Estimation of arterial oxygen and carbon dioxide tensions by a single transcutaneous sensor

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SUMMARY A transcutaneous electrochemical sensor designed to estimate arterial oxygen (PaO_2) and carbon dioxide (PaCO_2) tensions simultaneously and continuously was evaluated in newborn infants with respiratory illnesses. After calibration with two dry gas mixtures the sensor gave estimates of PaO_2 and PaCO_2 that were comparable with those obtained by two separate electrodes that are already established in clinical use.

Estimation of arterial oxygen (PaO_2) and carbon dioxide (PaCO_2) tensions by transcutaneous (tc PO_2 and tc PCO_2) electrodes is a valuable technique for the management of sick newborn infants. The use of two separate electrodes, however, is time consuming, may require two sets of apparatus, and can be difficult in a very small infant with a limited amount of available skin.

We have previously shown that tc PO_2 and tc PCO_2 could be measured simultaneously by a prototype combined electrochemical sensor, but the scatter of results, when compared with arterial blood samples, was quite large, and in vivo calibration was required for clinical use.¹ This sensor has now undergone further development. We report here an evaluation of its accuracy after in vitro calibration.

Methods

Infants studied. Thirty studies were performed on 19 infants (six girls and 13 boys) with respiratory illnesses. The infants were born at 25 to 35 (mean 29) weeks of gestation weighing 849 to 2560 g (mean 1348 g). They were 6 to 139 (median 41) hours old at the start of the studies. Mechanical ventilation was in use during 26 studies and continuous positive airways pressure during one. For arterial blood sampling, an umbilical artery catheter was used in 25 studies, a cannula in the left radial artery in three, and on one occasion each, a cannula in the right radial artery or the left posterior tibial artery. Arterial blood pressure was always within the normal range and mean rectal temperature was 36.9°C (range 36.6 to 37.5°C).

The sensor. The combined sensor was constructed as described by Parker *et al*² with minor modifications. The electrolyte was 80% ethylene glycol and 20% water containing 0.1 mol/l KHCO_3 and 0.1 mol/l NaCl. The membrane was made of 25 μm -thick Teflon. The time constant (63% response time) of the sensor in vitro after a step change in ambient PO_2 was 8 seconds and for PCO_2 , 18 seconds. Mean drift of the tc PO_2 channel during 24 hours at a constant PO_2 of 12 kPa and of the tc PCO_2 channel at a PCO_2 of 5 kPa were both less than 0.02 kPa/hour.

Procedure. The sensor was heated to 44.0°C and calibrated in vitro with two certified dry gas mixtures, one containing 12% O_2 and 5% CO_2 , and the other 0% O_2 and 10% CO_2 . An appropriate allowance for barometric pressure was made. The sensor was then attached to the infant's skin with an adhesive ring. Abdominal skin was chosen when arterial sampling was from the umbilical or posterior tibial arteries, and the skin of the upper chest on the same side as the cannula when a radial artery was used. The outputs of the tc PO_2 and tc PCO_2 channels were displayed on a multichannel recorder (Fig. 1). For comparison, tc PO_2 and tc PCO_2 were also recorded from skin adjacent to the combined sensor by two separate skin electrodes, a Dräger tc PO_2 electrode (Drägerwerk, West Germany) and a Roche tc PCO_2 electrode (Hoffman-La Roche, Switzerland), both of which have previously been shown to give satisfactory estimates of PaO_2 and PaCO_2 in infants.^{3,4} Recordings were continued for between 4.0 and 4.5 hours (mean 4.15 hours). To determine the relation between transcutaneous and

Fig. 1 Transcutaneous P_{O_2} and tcP_{CO_2} recorded continuously by the combined sensor and the separate Dräger tcP_{O_2} and Roche tcP_{CO_2} electrodes.

The records should be read from right to left. Two blood samples were taken for measurement of P_{aO_2} and P_{aCO_2} as indicated by the arrows at either end of the records. These arrows also show the intervals between the chart-recorder pens. The infant weighed 1574 g at 32 weeks of gestation. He was 122 hours old at the time of the study and was being treated by intermittent mandatory ventilation with 30% oxygen for hyaline membrane disease.

arterial P_{O_2} and P_{CO_2} , three samples of arterial blood were taken during each study, when the records were stable, at a mean of 0.8 (range 0.4 to 1.6), 2.4 (1.8 to 3.3), and 3.8 (3.3 to 4.4) hours after the start of the studies. Measurements of P_{aO_2} were made with an Instrumentation Laboratories 1303 blood gas analyser, the accuracy of which was confirmed with tonometered blood. After removal of the transcutaneous electrodes, the state of the skin was documented daily until the residual red marks had disappeared.

Results

Figure 2 shows the relation between tcP_{O_2} and P_{aO_2} , and tcP_{CO_2} and P_{aCO_2} . Data for the combined sensor are given in Figs. 2(a) and (b), and for the separate electrodes in Figs. 2(c) and (d). The regression equations for transcutaneous on arterial values, calculated by the method of least squares, are given in the legend. Figure 3 shows tcP_{O_2}/P_{aO_2} and tcP_{CO_2}/P_{aCO_2} during the studies, derived from the data points closest to each half hour interval.

The red marks present on removal of the combined transcutaneous sensor were similar in appearance to those left by the separate electrodes: they disappeared within 1 to 5 (mean 3) days.

Comment

Figures 2 and 3 show that after in vitro calibration, tcP_{O_2} and tcP_{CO_2} recorded by the combined sensor gave estimates of P_{aO_2} and P_{aCO_2} that were almost as accurate as those provided by the separate electrodes. No deterioration in accuracy occurred during the four hours for which the studies were continued (Fig. 3). The overestimate of P_{aCO_2} by tcP_{CO_2} (Figs. 2(b), 2(d), and 3) was as expected on theoretical grounds.^{5,6} For clinical use, correction for this overestimate is required. Severinghaus has argued that in order to derive the most suitable correction factors, an intercept of 0.5 kPa on the tcP_{CO_2} axis can be assumed.^{5,6} Applying this approach to our data reduced the slope of tcP_{CO_2} on P_{aCO_2} for the combined sensor from 1.65 to 1.33, and for the Roche electrode from 1.62 to 1.32 (Fig.

Fig. 2 Relation between transcutaneous and arterial PO_2 and PCO_2 .

For the combined sensor (a) and (b), $tcPO_2 = 0.80 PaO_2 + 1.89$ kPa (SE of line = 1.10 kPa, $r = 0.87$); $tcPCO_2 = 1.65 PaCO_2 - 1.63$ kPa (SE = 1.34, $r = 0.90$). For the Dräger $tcPO_2$ electrode (c), $tcPO_2 = 0.80 PaO_2 + 2.41$ kPa (SE = 0.80, $r = 0.93$) and for the Roche $tcPCO_2$ electrode (d), $tcPCO_2 = 1.62 PaCO_2 - 1.50$ kPa (SE = 0.71, $r = 0.96$). The interrupted lines show the regressions calculated assuming a $tcPCO_2$ intercept of 0.5 kPa (see text). For all regressions, $P < 0.001$.

2(b) and (d). These values are very similar to those quoted for $tcPCO_2$ electrodes in general by Hazinski and Severinghaus.⁶ The data obtained in this study do not, however, show any advantage of assuming an intercept. Until more information is available, we think that estimation of $PaCO_2$ by the $tcPCO_2$ channel of the combined sensor will best be done by incorporating the indices of the regression equation into the calibration procedure without making an assumption about the position of the intercept.

Provided due care is taken with the interpretation of the results (as for any transcutaneous electrode) we suggest that the combined sensor is a suitable instrument for estimating PaO_2 and $PaCO_2$ continuously in infants.

Fig. 3 Transcutaneous PO_2/PaO_2 (a) and $tcPCO_2/PaCO_2$ (b).

Data points closest to each half-hour interval are shown ($\pm$ SE, $n = 4-15$, mean = 10). Closed circles = combined sensor, open circles = Dräger electrode (a), and Roche electrode (b).

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