, Perkins EJ. End tidal carbon dioxide is as reliable as transcutaneous monitoring in ventilated postsurgical neonates. *Arch Dis Child Fetal Neonatal Ed* 2013;98(2):F161-F164.
18. Tingay DG, Stewart MJ, Morley CJ. Monitoring of end tidal carbon dioxide and transcutaneous carbon dioxide during neonatal transport. *Arch Dis Child Fetal Neonatal Ed* 2005;90(6):F523-F526.
19. Schmalisch G. Current methodological and technical limitations of time and volumetric capnography in newborns. *Biomed Eng Online* 2016;15(1):104.
20. Kugelman A, Golan A, Riskin A, Shoris I, Ronen M, Qumqam N, et al. Impact of continuous capnography in ventilated neonates: A randomized, multicenter study. *J Pediatr* 2015;168:56-61.
21. Quine D, Stenson BJ. Does the monitoring method influence stability of oxygenation in preterm infants? A randomised crossover study of saturation versus transcutaneous monitoring. *Arch Dis Child Fetal Neonatal Ed* 2008;93(5):F347-F350.
22. Lakshminrusimha S, Manja V, Mathew B, Suresh GK. Oxygen targeting in preterm infants: a physiological interpretation. *J Perinatol* 2015;35(1):8-15.
23. Hirata K, Nishihara M, Oshima Y, Hirano S, Kitajima H. Application of transcutaneous carbon dioxide tension monitoring with low electrode temperatures in premature infants in the early postnatal period. *Am J Perinatol* 2014;31(5):435-440.
24. Poets CF, Bassler D. Providing stability in oxygenation for preterm infants: Is transcutaneous oxygen monitoring really better than pulse oximetry? *Arch Dis Child Fetal Neonatal Ed* 2008;93(5):F330-F331.