Accuracy of end-tidal PCO_2 measurements using a sidestream capnometer in infants and children ventilated with the Sechrist infant ventilator

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To determine the accuracy of end-tidal PCO_2 ($PETCO_2$) measurements analyzed with a sidestream capnometer in infants and children whose lungs were ventilated with a Sechrist infant ventilator and an Ayre's t-piece, we compared $PETCO_2$ measurements obtained from the proximal ($PETCO_2$-p) and distal ($PETCO_2$-d) ends of the tracheal tube to arterial PCO_2 ($PaCO_2$) in 37 healthy infants and children between 1.3 and 24.5 kg. Both $PETCO_2$-p and $PETCO_2$-d accurately approximated $PaCO_2$, however, the mean (± SD) arterial to end-tidal PCO_2 difference ($\Delta(a\text{-}ET)PCO_2$) was significantly greater with proximal (1.27 ± 1.54 mmHg) than with distal sampling (0.64 ± 1.64 mmHg) ($P < 0.01$). In the subgroup of patients who weighed < 12 kg, the $\Delta(a\text{-}ET)PCO_2$ using proximal gas sampling (1.94 ± 1.29 mmHg) was also significantly greater than it was using distal sampling (0.74 ± 1.31 mmHg) ($P < 0.001$). We conclude that although statistically different, both proximal and distal estimates of $PETCO_2$ provide acceptable estimates of $PaCO_2$ in healthy infants and children who are ventilated with a Sechrist infant ventilator and an Ayre's t-piece system.

Chez 37 enfants en bonne santé pesant de 1,3 à 24,5 kg, nous avons mesuré la PCO_2 en fin d'expiration ($PETCO_2$) avec un capnomètre à infrarouge qui aspirait soit au bout distal ($PETCO_2$-d) soit au bout proximal ($PETCO_2$-p) d'un tube endotrachéal branché sur un respirateur Sechrist ou sur une pièce en T de type Ayre. La $PETCO_2$-p et la $PETCO_2$-d représentaient toutes deux, un estimé adéquat de la PCO_2 artérielle. Toutefois la différence (moyenne ± écart-type) entre la PCO_2 artérielle et en fin d'expiration ($\Delta(a\text{-}ET)PCO_2$) était plus grande pour le site d'aspiration proximal que pour le site distal: 1,27 ± 1,54 mmHg vs 0,64 ± 1,64 mmHg, $P < 0,01$. Pour les patients de moins de 12 kg, ce gradient affichait le même comportement avec 1,94 ± 1,29 mmHg au site proximal et 0,74 ± 1,31 mmHg au site distal, $P < 0,001$. Malgré une certaine différence, les deux sites d'aspiration permettent donc d'obtenir une $PETCO_2$ estimant adéquatement la P^aCO_2 d'enfants en bonne santé, ventilés avec une pièce en T ou un respirateur Sechrist.

Key words
ANESTHESIA: paediatric;
CARBON DIOXIDE: alveolar, arterial, end-tidal;
MEASUREMENT TECHNIQUES: capnometry;
VENTILATION: mechanical.

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In previous studies the accuracy of end-tidal PCO_2 ($PETCO_2$) measurements as estimates of arterial PCO_2 ($PaCO_2$) were investigated in infants and children who were anaesthetized and whose lungs were mechanically ventilated.[1,2] We found that with a non-rebreathing Siemens Elema 900C Servo ventilator, measurements of $PETCO_2$ obtained from both the proximal ($PETCO_2$-p) and distal ($PETCO_2$-d) ends of the tracheal tube in infants and children closely approximated the $PaCO_2$. These findings held true even for infants who weighed less than 8 kg. However, when we repeated these studies with the Air Shields Ventimeter ventilator and the Ayre's t-piece breathing circuit, we found that while both $PETCO_2$-p and $PETCO_2$-d closely approximated the PaCOs in infants and children > 12 kg, only $PETCO_2$-d accurately approxi-

mated the $PaCO_2$ in infants < 12 kg.[2] These latter findings suggested that the inaccuracy of $PETCO_2$ measurements with the sidestream capnometry may be attributed, in part, to entrainment of fresh gas into the sampling line in infants with small tidal volumes and rapid respiratory rates.[3] If entrainment of gas were the most important determinant of these large arterial-end–tidal PCO_2 differences (Δ(a-ET)PCO_2), then we would expect similar differences in infants < 12 kg whose lungs were ventilated with other ventilators and the Ayre's t-piece breathing circuit.

The Sechrist Infant Ventilator (SIV) is used to ventilate the lungs of neonates and infants during anaesthesia and surgery. It is a continuous flow, pressure limited, time cycled device that is cycled by fluidic control using compressed air. During inspiration, an expiratory mushroom valve closes and the lungs inflate passively by the rapid inflow of gas into the breathing circuit. This gas comes from two sources: fresh gas from the anaesthetic machine and 100 per cent oxygen from the ventilator to prime the ventilator circuit. During expiration, the gas within the breathing circuit is actively vented down the expiratory limb by a venturi jet located at the expiratory valve. This jet generates a small negative pressure within the breathing circuit. We hypothesized that this active expiratory flow pattern improves the accuracy of $PETCO_2$ measurements as estimates of the $PaCO_2$, even when the $PETCO_2$ is sampled at the proximal end of the tracheal tube, and obviates the need for distal sampling in small infants. Thus, the present study was designed to determine the accuracy of $PETCO_2$ as an estimate of $PaCO_2$ in anaesthetized infants and children who were ventilated via a SIV and an Ayre's t-piece breathing circuit.

Methods

After obtaining approval from the Human Ethics Committee, 37 unpremedicated healthy infants and children, ages newborn to six years were studied. All patients were ASA physical status I or II, and scheduled for elective surgery. Patients with cardiopulmonary disease and those scheduled for thoracic or upper abdominal surgery were excluded. All patients were studied in the supine horizontal position. After thiopentone (5 $mg \cdot kg^{-1}$), atropine (0.020 $mg \cdot kg^{-1}$) and succinylcholine (1.5–2.0 $mg \cdot kg^{-1}$) were administered IV, the trachea was intubated. The size of the tracheal tube was chosen so that the tracheal tube passed through the cricoid ring easily but allowed no audible gas leak at 30 cmH_2O pressure. Ventilation was then controlled with a SIV and an Ayre's t-piece circuit (Jackson-Rees modification) (Figure 1).

Anaesthesia was maintained with 65 per cent N_2O in O_2 and either halothane (0.5–1.5 per cent inspired concentration), or isoflurane (0.5–2.0 per cent inspired concentration) and fentanyl (0.5–2.0 $\mu g \cdot kg^{-1}$). All patients were paralyzed with either d-tubocurarine or atracurium. The initial fresh gas flows were adjusted according to the formula of Rose and Froese to maintain the $PETCO_2$ between 26–44 mmHg.[4] The inspiratory:expiratory ratio (I:E) was set at 1:2 and the tidal volume was approximately 15 $ml \cdot kg^{-1}$ when peak inspiratory pressures were 20–30 cmH_2O. Respiratory rates were maintained at 20–30 breaths per minute. Positive end–expiratory pressure was 0–2 cmH_2O. The study was started after the lungs had been ventilated for at least 15 min at the desired ventilator setting. $PETCO_2$ was measured continuously by sampling gas (150 $ml \cdot min^{-1}$) via a 1.5 m non-water permeable sampling tube from the proximal and distal ends of the tracheal tube and analyzing the gas in a calibrated Puritan-Bennett infrared analyzer. The analyzer was calibrated with a five per cent CO_2 reference gas mixture.

The $PETCO_2$-p was sampled directly from the luer-lok port of the clear plastic elbow in the t-piece circuit. The $PETCO_2$-d measured from the distal end of the tracheal tube through a #19 G central venous catheter inserted via the luer-lok port to within 5 mm of the distal end of the tracheal tube.[2] All $PETCO_2$ measurements were corrected for the presence of 65 per cent nitrous oxide. The $PETCO_2$-p

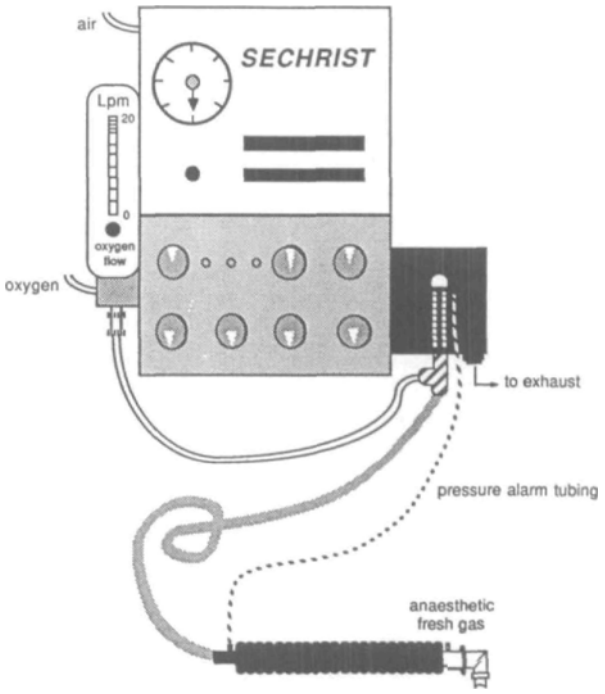

FIGURE 1 The configuration of the Sechrist Infant Ventilator and Ayre's t-piece breathing circuit (Jackson-Rees modification) used in this study. The expiratory valve is shown as the white semi-circle in the side-mounted black box.

and $PETCO_2$-d were measured in random order and within 15 min of each other during steady state. In most patients, both $PETCO_2$-p and $PETCO_2$-d were measured in the same patient. Arterial blood and $PETCO_2$ measurements were obtained simultaneously. The $PaCO_2$ was analyzed with a Corning 175 blood/gas analyzer using a CO_2 electrode that was calibrated before each use. Blood/gas analyses were not corrected for body temperature.

The differences between $PaCO_2$ and both $PETCO_2$-p and $PETCO_2$-d (Δ(a-ET)PCO_2-p and Δ(a-ET)PCO_2-d respectively) were compared to body weight using least squares linear regression analysis. The coefficient of determination (r^2) was determined for each regression. The slopes of the linear regressions were compared using the Student's t test.[5] The Δ(a-ET)PCO_2-p and -d were compared using the Student's t test for paired data. Statistical significance was accepted if $P \leq 0.05$.

Results

Thirty-seven patients were studied. Both $PETCO_2$-p and $PETCO_2$-d were compared with $PaCO_2$ in 31 patients; $PETCO_2$-p alone was compared in three additional patients and $PETCO_2$-d alone in another three. Although only one paired comparison ($PaCO_2$ vs $PETCO_2$-p or $PETCO_2$-d) was made in each of these additional six patients, these data were included because in each case the $PETCO_2$-p or $PETCO_2$-d was compared with the patient's own $PaCO_2$.

The mean (±SD) weight of the 37 patients studied was 9.7 ± 5.9 kg. Patients in the $PETCO_2$-p and $PETCO_2$-d groups did not differ in weight or in the number of patients with negative Δ(a-ET)PCO_2 values. The mean (±SD) Δ(a-ET)PCO_2-p (1.3 ± 1.5 mmHg) was significantly greater than that for distal measurements (0.6 ± 1.6 mmHg) ($P < 0.01$) (Table). For Δ(a-ET)PCO_2-p, Δ(a-ET)PCO_2 increased inversely but linearly with body weight, $y = -0.157x + 2.82$, $r^2 = 0.37$ ($P < 0.001$) where y is Δ(a-ET)PCO_2-p and x is body weight (Figure 2). However, for Δ(a-ET)PCO_2-d, $y = -0.023x + 0.85$, $r^2 = 0.006$ (P = NS). Qualitatively, the capnographic waveforms obtained using proximal sampling were similar to those obtained using distal sampling (Figure 3). However, when the slopes of the regression lines for proximal and distal $PETCO_2$ were compared, the slope for the proximal data was significantly greater than that for the distal measurements ($P < 0.01$). When only patients < 12 kg in weight were considered, the mean weight was 6.2 ± 2.5 kg. The mean Δ(a-ET)PCO_2-p (1.94 ± 1.29 mmHg) was significantly greater than that for distal measurements (0.7 ± 1.3 mmHg) ($P < 0.001$) (Table). The linear regressions between Δ(a-ET)PCO_2-p or -d and body weight were not significant (P = NS).

TABLE Demographic data and Δ(a-ET)PCO_2 values

	All patients	*Infants < 12 kg*
Number	37	25
Weight (kg)	9.74 ± 5.89	6.19 ± 2.49
Δ(a-ET)PCO_2 (mmHg):		
- proximal	1.27 ± 1.54	1.94 ± 1.29
- distal	0.64 ± 1.64*	0.74 ± 1.31†

Data are means ± SD.
*$P < 0.01$ compared with proximal in all patients.
†$P < 0.001$ compared with proximal in infants < 12 kg.

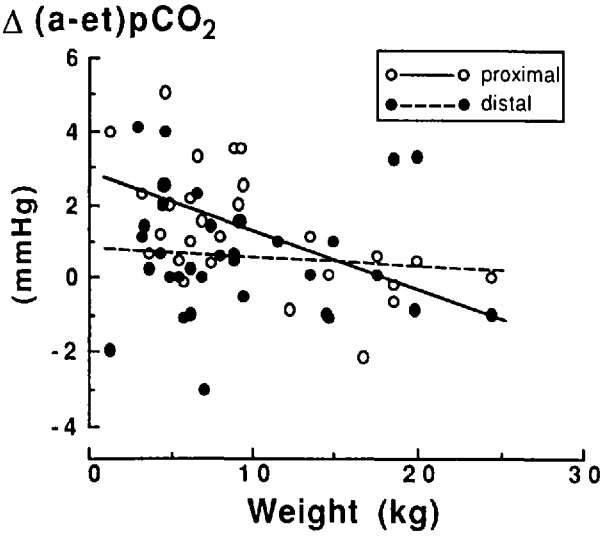

FIGURE 2 The difference between arterial and end-tidal PCO_2 values (Δ(a-ET)PCO_2) compared to body weight using sampling sites at the distal and proximal ends of the tracheal tube.

Discussion

We found that both $PETCO_2$-p and -d closely approximated the $PaCO_2$ in infants and children whose lungs were ventilated with the SIV and an Ayre's t-piece. These results are in agreement with the results of distal sidestream capnometry with the Air Shields Ventimeter Ventilator reported in one study[2] and proximal sidestream capnometry with the Siemen's Elema Ventilator in another.[1] The magnitude of the differences between proximal and distal sampling is known to depend on several factors which include the patient weight, type of ventilator and breathing circuit, fresh gas flow, and capnometer (gas sampling) characteristics.[1,2,6–9] In view of the many factors that can influence the accuracy of $PETCO_2$ measurements, we suggest that the interpretation of these results be applied with caution unless identical anaesthetic and monitoring equipment is used.

Several studies have demonstrated that the gas sampling site is an important determinant of the Δ(a-ET)PCO_2

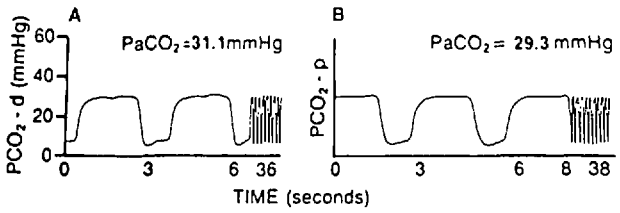

FIGURE 3 Capnographic waveforms obtained from the distal (A) and proximal (B) ends of the tracheal tube in a 3.3 kg newborn infant using the Sechrist Infant Ventilator. Fresh gas flow = 1.4 $L \cdot min^{-1}$, respiratory rate = 20 breaths $\cdot min^{-1}$, I:E ratio = 1:2 and airway pressure = 25/2 cmH_2O.

in small infants who are monitored with sidestream capnometry.[2,10] Many clinicians prefer proximal site capnometry in lieu of distal site capnometry because the former is easy to use, requires little maintenance, and has minimal risk of blockage or contamination. Difficulties associated with distal site sampling include an increased risk of disconnection at the site of insertion of the catheter into the tracheal tube, and blockage of the catheter. Previous studies have recommended proximal site sidestream capnometry for accurate estimates of $PaCO_2$ during anaesthesia and surgery in healthy infants and children except when partial rebreathing circuits are used with infants < 12 kg in weight.[1,2] In the latter instance, distal site capnometry is preferred. The results of this study indicate that although $\Delta(a\text{-}ET)PCO_2$-d is statistically significantly less than $\Delta(a\text{-}ET)PCO_2$-p, these differences are small and are not likely to dictate the site of $PETCO_2$ monitoring in infants and children using an Ayre's t-piece and SIV.

In a previous study, we identified a clinically significant difference between $PETCO_2$-p and $PETCO_2$-d estimates of $PaCO_2$ in patients weighing < 8 kg[1] and < 12 kg[2] using an Air Shields Ventimeter and an Ayre's t-piece. However, the differences between $PETCO_2$-p and $PETCO_2$-d estimates of $PaCO_2$ in this study were not as large. To explain this difference, we examined the design and function of the SIV in relation to end–tidal gas sampling.[11] Cycling from inspiration to expiration occurs when the expiratory valve opens and the gas within the breathing circuit is vented through the valve (Figure 1). To ensure complete removal of expired gases from the breathing circuit, i.e., to avoid inadvertent PEEP, negative pressure is applied to the patient side of the expiratory valve of the SIV. This negative pressure is generated by a venturi jet that is located at the expiratory valve. The net effect is to divert fresh gas that might otherwise be entrained into the sampling line during expiration away from the proximal sampling site. This unique design attenuates the difference between proximal and distal $PETCO_2$ estimates of $PaCO_2$ and provides more accurate proximal gas sampling with the SIV and Ayre's t-piece even in infants <12 kg.

In summary, we found that when using the SIV with an Ayre's t-piece breathing circuit for infants and children, $PETCO_2$-p provides accurate estimates of the $PaCO_2$ even in infants <12 kg.

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