Noninvasive Monitoring of Carbon Dioxide During Respiratory Failure in Toddlers and Infants: End-Tidal Versus Transcutaneous Carbon Dioxide

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We prospectively compared the accuracy of two noninvasive monitors of arterial CO_2 (end-tidal and transcutaneous) in mechanically ventilated infants and toddlers with respiratory failure. The study included infants and toddlers less than 48 mo of age who required tracheal intubation and mechanical ventilation for respiratory failure. In each patient, both $ETco_2$ and transcutaneous CO_2 (TC-CO_2) were simultaneously monitored and compared with $Paco_2$ when an arterial blood gas analysis was performed. The cohort for the study included 25 toddlers and infants ranging in age from 1 to 40 mo and in weight from 3.3 to 19.1 kg. A total of 100 sample sets ($Paco_2$, $ETco_2$, TC-CO_2) was compared. The $ETco_2$ to $Paco_2$ difference was 6.8 ± 5.1 mm Hg, while the TC-CO_2 to $Paco_2$ difference was 2.3 ± 1.3 mm Hg ($P < 0.0001$). The absolute difference of the TC-CO_2 and $Paco_2$ was 4 mm Hg or less in 96 of the 100 values, while the $ETco_2$ to $Paco_2$ difference was 4 mm Hg or less in 38 of the 100 values ($P < 0.0001$). Bland-Altman analysis revealed a bias of −0.68 with a precision of ±2.35 when comparing the TC-CO_2 and the $Paco_2$ and a bias of −6.68 with a precision of ±5.01 when comparing $ETco_2$ with $Paco_2$. In neonates and infants with respiratory failure, TC-CO_2 monitoring provided a more accurate estimation of $Paco_2$ than $ETco_2$ monitoring.

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The noninvasive estimation of CO_2 provides a continuous measure by which to document the adequacy of ventilation. An accurate means of monitoring CO_2 may limit the need for repeated arterial blood gas analysis and thereby limit costs. In patients with normal pulmonary function and matching of ventilation-perfusion, $ETco_2$ provides an accurate estimation of $Paco_2$ (1–3).

Several factors may alter the accuracy of noninvasive monitors of $Paco_2$. With $ETco_2$ monitoring, sampling errors and alterations in the ventilation-perfusion status of the patient may alter the accuracy of the device. Although sampling errors may be more common with the lower tidal volumes used for neonates and infants, previous studies (1–3) have demonstrated that $ETco_2$ can be used to estimate $Paco_2$ in infants. However, these studies included only patients with normal pulmonary function.

Aside from sampling errors, alterations in the cardiorespiratory status of the patient may influence the correlation between $Paco_2$ and $ETco_2$. These may include increases in either dead space or shunt fraction (4,5). Dead space refers to those lung units that do not participate in gas exchange. The total physiologic dead space includes both the conducting airways (anatomic dead space) and those areas of the lung that have high ventilation/perfusion ratios (alveolar dead space). In the latter segments, the $ETco_2$ to $Paco_2$ difference increases. As these segments empty, they dilute the CO_2 from other segments with normal ventilation/perfusion ratios.

An additional cause of an increased $ETco_2$ to $Paco_2$ difference during mechanical ventilation in the pediatric intensive care unit patient is shunt. In these areas of the lung, there is little ventilation with normal or increased blood flow. The shunt may be intrapulmonarily related to pulmonary parenchymal disease or extrapulmonary related to congenital, cyanotic heart disease. Although these areas do not directly affect alveolar CO_2 concentrations, the admixture of this blood into the arterial system increases the $Paco_2$, thereby increasing the $ETco_2$ to $Paco_2$ difference. The magnitude of this effect is dependent on the shunt fraction (5,6).

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Because of these problems, in the pediatric intensive care unit setting, especially in neonates and infants with pulmonary parenchymal disease, our experience suggests that measuring $ETco_2$ is generally a poor way to estimate $Paco_2$. The current study prospectively compares two noninvasive measures of $Paco_2$: $ETco_2$ and transcutaneous CO_2 (TC-CO_2) monitoring.

Methods

The study was approved by the Institutional Review Board and the Committee for the Protection of Human Subjects of the University of Missouri. Written consent was not deemed necessary, but oral consent was obtained from each patient's parent. The patient population included patients less than 48 mo of age who required tracheal intubation and mechanical ventilation for respiratory failure.

$ETco_2$ was measured by using infrared spectroscopy with a sidestream aspirator with a flow rate of 150 mL/min (Nellcor N-2500 Capnograph, Nellcor, Inc., Hayward, CA) using a previously described technique (2). The digital readout on the $ETco_2$ monitor is based on an algorithm that evaluates two successive waveforms and the valley between them. The $ETco_2$ reported by the monitor is the maximum value achieved on the first waveform. TC-CO_2 was measured using a standard TC-CO_2/O_2 device (Radiometer, Copenhagen, Denmark). The protocol for TC-CO_2 monitoring included placement and maintenance of the monitor by the respiratory therapy staff. Prior to placement, the electrode membrane was cleaned and calibrated. The monitoring site was changed every 3–4 h to avoid thermal injury, and the electrode was recalibrated prior to placement at a new site. The working temperature of the electrode was kept at 41–42°C.

When clinically indicated, ABGs were obtained. At that time, the $ETco_2$ and the TC-CO_2 were noted and recorded on the data sheet. The $ETco_2$ and the TC-CO_2 were monitored for 15 s, and the average reading during this time was noted. ABGs were measured at 37°C and corrected to the patient's temperature. Three to five sample sets (arterial blood gas, $ETco_2$ and TC-CO_2) were collected for each patient. To avoid biasing the data, no more than five sample sets were collected from any single patient.

The absolute difference between the noninvasive monitor ($ETco_2$/TC-CO_2) and the $Paco_2$ was calculated. No negative numbers were used since this would have artificially lowered the mathematical mean of the differences in the values between the noninvasive monitors' estimate of CO_2 and the $Paco_2$. For example, if the noninvasive reading deviated 7 mm Hg from the actual reading, 7 mm Hg was used, not −7 or 7. The $ETco_2$ to $Paco_2$ and TC-CO_2 to $Paco_2$ differences (absolute differences) were analyzed using a two-tailed Wilcoxon's signed rank test for pairs. Additionally, using the raw data (positive and negative numbers), a Bland-Altman analysis was performed (7). Bias, the mean difference between values, and precision, SD of the bias, were determined for TC-CO_2 versus $Paco_2$ and $ETco_2$ versus $Paco_2$. χ^2 analysis with Yates' correction using a contingency table was used to compare the number of $ETco_2$ and TC-CO_2 values whose absolute difference deviated 4 mm Hg or less from the $Paco_2$ value with those that deviated 5 mm Hg or more from the actual $Paco_2$. All data are expressed as the mean ± SD. $P < 0.05$ was considered significant.

Results

The patient population included 25 toddlers and infants ranging in age from 1 to 40 mo (10.3 ± 11.0) and in weight from 3.3 to 19.1 kg (8.9 ± 4.4). There were 18 boys and 7 girls. The underlying illnesses included pulmonary edema (cardiogenic and noncardiogenic), pneumonia (bacterial and viral), bronchiolitis, asthma, and pulmonary contusion. A total of 100 sample sets was analyzed.

The $ETco_2$ to $Paco_2$ difference was 6.8 ± 5.1 mm Hg, while the TC-CO_2 to arterial CO_2 difference was 2.3 ± 1.3 mm Hg ($P < 0.0001$). When considering the TC-CO_2 to $Paco_2$ difference, the absolute value of the TC-CO_2 deviated 4 mm Hg or less from the arterial value in 96 of the 100 values, while it deviated 5 mm Hg or more from the $Paco_2$ value four times. When considering the $ETco_2$ to $Paco_2$ difference, the absolute value of $ETco_2$ deviated 4 mm Hg or less from the $Paco_2$ value in 38 of the 100 values, while it deviated 5 mm Hg or more from the $Paco_2$ on 62 occasions ($P < 0.0001$). Bland-Altman analysis revealed a bias of −0.68 with a precision of ±2.35 when comparing the TC-CO_2 and the $Paco_2$ and a bias of −6.68 with a precision of ±5.01 when comparing $ETco_2$ and $Paco_2$ (Figures 1 and 2).

Discussion

The current study demonstrates that in infants and toddlers with respiratory failure who require mechanical ventilation, TC-CO_2 reflects $Paco_2$ more accurately than $ETco_2$. Although previous studies have evaluated the accuracy of one of the noninvasive monitors ($ETco_2$ or TC-CO_2), we are unaware of previous reports that directly compare these techniques. The current study used both monitors for the same patients and directly compared the reliability of the two techniques in infants and toddlers with pulmonary

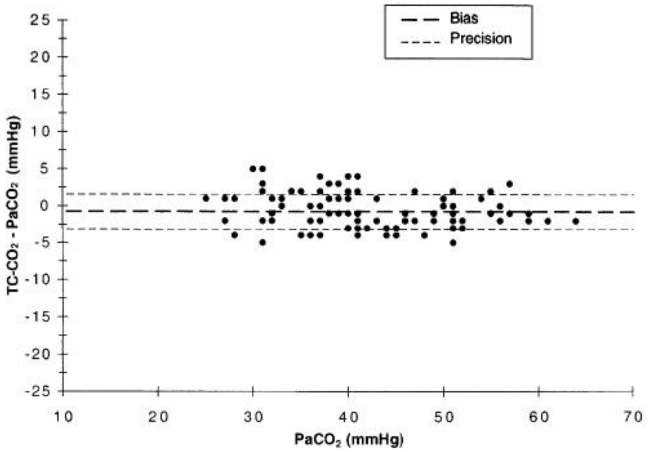

Figure 1. Differences of transcutaneous CO_2 (TC-CO_2) minus $Paco_2$ (y axis) plotted against the $Paco_2$ (x axis). The bias and precision are labeled.

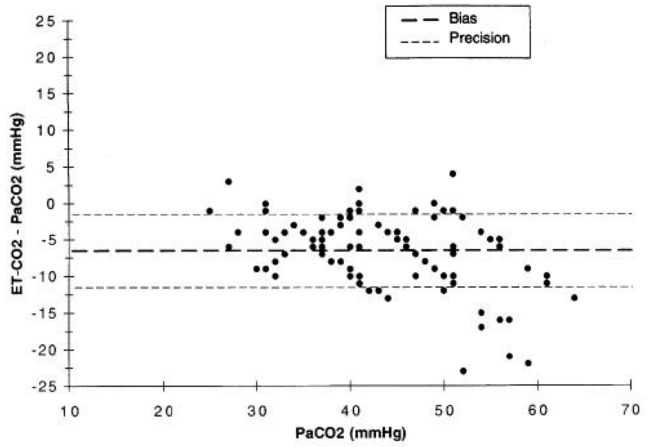

Figure 2. Differences of end-tidal CO_2 ($ETco_2$) minus $Paco_2$ (y axis) plotted against the $Paco_2$ (x axis). The bias and precision are labeled.

parenchymal diseases. TC-CO_2 monitoring proved to be a more accurate estimation of $Paco_2$ than $ETco_2$, with a lower mean absolute difference from $Paco_2$, a greater number of values that deviated 4 mm Hg or less from the actual $Paco_2$, and a better bias and precision using Bland-Altman analysis. The inaccuracy of $ETco_2$ monitoring was greatest at higher CO_2 values (Figure 2). This may be explained by the fact that the highest CO_2 values occurred in those patients with the most severe lung disease treated with permissive hypercapnia.

Previous studies have validated the accuracy of TC-CO_2 monitoring in the neonatal population (8). Its applications outside the neonatal population have been limited. The current study documents its efficacy in patients up to 40 months of age who weigh up to 19.1 kg. Further studies are needed to determine its accuracy in older patients. Although we found TC-CO_2 monitoring to be of value, previous studies have demonstrated that transcutaneous O_2 is not generally reliable (9). Therefore, we did not attempt to use transcutaneous O_2 monitoring in our patient population.

The technique for TC-CO_2 monitoring has been previously described (10). Proper use and accuracy of this technique is dependent on appropriate training and the expertise of personnel. Although we found TC-CO_2 to be an accurate reflection of $Paco_2$ in most patients, several factors may affect this accuracy. Technical variables, such as trapped air bubbles, improper placement technique, damaged membranes, and inappropriate calibration techniques, can be avoided by careful use of the equipment and training of the respiratory therapy staff. Aside from technical problems, patient problems may affect the accuracy of TC-CO_2 monitoring. These may include variations in skin thickness, the presence of edema, tissue hypoperfusion, or the administration of vasoconstricting drugs. All of these factors affect the ability of CO_2 to diffuse from the capillary bed to the membrane of the monitor. Martin et al. (11) also demonstrated that the TC-CO_2 to $Paco_2$ gradient may widen as the $Paco_2$ increases due to an imbalance between local tissue CO_2 production and removal. We noted no such inaccuracy in our patients with hypercarbia; however, there was a limited number (29 of 100) of $Paco_2$ values that were 50 mm Hg or greater.

In summary, the current study demonstrates that in infants and toddlers with respiratory failure, TC-CO_2 provides a more accurate estimate of $Paco_2$ than does $ETco_2$ monitoring. Because no technique can be expected to be 100% reliable, periodic calibration with $Paco_2$ values is recommended. Although the current study included only tracheally intubated and mechanically ventilated patients, TC-CO_2 monitoring can be used in spontaneously breathing patients without an artificial airway. The two noninvasive monitors of $Paco_2$ ($ETco_2$ and TC-CO_2) should be used to compliment rather than to exclude one another. When one proves to be inaccurate, the other should be tried. In this way, the optimal noninvasive monitor for each individual patient can be determined. Although TC-CO_2 monitoring may be a more accurate means of estimating $Paco_2$, $ETco_2$ provides additional useful information since it documents the intratracheal position of the endotracheal tube and serves as an additional safety monitor to alert one to a ventilator disconnection. These additional features are not provided by the TC-CO_2 monitor.

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