Transcutaneous \( p_{CO_2} \) electrode response time was optimized by use of a new electrode composed of NaCl/NaHCO\(_3\) electrolyte buffer (100 and 20 mmol/L, respectively) in an equimolar mixture of glycerol and water. The 95% response time to a step change in \( p_{CO_2} \) was 49.9 ± 2.8 s (\( \bar{x} \pm SD \)) when there was no spacer between the membrane and glass of the electrode. Use of this filling solution during monitoring of severely ill premature infants with cardiopulmonary disease allowed identification of large, unpredictable transient changes in transcutaneous \( p_{CO_2} \), and therefore presumably in arterial \( p_{CO_2} \), that occurred during capillary blood gas sampling. The changes, which occurred in 19 of 20 samplings, ranged from -1.06 to +2.53 kPa (−8 to +19 Torr). The maximum relative change observed was +29%. These results indicate that the standard protocol for capillary blood collection induces significant transient fluctuations in blood gas tensions. We believe these fluctuations decrease the reliability of capillary \( p_{CO_2} \) values for use in clinical management in patient populations similar to ours.

**Additional Keyphrases:** newborns · premature infants · cardiopulmonary disease

Capillary blood \( p_{CO_2} \) correlates poorly with arterial blood \( p_{CO_2} \) in very young full-term infants (1). Infants with impaired cardiopulmonary function show poor correlation irrespective of age (2). The correlation may worsen because of crying during skin lancing (1), respiratory rate changes during the sampling period (3), or lack of adherence to technical prerequisites, e.g., hyperemization (2-4). We formulated an innocuous electrolyte-buffer filling solution for transcutaneous \( p_{CO_2} \) electrodes. This new solution facilitates optimization of electrode response time, and has allowed us clearly to identify unpredictable transient changes in transcutaneous \( p_{CO_2} \) resulting from capillary blood gas determinations.

**Methods and Materials**

We obtained transcutaneous \( p_{CO_2} \) measurements with a TCM10 carbon dioxide monitor and matching electrodes for the TCM10 system (Radiometer America Inc., Cleveland, OH 44145). For two-point calibration we used a Radiometer TCM102 tonometer unit and a GMA2 precision gas supply. CO\(_2\) contents of the calibrating gases were 5.61 vol/100 vol (about 40 Torr) and 11.22 vol/100 vol (about 80 Torr). To test electrode linearity, we used a Model 192 precision gas mixer (Corning Glass Works, Medfield, MA 02052). A dual-pen Omniscrbe (Houston Instruments, Austin, TX 78753) recorder was used for chart tracings. Electrode and tonometer calibration temperature settings were 44 °C in all studies. We determined in vitro response time from several chart tracings by measuring the time required for the electrodes to achieve 63, 90, and 95% of the final \( p_{CO_2} \) value during identical step changes (about 80 Torr) in ambient \( CO_2 \) tension. Mean response curves for each of three electrodes were averaged.

We chose glycerol for use in the electrode filling solution because it not only inhibits bubble formation and is safe, but also has excellent compatibility with the electrolyte buffer and is bacteriostatic. Aqueous glycerol solutions, ranging from 0 to 800 mL of glycerol per liter, were evaluated. The electrolyte buffers tested were NaCl/NaHCO\(_3\) (100 and 20 mmol/L, respectively) and KCl/KHCO\(_3\) (100 mmol/L each). We did in vitro studies, both with and without a 50-µm nylon mesh spacer between the pH-sensitive glass of the transcutaneous \( p_{CO_2} \) electrode and the 12-µm Teflon membrane (Radiometer D602) that covers the face of the electrode and holds the filling solution in place. For transcutaneous \( p_{CO_2} \) recordings in patients, we used a filling solution composed of the NaCl/NaHCO\(_3\) electrolyte buffer (100 and 20 mmol/L, respectively) in an equimolar mixture of glycerol and water, and no spacer.

The five patients were acutely ill premature infants whose weights ranged from 860 to 3300 g and whose postnatal age ranged from 6 to 99 days. All had cardiopulmonary disease. The average gestational age was 28 weeks, and the average birth weight was 1048 g. Transcutaneous \( p_{CO_2} \) electrodes were placed on the abdomen or chest. Capillary blood was collected from the heel area according to standard protocol (4); every attempt was made to obtain samples when the infant was resting quietly. Blood gases were measured at 37 °C with an ILB13 blood gas analyzer (Instrumentation Laboratory, Lexington, MA 02173), with use of accepted quality-control routines for this instrumentation.

**Results**

The best TCM10 electrode response time was achieved by using a filling solution of equimolar glycerol and water, with the NaCl/NaHCO\(_3\) electrolyte buffer and no spacer (Figure 1). The 95% response time to a step change in \( p_{CO_2} \) was 49.9 ± 2.8 s (\( \bar{x} \pm SD \)), the 90% time was 33.4 ± 1.8 s, and the 63% time was 13.3 ± 0.7 s. In vitro drift with this filling solution was generally negligible (less than ±2 Torr) when tested for peri-

![Fig. 1. Mean 63%, 90%, and 95% response times of TCM10 transcutaneous \( p_{CO_2} \) electrodes as functions of the volume of glycerol in the electrode filling solution](image-url)
ods as long as 72 h, if the temperature of the system remained constant. The transcutaneous $p_{CO_2}$ response to different steady-state ambient CO$_2$ tensions was accurate and linear to within 4%. We observed no in vitro or in vivo bubble formation with the equimolar glycerol/water mixture. With less than 350 mL of glycerol per liter, however, bubbles tended to form under the Teflon membrane, especially in vivo after prolonged use, electrode motion, or with higher $p_{CO_2}$ values.

When electrodes were tested with a 50-$\mu$m nylon mesh spacer in place, the response time was slower. For the NaCl/NaHCO$_3$ electrolyte buffer, the 95% response time was 82.5 ± 4.9 s (3 ± SD), 90% was 54.9 ± 5.9 s, and 63% was 22.5 ± 2.3 s. The minimum response time occurred with 350 mL of glycerol per liter. Response time was excessively prolonged with the higher glycerol concentrations (650 and 800 mL/L). The KCl/KHCO$_3$ electrolyte buffer, even without a spacer in place, also resulted in slow response times, although the point of minization was at 500 mL of glycerol per liter, and the overall shapes of the time-response curves resembled those in Figure 1. The 95% response time was 85.5 ± 14.3 s, 90% was 50.1 ± 5.5 s, and 63% and 16.8 ± 0.6 s.

Patients' transcutaneous $p_{CO_2}$ was recorded continuously during 17 recording sessions (average duration 3.2 h). In vivo transcutaneous $p_{CO_2}$ calibration drift was 0.5 ± 1.9 Torr/h (3 ± SD) for the low $p_{CO_2}$ calibration level, and 1.0 ± 5.0 Torr/h for the high $p_{CO_2}$ calibration level. We analyzed 20 capillary blood sampling periods for transcutaneous $p_{CO_2}$ fluctuations; transcutaneous $p_{CO_2}$ was relatively stable for long periods before each sampling period. Figure 2A illustrates two examples of transcutaneous $p_{CO_2}$ patterns of variation. Patterns like these occasionally could be correlated with the clinical behavior of the infants at the time of capillary blood gas determinations. The histogram in Figure 2B shows the frequency of maximum transcutaneous $p_{CO_2}$ changes that occurred during sampling periods, measured from the point of lancing (Phase II). The range of maximum change in transcutaneous $p_{CO_2}$ was from −8 to +19 Torr. These maxima were not predictable, either in magnitude (mean 6.0, SD 4.5 Torr) or direction (eight up, 11 down, and one no change). The largest relative change was +29%. Both an increase and a decrease in transcutaneous $p_{CO_2}$ frequently could be observed during a single sampling period. Capillary blood sampling periods averaged 4 min, during which two or three samples were collected.

Transcutaneous $p_{CO_2}$ (y) averaged 70.3 (SD 17.9) Torr (range 45–106 Torr). Capillary $p_{CO_2}$ (x) averaged 49.0 (SD 9.4) Torr (range 35–70 Torr). Linear regression by least squares yielded the following equation (in Torr): $y = 13.1 + 1.17x$. The standard error of estimate (standard deviation about the regression line) was 14.5. The standard deviation of the slope was 0.36. The standard deviation of the intercept was 17.7. For this regression, $r^2 = 0.37$ and $r = 0.61$.

Discussion

The equimolar mixture of glycerol and water with the NaCl/NaHCO$_3$ (100 and 20 mmol/L, respectively) electrolyte buffer and no spacer gave the best TCM10 electrode response time for transcutaneous $p_{CO_2}$. Glycerol is safe for use in vivo, avoiding the potential toxicity associated with ethylene glycol, which has been used previously in electrode filling solutions (5–8). Use of a nylon mesh spacer under the Teflon membrane slowed electrode response time without affecting any special advantages during in vivo monitoring, and can thus be omitted. The KCl/KHCO$_3$ (100 mmol/L each) electrolyte buffer, with its greater concentration of HCO$_3$-, has been used in a combination transcutaneous $p_{O_2}$-$p_{CO_2}$ electrode to diminish effects attributed to the pH-sensitive glass and to increase stability of $p_{CO_2}$ measurement (7). However, during our recording sessions (typically 3–4 h), in vivo drift was generally small without the use of the more concentrated electrolyte buffer. For better monitoring of the relatively rapid clinical fluctuations in transcutaneous $p_{CO_2}$ in vivo, a lower concentration of HCO$_3$- (as in the NaCl/NaHCO$_3$ electrolyte buffer) produces a faster responding electrode.

Transcutaneous $p_{CO_2}$ values are greater than actual arterial $p_{CO_2}$ values, but correlate favorably and linearly with them (5–7). Regression analysis of transcutaneous and capillary $p_{CO_2}$ revealed a weak ($r^2 = 0.37, r = 0.61$) linear relationship. Unpredictable transient changes in transcutaneous $p_{CO_2}$ and therefore presumably in arterial $p_{CO_2}$, occur during capillary blood gas determinations in severely ill premature infants with cardiopulmonary disease, which we feel decreases the reliability of capillary $p_{CO_2}$ values for use in clinical management. These fluctuations may help to explain why other investigators (1–3) have found poor correlation of arterial and capillary $p_{CO_2}$ in similar patient populations. Any effects of electrode time lag in vivo (estimated to be somewhat greater than in vitro) would not alter this conclusion, because transient changes in transcutaneous $p_{CO_2}$ values were observed from the time of lancing until several minutes after the end of capillary blood-sample collection.

Transcutaneous $p_{O_2}$ may also fluctuate unpredictably during capillary blood sampling periods (10). The fluctuations in arterial $p_{O_2}$, which the transcutaneous $p_{O_2}$ measurements presumably reflect, tend also to decrease the reliability of measurements of capillary blood $p_{O_2}$ data for use in clinical
management (10). For both $p_{O_2}$ and $p_{CO_2}$ the changes usually are not associated with antecedent ongoing dynamic fluctuations, and are not consistently correlated with such factors as crying and changes in respiratory rate that may result from prolonged warming, painful lancing, and an extended blood-collecting procedure. The sudden changes in transcutaneous $p_{CO_2}$ observed after lancing sometimes resemble those that we have seen during other clinical events, including suctioning, feeding, and chest physical therapy. During routine patient care, transcutaneous monitoring may help one to select a propitious moment for blood sample collection, so as to avoid bias from both predictable and other unpredictable clinical perturbations.

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