Transcutaneous Carbon Dioxide Pressure Monitoring in a Specialized Weaning Unit

Douglas C Johnson MD, Salma Batool MD, Ronald Dalbec RRT

OBJECTIVE: To evaluate transcutaneously measured $P_{\text{tcCO}_2}$ ($P_{\text{tcCO}_2}$) values during ventilator weaning and during bronchoscopies on ventilated patients, and to compare $P_{\text{tcCO}_2}$ values to $P_{\text{aCO}_2}$ values from arterial blood analysis and end-tidal $P_{\text{CO}_2}$ ($P_{\text{ETCO}_2}$) values from capnography. METHODS: In our specialized weaning unit we measured $P_{\text{tcCO}_2}$ in tracheostomized patients with prolonged weaning failure during daytime spontaneous breathing trials (SBTs) (23 measurement sessions in 15 patients), during their first nights off the ventilator (12 measurement sessions in 12 patients), during bronchoscopy while ventilated (80 measurement sessions in 21 patients), simultaneous with arterial blood draw for blood gas analysis (48 measurements in 38 patients), and simultaneous with $P_{\text{ETCO}_2}$ measurements (39 measurements in 31 patients). RESULTS: There were often large changes (> 10 mm Hg) in $P_{\text{tcCO}_2}$ during daytime SBTs (23%) and the initial overnight off-the-ventilator periods (42%), which influenced the decisions of whether to continue the SBT. $P_{\text{tcCO}_2}$ often rose during bronchoscopy (mean ± SD increase of 10.7 ± 5.8 mm Hg), which influenced the physician to change the ventilator settings 44% of the time. $P_{\text{aCO}_2}$ closely matched $P_{\text{tcCO}_2}$ (mean ± SD difference of 0.5 ± 4.1 mm Hg). There was a greater difference between $P_{\text{aCO}_2}$ and $P_{\text{ETCO}_2}$ (3.7 ± 7.7 mm Hg during prolonged exhalation, and 6.8 ± 7.2 mm Hg during tidal breathing). CONCLUSIONS: Monitoring $P_{\text{tcCO}_2}$ is very helpful in assessing and managing patients undergoing SBTs, during the first night off the ventilator, and during bronchoscopy on ventilated patients. $P_{\text{tcCO}_2}$ more closely matches $P_{\text{aCO}_2}$ than does $P_{\text{ETCO}_2}$. Key words: capnometry, capnography, carbon dioxide, bronchoscopy, physiologic monitoring, weaning. [Respir Care 2008;53(8):1042–1047. © 2008 Daedalus Enterprises]

Introduction

Patients with respiratory failure are at risk for worse hypercapnia when off the ventilator, as well as during bronchoscopy. Assessment of hypercapnia and changes in arterial $P_{\text{CO}_2}$ ($P_{\text{aCO}_2}$) are often used to determine whether a patient receiving a high level of ventilatory support can be considered for a spontaneous breathing trial (SBT) and whether the patient is tolerating the SBT. Typically, $P_{\text{aCO}_2}$ is assessed by drawing an arterial blood gas sample. However, drawing arterial blood is time-consuming and often painful, there is a delay until results are known, and the results provide only a snapshot of the patient’s gas exchange, which may be misleading if the patient’s ventilation increased due to the painful arterial puncture.

Other methods to assess hypercapnia include end-tidal $P_{\text{CO}_2}$ ($P_{\text{ETCO}_2}$) and transcutaneous $P_{\text{CO}_2}$ ($P_{\text{tcCO}_2}$) monitoring. $P_{\text{ETCO}_2}$ monitoring has been used during weaning from mechanical ventilation. $P_{\text{tcCO}_2}$ monitoring has been used during noninvasive ventilation. Though $P_{\text{ETCO}_2}$ closely matches $P_{\text{aCO}_2}$ in patients with normal lungs and normal tidal volume ($V_T$), it does not match $P_{\text{aCO}_2}$ as well in patients with severe lung disease or in patients with normal lungs undergoing endoscopy, and is impractical during bronchoscopy.

Though $P_{\text{tcCO}_2}$ monitors have been used for years, especially in pediatrics, recent advances in technology have provided easy-to-use, self-calibrating devices that contin-
Transcutaneous Carbon Dioxide Pressure Monitoring in a Specialized Weaning Unit

We wanted to evaluate the role of $P_{tcCO_2}$ monitoring in our 8-bed specialized weaning unit in a rehabilitation/long-term-acute-care hospital, which receives patients from acute-care hospitals for ventilator weaning. Our hypotheses were:

- $P_{tcCO_2}$ would detect important changes in alveolar ventilation during SBTs in the day and overnight, and alter ventilator management
- $P_{tcCO_2}$ would detect important changes in alveolar ventilation during bronchoscopy in ventilator-dependent patients, and lead to changes in ventilator settings
- $P_{tcCO_2}$ would better reflect $P_{aCO_2}$ in ventilator-dependent patients than does $P_{ETCO_2}$

Methods

We have routinely used $P_{tcCO_2}$ monitoring since November 2004. All patients in our ventilator weaning program from December 2004 to December 2005 were eligible for the study. Patients were studied prospectively, with results included from patients who consented to our institutional-review-board-approved protocol to allow use of their data. All the subjects had tracheostomy tubes, were ventilator-dependent for at least 2 weeks, and met the criteria for prolonged weaning failure.

$P_{tcCO_2}$ was measured (Digital Monitoring System, Sentec, Therwil, Switzerland) during blood draws for arterial blood gas (ABG) analysis, during bronchoscopies on ventilated patients, during SBTs, and during the patient’s first night off the ventilator. $P_{etCO_2}$, respiratory mechanics, and Borg dyspnea scale were measured at the start and the end of the SBTs in most patients. The respiratory mechanics measurements included respiratory rate, $V_T$, rapid shallow breathing index, maximum inspiratory pressure, maximum expiratory pressure, and vital capacity.

The sensor combines a pulse oximeter and a membrane-covered electrochemical sensor to measure $P_{tcCO_2}$, and warms the skin to 42°C. The monitor provides a digital display of $P_{tcCO_2}$, oxygen saturation, heart rate, and graphic trend data. The display is updated once per second, with no software averaging of $P_{tcCO_2}$, and about 4-second averaging of oxygen saturation. There is a docking station for the sensor, which automatically keeps the sensor calibrated, using a calibration gas cylinder. The sensor is also recalibrated each time it is placed back in the docking station. The calibration usually takes 2–5 min. For patient use, the sensor (which is 15 mm in diameter, 8 mm in height) is removed from the docking chamber, put in an ear clip, a drop of sensor gel is placed on the sensor, and the sensor is clipped to the ear lobe. It usually takes 2–4 min to reach a stable $P_{tcCO_2}$ reading, with changes in $P_{tcCO_2}$ starting within a minute of abrupt changes in ventilation.

The sensor was kept in place throughout the bronchoscopy, SBT, or overnight period, and $P_{tcCO_2}$, oxygen saturation, and heart rate data were collected every 10 s with a data-logging device (Pocket-Logger, Pace Scientific, Moorsville, North Carolina) attached to the $P_{tcCO_2}$ monitor. The data-logging device collects up to 4 days of data and allows computer download, display, and analysis of results. The sensor membrane was routinely changed every 2 weeks. Occasionally the membrane needed to be changed sooner if the monitor displayed a message to change the membrane.

For $P_{tcCO_2}$, ABG, and $P_{ETCO_2}$ measurements the first step was placing the $P_{tcCO_2}$ monitor on the patient and waiting for a stable $P_{tcCO_2}$ reading. $P_{ETCO_2}$ was then also monitored (NICO, Novametrix Medical Systems, Wallingford, Connecticut). The $P_{ETCO_2}$ during tidal breathing (the highest $P_{ETCO_2}$ of at least 4 regular breaths) and $P_{tcCO_2}$ were then recorded at the time the arterial blood sample was drawn. Then $P_{ETCO_2}$ was measured with a prolonged exhalation (the highest $P_{ETCO_2}$ of at least 2 efforts), with the patient asked to take a breath in, and then blow all the way out (for at least 5 s). The $P_{tcCO_2}$, ABG, and $P_{ETCO_2}$ measurements were done when ABG analysis was ordered for clinical purposes. Most patients had an initial ABG analysis with simultaneous $P_{tcCO_2}$ and $P_{ETCO_2}$ measurements. Thereafter, $P_{CO_2}$ was followed with $P_{ETCO_2}$ and/or $P_{tcCO_2}$; additional arterial blood samples were rarely drawn.

SBTs were performed as tolerated by the patient, up to the duration specified by the physician, with baseline $P_{tcCO_2}$ taken once the $P_{tcCO_2}$ reading was stable. Overnight off-the-ventilator periods were begun once the patient had stable $P_{tcCO_2}$ (or $P_{ETCO_2}$) and stable respiratory mechanics during prolonged (usually 16-h) SBTs in the day. Baseline $P_{tcCO_2}$ was taken at the start of the evening measurements (usually near 9:00 PM). The peak $P_{tcCO_2}$ was compared to baseline.

Bronchoscopy was performed via the tracheostomy tube, under conscious sedation with fentanyl and midazolam, while the patient was being ventilated with a pressure control mode and a set inspiratory pressure, positive end-expiratory pressure, inspiratory time, and backup respiratory rate. The ventilator was usually initially set to match the patient’s baseline respiratory rate and pre-sedation $V_T$. Most bronchoscopies lasted more than 30 min in patients with mucus plugging and lobar or segmental atelectasis. Most bronchoscopies involved repeated insertions and re-
mova of the bronchoscope, acetylcysteine/saline installa-
tions, and air insufflation to segmental bronchi in the
atelectatic areas. As a rule, the bronchoscopist adjusted the
ventilator’s minute volume by increasing the inspiratory
pressure and/or respiratory rate if $P_{tcCO_2}$ rose to $>50$ mm Hg and
> 10 mm Hg above baseline.

The results are expressed as mean ± standard deviation.
The differences between $P_{acCO_2}$ and $P_{tcCO_2}$ and between
$P_{acCO_2}$ and $P_{ETCO_2}$ were compared with a paired Student’s $t$ test. Values from patients with and without chronic ob-
structive pulmonary disease (COPD) were compared with
an unpaired Student’s $t$ test. Correlation coefficients are
reported for $P_{acCO_2}$ and $P_{ETCO_2}$ versus $P_{acCO_2}$. A Bland-
Altman analysis was performed of $P_{acCO_2}$ minus $P_{tcCO_2}$ versus $P_{acCO_2}$.

**Results**

Forty-one patients were studied. $P_{acCO_2}$ was measured
during 48 simultaneous arterial blood draws in 38 patients,
39 simultaneous blood draws/P$_{ETCO_2}$ measurements in 31
patients, 80 bronchoscopies in 21 patients, 23 SBTs in 15
patients, 14 SBTs with starting/ending respiratory mechan-
ic in 11 patients, and 12 initial nights off the ventilator in
12 patients. Though the recommended maximum duration for
sensor placement is 8 hours because of concern about
heating the skin to 42°C, none of the patients had any
complaints of discomfort or evidence of skin damage or
irritation from the sensor being on the ear overnight, for up
to 10 hours.

$P_{acCO_2}$ closely matched $P_{tcCO_2}$ in the Bland-Altman anal-
ysis (Fig. 1). The mean $P_{acCO_2}$ minus $P_{tcCO_2}$ difference was
0.5 ± 4.1 mm Hg ($n = 48$), and the mean of the absolute
differences was 2.9 ± 2.9 mm Hg.

$P_{tcCO_2}$ matched $P_{acCO_2}$ (the $P_{acCO_2}$ minus $P_{tcCO_2}$ difference
was 0.4 ± 4.4 mm Hg, $n = 39$) more closely than did
prolonged-exhalation $P_{ETCO_2}$ ($P = .006$) or tidal-breathing
$P_{ETCO_2}$ ($P < .001$) (Fig. 2). The $P_{acCO_2}$ minus $P_{ETCO_2}$ dif-
ference was lower ($P < .001$) during prolonged exhalation
(3.7 ± 7.7 mm Hg, $n = 39$) than during tidal breathing
(6.8 ± 7.2 mm Hg, $n = 39$).

The 31 patients with matched $P_{acCO_2}$, $P_{tcCO_2}$, and $P_{ETCO_2}$
measurements had a mean age of 61 ± 15 y, and
included 21 complex medical patients, of whom 9 had a
history of COPD, 6 had spinal cord injury (of whom 1 had
COPD), and 4 had respiratory muscle weakness from other
neurologic diseases. Table 1 shows the results of the $P_{acCO_2}$,
$P_{tcCO_2}$, and $P_{ETCO_2}$ differences in patients with and without
COPD.

During the SBTs (Fig. 3), $P_{acCO_2}$ rose 7.4 ± 7.3 mm Hg
(from 46.9 ± 6.3 mm Hg to 54.3 ± 10.3 mm Hg), and it
rose > 10 mm Hg in 6 (23%) of 23 SBTs. The 15 patients
in the SBT group had a mean age of 73 ± 12 y, and
included 14 complex medical patients, of whom 6 had
COPD, and 1 had amyotrophic lateral sclerosis and pneu-
monia. Table 2 shows the respiratory mechanics results
from the 14 SBTs. Some patients had large $P_{tcCO_2}$ rises
with stable respiratory mechanics, and others had stable
$P_{tcCO_2}$ despite worse respiratory mechanics.

During the initial night off the ventilator (Fig. 4), $P_{tcCO_2}$
rose 12.8 ± 10.9 mm Hg (from 47.2 ± 4.1 mm Hg to
59.9 ± 13.2 mm Hg), and it rose > 10 mm Hg in 5 (42%)
of 12 patients. Those 12 patients’ mean age was 64 ± 17 y,
and they included 10 complex medical patients, of whom
3 had COPD, and 2 had C4 spinal cord injury with quad-
riplegia and pneumonia. With 9 of the patients we then attempted to keep them off the ventilator thereafter (2 whose \( P_{\text{tcCO}_2} \) rose \( > 10 \text{ mm Hg} \), and 7 whose \( P_{\text{tcCO}_2} \) rose \( \leq 10 \text{ mm Hg} \)). Five of those 9 patients were able to stay off the ventilator permanently, and 4 had to go back on the ventilator (after 3, 3, 6, and 15 d). Those 4 patients (ages 56, 72, 85, and 86 y) all had complex medical problems and increased pulmonary secretions at the time of needing renewed ventilator support.

\( P_{\text{tcCO}_2} \) often rose during bronchoscopy (Fig. 5) (a rise of \( 10.7 \pm 5.8 \text{ mm Hg} \), from \( 43.4 \pm 7.3 \text{ mm Hg} \) to \( 54 \pm 9.8 \text{ mm Hg} \) \( n = 80 \)). The \( P_{\text{tcCO}_2} \) findings influenced the physician to change ventilator settings by increasing minute volume (by raising the pressure-control level and/or the respiratory rate) during 44% of the bronchoscopies, and many patients were managed by removing the bronchoscope until \( P_{\text{tcCO}_2} \) improved. It is likely the \( P_{\text{tcCO}_2} \) would have risen even more if \( P_{\text{tcCO}_2} \) had not been monitored. During half the bronchoscopies, \( P_{\text{tcCO}_2} \) rose at least \( 10 \text{ mm Hg} \) and peak \( P_{\text{tcCO}_2} \) was at least \( 50 \text{ mm Hg} \). The bronchoscopist increased minute volume in 27 of those 40 bronchoscopies, but in only 8 of the 40 bronchoscopies that had \( P_{\text{tcCO}_2} \) rises of \( < 10 \text{ mm Hg} \) or peak \( P_{\text{tcCO}_2} \) \( < 50 \text{ mm Hg} \). Without ventilator adjustments, it is likely that 48 (60%) of the 80 bronchoscopies would have had a \( P_{\text{tcCO}_2} \) rise of at least \( 10 \text{ mm Hg} \) and peak \( P_{\text{tcCO}_2} \) of at least \( 50 \text{ mm Hg} \).

**Discussion**

We found continuous and noninvasive \( P_{\text{tcCO}_2} \) measurement very helpful in assessing and managing patients dur-
ing SBTs, and during bronchoscopies on ventilated patients. PtcCO2 monitoring is comfortable and well tolerated by adult patients. Our study confirms the findings of others,4,7,8 that PtcCO2 values from the Sentec monitor closely match PaCO2 values from arterial blood analysis.

We found PtcCO2 a better measure of PaCO2 than PETCO2. Though PETCO2 during prolonged exhalation was close to PaCO2 in patients without COPD, it significantly underestimated PaCO2 in patients with COPD, who probably had increased dead space. PETCO2, during tidal breathing underestimated PaCO2 in patients with and without COPD. Thus, PETCO2 seems a good measure only in patients without COPD during a prolonged exhalation maneuver, whereas PtcCO2 is a good measure for continuous monitoring in all patients.

PtcCO2 significantly increased in some patients during SBTs and their initial nights off the ventilator. Though most of our patients with stable respiratory mechanics had stable PtcCO2 during SBTs, some patients had stable respiratory mechanics with substantial elevations in PaCO2, and others had worsening respiratory mechanics but stable PtcCO2. We suspect that differences in respiratory drive accounted for the discrepancies between PtcCO2 and respiratory mechanics. Patients with a high respiratory drive would preserve PaCO2 despite worse mechanics, whereas those with a low respiratory drive would increase PaCO2 despite fairly stable respiratory mechanics.

The criteria to determine if a patient receiving a high level of ventilatory support can be considered for an SBT include adequate oxygenation, stable cardiovascular status, and no substantial respiratory acidosis.1 This assessment typically includes ABG analysis. PtcCO2 monitoring allows a noninvasive assessment of PaCO2 that accurately reflects PtcCO2, even in patients with substantial lung disease, whereas PETCO2 often underestimates PaCO2. Therefore, PtcCO2 monitoring should allow fewer arterial blood draws and reduce the need for arterial lines.

The criteria of SBT success include subjective variables (eg, worse mental status, patient discomfort, diaphoresis, and signs of increased work of breathing) and objective measurements, including hemodynamic stability and gas exchange acceptability (oximetry-measured oxygen saturation > 85–90%, pH > 7.32, PaCO2 increase < 10 mm Hg).1 Though continuous oximetry and intermittent subjective clinical assessment during SBT are routine, PaCO2 is not typically measured. PETCO2 and PtcCO2 allow noninvasive assessment of the other component of gas exchange: PaCO2.

Variables that have been studied as predictors of the outcome of ventilator discontinuation include minute volume, maximum negative inspiratory pressure, and the CROP (compliance, rate, oxygenation, and pressure) index while on the ventilator; and respiratory rate, Vt, and rapid shallow breathing index during a brief SBT.1 Daily screening of respiratory function can shorten the duration of mechanical ventilation and improve the re-intubation rate.10 PETCO2 was one of the elements of a computer-driven weaning protocol that shortened weaning duration and total ventilation duration in intensive-care patients who did not have tracheostomy tubes.11 PtcCO2 matches PaCO2 better than does PETCO2, so PtcCO2 monitoring has an advantage over PETCO2 monitoring.

Though respiratory mechanics and tolerance of an SBT help predict whether the patient can stay off the ventilator, many patients still fail extubation; studies have reported re-intubation rates of 4%,10 7%,12 10%,10 and 18%.13 Prolonged-weaning-failure patients include those who need more than 3 SBTs or more than 7 days of weaning after the first SBT, and are estimated to be about 15% of ventilated patients.9

Our approach to managing prolonged weaning failure includes: optimizing lung function by treating infections; bronchodilators if indicated; secretion-clearance, including mechanical in-exsufflation; changing the tracheostomy tube if needed, to allow use of a speaking valve when off the ventilator; and bronchoscopy with acetylcysteine lavage, then air insufflation in patients with atelectasis. On admission we obtained simultaneous PETCO2, PtcCO2, and PaCO2 measurements. The subjects had continuous oximetry monitoring and morning assessment of respiratory mechanics and PETCO2 followed by an SBT if they passed the morning assessment, then another assessment of respiratory mechanics and PETCO2 at the end of the SBT. We monitored continuous PtcCO2 during the initial SBT and during the first night off the ventilator. We also did spot checks of PtcCO2 in patients whose PETCO2 did not closely match their PaCO2.

We had only one PtcCO2 monitor, so we had to set an order of priority for its use. We prioritized bronchoscopy over SBT. In general, we extended the time off the venti-
tilator in patients who had both stable respiratory mechanics and stable $P_{tcCO_2}$, but not in patients who had worse respiratory mechanics or worse $P_{tcCO_2}$. If a patient maintained stable mechanics and stable $P_{tcCO_2}$ during SBT and overnight off the ventilator, we then tried discontinuing ventilator support. $P_{tcCO_2}$ monitoring influenced our decisions on the duration of SBT and whether to end ventilatory support.

$P_{CO_2}$ rise has been reported in moderate-sedation procedures, including thoracoscopy, colonoscopy, and bronchoscopy in non-ventilated patients. In non-ventilated sedated patients undergoing bronchoscopy, Chhajed et al found a $P_{tcCO_2}$ rise of 9.5 ± 5.3 mm Hg. We found that $P_{tcCO_2}$ also often increases during bronchoscopy on ventilated patients; $P_{tcCO_2}$ rose ≥ 10 mm Hg above baseline to at least 50 mm Hg in 50% of the bronchoscopies. Prior to $P_{tcCO_2}$ monitoring we relied on changes in oxygen saturation, respiratory rate, and $V_T$ (in ventilated patients) as the indicator that $P_{aCO_2}$ might be rising. With $P_{tcCO_2}$ monitoring we know whether to adjust the fraction of inspired oxygen (if oxygen saturation decreased), remove the bronchoscope for a while, or increase the ventilator rate and/or pressure-control level (if increased $P_{tcCO_2}$), or could continue with the procedure without changes (if oxygen saturation and $P_{tcCO_2}$ were stable).

Continuous oximetry was a great advance for monitoring patients with respiratory problems, and is now routinely used to monitor patients with respiratory failure and during moderate-sedation procedures. Continuous combined monitoring of $P_{tcCO_2}$ and oxygen saturation shows great promise to further improve the care of patients in respiratory failure and during moderate sedation. Further studies are needed to evaluate whether $P_{tcCO_2}$ monitoring improves patient outcomes.

Conclusions

$P_{tcCO_2}$ provides continuous and noninvasive measurement of $P_{CO_2}$ that closely matches $P_{tcCO_2}$ and $P_{tcCO_2}$ is a better measure of $P_{tcCO_2}$ than is $P_{ETCO_2}$. $P_{tcCO_2}$ rises substantially in some patients during SBTs and during the first night off the ventilator, and often rises during bronchoscopy on ventilated patients, so $P_{tcCO_2}$ can help guide the duration of SBTs, discontinuation of ventilator support, and ventilator settings during bronchoscopy.

REFERENCES