Transcutaneous and Capillary $p_{CO_2}$ and $p_{O_2}$ Measurements in Healthy Adults

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Transcutaneous carbon dioxide and oxygen tensions (tc-$p_{CO_2}$ and tc-$p_{O_2}$) were measured in seven healthy adult volunteers during hyperventilation in atmospheric air and during CO$_2$ inhalation. Three skin sensors were applied to each subject: an O$_2$ electrode, a CO$_2$ electrode, and a combined O$_2$–CO$_2$ electrode, each heated to 44°C. We observed close correlation between tc-$p_{CO_2}$ and capillary-$p_{CO_2}$, the relation being close to that calculated from the anaerobic temperature coefficient of $p_{CO_2}$ in blood. For O$_2$, on the other hand, the relationship between transcutaneous and capillary values appeared more complex. Electrode drift during in-vivo monitoring was greater for tc-$p_{O_2}$ (up to 12%) than for $p_{O_2}$ (up to 7%), but generally we observed no differences in drift between the combined and the single electrodes. We conclude that tc-$p_{CO_2}$ measured with a single or a combined electrode reliably predicts capillary-$p_{CO_2}$ in healthy adults and that changes are rapidly observed. Our conclusions regarding tc-$p_{O_2}$ values are less definite because of uncertain interpretation of the capillary-$p_{O_2}$ values.

Additional Keyphrases: blood gases • electrodes

Transcutaneous oxygen electrodes are now widely used as an indicator of arterial $p_{O_2}$ in newborn infants with respiratory insufficiency (1–4). In adults, however, transcutaneous $p_{O_2}$ is more dependent on the cutaneous oxygen consumption and blood flow, resulting in a more complex relationship between transcutaneous and arterial $p_{O_2}$ (5, 6). The recently introduced transcutaneous carbon dioxide electrodes show a good correlation of tc-$p_{CO_2}$ with arterial $p_{CO_2}$ in sick neonates (7–9) although their use in adult monitoring is less clear (10, 11). The future will show whether clinical chemists will, as has been proposed (12), play an active role in establishing performance standards for transcutaneous monitoring.

The purpose of this study was to evaluate the use of transcutaneous CO$_2$ and O$_2$ electrodes at 44°C in healthy adults over a wide range of $p_{CO_2}$ values. Arterialized capillary blood was used as the reference value, many studies having shown concordance between capillary and arterial blood with respect to $p_{CO_2}$, though not always for $p_{O_2}$ (13).

Materials and Methods

Subjects. The seven healthy volunteers were five men and two women, ages 23 to 32 years.

Transcutaneous electrodes. Transcutaneous $p_{O_2}$ and $p_{CO_2}$ (tc-$p_{O_2}$ and tc-$p_{CO_2}$) were measured with both a commercially available system (electrodes E 5242 and E 5230, monitor TCM 222; Radiometer, Copenhagen, Denmark) and a combined O$_2$–CO$_2$ prototype electrode (E 5270, Radiometer). The oxygen sensor of the prototype electrode was covered with two overlapping membranes (12-μm-thick Teflon and 15-μm-thick polypropylene), whereas the carbon dioxide sensor was covered with only the Teflon membrane. The $CO_2$ electrodes were calibrated in two unhumidified gas mixtures (CO$_2$, 50 and 100 mL/L), and the O$_2$ electrodes in either ambient air or in an unhumidified gas mixture (O$_2$, 100 mL/L). Electrode calibrations and measurements were made at 44°C, with simultaneous calibrations of the combined electrode for $p_{CO_2}$ and $p_{O_2}$. The electrodes were attached to the skin of the upper thorax by self-adhesive rings.

To document electrode drift, we recorded the electrode readings for the calibration gases at the end of each study.

Procedure. After a 30-min rest period, the subjects hyperventilated in ambient air for 10 min. After a further resting period of 20 min, the subjects inhaled a CO$_2$/ambient air mixture (10/90 by vol); in two subjects the ambient air in the mixture was replaced with oxygen. When the transcutaneous electrodes had stabilized, we collected samples of arterialized capillary blood from the ear lobe anaerobically into heparinized glass capillary tubes at intervals of 5 to 20 min, collecting five to seven blood samples from each subject over a period of about 2 h. The samples were immediately placed on ice and then analyzed for $p_{O_2}$, $p_{CO_2}$, and pH (ABL-2, Radiometer) within 30 min of collection.

Results

Hyperventilating for 10 min produced a marked decrease in both tc- and capillary (cap)-$p_{CO_2}$ with clinical tetany (Figure 1). Values for tc- and cap-$p_{O_2}$, after a brief initial increase, decreased to a minimum during the following rest period, when the subjects tended to hyperventilate. Both $p_{O_2}$ and $p_{CO_2}$ increased during the subsequent CO$_2$ inhalation (Figure 1).

For both the conventional and the prototype combined electrode, the close correlation between tc-$p_{CO_2}$ and cap-$p_{CO_2}$ (Figure 2) was excellent, much better than between tc- and cap-$p_{O_2}$ (Figure 3).

In all subjects the transcutaneous electrode values for $p_{O_2}$ and $p_{CO_2}$ responded within 5 to 10 s of starting either hyperventilation or CO$_2$ inhalation (see Figure 1 for an example). Furthermore, capillary samples taken during short changes in $p_{O_2}$ and $p_{CO_2}$ did not reflect any delay in detection of these changes.

The time taken to stabilize after electrode application to the subjects was generally shorter for tc-$p_{O_2}$ than tc-$p_{CO_2}$. In all cases tc-$p_{CO_2}$ stabilized more quickly with the prototype combined electrode than with the conventional single electrode (mean, 11 vs 20 min). The electrode drift recorded after each period of in-vivo monitoring was in general greater for $p_{CO_2}$ (0–12%) than for $p_{O_2}$ (0–7%). On one occasion the combined electrode showed an inexplicably large drift of −27% for $p_{CO_2}$ and +13% for $p_{O_2}$, but there was otherwise no difference in electrode drift between the conventional single electrodes and the combined electrode. Electrode drift was greater for samples taken with skin application than in calibration gases.

Discussion

Relation between tc-$p_{CO_2}$ and cap-$p_{CO_2}$. Tc-$p_{CO_2}$ values are higher than the corresponding capillary and arterial values (7–11, 14), a phenomenon that continues to be misinterpret-
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Thus blood at 37°C was measured. The measured value in this study of 1.46 with the single electrode (Figure 2, left). The higher value of 1.51 measured with the combined electrode (Figure 2, right) is, however, significantly different (p < .02) from 1.40.

The combined electrode measured significantly higher pCO₂ values than the single conventional electrode (Δ = 0.76 kPa, s₂ = 0.54 kPa, p < .001). This finding is unexplained.

Correction of the measured tc-pCO₂ values in this study to 37°C by using the coefficient (pCO₂)44/(pCO₂)37 = 1.403 gives the following linear regression equations:

single electrode: tc-pCO₂ = 1.04 · cap-pCO₂ + 0.15
combined electrode: tc-pCO₂ = 1.07 · cap-pCO₂ + 0.51

Although close to the line of identity, the corrected tc-pCO₂ values are still marginally but statistically significantly higher (p < .001) than the corresponding capillary values. Possible reasons for this could be CO₂ production in the skin, or loss of CO₂ from the capillary samples.
In attempts to clarify further the influence of electrode temperature on the measured tc-value, we currently measure tc-pCO₂ at different electrode temperatures (ranging from 37 to 45 °C) simultaneously in the same subject. Until more definitive data are available, we consider that much of the confusion experienced by clinicians could be avoided if manufacturers of tc-pCO₂ monitors provided an optional facility for the automatic correction of the measured tc-pCO₂ to a temperature of 37 °C, using the anaerobic temperature coefficient of pCO₂ in blood (15).

Relation between tc-pO₂ and cap-pO₂. The poorer correlation between tc-pO₂ and cap-pO₂ was not unexpected (6). Capillary samples may not have been fully arterialized and would tend to have lower pO₂ values than the corresponding arterial samples. We found, however, that for 45 paired measurements the two tc-pO₂ electrodes measured approximately the same values (Δ = 0.48 kPa, sΔ = 1.92 kPa, p > .10). Transcutaneous values, however, are known to be determined not only by the arterial pO₂ but also by skin oxygen consumption and blood flow (5). The blood flow will have been particularly variable in this study, because of the large changes in pCO₂.

Combined vs single electrodes. The prototype combined transcutaneous electrode offered the same high degree of correlation with cap-pCO₂ as the conventional single electrode, but the tc-pCO₂ values were higher with the combined electrode. The tc-pO₂ values were the same for either electrode. Except in one case, electrode drift was no greater with the combined electrode, and stabilization time was shorter.

Use of the combined electrode may therefore be advantageous in some instances, e.g., where the available skin area is limited, as in infants.

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References