End-tidal carbon dioxide measurements in critically ill neonates: a comparison of sidestream and mainstream capnometers

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To determine whether end-tidal PCO_2 ($P_{ET}CO_2$) measurements obtained with two infrared capnometers accurately approximates the arterial PCO_2 ($PaCO_2$) in critically ill neonates, simultaneous measurements of $P_{ET}CO_2$ were obtained from the distal and proximal ends of the tracheal tube with a sidestream capnometer (Puritan Bennett/Datex – BP/D) and from the proximal end with a mainstream capnometer (Hewlett-Packard – HP) in 20 intubated neonates. Distal sidestream $P_{ET}CO_2$ and mainstream $P_{ET}CO_2$ correlated with the $PaCO_2$ ($r^2 = 0.66$ and 0.61, respectively) within the range of 26–57 mmHg $PaCO_2$. However, proximal $P_{ET}CO_2$ with the sidestream capnometer correlated very poorly ($r^2 = 0.09$) with $PaCO_2$. The slope of the least square regression line for the distal sidestream capnometer, 0.67, was significantly less than that for the mainstream capnometer, 0.78 but both were significantly greater than that for the proximal sidestream capnometer, 0.39 ($P < 0.05$). The slope of the regression for the proximal sidestream capnometer did not differ significantly from horizontal. Insertion of the mainstream sensor for the HP capnometer significantly increased the transcutaneous CO_2 when compared with pre-insertion values. We conclude that both distal sidestream and mainstream capnometry provide accurate estimates of the $PaCO_2$ in critically ill neonates.

Key words
ANAESTHESIA: neonatal, paediatrics;
CARBON DIOXIDE: end-tidal tension, arterial, alveolar;
MEASUREMENT TECHNIQUES: capnometry;
VENTILATION: mechanical.

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En enregistrant simultanément la PCO_2 en fin d'expiration ($P_{ET}CO_2$) par capnomètre aspirant (Puritan Bennett/Datex – PB/D) à partir du bout distal et du bout proximal d'un tube endotrachéal et par capnomètre passif (Hewlett-Packard – HP) au bout proximal du tube, nous avons mesuré l'efficacité de ces techniques d'estimation à l'infrarouge de la PCO_2 artérielle ($PaCO_2$) chez 20 nouveaux-nés. Pour des $PaCO_2$ de l'ordre de 26 à 57 mmHg, la pente de la ligne de régression entre la $P_{ET}CO_2$ et la $PaCO_2$ était de 0,78 avec le capnomètre passif (r^2 = 0,61), significativement plus grande que la pente de 0,67 du capnomètre aspirant au bout distal (r^2 = 0,66) mais toutes deux se détachaient ($P < 0,05$) de celle du capnomètre aspirant au bout proximal qui, avec une valeur de 0,39, pouvait être confondue avec l'horizontale (r^2 = 0,09). Pour sa part, l'insertion dans le circuit de la fenêtre de mesure du capnomètre passif contribuait à augmenter la PCO_2 trans-cutanée. La capnométrie passive ou par aspiration du bout distal donne donc un bon estimé de la $PaCO_2$ des nouveaux-nés gravement malades.

End-tidal PCO_2 ($P_{ET}CO_2$) monitoring is a simple, non-invasive technique for accurately estimating arterial PCO_2 ($PaCO_2$) in critically ill neonates.[1–4] Two of the capnometers currently used to measure $P_{ET}CO_2$ in neonates: the sidestream capnometer, Puritan-Bennett/Datex (PB/D), and the mainstream capnometer, Hewlett-Packard (HP), differ in the design of their gas sampling systems. The PB/D (sidestream capnometer) removes gas continuously from the breathing circuit and measures the $P_{ET}CO_2$ in a remote infrared sensor, whereas the HP (mainstream capnometer) measures the $P_{ET}CO_2$ in expired gas within the breathing circuit with an in-line optical infrared sensor. This difference in the gas sampling systems might affect the accuracy of $P_{ET}CO_2$ measurements in neonates and small infants since they have small tidal volumes and rapid respiratory rates. Previously, we investigated the accuracy of the PB/D

capnometer. We found that $P_{ET}CO_2$ measurements obtained from the distal end of the tracheal tube estimated $PaCO_2$ more accurately than did $P_{ET}CO_2$ measurements obtained from the proximal end with this sidestream capnometer in both neonates[4] and infants <12 kg.[5] We attributed the small difference between the $PaCO_2$ and distal $P_{ET}CO_2$ measurements in part to a reduction in the mixing of end-tidal and fresh gases at the distal end of the tracheal tube compared with the proximal end. Epstein and co-workers compared the accuracy of the HP (mainstream) capnometer and transcutaneous PCO_2 monitor as estimates of $PaCO_2$ in infants.[3] They found that although the HP capnometer was a valuable tool, $PaCO_2$ increased in the majority of infants when the HP neonatal sensor was inserted into the breathing circuit.

Because the HP capnometer analyzes gas within the breathing circuit, we speculated that the proximal $P_{ET}CO_2$ measurements obtained with the HP capnometer may be as accurate an estimate of the $PaCO_2$ as distal $P_{ET}CO_2$ measurements obtained with the PB/D. If this were true, then $P_{ET}CO_2$ determinations with the mainstream sensor would obviate the need to insert a catheter into the tracheal tube in infants <12 kg.[4,5] Therefore, we sought to compare the accuracy of the $P_{ET}CO_2$ measurements by the PB/D and HP capnometers in estimating the $PaCO_2$ in critically ill neonates.

Methods

After approval from the Human Subjects Review Committee in our institution, simultaneous measurements of $P_{ET}CO_2$ and $PaCO_2$ were obtained from 20 neonates whose tracheas were intubated (tracheal tube size 3.0 mm or greater internal diameter) and who were either mechanically ventilated or breathing spontaneously with continous positive airway pressure in the Neonatal Intensive Care Unit.

End-tidal gas was aspirated from both the proximal and distal ends of the tracheal tube. Distal measurements were obtained through a sterile 19G catheter that was inserted through a modified elbow in the anaesthetic circuit whereas proximal measurements were obtained at the elbow.[5] The aspirated gas was analyzed in a Puritan-Bennett capnometer. The PB/D capnometer was calibrated with five per cent CO_2 in air and corrected for ambient pressure and humidity at 37° C. The total delay time which is the sum of the transit time and the rise time for the PB/D capnometer sampling at 150 ml · min^{-1} with 1 m of sampling tubing and a 19G tracheal sampling catheter was 0.85 sec. This was determined by measuring the response to a step-wise change in CO_2 concentration as described previously.[6]

The HP capnometer was calibrated using the internal reference cells, according to the manufacturer's instructions and measurements were corrected for the pressure-broadening effects of water vapour. The neonatal sensor (14363A) (internal volume 2 ml) of the Hewlett-Packard (47210A) capnometer was then inserted into the breathing circuit.

A transcutaneous PO_2/PCO_2 sensor was applied to the anterior thorax for 20 minutes before the capnometers were inserted into the circuit. Transcutaneous oxygen ($PtcO_2$) and carbon dioxide ($PtcCO_2$) tensions were measured with a Kontron Microgas 7640 PO_2/PCO_2 Combisensor. The Combisensor was calibrated with both five and ten per cent CO_2 and then corrected to estimate $PaCO_2$ at 44° C.[7]

$PtcO_2$ and $PtcCO_2$ were recorded both before and 15 min after the mainstream and sidestream sampling sensors were inserted into the breathing circuit. An arterial blood sample was then obtained from an indwelling arterial catheter and analyzed in a Corning 178 pH/blood gas analyzer. Distal sidestream (PB/D) and mainstream (HP) $P_{ET}CO_2$ were recorded on a two-channel Gould 2200S recorder (frequency response >20 Hz). The sidestream sampling catheter was then withdrawn to the elbow of the breathing circuit and the proximal sidestream $P_{ET}CO_2$ was analyzed with the PB/D capnometer. The end-expiratory plateau on the CO_2 waveform was recorded as the $P_{ET}CO_2$ (mmHg). When an end-expiratory plateau was absent, the $P_{ET}CO_2$ was taken to be the peak-expired PCO_2.

Statistical significance of $P < 0.05$ was accepted. Regressions between $PaCO_2$ and the three measurements of $P_{ET}CO_2$ were determined using least squares linear regression analyses and reported as the coefficients of determination (r^2). The 95 per cent confidence intervals for the true means of the $P_{ET}CO_2$ for the best-fit lines were determined for the distal sidestream and mainstream $P_{ET}CO_2$ measurements. The slopes of the three regression lines were compared using an unpaired Student's t test. The correlation coefficients (r) of the three lines were compared using Fisher's Z-transformation and the Newman-Keuls multiple range test.[8] The differences between arterial and end tidal P_{CO_2} measurements, $\Delta(a\text{-}ET)PCO_2$ for the three $P_{ET}CO_2$ measurement techniques were compared using one-way ANOVA and the Newman-Keuls multiple range test. Differences in the incidence of $\Delta(a\text{-}ET)$ PCO_2 gradients ≤5 mmHg were analyzed using the chi-square analysis with the Yates correction for continuity. $PtcO_2$ and $PtcCO_2$ before and after end-tidal samples were compared using paired Student's t tests.

Results

The mean weight (±SD) of the 20 infants was 2.41 ± 0.64 kg, and the mean post-conceptual age was 36 ± 3 wk. In seventeen patients the lungs were ventilated for respiratory disease (including 13 with respiratory distress

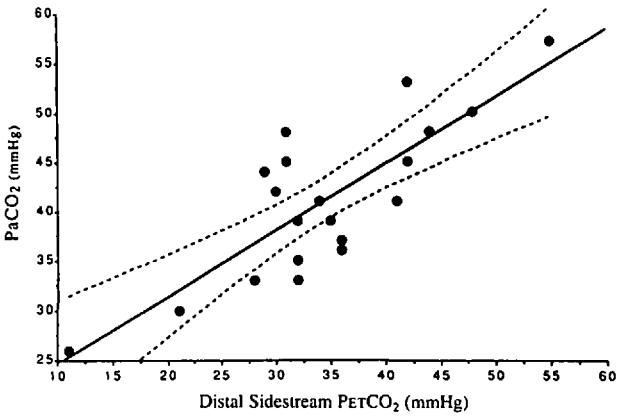

FIGURE 1 Distal sampling of $PETCO_2$ with a sidestream (Puritan-Bennett/Datex – PB) capnometer accurately estimated $PaCO_2$ (r^2 = 0.66). The equation of the least square linear regression analysis was $PaCO_2 = 0.67 \cdot PETCO_2 + 18.0$. Dashed curves indicate the 95 per cent confidence limits for the true mean of $PaCO_2$.

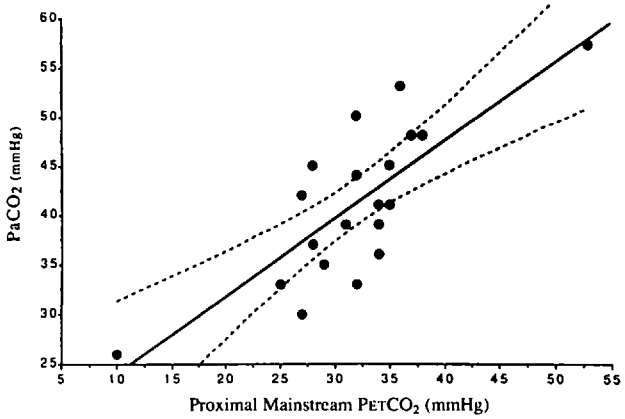

FIGURE 2 Proximal measurements of $PETCO_2$ with a mainstream infrared (Hewlett-Packard – HP) capnometer approximated the $PaCO_2$ (r^2 = 0.61). The equation of the least square linear regression analysis was $PaCO_2 = 0.78 \cdot PETCO_2 + 16.2$. Dashed curves indicate the 95 per cent confidence limits for the true mean of $PaCO_2$.

syndrome). Three patients with severe lung disease had persistent fetal circulation and one infant had an A-V canal defect.

The $\Delta(a\text{-}ET)PCO_2$ differed significantly among the groups: distal sidestream = mainstream < proximal sidestream ($P < 0.05$) (Table).

The least square regression lines for $PaCO_2$ versus $PETCO_2$ for the three capnometer techniques differed significantly (Table) (Figures 1 and 2). The correlation coefficient for distal sidestream was significantly greater than that for proximal sidestream but did not differ from that for mainstream. The slopes of the regression lines were: distal mainstream > sidestream > proximal sidestream ($P < 0.05$) (Table). The slope of the proximal sidestream did not differ significantly from zero.

In the 12 infants with mild respiratory dysfunction defined by an $FIO_2 < 0.35$ and respiratory rate < $90 \cdot min^{-1}$, the $\Delta(a\text{-}ET)PCO_2$ using the distal $PETCO_2$ measurements with the sidestream capnometer correlated better with the extent of respiratory disease (as indicated by the FIO_2) than did the $\Delta(a\text{-}ET)PCO_2$ with the mainstream capnometer: 13 patients had mild respiratory dysfunction ($\Delta(a\text{-}ET)PCO_2 \leq 5$ mmHg) according to the sidestream PB/D capnometer whereas only five had mild respiratory dysfunction according to the mainstream HP capnometer ($P < 0.02$).

The $PtcO_2$ did not change significantly after the mainstream HP neonatal adaptor was present in the breathing circuit for 15 minutes: mean (±SD) $PtcO_2$ before insertion of 66.2 ± 11.9 mmHg compared with 69.7 ± 13.3 mmHg after insertion (NS). However, the $PtcCO_2$ did increase significantly after inserting the adaptor into the breathing circuit, from 38.3 ± 9.8 mmHg, before insertion to 40.3 ± 10.3 mmHg after insertion ($P < 0.001$). Two infants, weighing 0.97 and 1.95 kg, had clinically significant increases in $PtcCO_2$ of 6 mmHg after insertion of the mainstream HP adaptor into the breathing circuit.

TABLE Regression and $\Delta(a\text{-}ET)CO_2$ data

	Distal sidestream	*Mainstream*	*Proximal sidestream*
Number of patients	20	20	20
$\Delta(a\text{-}ET)PCO_2$	6.6 ±5.89	9.25 ±5.24	25.5*† ±8.42
Linear regression:			
– Correlation coefficient (r)	0.81	0.78	0.30*
– Coefficient of Determination (r^2)	0.66	0.61	0.09
– Slope	0.67	0.78*	0.39*†‡

Data are means ± SD.
*$P < 0.05$ compared with distal sidestream.
†$P < 0.05$ compared with mainstream.
‡P = NS compared with a zero slope.

Insertion of the distal sampling catheter for the sidestream capnometer did not affect the $PETCO_2$ values measured with the HP capnometer.

Discussion

Although non-invasive techniques for assessing ventilation are rapidly gaining popularity in clinical anaesthetic practice, the accuracy of one of these techniques, capnometry, in neonates and small infants has recently been questioned.[1,9–12] The concerns regarding the accuracy of sidestream capnometry are based on reports in which proximal $PETCO_2$ measurements obtained with sidestream capnometry underestimated the $PaCO_2$.[10–12] However, in a previous study we established the accuracy of end–tidal PCO_2 measurements in infants < 12 kg who were monitored with a sidestream capnometer.[4] We found that distal $PETCO_2$ approximated the $PaCO_2$ more accurately than did proximal $PETCO_2$ sidestream measurements.[4] The results of the present study in critically ill neonates support those findings. Indeed in the present study, proximal $PETCO_2$ did not correlate significantly with $PaCO_2$ (the slope did not differ from the horizontal, Table). We conclude that sidestream capnometry can be used to obtain accurate estimates of $PaCO_2$ in critically ill neonates and older infants who are ventilated with a partial rebreathing circuit, providing distal tracheal tube sampling is used.

Several factors may contribute to the large $\Delta(a\text{-}ET)PCO_2$ noted with proximal sidestream capnometry in this study. These include the weight of the patient, type of breathing/ventilator circuit, sample flow rate and response time of the capnometer.[4–6,13–16] The $\Delta(a\text{-}ET)PCO_2$ with proximal sidestream measurements is large in infants and children <12 kg because the tidal volumes are small compared to the fresh gas flows.[4,5] This holds true for infants whose lungs are ventilated with the Air Shields ventilator and a partial rebreathing circuit but may not hold true when the lungs are ventilated with a non-rebreathing circuit or other types of ventilators.[14,17] Although low sample flow rates may be appropriate for use in capnometers with very small sample cell volumes, these sample flow rates may not capture the peak expired CO_2 during the expiratory period. It has been our experience that flow rates of 150 $ml \cdot min^{-1}$ yield consistently accurate estimates of $PaCO_2$ and acceptable capnograms in neonates, infants and children.[4,5,17] In view of the many factors that interfere with the accuracy of proximal sidestream capnometry, distal monitoring is preferable to proximal sidestream monitoring in neonates and infants <12 kg in weight.

We found that approximately two-thirds of the total variation in the $PaCO_2$ is accounted for by the fitted linear regression with $PETCO_2$ measurements obtained with distal sidestream and mainstream capnometry ($r^2 = 0.66$ and 0.61 respectively). Although this is consistent with data published previously from our institution,[4] it exceeds correlations reported from two other centres.[1,12] The lower r^2 values in the latter studies may be attributed to several possible causes: (1) in some neonates the tracheas were not intubated, (2) some had severe intrapulmonary shunting, and (3) the end–tidal gas was aspirated proximally, from only 1 cm beyond the neck of the tracheal tube or from the nares. The data from this study indicate that most of the variation in $PaCO_2$ is attributed to the linear regression with $PETCO_2$ even in critically ill neonates providing distal sidestream or mainstream capnometry is used.

It has been suggested that a flat alveolar plateau should be present for accurate $PETCO_2$ measurements. In this study, neither distal $PETCO_2$ obtained with the sidestream capnometer nor $PETCO_2$ obtained with the mainstream capnometer produced $PETCO_2$ plateaus in every instance. This may be attributed, in part, to the rapid respiratory rates, small tidal volumes and ventilation/perfusion mismatch in infants with respiratory disease. Despite the lack of an end–tidal plateau in some instances, both distal sidestream and mainstream $PETCO_2$ measurements approximated the $PaCO_2$. Thus, $PETCO_2$ can be used to estimate the $PaCO_2$ even in the absence of a flat alveolar plateau.

We found, as did Epstein *et al.*,[3] that when the mainstream sensor was inserted into the breathing circuit, the PCO_2 increased. While this is not likely to affect significantly the PCO_2 in patients who are fully ventilated, it may increase the PCO_2 in infants who are being weaned from mechanical ventilation to such an extent that fatigue or respiratory failure occurs. We found that when the sampling catheter of the sidestream capnometer was inserted into the tracheal tube, the PCO_2 did not change significantly. In this study $PETCO_2$ as measured by mainstream capnometry did not change when the sampling catheter was inserted into the breathing circuit and in both this study and a previous study, $PtcCO_2$ did not change.[4]

Accurate estimates of $PETCO_2$ may be important in order to determine the $\Delta(a\text{-}ET)PCO_2$ and physiological dead space. These values have been used to quantify the degree of lung disease in neonates and their response to treatment.[18,19] Although mainstream capnometry overestimates the $\Delta(a\text{-}ET)$ (and therefore the degree of ventilation/perfusion mismatch) in neonates without severe lung disease, and may cause significant CO_2 retention in some instances, the slope of the linear regression between it and $PaCO_2$ is significantly closer to the slope of the line of identity than is the regression between distal sidestream and the $PaCO_2$. In view of the

advantages and disadvantages of both of these capnometers, we conclude that either distal sidestream or mainstream capnometry may be used to estimate the $PaCO_2$ in critically ill neonates.

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References

1 *Meny RG, Bhat AM, Aranas E.* Mass spectrometer monitoring of expired carbon dioxide in critically ill neonates. Crit Care Med 1985; 13: 1064–6.

2 *Nelson NM, Prod'hom LS, Cherry RB, Lipsitz PJ, Smith CA.* Pulmonary function in the newborn infant II. Perfusion – estimation by analysis of the arterial-alveolar carbon dioxide difference. Pediatrics 1962; 30: 975–89.

3 *Epstein MF, Cohen AR, Feldman HA, Raemer DB.* Estimation of $PaCO_2$ by two noninvasive methods in the critically ill newborn infant. J Pediatr 1985; 106: 282–6.

4 *McEvedy BAB, McLeod ME, Mulera M, Kirpalani H, Lerman J.* End–tidal, transcutaneous and arterial CO_2 measurements in critically ill neonates: a comparative study. Anesthesiology 1988; 69: 112–6.

5 *Badgwell JM, McLeod ME, Lerman J, Creighton RE.* End–tidal PCO_2 measurements sampled at the distal and proximal ends of the endotracheal tube in infants and children. Anesth Analg 1987; 66: 959–64.

6 *Schena J, Thompson J, Crone RK.* Mechanical influences on the capnogram. Crit Care Med 1984; 12: 672–4.

7 *Eberhard P, Mindt W, Schafer R.* Methodologic aspects of cutaneous pCO_2 monitoring. Intensive Care Med 1981; 7: 249–64.

8 *Zar JH.* Biostatistical Analysis. Second edition. Prentice-Hall: Englewood Cliffs, 1984, pp. 309–11, 315–7.

9 *Scheiber RA, Namnoum A, Sugden A, Saville AL, Orr RA.* Accuracy of expiratory carbon dioxide measurements using the coaxial and circle breathing circuits in small subjects. J Clin Monit 1985; 1: 149–55.

10 *Hand IL, Shepard EK, Krauss AN, Auld PAM.* Discrepancies between transcutaneous and end–tidal carbon dioxide monitoring in the critically ill neonates with respiratory distress syndrome. Crit Care Med 1989; 17: 556–9.

11 *Pascucci RC, Schena JA, Thompson JE.* Comparison of a sidestream and mainstream capnometer in infants. Crit Care Med 1989; 17: 560–2.

12 *Watkins AMC, Weindling AM.* Monitoring of end tidal CO_2 in neonatal intensive care. Arch Dis Child 1987; 62: 837–9.

13 *Dumpit FM, Brady JP.* A simple technique for measuring alveolar CO_2 in infants. J Appl Physiol 1978; 45: 648–50.

14 *Hillier SC, Badgwell JM, McLeod ME, Lerman J, Creighton RE.* End–tidal PCO_2 measurements in infants and children ventilated with the Sechrist infant ventilator. Can J Anaesth 1989; 37: 318–21.

15 *Mogue LR, Rantala B.* Capnometers. J Clin Monit 1988; 4: 115–21.

16 *Gravenstein N.* Capnometry in infants should not be done at lower sampling flow rates. Clin Monit 1989; 5: 63.

17 *Badgwell JM, Wolf AR, Morton WD, Lerman J, McLeod ME, Creighton RE.* Fresh gas flow formulae do not accurately predict end–tidal pCO_2 in paediatric patients. Can J Anaesth 1988; 35: 581–6.

18 *Nelson NM, Prod'hom LS, Cherry RB, Lipsitz PJ, Smith CA.* Pulmonary function in the newborn infant. I: Methods: ventilation and gaseous metabolism. Pediatrics 1962; 30: 963–74.

19 *McCann EM, Lewis K, Deming DD, Donovan MJ, Brady JP.* Controlled trial of furosemide therapy in infants with chronic lung disease. J Pediatr 1985; 106: 957–62.