Transcutaneous Oxygen and Carbon Dioxide Monitoring in Sick Neonates Using a Combined Sensor*

Rama Bhat, M.D.; † Javier Diaz-Blanco, M.D.; ‡ Urmila Chaudhry, M.D.; § and D. Vidyasagar, M.D. ||

Using a combined O₂-CO₂ sensor, we evaluated the effect of cathode size and membrane thickness and incorporation of correction factor upon transcutaneous O₂-CO₂ readings. The present studies were carried out in three phases in newborns less than a week of age. The data from these studies indicate that a combined O₂-CO₂ sensor with a smaller cathode, Teflon membrane and with a built-in correction factor can accurately reflect arterial O₂ and CO₂ tension and can replace the present two heated sensors.

At present, transcutaneous oxygen (tcPO₂) monitoring of critically-ill neonates is a standard practice in most neonatal intensive care units in the United States.1,2 However, transcutaneous carbon dioxide (tcPCO₂) electrodes have not been well accepted for routine use because of varying results reported by several investigators.3-6 Since both oxygen and carbon dioxide diffuse through skin easily, it seems logical to measure both the gases using a single heated sensor. Whitehead et al7 first reported clinical experience with such a combined sensor developed in their laboratories. Their findings were encouraging and have led to the development of similar sensors by others.7 The purpose of the present study was to evaluate a newly developed combined sensor (Biochem International, Inc) with different cathode size, different membranes, and the use of correction factor in three different phases in critically-ill neonates.

METHODS

Critically-ill neonates requiring ventilatory support and umbilical artery catheterization were selected for the study. The electrode consisted of polarographic Clark Po₂ electrode8 with a platinum microcathode silver chloride anode, and a Stowé® Severinghaus® CO₂ electrode. The heating element consisted of nichrome wire underneath the anode (Fig 1). The electrolyte solution contained potassium chloride, sodium bicarbonate, and ethyleneglycol. The electrode weighed 7.0 g. The in vitro response time (± 90 percent) was less than 30 seconds. The electrode was calibrated using 5

![Diagram](image)

**FIGURE 1.** Cross sectional view of the combined O₂-CO₂ sensor.
Data (Weeks)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th>Data Points</th>
<th>Correlation Coefficient</th>
<th>Slope</th>
<th>Intercept</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase 1*</td>
<td>11</td>
<td>101 O₂</td>
<td>0.55</td>
<td>0.41</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td></td>
<td>95 CO₂</td>
<td>0.68</td>
<td>1.41</td>
<td>14</td>
</tr>
</tbody>
</table>

* Cathode size 64 μm and polypropylene membrane 13 μm thickness.

Table 2—Clinical Data

<table>
<thead>
<tr>
<th></th>
<th>Birth Weight (kg)</th>
<th>Gest Age (Weeks)</th>
<th>Data Points</th>
<th>Correlation Coefficient</th>
<th>Slope</th>
<th>Intercept</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase 2</td>
<td>24</td>
<td>1.88±0.89</td>
<td>33±0.89</td>
<td>243 O₂*</td>
<td>0.84*</td>
<td>0.55*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>251 CO₂</td>
<td>0.87</td>
<td>1.31</td>
<td>7.00</td>
<td></td>
</tr>
<tr>
<td>Phase 3</td>
<td>7</td>
<td>2.22±0.44</td>
<td>34±3.0</td>
<td>90 O₂</td>
<td>0.90</td>
<td>0.61</td>
</tr>
<tr>
<td></td>
<td></td>
<td>90 CO₂</td>
<td>0.90</td>
<td>0.91</td>
<td>1.46</td>
<td></td>
</tr>
</tbody>
</table>

*The slope and the intercept are for total number (n = 243) obtained during phase 2.

percent CO₂ with 95 percent N₂ for the low CO₂ and zero oxygen tension and 10 percent CO₂ with 21 percent O₂ for high point calibration of O₂ and CO₂.

The study was carried out in three phases. During phase I, the cathode was 64 μm size and the membrane used was 13 μm thick polypropylene. The electrode was calibrated and applied at 43.5°C. Eleven patients were studied during this phase. The transcutaneous oxygen values from this phase of the study were significantly lower than the arterial values. In addition, the in vitro oxygen consumption of this sensor by the ethyleneglycol method1 showed a higher oxygen consumption by the sensor (see results). Because of these results, the following modifications were made in the sensor during the second phase. The cathode size was decreased to 25 μm and the polypropylene membrane was replaced by a 25 μm Teflon membrane for better stabilization. The sensor temperature during the second phase was increased to 44°C because of the thicker membrane used. Using this sensor, 24 neonates were studied. During the third phase, there were no changes in sensor; instead, a carbon dioxide correction factor was built into the display monitor which could be turned on after sensor application to skin. The correction factor was based on the anaerobic heating coefficient of blood (1.37 at 44°C) and skin metabolism (4 mm Hg). Using this technique, seven patients were studied in this phase.

The sensor application sites selected for monitoring were chest (infracalavicular region), flanks (either side), and inner aspect of thighs. The sensor application sites were changed every four hours to Figure 2. Correlation of transcutaneous CO₂ to arterial CO₂ during phase II with 95 percent confidence bands.
prevent heat burns. The electrode was checked for drift for both O$_2$ and CO$_2$ readings every four hours in calibration gases, and recalibrated if necessary before reapplication. The membrane was changed when significant drifts were noted during calibration. Blood was obtained from the umbilical artery catheter and analyzed immediately using ABL blood gas analyzer. The transcutaneous CO$_2$ readings were not corrected for anaerobic heating coefficient during the first and second phase. All infants were less than a week old and had no evidence of significant ductus arteriosus during the monitoring period. Statistical analysis was performed using Pearson’s linear regression method$^4$ to determine the correlation of transcutaneous values with the arterial values.

RESULTS

Table 1 shows clinical data and the correlation of arterial oxygen and carbon dioxide tension with transcutaneous values for the first phase of the study. A total of 101 oxygen and 95 carbon dioxide values were available for analysis from this phase. The transcutaneous PO$_2$ values correlated well with the arterial values ($r=0.55$, slope 0.41), were lower than arterial values (PaO$_2=82\pm28$ mm Hg, tcPO$_2=66\pm21$ mm Hg, M±SD, p<0.00005). The transcutaneous carbon dioxide values correlated better with the arterial PCO$_2$ (slope 1.41, r = 0.68). The in vitro oxygen consumption studies on this sensor showed 21 percent oxygen consumption ($\phi=1.21$). Following the reduction of cathode size and changing the membrane to 25 μm Teflon, the oxygen consumption decreased from 21 percent to 5 percent ($\phi=1.05$).

In the second phase, 24 neonates were studied and their clinical data are shown in Table 2. Figure 2 shows the correlation of arterial CO$_2$ to tcPCO$_2$ from these 24 patients. There were 251 data points available for analysis. The tcPCO$_2$ correlated well with PaCO$_2$ (Fig 2) (n=251, r = 0.87, y = 7.0, + (1.31)x, p<0.00005). These CO$_2$ data were consistent with the data obtained from a single CO$_2$ sensor.$^6$ Similarly, the tcPO$_2$ readings correlated well with arterial values but still significantly lower than PaO$_2$ (n=243, r = 0.84, y = 26 + (0.55)x, p<0.00005, Table 2). The mean PaO$_2$ was 101±61 mm Hg and tcPO$_2$ was 82±40 mm Hg, M±SD, p<0.05. This difference between arterial and transcutaneous oxygen could be due to the fact that 88/243 tcPO$_2$ and PaO$_2$ values were more than 100
mm Hg. Hence, separate analyses were carried out for values <100 mm Hg, and for more than 100 mm Hg, respectively. The tcPO₂ correlated better with PaO₂ when the PaO₂ was <100 mm Hg (n = 155, r = .77, y = 4.4 + (0.85)x, PaO₂ = 69 + 17 mm Hg, tcPO₂ = 63 ± 19 mm Hg). (Fig 3, top). A separate regression analysis for oxygen values more than 100 mm Hg (Fig 3, bottom) revealed that transcutaneous values were significantly lower than the arterial values and the slope was not linear (n = 88, r = 0.07 slope 0.46). Mean arterial and transcutaneous oxygen tension values were 162 ± 66 mm Hg and 117 ± 43 mm Hg (M ± SD), respectively. The data points represented by the open circle in Figure 3, bottom, were obtained from one patient with β-Streptococcus group B sepsis with poor peripheral perfusion.

During the third phase, a correction factor for tcPO₂ readings was incorporated into the monitor. Seven patients were monitored during this phase. A total of 90 simultaneously obtained arterial blood gas and transcutaneous O₂ and CO₂ values were available for regression analysis. Figure 4 shows the data for the third phase. Transcutaneous sensor accurately predicted the arterial CO₂ (r = 0.90, slope 0.91). The relationship of tcPO₂ and PaO₂ remained unchanged compared to the second phase (Table 2). The mean drift of tcPO₂ readings after four hours of use was -0.26 ± 0.6 mm Hg/hour in 5 percent CO₂ and 0.11 ± 0.6 mm Hg (M ± SD) in 10 percent CO₂. The drift for oxygen reading was 1 ± 0.5 mm Hg/hour. The membrane required changing at a mean interval of 11 ± 1.8 days (M ± SD). A transient erythema was noted after three to four hours of use. The transcutaneous electrode functioned equally well in all sites (chest, flank, and thighs) studied.

**DISCUSSION**

The present data derived from the combined sensor extends that of two previous preliminary studies using different sensors. The benefits of using transcutaneous oxygen and carbon dioxide monitors have been reported by a number of investigators during the past two years. Parker et al first showed that by using a single sensor, it was possible to measure PaO₂ and PaCO₂ transcutaneously. Subsequently, using an in vivo method for the calibration of the combined sensor, Whitehead et al were able to improve the accuracy of estimation of PaO₂ and PaCO₂. The initial problems with underestimation of PaO₂ and overestimation of PaCO₂ in the first phase of our present study may partly be due to the relatively large cathode which increased the oxygen consumption by the sensor. Our in vitro studies in fact proved that this was the case. Following reduction of the cathode size from 64 μm to 25 μm and changing the membrane from 13 μm polypropylene to 25 μm Teflon, the oxygen consumption decreased from 21 percent to 5.0 percent (1.21 to 1.05). This can be further compensated by setting the calibration readings for oxygen in room air (21 percent oxygen) 7 mm Hg higher than that expected. However, studies in this regard are needed to confirm this hypothesis. We attribute the better correlation between arterial and transcutaneous oxygen values seen during the second phase of this investigation to the decreased oxygen consumption by the smaller cathode.

![Figure 4. Correlation of transcutaneous CO₂ to arterial CO₂ following the introduction of correction factor (phase 3). The dotted line shows the line of identity.](http://journal.publications.chestnet.org/pdfaccess.ashx?url=data/journals/chest/21498/)
All studies described so far using the single transcutaneous CO₂ sensor without any correction factor have reported that the transcutaneous readings were always higher than arterial values. This has been attributed to (a) the heat-induced increased skin metabolism; (b) the anaerobic heating coefficient of blood; (c) the counter gradient transport of CO₂. The results from the phase 1 and 2 of this study are consistent with the earlier published reports. The introduction of correction factor in phase 3 showed a very good correlation between the transcutaneous and arterial values. However, the data are preliminary and the range of arterial CO₂ was from 15 to 50 mm Hg. Hence, further studies are needed to establish its reliability during hypercarbia. Monaco et al., using a single CO₂ sensor, have reported that incorporation of correction factor can improve the accuracy of tcPCO₂ at all ranges. Our studies also indicate that a sensor temperature of 44°C improves the tcPO₂ reading while other investigators have shown that the response time was also shorter at this temperature. Maintaining the sensor temperature at 44°C may also decrease the cooling of the electrode at skin surface because of the thicker membrane. This is an important factor, as keeping the sensor temperature at lower levels (eg, 43°C or 43°C) may not achieve adequate vasodilatation of cutaneous capillaries. For tcPO₂, the accuracy of estimation was better when PaO₂ was <100 mm Hg than when it was >100 mm Hg (slope of 0.85 vs 0.46, respectively). A similar relationship was also reported with single tcPO₂ sensors. The mean drift of the combined sensor (both O₂ and CO₂) after four hours of use at either 5 percent or 10 percent CO₂ was insignificant.

The present data suggest that combined sensors can safely replace separate heated sensors for transcutaneous measurement of O₂ and CO₂ in critically-ill neonates.

ACKNOWLEDGMENT: The authors acknowledge the technical assistance from Mr. Allen Beder, Biochem International Inc. and secretarial help of Natalie Henry.

REFERENCES

1 Hansen TN, Tooley WH. Skin surface carbon dioxide tension in sick infants. Pediatrics 1979; 64:942-45
3 Herrell N, Martin RJ, Pultusker M, Lough M, Fanaroff A.

Optimal temperature for the measurement of transcutaneous carbon dioxide tension in the neonate. J Pediatr 1986; 97:114-17
7 Severinghaus JW. A combined transcutaneous PO₂-PCO₂ electrode with electrochemical HCO₃⁻ stabilization. J Appl Physiol: Respir Environ Exer Physiol 1981; 51:1027-32
9 Stowe RWB, Baer RF, Randal BF. Rapid measurement of tension of carbon dioxide in the blood. Arch Phys Med Rehab 1987; 58:646-50

Monitoring Sick Neonates with Combined Sensor (Bhat et al)