PERFORMANCE OF TRANSCUTANEOUS $\text{PO}_2$ AND $\text{PCO}_2$ DUAL ELECTRODES IN ADULTS

C. LANIGAN, J. PONTE AND J. MOXHAM

Systems permitting the transcutaneous monitoring of blood-gas values are used widely in neonatal intensive care units. Improvements in electrode and monitor design, simplified calibration procedures and the arrival of the combined oxygen and carbon dioxide electrode [1] are likely to increase their use in operating theatres and adult intensive care units [2]. The ideal monitor should be easy to use and calibrate, accurately reflect changes in arterial blood-gas tensions, and have little drift of its own [3]. How good are current combined transcutaneous monitors? The earlier models of dual electrodes provided transcutaneous oxygen and carbon dioxide ($\text{Ptc} \text{O}_2$ and $\text{Ptc} \text{CO}_2$) values which were highly correlated with blood-gas tensions in infants [4]. Relatively few data on the performance of this type of device in adults exist to guide one's choice of presently available commercial systems.

SUBJECTS, MATERIALS AND METHODS

Methods

We evaluated three commercial dual electrodes (Microgas Combisensor, Kontron Ltd; Novametrix 850 Commonsensor, Vickers Medical Ltd; and Radiometer E5270 electrode, V.A. Howe Ltd) in normal adults as follows: (A) an in vitro assessment of the response times and stability of the electrodes; (B) an in vivo assessment of response times, accuracy and drift of the dual electrodes compared with end-tidal gas concentrations.

Twelve non-smoking healthy adults (7 male; ages 23–48 yr) recruited from both Departments following informed consent, took part in the investigation, which had the approval of the hospital Ethics Committee. Each electrode was used within 5 days of being remembraned, and was given a 2-point dry gas calibration at 45 °C before use according to manufacturers' instructions, which allowed for barometric pressure and the "gas/skin ratio". Electrodes were exposed to a certified gas calibration standard (5% carbon dioxide + 12% oxygen + 83% nitrogen, Corning Medical Ltd) before and after each study; we defined a "calibration shift" as the difference between these two in vitro readings. The electrodes were fixed to the skin over the biceps using double-sided adhesive rings, after the skin was cleaned with alcohol, rubbed until red, and contact liquid applied. The electrodes were operated at 45 °C and allowed to stabilize for 30 min before recordings were made. Arterial blood-gas

SUMMARY

Three commercially-available combined $\text{PO}_2$–$\text{PCO}_2$ electrodes were assessed in vitro, and in adults breathing air, hypoxic and hypercapnic mixtures, for speed of response, correlation with end-tidal gas tensions and drift. Differences in the 90% response time of the individual electrodes were more marked in vitro than in vivo. Changes in end-tidal gas tensions were reflected by proportionate changes in transcutaneous oxygen and carbon dioxide ($\text{Ptc} \text{O}_2$ and $\text{Ptc} \text{CO}_2$) but, in the individual subject, $\text{Ptc} \text{O}_2$ and $\text{Ptc} \text{CO}_2$ were generally poor indicators of the end-tidal values. During steady-state recordings, the $\text{Ptc} \text{O}_2$ signal drifted upwards by more than 12 mm Hg during 140 min in vivo recording in all three electrodes, without changes in either $\text{Ptc} \text{CO}_2$ or end-tidal values. The dual electrodes tested provide non-invasive estimates of qualitative, but not quantitative, change in blood-gas tensions and are likely to have only a limited role to play in adult anaesthetic practice.
values were estimated by averaging peak and trough end-tidal concentrations (\(P_{\text{E}}CO_2\) and \(P_{\text{E}}O_2\)) over 2 min [5] in expired gas sampled through a fine-bore tube taped to the nose or mouthpiece. The use of end-tidal gas avoided the hazards of arterial cannulation, yet provided values which closely reflect arterial blood-gas tensions in normal subjects [5, 6]. Gas concentrations were measured by a quadrupole mass spectrometer (MGA 2000, Airspec Ltd, drift < 0.1% per hour), previously calibrated using room air and a certified gas mixture as for the electrodes, and correcting for barometric pressure; the arterio-alveolar difference for oxygen was assumed to be 5 mm Hg breathing 21% oxygen and 0 mm Hg breathing hypoxic gases. The analogue outputs from the monitors and mass spectrometer were displayed on a six-channel recorder (Linear Chartrecorder Ltd) with a paper speed of 5–25 mm min\(^{-1}\).

**Procedures**

**In vitro studies.** The three electrodes were mounted on a template and allowed to stabilize in room air before rapid insertion into a 100-ml pot receiving a constant flow of the gas calibration standard. Once readings were stable (< 3 min), the electrodes were rapidly removed and re-exposed to air. The procedure was repeated six times. We defined the lag time as the time interval (s) between changing the gas tensions and the first detection of that change by the electrodes, and the 90 % response time (90 % RT) as the time interval (s) between detecting and reaching 90% of the change in partial pressure caused by the step change in gas tension [7]. Before and after each in vivo study, each electrode was placed in a cuvette, perfused with the certified gas mixture, and allowed to reach a steady-state reading for estimation of the calibration shift.

**In vivo studies.** The subjects were seated comfortably on a couch breathing air or, on separate days, hypoxic or hypercapnic mixtures through a two-way valve from a 250-litre Douglas bag. Steady state values for \(P_{\text{tc}} CO_2\), \(P_{\text{tc}} O_2\), \(P_{\text{E}} CO_2\), and \(P_{\text{E}} O_2\) were averaged over 2 min in 12 subjects breathing air, eight breathing a hypoxic mixture for 12 min (mean inspired oxygen = 12.8%, range 11.8–13.5%) and eight breathing a hypercapnic mixture for 8 min (mean inspired carbon dioxide = 5.9%, range 4.2–6.7%). The lag and 90 % response time were recorded, as previously defined. On a separate occasion, 30 min after applying the electrodes, in vivo drift (\(= in \text{vivo}\) change from baseline values with time) was calculated by averaging transcutaneous and end-tidal values over 4 min at eight consecutive 20-min intervals in six resting subjects breathing air (total time 2.5 h).

**Analysis**

The relationship between transcutaneous and end-tidal values was assessed using least squares regression equations and calculating the correlation coefficients for each electrode. To minimize bias, we analysed only one pair of measurements in each subject from each steady-state condition, and at set time intervals unknown to the subjects. In addition, the average difference between the two measurements and the 95 % confidence limits for that difference were calculated and plotted against the average measurement of oxygen and carbon dioxide [8, 9]. Finally, differences between electrodes were assessed using the paired Wilcoxon signed rank test with a statistical significance value of \(P < 0.05\).

**RESULTS**

**In vitro studies**

The lag and 90 % response times for the three dual electrodes were greater for carbon dioxide than for oxygen (table I). Changes in oxygen were detected most rapidly by the Novametrix electrode—the 90 % response time was two to three times shorter than with the other electrodes (\(P < 0.01\)). A reduction in carbon dioxide tension was most rapidly detected by the Radiometer electrode, while an increase in carbon dioxide was more rapidly detected by the Novametrix electrode. The Kontron electrode was the slowest to detect changes in all situations. There were minimal calibration shifts for the three electrodes following the in vivo studies: Kontron +2.7 (3.3), Radiometer +1.8 (2.8), and Novametrix −0.2 (2.3) for oxygen, and −0.67 (1.0), −0.2 (0.8), and +1.0 (2.5) for carbon dioxide (mean values (SD) in mm Hg), respectively.

**In vivo studies**

The lag and 90 % response times were much greater in vivo than in vitro, and the 90 % response times were greater for oxygen than for carbon dioxide (table II). Lag times ranged from 23 to 36 s for changes in oxygen, and from 31 to 56 s for carbon dioxide. In all instances, 90 % response
TABLE I. In vitro response to changes in blood-gas tensions (mean ± 1 SD; n = 6). RT = Response time

<table>
<thead>
<tr>
<th>Electrode</th>
<th>Oxygen Change from 21 to 12%</th>
<th>Oxygen Change from 12 to 21%</th>
<th>Carbon dioxide Change from 5 to 0%</th>
<th>Carbon dioxide Change from 0 to 5%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lag (s) 90% RT (s)</td>
<td>Lag (s) 90% RT (s)</td>
<td>Lag (s) 90% RT (s)</td>
<td>Lag (s) 90% RT (s)</td>
</tr>
<tr>
<td>Novametrix</td>
<td>1.9 ± 0.8</td>
<td>8.8 ± 3.2</td>
<td>0.9 ± 0.1</td>
<td>27.9 ± 2.7</td>
</tr>
<tr>
<td>Radiometer</td>
<td>3.2 ± 0.7</td>
<td>2.2 ± 0.2</td>
<td>3.0 ± 0.5</td>
<td>15.8 ± 2.3</td>
</tr>
<tr>
<td>Kontron</td>
<td>4.2 ± 0.4</td>
<td>20.3 ± 5.2</td>
<td>3.5 ± 0.7</td>
<td>16.7 ± 0.6</td>
</tr>
</tbody>
</table>

times were faster for carbon dioxide than for oxygen: 58–160 s compared with 261–317 s. Finally, differences in 90% response time between the dual electrodes were more variable and less marked in vivo than in vitro. The lag time between a change in the inspired mixture and a change in the end-tidal value was 5–7 s (or one breath interval) for both $P_{te}O_2$ and $P_{te}CO_2$. End-tidal gases stabilized at the new value within 300 s.

$P_{tc}O_2$ was closely correlated with $P_{te}O_2$ for all three electrodes, but underestimated $P_{te}O_2$ by an average of 8.9–11.4 mm Hg (table III). However, the $P_{tc}O_2$ value recorded by the three electrodes was highly variable in any one individual; while the 95% confidence intervals for the average difference between $P_{tc}O_2$ and $P_{te}O_2$ recorded by any one electrode using group data were −15 to +33 mm Hg at best. In contrast, $P_{tc}CO_2$ values were much closer to $P_{te}CO_2$; the Kontron electrode recorded values which, 19 times out of 20, were between −5.6 to +4.7 mm Hg of the observed $P_{te}CO_2$ value. The results for the other two electrodes were less good, but in keeping with other reports [10]. $P_{te}O_2$ and $P_{te}CO_2$ remained stable during the in vivo drift study: baseline values (in mm Hg and with SD in brackets) were 99 (4.8) and 41 (4.0) for oxygen and carbon dioxide, respectively, with maximum 4-min average changes during the study of −2.0 to +3.5 mm Hg for oxygen and −2.0 to +1.0 mm Hg for carbon dioxide. However, $P_{tc}CO_2$ values increased significantly in all three electrodes ($P < 0.01$), reaching a plateau between 100 and 120 min for the Novametrix and Radiometer electrodes (fig. 1). These increases were present despite an initial stabilization period.

TABLE III. The relationship and differences between transcutaneous and end-tidal values. n = number of paired samples; a, b = intercept and slope for regression equation where $P_{tc}O_2 = a + b (P_{te}O_2) \text{ mm Hg}$; r = correlation coefficient, $P < 0.001$; d = mean difference = $P_{te}O_2 - P_{tc}O_2 \text{ mm Hg}$; $d + 2s = 95\%$ confidence intervals for the mean difference; **$P < 0.02$

<table>
<thead>
<tr>
<th>Electrode</th>
<th>Oxygen</th>
<th>Carbon dioxide</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n</td>
<td>a</td>
</tr>
<tr>
<td>Novametrix</td>
<td>26</td>
<td>13.4</td>
</tr>
<tr>
<td>Kontron</td>
<td>27</td>
<td>−11.3</td>
</tr>
<tr>
<td>Radiometer</td>
<td>25</td>
<td>−14.0</td>
</tr>
</tbody>
</table>
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Fig. 1. Steady-state end-tidal (■/■) and transcutaneous values for oxygen and carbon dioxide. Mean values for six adults. Bars represent SEM. Open symbols = oxygen; closed symbols = carbon dioxide.

Novametrix = ○/○; Radiometer = △/△; Kontron = ○/○.

of 30 min, and were not accounted for by *in vitro* calibration shifts of the electrodes. In contrast, \(P_{tco_2}\) remained fairly stable during the study (Fig. 1).

All subjects reported mild redness of the skin for at least 24 h following the studies. From a total of 66 electrode applications, only one application caused a significant skin burn, with blistering and scarring over a 0.5-cm² area.

**DISCUSSION**

Combined sensors to measure \(P_{a_o_2}\) and \(P_{a_c_o_2}\) were described first in 1979 [1, 11], but the production of hydroxyl ions at the oxygen electrode affected the stability of the \(P_{c_o_2}\) reading [10]. Changes in the design of the electrode and the use of different electrolyte solutions have improved their performance [10, 12]. Using single electrodes, the greater differences between \(P_{tco_2}\) and \(P_{a_o_2}\) recorded in adults, compared within infants, have been explained by differences in electrode methodology [13], skin thickness [14], skin metabolism [15], cardiac output and peripheral perfusion [16].

*Estimation of \(P_{a_o_2}\) from \(P_{tco_2}\)*

Transcutaneous gas tensions are not simply non-invasive measures of arterial gas tensions, but also reflect cardiac output [17], local skin metabolism [15] and capillary blood flow [16]. Nevertheless, under stable haemodynamic conditions, transcutaneous gas tensions are widely used as trend monitors of arterial blood-gas tensions [18]. Differences between the two sets of tensions have been reduced by better electrode design and empirical readjustment of the *in vitro* calibration settings [19]. However, the differences between \(P_{tco_2}\) and \(P_{a_o_2}\) cannot be eliminated entirely, because of the nature of the technique [20]. The underestimation of \(P_{e_o_2}\) by the three dual electrodes is unlikely to be the result of an overestimation of the true \(P_{a_o_2}\) by \(P_{e_o_2}\), and is in keeping with reports using single [18, 20, 21] and dual electrodes in adults [22]. Indeed, the mean difference between age-predicted \(P_{a_o_2}\) [23] and observed \(P_{e_o_2}\) was only 3.2 mm Hg. In contrast, the range of the difference between \(P_{tco_2}\) and \(P_{e_o_2}\) in the individual was considerable: consequently, \(P_{tco_2}\) should not be used alone to estimate \(P_{a_o_2}\) in the adult [20]. Nevertheless, large
changes in \( PtcO_2 \) over the range 42–145 mm Hg were invariably detected by all three electrodes.

**Estimation of \( PaCO_2 \) from \( PtcCO_2 \)**

\( PtcCO_2 \) will overestimate \( PaCO_2 \) in adults [24] despite excellent correlation between the two, because the final \( PtcCO_2 \) value is dependent on: (1) the carbon dioxide content of capillary blood; (2) the solubility of carbon dioxide in plasma; (3) the increased metabolism and shift of the carboxyhaemoglobin curve produced by the heating electrode; (4) cooling of the pH-sensitive glass electrode by the skin [25]. These factors combined to give a \( PtcCO_2 \) reading which was higher than \( PaCO_2 \) values [26], but could be corrected by adjusting the \textit{in vitro} calibration settings [24, 27]. Our results indicate that dual electrodes produce \( PtcCO_2 \) readings which closely reflect \( PteCO_2 \) values under steady state conditions.

**In vivo response times**

The \textit{in vivo} response time of the transcutaneous electrodes was more than one order of magnitude slower than the \textit{in vitro} responses, which suggests that, in practice, the former depends almost entirely on local perfusion factors. Faster response times are seen with higher electrode operating temperatures [28, 29] but, in general, this subject has received relatively little attention [7, 30]. A sudden change of inspired gases is the nearest approximation to a step change in partial pressures in capillary blood-gas tensions for testing the response time of the electrodes [31]. Rapid occlusion of the arterial blood supply to the arm is an alternative which likewise produces a ramp rather than a step change [7]. Neither technique indicates how quickly the sensor can detect a sudden change in arterial blood-gas tensions alone, but the former more closely simulates how quickly anaesthetic mishaps can be detected.

An interesting finding, previously noted by other workers [7], was that a change from air to hypoxia was more rapidly detected than a change from hypoxia to air. This may reflect changes in ventilation and cardiac output—variables which were not assessed in this study. In part, the shorter response times for carbon dioxide compared with oxygen can be attributed to increased capillary perfusion, cardiac output and minute ventilation caused by hypercapnia, and the more rapid diffusion of carbon dioxide across the skin. Nevertheless, these results indicate that, in adults, sudden changes in either \( PaCO_2 \) or \( PaO_2 \) are unlikely to be fully recorded using transcutaneous dual electrodes until 3–5 min has elapsed. The \textit{in vivo} response time of the electrodes should be considered when alarm limits for these monitors are being set by the operator.

**\( PtcO_2 \) drift**

Drift is analogous to very low frequency "noise" and, in our study, implies change in measurement over the course of hours without a corresponding change in "signal". It is only of interest in the long-term estimation of \( PaO_2 \) and \( PaCO_2 \) from transcutaneous tensions. The \textit{in vitro} drift of a dual electrode is influenced by the electrode design, the electrode membrane and the electrolyte composition [10] and is usually less than 1 \% h\(^{-1}\). Calibration shifts reported in clinical studies may be much greater than \textit{in vitro} drift values [29], being influenced by both the application and removal procedure of the electrode at the measuring site [32]. In our study, the calibration shifts were very small, which makes it difficult to attribute the recorded upward trend in \( PtcO_2 \) to the electrode itself. Assuming that blood-gas tensions vary little at rest [33], that variations should occur randomly over time, and that variations in blood-gas tensions are detected by end-tidal measurement, the observed upward trend in \( PtcO_2 \) must be the result of a change at the skin measurement site. This is supported by the finding that the change was not matched by a corresponding change in \( PtcCO_2 \). Increases in local capillary perfusion [20] and decreases in local tissue oxygen consumption as a result of thermal injury [15] would affect \( PtcO_2 \) more than \( PtcCO_2 \), and might explain the results. However, the prerequisite for \( PtcO_2 \) measurement is indeed a "limited" thermal injury—that is, heat-induced hyperaemia—and the electrode temperature used is a compromise between producing sufficient hyperaemia and avoiding burning [34].

Systems based on transcutaneous dual electrodes are expensive, but presently available cheaper alternatives also have problems. Pulse oximeters are not accurate indicators of normal or high \( PaO_2 \) values, and end-tidal gas monitors are inaccurate in many patients with lung disease. Transcutaneous monitoring does reflect large changes in arterial gas tensions at all values of inspired oxygen and carbon dioxide and their sensitivity to changes in cardiac output and local capillary perfusion is clinically useful if correctly interpreted. There was little to choose between
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the three dual electrodes tested based on their in vivo performance, despite considerable differences in price and in in vitro response times. The current models have a limited role to play in adult anaesthetic practice, because of long initial stabilisation periods, the need to resite the electrode every 4 h, and their slow response times. Future models are less likely to cause significant thermal injury, may have shorter response times, and some will incorporate two oxygen electrodes, allowing continuous use without resiting for up to 12 h [35].

ACKNOWLEDGEMENTS

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REFERENCES


