Response Characteristics of a Dual Transcutaneous Oxygen/Carbon Dioxide Monitoring System*

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We tested the response characteristics of a dual transcutaneous (tc) PO2/Pco2 monitoring system in healthy subjects who breathed various gas mixtures, and we compared steady-state tc readings to simultaneous arterial blood gas analysis in 20 stable respiratory outpatients. The electrodes were simple to apply, required very little skin preparation, and had trivial signal drift. In healthy subjects, tcPco2 lag time during CO2 rebreathing was 16.8 seconds, with a 90 percent response time of 77.9 seconds after CO2 breathing was discontinued. The 90 percent response times of the O2 electrode when subjects breathed a hypoxic mixture was 257 seconds after a lag of 31 seconds. When inhaled gas mixtures were changed from hypoxia to room air, the lag time was shorter (12.5 seconds), but 90 percent response time exceeded 5 minutes. In stable patients with respiratory disease, tcPco2 and tcPO2 were linearly related to PaCO2 (range, 19 to 53 mm Hg) and PaO2 (range, 45 to 99 mm Hg), respectively (tcPco2 = 1.4 PaCO2 - 9.44, with r = 0.90 and SEE =5.35 mm Hg; tcPO2 = 0.56 PaO2 + 20.4, with r = 0.53 and SEE = 11.7 mm Hg). We conclude that the response of the dual transcutaneous monitoring system is more rapid for CO2 than the O2 electrode and may be rapid enough to be useful in some clinical settings; however, the O2 system fails to offer the response characteristics and accuracy that would allow it to be substituted for arterial gas tensions in unstable clinical situations.

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tcPO2 = transcutaneous oxygen tension; tcPco2 = transcutaneous carbon dioxide tension

The gold standard for evaluation of the adequacy of alveolar ventilation is the assessment of arterial blood gas levels. While PaCO2 and PaO2 can be measured with a high degree of accuracy, the measurement is invasive and noncontinuous and, for logistic reasons, is difficult to obtain on a moment-to-moment basis. Accordingly, attention has been directed toward developing improved technology for monitoring blood gas levels noninvasively and continuously. Continuous real-time evaluation of oxygenation by oximetry has become routine practice during anesthesia and in intensive care units and sleep disorders clinics. Fingertip or earlobe oximeters measure oxygen saturation reliably in the physiologic range with clinically useful alarm systems.1,2 By contrast, transcutaneous monitors for measuring PO2 and Pco2 have not been as widely accepted in adult clinical practice; they have, in some studies, proven inaccurate and slow to respond to sudden changes in blood gas tensions and may require fastidious skin preparation before any useful information can be obtained.3-8

Tobin* has suggested that while transcutaneous monitoring is useful in the neonatal setting, its value in critically ill adults is unclear. More recently, a dual transcutaneous O2/CO2 monitoring system that combines a heating element, two temperature sensors, a Clark-type O2 electrode, and a Severinghaus-type CO2 electrode in a single unit has become available to us for evaluation. We therefore assessed the response characteristics of this dual transcutaneous O2/CO2 monitoring system under a variety of conditions of breathing gas mixtures in healthy volunteers. We also compared arterial blood gas tensions and transcutaneous measurements in patients with pulmonary disease.

Materials and Methods

The transcutaneous combined PO2/Pco2 monitor (Radiometer TCM3) is 24 x 8 x 23 cm and weighs 2.7 kg. The front panel displays time or site temperature, PO2, and Pco2. The unit is powered by battery or a standard electrical outlet. It is capable of analog or serial digital outputs. The combined electrode is 15 mm in diameter and 11 mm in height and weighs 3.8 g.

Application of Transcutaneous Electrode

The electrode temperature was set at 44°C, and calibration values were set according to the barometric pressure measured in the pulmonary function laboratory. Calibration of the electrode was performed with a 5 percent CO2 and 20.9 percent O2 standard calibration gas prior to use in each subject. The chest was chosen as the monitoring site, as recommended in the manufacturer's handbook. The area was shaved if necessary and cleaned with alcohol. The device was applied in accordance with the manufacturer's instructions. The electrode was kept on the skin surface for at least 15 minutes prior to each experiment to allow the signal to stabilize.

The transcutaneous blood gas electrode was assessed under a variety of conditions. First, we defined the spontaneous drift of the signal at steady-state resting conditions and without manipulation of blood gas tensions. We then followed the response characteristics of the electrode in healthy subjects during induced hypercapnia.

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hypoxia, and hyperoxia. Finally, we compared arterial blood gas tensions with transcutaneous measurements in patients with pulmonary disease.

**Signal Drift**

The transcutaneous electrode was applied to ten healthy individuals who rested quietly in a sitting position. After a 15-minute period of electrode stabilization, tcPO2 and tcPCO2 were recorded continuously for 10 more minutes.

**Hypercapnia**

Hypercapnia was induced by a rebreathing technique in nine healthy subjects using a bag-in-box rebreathing circuit.* Analog data from the infrared CO2 monitor (Gould-Godart Capnograph Mark III) were recorded on a multichannel strip-chart recorder (Hewlett-Packard 7404A) while each change in tcPCO2 was recorded manually on the strip-chart record. The bag contained an initial gas mixture of CO2:O2 of 7:93. After resting end-tidal PCO2 had stabilized, the subject rebreathed the bag of gas for approximately 4 minutes while PaCO2 and tcPCO2 were recorded. After 4 minutes a valve was turned to open the circuit to room air. Recording of PaCO2 and tcPCO2 was continued until the transcutaneous signal had again stabilized for at least 1 minute.

**Hypoxia**

Steady-state hypoxia was induced in six healthy subjects breathing through a Rudolph valve. The F1O2 was adjusted to 16 percent with gas flow rates maintained at 20 L/min. The F1O2 was monitored continuously (Engstrom Eliza Duo CO2 and O2 Analyzer); tcPO2 was recorded every 5 seconds until the signal had stabilized for at least 1 minute. The mask was then removed and the subject exposed to room air; tcPO2 was recorded every 5 seconds until the signal had stabilized for at least 1 minute. This procedure was repeated twice for a total of three experiments per subject.

**Hyperoxia**

Steady-state hyperoxia was induced in six normal subjects who breathed from a Venturi mask set to deliver an F1O2 of 40 percent (oxygen at 8 L/min through the mask). The tcPO2 was recorded every 5 seconds until the signal had stabilized for at least 1 minute. The mask was then removed and the subject exposed to room air; tcPO2 was recorded every 5 seconds until the signal had stabilized for at least 1 minute. This procedure was repeated twice for a total of three experiments per subject.

**Comparison of Transcutaneous Reading with Arterial Blood Gas Tensions**

In 20 ambulatory subjects with a variety of respiratory illnesses who had been referred to the pulmonary function laboratory of the Toronto Western Hospital for arterial blood gas analysis, tcPO2 and tcPCO2 were recorded during the performance of arterial puncture. All subjects were hemodynamically stable. Respiratory illnesses in the subjects included COPD (nine patients), chronic ventilatory insufficiency secondary to kyphoscoliosis (two patients), recently recovered *Pneumocystis carinii* pneumonia (five patients), sleep apnea (three patients), and sarcoidosis (one patient).

**Data Analysis**

Results are expressed as means ± 1 SD. Lag time was defined as the time from the initiation of the intervention to the initial response of the sensor. The onset of instrument response for calculation of lag time and the appearance of a steady state for calculation of response time were determined by visual inspection of the graphic record. The relationships between arterial and transcutaneous gas tensions were described by least-squares linear regression. The ratio of transcutaneous to arterial values was calculated separately for CO2 and O2 for each individual. These ratios were compared among individuals by one-way analysis of variance. Differences were considered significant at the level of p<0.05.

**RESULTS**

The application of the dual transcutaneous monitor was simple and involved only brief skin preparation (cleaning with an alcohol swab). No subject complained of discomfort associated with the monitor. There was mild transient erythema over the site following prolonged use (ie., 2 hours).

**Signal Drift**

The mean difference between the minimum and maximum values over ten-minute epochs at rest was 5.3 ± 0.6 mm Hg for tcPO2 and 1.8 ± 0.2 mm Hg for tcPCO2.

**Hypercapnia**

The mean lag time during hypercapnia was 16.8 ± 1.2 seconds. When the subjects resumed breathing room air from hypercapnia, the mean lag time was 14.2 ± 1.4 seconds, with a 90 percent response time of 77.9 ± 6.7 seconds (Fig 1). The mean times for the transcutaneous signal to exceed maximum signal drift upon initiation and termination of

![Graph](image-url)

**Figure 1.** Changes in tcPCO2 (dashed line) and PaCO2 (solid line) during rebreathing in representative subject.

**Table 1—Response Characteristics for Induction of Hypoxia and Hyperoxia**

<table>
<thead>
<tr>
<th>Condition</th>
<th>RA→16%</th>
<th>16% →RA</th>
<th>RA→40%</th>
<th>40% →RA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lag time, s</td>
<td>31.1 ± 3.5</td>
<td>12.5 ± 1.8</td>
<td>9.7 ± 1.0</td>
<td>12.8 ± 1.2</td>
</tr>
<tr>
<td>50 percent response, s</td>
<td>116 ± 17</td>
<td>75 ± 19</td>
<td>96 ± 8.3</td>
<td>60 ± 4.9</td>
</tr>
<tr>
<td>90 percent response, s</td>
<td>257 ± 25</td>
<td>303 ± 45</td>
<td>300 ± 30</td>
<td>179 ± 27</td>
</tr>
</tbody>
</table>

*n* = 6 (three runs per subject).

RA = room air; 16% = F1O2 of 0.16; 40% = F1O2 of 0.40.
the rebreathing were 28.4 and 20.0 seconds, respectively.

**Hypoxia and Hyperoxia**

A summary of the response characteristics is listed in Table 1. Mean lag times varied between 9.7 and 31.1 seconds. The lag time for induction of hypoxia (31.1 seconds) was appreciably longer than the other conditions (9.7 to 12.8 seconds). The mean 50 percent response time varied between 60 and 116 seconds, with the longest time again associated with induction of hypoxia; however, the 90 percent response time for the induction of hypoxia was intermediate among response times for the various manipulations of \( \text{PO}_2 \). The shortest mean response times were associated with resumption of breathing room air from hyperoxia. The mean times for the transcutaneous signal to exceed maximum signal drift upon initiation of hyperoxia and hypoxia were 24.4 and 66.4 seconds, respectively.

**Comparison to Arterial Gas Tensions**

The \( \text{tcPCO}_2 \) was linearly related to \( \text{PaCO}_2 \) in the tested range of \( \text{PaCO}_2 \) (from 19 to 53 mm Hg, corresponding to a range in \( \text{tcPCO}_2 \) from 18 to 61 mm Hg). The regression relationship for pooled data from all subjects was described by the equation, 

\[
\text{tcPCO}_2 = 1.40 \times \text{PaCO}_2 - 9.44 
\]

\( r = 0.90; \ n = 20; \ \text{SEE} = 5.35 \) mm Hg. The relationships between \( \text{tcPCO}_2 \) and \( \text{PaCO}_2 \) also differed significantly among subjects (p<0.05). The mean ratio of \( \text{tcPCO}_2 \) to \( \text{PaCO}_2 \) for all measurements was 1.15, while the ratio for each subject ranged from 0.78 to 1.33 (Fig 2).

Values for \( \text{tcPO}_2 \) were linearly related to \( \text{PaO}_2 \) over the tested range of \( \text{PaO}_2 \) (from 45 to 99 mm Hg, corresponding to a range in \( \text{tcPO}_2 \) from 32 to 81 mm Hg). The regression relationship for pooled data from all subjects was described by the equation, 

\[
\text{tcPO}_2 = 0.56 \times \text{PaO}_2 + 20.4 
\]

\( r = 0.53; \ n = 20; \ \text{SEE} = 11.7 \) mm Hg. The relationships between \( \text{tcPO}_2 \) and \( \text{PaO}_2 \) differed significantly among subjects (p<0.05). The mean ratio of \( \text{tcPO}_2 \) to \( \text{PaO}_2 \) for all measurements was 0.84, while the ratio for each subject ranged from 0.5 to 1.05 (Fig 3).

**DISCUSSION**

In our previous experience with transcutaneous electrodes, we reported on the traumatizing effects on the skin, the fastidious care that was necessary in skin preparation, and the inaccuracies that arose when preparation was fastened or incomplete.3 By contrast, the system reported herein was simple to apply, took no longer than 10 minutes to obtain stable readings, and caused no skin trauma either from abrasion or heat in the period tested. As to the performance of the monitoring system, we found lag times under 15 seconds (except for induction of hypoxia, where lag time was 31 seconds) and, in general, 90 percent response times within 5 minutes. Ninety percent response time was shortest during recovery from hypercapnia but more closely approximated 50 percent response times during the hypoxia/hyperoxia studies; this may have been influenced by the different modes of presentation of inspired gas concentrations. There was little drift in signal under ambient conditions in normal subjects. Finally, the electrode was applied in a more realistic clinical scenario: ambulatory patients with stable respiratory disease. Although a linear relationship was found with respect to arterial blood gas levels, there was wide variability among subjects.

If noninvasive assessment of the adequacy of ventilation is to be of practical clinical value, gas tensions should be amenable to continuous monitoring with
the consequences of changes and trends in ventilation detected within a reasonable period of time. Earlobe and fingertip oximetry for arterial oxygen saturation has become routine in many settings, but readings are affected by peripheral perfusion and overestimate low oxygen saturation values. In conditions of hyperoxia, such as anesthesia, no useful quantitative information can be obtained. Furthermore, while oximeters display oxygenation trends, arterial puncture is required for a measure of PaCO2 and, hence, assessment of the adequacy of alveolar ventilation. Transconjunctival PO2 electrodes have been used in an attempt to overcome some of these limitations, but they are uncomfortable and have a variable relationship to PaO2 among individuals. End-tidal PCO2 measurements, while giving instantaneous continuous readings, do not reflect PaCO2 accurately in disease states where ventilation/perfusion mismatch disrupts the PaCO2/PaCO2 relationship. Transcutaneous gas tensions are problematic in that they reflect both arterial and tissue gas tensions and are affected by capillary blood flow, cardiac output, and metabolic processes. Skin temperature may also alter transcutaneous gas tensions; however, if the electrode is stabilized on the skin at a particular electrode temperature, the values are relatively independent of skin or body temperature elsewhere.

Transcutaneous devices use a Clark polarographic electrode to measure PO2 and a Severinghaus electrode to measure PCO2. The electrode investigated in this study combines a heating element, two temperature sensors, a Clark-type O2 electrode, and a Severinghaus-type CO2 electrode in a single unit. To enhance gas permeability, a local heat source is a ubiquitous feature of transcutaneous systems. Increased temperature vasodilates skin and thereby raises skin PO2 and lowers skin PCO2, while ongoing metabolism through the skin decreases tcPO2 and increases tcPCO2. Studies in subjects with thin skin (ie, neonates) have shown a high degree of accuracy with little variability. In adults, transcutaneous measurements of PO2 may show significant variability when compared to simultaneous arterial blood gas levels among individuals, while tcPCO2 electrodes seem to function more reliably.

The two electrodes we assessed clearly had different accuracies and response characteristics. The shorter response time for tcPCO2 as compared to tcPO2 seen in this study is consistent with work by others and is likely explained by hypercapnia-induced increases in cardiac output, capillary perfusion, and faster diffusion across cutaneous barriers. A 5-minute 90 percent response time in tcPO2 may be acceptable in nonlife-threatening situations, such as polysomnography, but is excessive in the management of the ventilated patient where a rapid response and appropriate alarms are mandatory. Even within polysomnography, attention should be drawn to the potential difficulties when attempting to correlate respiratory and electroencephalographic events recorded on paper moving at 10 to 25 mm/s with a transcutaneous signal appearing up to 5 minutes later.

In summary, our evaluation of this dual transcutaneous O2/CO2 monitoring system demonstrates that (1) the electrode is easy to apply, needs minimal skin preparation, and is comfortable to wear; (2) the tcPCO2 electrode responds more quickly to changes in arterial blood gas tensions and appears to have a more consistent linear relationship to arterial blood gas tensions than the tcPO2 electrode; (3) the response of the dual transcutaneous monitoring system is such that it may be useful in some clinical settings, such as perhaps polysomnography; and (4) the variability of the relationships between the arterial and transcutaneous measurements does not permit accurate estimation of arterial gas tensions in individuals. While the present combined electrode system offers some advantages over its predecessors in that it is a single unit, is easy to apply, and does not require extensive skin preparation, it fails to offer the response characteristics and accuracy in predicting arterial values that are mandatory in acute care settings.

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