wave developed, even though hypokalemia was present. These benign responses might have been a result of an antiarrhythmic action of lidocaine.

The results of the present study indicate that the decrease in amplitude of the T wave, development of U waves, and hypokalemia after axillary blockade with lidocaine and epinephrine were induced by epinephrine, and that these were prevented by pretreatment with propranolol. Hypokalemia can be associated with a variety of cardiac dysrhythmias. On the basis of our findings, we recommend that the ECG should be monitored during blockade, and that pretreatment with beta-adrenergic blockade may be beneficial when local anesthetics with epinephrine are given. Also, epinephrine should be avoided in patients with K^+ deficiency.

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End-tidal, Transcutaneous, and Arterial p_{CO_2} Measurements in Critically Ill Neonates: A Comparative Study

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Non-invasive estimates of arterial CO_2 (Pa_{CO_2}), such as end-tidal ($PetCO_2$) and transcutaneous CO_2

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($PtcCO_2$), are alternatives to frequent arterial sampling.[1–4] However, the accuracy of $PetCO_2$ measurements in neonates has been questioned.[5,6] Badgwell *et al.* determined the accuracy of $PetCO_2$ measurements in healthy infants (≦12 kg in weight), and found that, with an aspirating capnometer, $PetCO_2$ is significantly more accurate when gas is sampled from the distal end of the endotracheal tube rather than the proximal end.[7] We speculated that distal $PetCO_2$ measurements might also improve the accuracy of end-tidal estimates of Pa_{CO_2} in preterm and full-term neonates. Therefore, we compared the accuracy of $PetCO_2$ and $PtcCO_2$ measurements as estimates of Pa_{CO_2} in neonates.

Materials and Methods

After approval from the Committee on Human Research, $PetCO_2$, $PtcCO_2$ and Pa_{CO_2} measurements were recorded in 27 tracheally intubated preterm and full-term neonates (endotracheal tube sizes 3.0 or 3.5 mm internal diameter) in the Neonatal Intensive Care Unit. All neonates were either mechanically ventilated with a pressure-limited ventilator or breathing spontaneously with continuous positive airway pressure (≦5 cm H_2O). Forty-six sets of distal $PetCO_2$, $PtcCO_2$, and Pa_{CO_2} measurements and 36 sets of proximal and distal $PetCO_2$ measurements were recorded. Measurements were repeated in neonates when either improvement or deterioration occurred and ventilation was changed.

$PetCO_2$ was measured with a Puritan-Bennett/Datex capnometer (sampling flow rate 150 ml/min). The capnometer was calibrated with a standard gas mixture (5% CO_2 in air) and corrected for ambient pressure. Capnograms were recorded on a calibrated Puritan-Bennett/Datex recorder.

Distal $PetCO_2$ was measured from the distal end of the endotracheal tube through a 19-g sampling catheter that was inserted through a modified elbow in the breathing circuit. Proximal $PetCO_2$ was measured from the elbow of the circuit. The total delay time (defined as the time from a step-wise increase in CO_2 to a 90% rise time) of the Puritan-Bennett sampling system with a 19-g catheter was measured. Although the accuracy of the Puritan-Bennett Datex capnometer decreases when the respiratory rate exceeds 75 breaths per minute¶ (even at the higher sampling rate) and when severe lung disease is present, all neonates were included for comparisons with $PtcCO_2$.

$PtcCO_2$ was measured with a Kontron Microgas® 7640 p_{O_2}/p_{CO_2} monitor $\bar{c}$ model 81 CombiSensor®. The combisensor was calibrated at 44° C with 5% and 10% CO_2 using an algorithm derived from correlation studies to estimate Pa_{CO_2} (as per manufacturer's instructions). The transcutaneous sensor was then applied to the anterior thorax of each neonate.

To determine the effect of the sampling catheter within the endotracheal tube on ventilation and oxygenation, $PtcCO_2$ and transcutaneous oxygen tension ($PtcO_2$) were recorded before, and at least 15 min after, the sampling catheter was inserted to the distal end of the endotracheal tube.

After the distal $PetCO_2$ and $PtcCO_2$ measurements were stable for at least 15 min, an arterial blood sample was obtained from an indwelling arterial cannula and analyzed. The capnometer sampling catheter was then withdrawn to the level of the breathing circuit elbow to measure the proximal $PetCO_2$. Peak inspiratory pressure, respiratory rate, and inspired fraction of oxygen (FI_{O_2}) were recorded.

To compare the accuracy of these estimates of P_{CO_2}, four ratios were determined: proximal to distal $PetCO_2$, distal $PetCO_2$ (with and without the excluded patients) to Pa_{CO_2}, and $PtcCO_2$ to Pa_{CO_2}.

Statistical significance ($P < 0.05$) was determined using paired and unpaired Student's *t* tests. Least squares linear regression analysis and the coefficient of determination (r^2) were determined for distal $PetCO_2$ and $PtcCO_2$ *versus* Pa_{CO_2}. The regression between distal $PetCO_2$ and Pa_{CO_2} was repeated after we excluded the results from those neonates with respiratory rates greater than 70 breaths per minute or an FI_{O_2} greater than 0.7 (see below).

Results

The mean (±SD) gestational age of the 27 neonates was 34.0 ± 5 weeks. The mean (±SD) post-natal age and weight at the time of the study were 3.9 ± 5.7 days and 2.4 ± 0.9 kg, respectively. Twenty-two neonates had ventilation controlled primarily for lung disease; 18 had respiratory distress syndrome as a result of lung immaturity, ten had a history of birth asphyxia, and five had uncorrected congenital heart defects. None of the neonates was in shock. Five neonates subsequently died.

Distal and proximal $PetCO_2$ waveforms from two neonates are shown in figure 1. The distal waveforms demonstrate maximum $PetCO_2$ values that are greater than those on the proximal waveforms. Distal $PetCO_2$ measurements were significantly greater than all corresponding proximal measurements ($P < 0.001$) and more closely approximated Pa_{CO_2} values than did the proximal measurements (n = 35) (fig. 2).

The coefficient of determination for the linear regression between distal $PetCO_2$ and Pa_{CO_2} for the entire group of neonates was 0.39. When neonates with respi-

¶ Puritan-Bennett Corporation CO_2 monitor and recorder operating instructions.

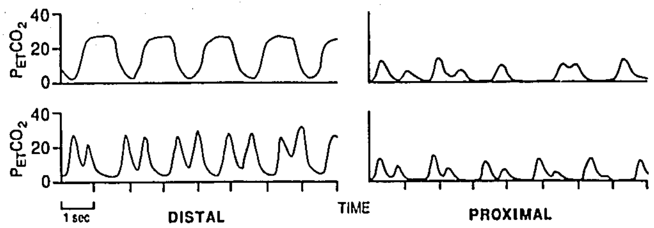

FIG. 1. Distal and proximal capnograms from two neonates. The upper recording was obtained from a neonate who was mechanically ventilated, and the lower from a neonate who was breathing spontaneously with an intermittent mandatory rate of 40/min. The differences in $PetCO_2$ between distal and proximal sites were approximately 16 mmHg for both neonates.

ratory rates > 70/min (based on the total delay time of the sampling system) or severe lung disease ($F_{IO_2} > 0.7$) were excluded, the coefficient of determination increased to 0.72 (fig. 3). The mean (±SD) respiratory rate and F_{IO_2} were 49.2 (±11.95) breaths per minute and 0.34 (±0.15). Sixteen sets of measurements in 13 infants were excluded according to these criteria: nine because of respiratory rate alone, three because of F_{IO_2} alone, and four because of both criteria. The mean (±SD) respiratory rate in this group was 75 (±13) breaths per minute, and the mean F_{IO_2} was 0.62 (±0.25).

The coefficient of determination between $PtcCO_2$ and Pa_{CO_2} for all neonates was 0.76 (fig. 4).

The ratio $PtcCO_2/Pa_{CO_2}$ was the most accurate ratio determined (1.0 ± 0.10) (table 1). Both $PetCO_2$ distal/Pa_{CO_2} ratios were significantly less accurate than the $PtcCO_2/Pa_{CO_2}$ ($P < 0.02$). Furthermore, the $PetCO_2$ distal/Pa_{CO_2} ratio for all neonates was significantly less

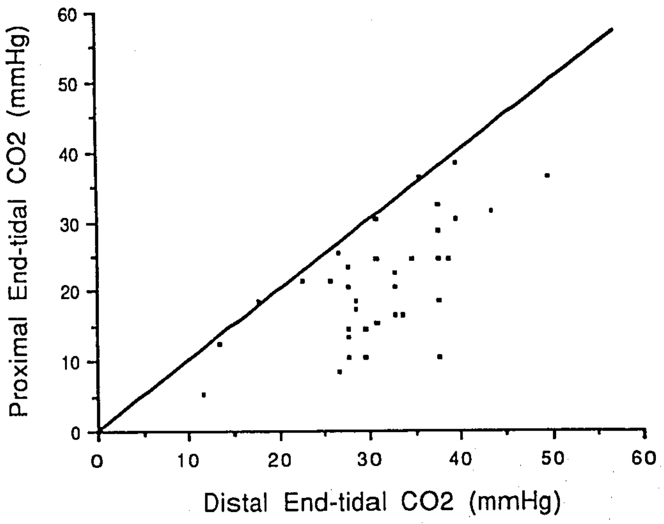

FIG. 2. Distal $PetCO_2$ measurements were consistently greater than proximal measurements (n = 35) ($P < 0.001$). The line of identity is included.

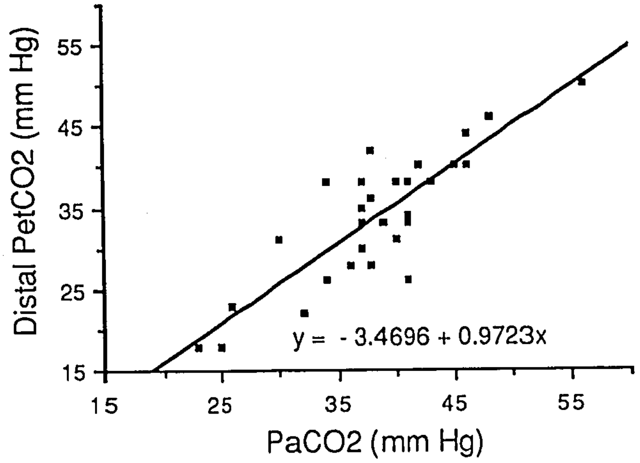

FIG. 3. Distal $PetCO_2$ accurately predicted Pa_{CO_2} ($r^2 = 0.72$) for neonates with mild to moderate lung disease (respiratory rate < 70/min and $F_{IO_2} < 0.7$) (n = 30).

than that for neonates with respiratory rates < 70 breaths per minute and $F_{IO_2} < 0.7$ ($P < 0.05$). The mean $PetCO_2$ proximal/distal ratio of 0.65 demonstrated the inaccuracy of proximal measurements in neonates.

Arterial to end-tidal (a-et) CO_2 differences were determined using distal $PetCO_2$ measurements. The range of these differences in neonates with minimal lung disease ($F_{IO_2} < 0.3$), −4 to 7 mmHg, was significantly less than in neonates with moderate to severe lung disease ($F_{IO_2} > 0.5$), 5–20 mmHg ($P < 0.001$).

The reduction in the cross-sectional area of the endotracheal tube attributable to the 19-g sampling catheter was 13.5% for the 3.0-mm (internal diameter) tube and 9.9% for the 3.5-mm endotracheal tube. These de-

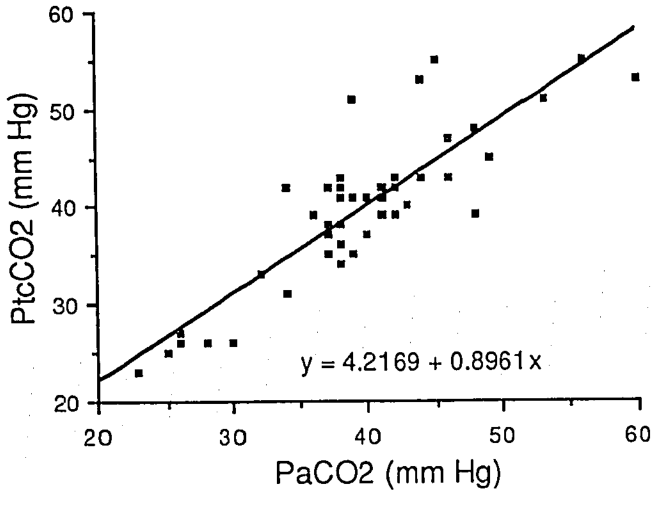

FIG. 4. Transcutaneous CO_2 accurately predicted Pa_{CO_2} for all neonates (n = 46) ($r^2 = 0.76$).

TABLE 1. Comparison of P_{CO_2} Ratios

	Number of Measurements	P_{CO_2} Ratio
$PetCO_2$ prox/$PetCO_2$ dist	35	0.65 ± 0.21
$PetCO_2$ dist/Pa_{CO_2}	46	0.79 ± 0.16†‡
$PetCO_2$ dist*/Pa_{CO_2}	30	0.88 ± 0.12†
$PtcCO_2$/Pa_{CO_2}	46	1.0 ± 0.10

Data are mean ± SD.
* Excludes neonates with respiratory rates > 70/min or $FI_{O_2} > 0.7$.
† $P < 0.001$ compared to $PtcCO_2/Pa_{CO_2}$.
‡ $P < 0.02$ compared to $PetCO_2$ dist*/Pa_{CO_2}.

creases in cross-sectional area did not significantly affect the mean (±SD) $PtcO_2$ before insertion of the catheter, 65 (±17) mmHg, compared to the mean value after insertion of the catheter, 68 (±15) mmHg, or the mean (±SD) $PtcCO_2$, 40 (±8) mmHg both before and after insertion of the catheter. There were no complications from the presence of the sampling catheter within the endotracheal tube.

The total delay time of the sampling system was 0.85 s. This corresponds to a maximum respiratory rate of 70.5 breaths per minute for accurate $PetCO_2$ measurements.

DISCUSSION

Non-invasive end-tidal gas monitoring has become increasingly important in the perioperative management of all patients, and, in particular, the critically ill neonate. However, the usefulness of this monitor is limited by several factors, including its accuracy in infants ≤ 12 kg. The results of this study demonstrate that, in critically ill neonates, distal $PetCO_2$ measurements more accurately approximate Pa_{CO_2} than do proximal $PetCO_2$ measurements. Furthermore, distal $PetCO_2$ measurements are significantly greater than proximal measurements (fig. 2; table 1). This latter discrepancy between distal and proximal end-tidal measurements may be attributed, in part, to the position of the catheter within the endotracheal tube and breathing circuit. That is, the mixing of end-tidal and fresh gases is less at the distal end of the endotracheal tube than at the proximal end. The extent of this mixing is determined, in part, by the gas flows used. Although the sampling flow rate of the capnometer (150 ml/min) is large compared to the minute volume of the neonate (250–400 $ml \cdot kg^{-1} \cdot min^{-1}$),[8] it is small compared to the fresh gas flow (5–6 l/min) used with these infant ventilators. Thus, the increased accuracy of distal compared to proximal $PetCO_2$ measurements may be attributed, in part, to a decrease in the dilution of end-tidal gas by fresh gas.

The total delay time (TDT) in the present study (0.85 s) is slightly longer than expected according to the manufacturer's specifications, which predict accurate measurements of p_{CO_2} up to 75 breaths per minute.** We attributed the increase in TDT in our system to the addition of the endotracheal sampling catheter.[9] It is for this reason that a maximum respiratory rate of 70 breaths per minute was used.

Although multiple measurements were obtained in ten neonates, we do not feel that this invalidates our results. Studies were repeated only when an improvement or deterioration in gas exchange occurred and changes in ventilation or inspired oxygen were made. Six of these neonates appear in both the <70 and the >70 breaths per minute groups. Since these changes tended to occur in sicker neonates, the inclusion of multiple measurements actually biases our data towards a poorer correlation.

An alveolar plateau may be necessary for accurate end-tidal capnometry. Studies have documented a significant correlation between $PetCO_2$ and Pa_{CO_2} in healthy neonates when an alveolar plateau is obtained.[10] We found an excellent correlation between distal $PetCO_2$ and Pa_{CO_2}, despite the fact that an alveolar plateau was not present in every instance. Several factors may account for our failure to achieve an alveolar plateau: 1) the rapid respiratory rate, 2) the presence of respiratory disease, and 3) unfavorable characteristics of the capnometer (high gas sampling flow rate and slow response time).[10] Despite the lack of a plateau during expiration, distal $PetCO_2$ accurately estimates Pa_{CO_2} in critically ill neonates whose respiratory rates are less than 70/min and in whom the lung disease is not severe ($FI_{O_2} < 0.7$).

$PetCO_2$ measurements facilitate calculation of the arterial-end-tidal (a-et) P_{CO_2} differences, a measure of ventilation/perfusion mismatch.[8] Serial (a-et) P_{CO_2} differences have been used to follow the course and response during the treatment of respiratory distress syndrome,[11] to assess lung function, and to estimate pulmonary blood flow during anesthesia.[12] In the present study, the a-et distal P_{CO_2} differences in neonates with minimal lung disease ($FI_{O_2} < 0.3$) compared favorably with CO_2 differences for healthy term infants (−2 to 4 mmHg).[9,13] Hence, distal $PetCO_2$ measurements can be used in the calculation of a-et P_{CO_2} differences in neonates.

$PtcCO_2$ measurements are used extensively in neonatal intensive care units to monitor changes in Pa_{CO_2}.

** Puritan-Bennett Corporation CO_2 monitor and recorder operating instructions.

Although $PtcCO_2$ is an accurate estimate of Pa_{CO_2} (fig. 4), $PtcCO_2$ monitoring during anesthesia is sometimes impractical. Factors that limit its intraoperative use include the relatively long calibration and stabilization periods, the need to change the sensor site every 2–4 h, and the difficulty in finding a site for the sensor away from the surgical field in the small premature neonate who requires numerous monitors. In the intensive care unit, $PtcCO_2$ is more commonly used because it is accurate during the acute phase of respiratory disease. However, $PetCO_2$ remains an alternative site of monitoring in those neonates with less severe disease.

In conclusion, we found that, in the critically ill neonate with mild to moderate lung disease, both distal $PetCO_2$ and $PtcCO_2$ more accurately approximate Pa_{CO_2} than proximal $PetCO_2$. However, in the neonate with severe lung disease, $PtcCO_2$ is the more accurate estimate of Pa_{CO_2}.

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Anesthesia for Cerebral Aneurysm Surgery: Use of Induced Hypertension in Patients with Symptomatic Vasospasm

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There are approximately 25,000 cases per year of aneurysmal subarachnoid hemorrhage (SAH) in the United States. Despite modern neurosurgical and neuroanesthetic techniques, the outlook for patients suffering SAH remains bleak. Twenty percent of these patients die before reaching hospital, and another 30% die in the ensuing days and weeks.[1] About 80% of patients admitted to neurosurgical centers in the recent Cooperative Aneurysm Study were initially in good condition, but only 56% had favorable outcomes, despite current medical therapy.[2] Symptomatic vasospasm was the most common cause of death and disability for patients surviving the initial hemorrhage and reaching neurosurgical care.[3]

Angiographic vasospasm occurs in 40–70% of patients presenting for treatment.[3] Clinical vasospasm, the syndrome of ischemic consequences of cerebral arterial narrowing, parallels the time course for that of angiographic vasospasm, but only produces ischemic symp-

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