RELATIONSHIP BETWEEN ARTERIAL CARBON DIOXIDE AND END-TIDAL CARBON DIOXIDE WHEN A NASAL SAMPLING PORT IS USED

Stephen E. McNulty, DO, John Roy, MD, PhD, Marc Torjman, MEd, and Joseph L. Seltzer, MD

McNulty SE, Roy J, Torjman M, Seltzer JL. Relationship between arterial carbon dioxide and end-tidal carbon dioxide when a nasal sampling port is used.

J Clin Monit 1990;6:93–98

ABSTRACT. End-tidal carbon dioxide ($ETCO_2$) values obtained from awake nonintubated patients may prove to be useful in estimating a patient's ventilatory status. This study examined the relationship between arterial carbon dioxide tension ($PaCO_2$) and $ETCO_2$ during the preoperative period in 20 premedicated patients undergoing various surgical procedures. $ETCO_2$ was sampled from a 16-gauge intravenous catheter pierced through one of the two nasal oxygen prongs and measured at various oxygen flow rates (2, 4, and 6 L/min) by an on-line $ETCO_2$ monitor with analog display. Both peak and time-averaged values for $ETCO_2$ were recorded. The results showed that the peak $ETCO_2$ values (mean = 38.8 mm Hg) correlated more closely with the $PaCO_2$ values (mean = 38.8 mm Hg; correlation coefficient r = 0.76) than did the average $ETCO_2$ values irrespective of the oxygen flow rates. The time-averaged $PaCO_2$–$ETCO_2$ difference was significantly greater than the $PaCO_2$–peak $ETCO_2$ difference ($P < 0.001$). Values for subgroups within the patient population were also analyzed, and it was shown that patients with minute respiratory rates greater than 20 but less than 30 and patients age 65 years or older did not differ from the overall studied patient population with regard to $PaCO_2$–$ETCO_2$ difference. A small subset of patients with respiratory rates of 30/min or greater (n = 30) did show a significant increase in the $PaCO_2$–$ETCO_2$ difference ($P < 0.001$). It was concluded that under the conditions of this study, peak $ETCO_2$ values did correlate with $PaCO_2$ values and were not significantly affected by oxygen flow rate. However, obtaining peak $ETCO_2$ values is clinically more difficult, especially when partial airway obstruction is present.

KEY WORDS. Carbon dioxide: arterial, end-tidal. Measurement techniques: capnography. Monitoring: carbon dioxide, capnography.

The use of end-tidal carbon dioxide ($ETCO_2$) monitoring has improved the care of anesthetized patients and may provide valuable information relating to ventilation in the operative and critical care settings. Numerous reports have correlated $ETCO_2$ from intubated patients undergoing general anesthesia with the $PaCO_2$ measured by analysis of an arterial blood sample [1–3]. The application of expiratory CO_2 monitoring to sedated patients has recently been advanced [4–8], although the value of this monitoring has yet to be established. A recently described method for measuring $ETCO_2$ involves the use of nasal prongs through which a teflon intravenous catheter attached to a capnometer sampling line is inserted [9]. However, the method's accuracy has been questioned because the expired gas may be substantially diluted by oxygen flow through the nasal prongs [10]. The study presented here compares $ETCO_2$ values for spontaneously breathing, premedicated patients obtained from a nasal sampling port

From the Department of Anesthesiology, Jefferson Medical College, Thomas Jefferson University, Philadelphia, PA.

Received Nov 8, 1988, and in revised form Feb 23, 1989. Accepted for publication Jul 14, 1989.

Address correspondence to Dr McNulty, Thomas Jefferson University, Department of Anesthesiology, 11th & Walnut Streets, Philadelphia, PA 19107.

with the actual measured $PaCO_2$ values obtained from arterial samples. An analysis of some variables that may affect interpretation of capnography using this method is also presented.

METHODS AND MATERIALS

After approval by the institutional review board, human subjects research committee, 20 patients with ASA physical status II through IV were selected for study. Written informed consent was obtained from each patient. Patients scheduled for a surgical procedure in which direct arterial blood pressure monitoring was appropriate were eligible for the study. Operations included cardiac (n = 7), neurosurgical (n = 9), vascular (n = 2), and orthopedic (n = 2) procedures. Pulmonary status was not a discriminating factor for the study, but no patients had a history of significant pulmonary dysfunction.

The $ETCO_2$ monitoring system was constructed from an INSYTE 16-gauge, 5-cm intravenous catheter (Deseret Medical, Inc; Sandy, UT) that was pierced through one of the two nasal cannula ports (Marquest Medical Products, Inc; Englewood, CO) so that 1.0 to 1.5 cm of catheter extended beyond the tip of the nasal prongs. The proximal part of the catheter was connected to a 120-in Datex sampling tube (Dryden, Corp; Indianapolis, IN) and then to a Puritan-Bennett Datex 254 gas analyzer monitor with model 250 video display (Datex Instrumentation Corp; Helsinki, Finland). Arterial blood gas samples were analyzed with a Radiometer ABL 330 (Radiometer America, Inc; Westlake, OH). A two-point calibration of the Datex gas monitor was performed before the study for each patient using a monitor calibration gas mixture (Puritan-Bennett, Wilmington, MA).

The choice of preanesthetic medication on the day of surgery was at the discretion of the attending anesthesiologist. Following the placement of the indwelling radial artery catheter, supplemental oxygen was administered using the modified nasal prongs described previously. Each patient received oxygen at three different flow rates (2, 4, or 6 L/min) selected randomly and changed at 5-minute intervals. In the last minute of each 5-minute interval, all expiratory CO_2 waveforms having the component parts of a normal capnogram—ascent, plateau, descent, and baseline—were observed, averaged, and recorded. In the last 30 seconds of each 5-minute interval, a value for the best waveform was recorded. The best waveform was distinguished by a steep ascending slope and a shallow ascending plateau with a sharp descent to baseline. The angle formed at the junction of the ascent and plateau lines as well as the angle formed at the junction of the plateau and descent lines most closely approximated 90 degrees. The amplitude of the transition between ascent and plateau phases was usually higher in the peak waveform compared with average waveforms. The peak plateau capnogram was not always the highest digital reading, although the mean value of the average waveforms was always lower than the value for the peak waveform. In Figure 1, the difference between a peak waveform and an average waveform is demonstrated. Although the capnogram average waveform clearly indicates abnormal ventilatory dynamics (nonturbulent partial airway obstruction), it still possesses all of the component parts of a normal waveform and therefore would be included for averaging.

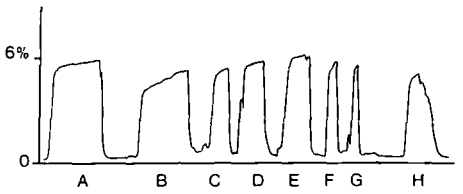

Fig 1. Actual capnogram waveforms for an individual patient using a nasal sampling catheter: peak plateau (A), average plateau (B), acceptable plateaus obtained during rapid breathing (C, D, E), and unacceptable waveforms (F, G, H).

When the peak $ETCO_2$ capnogram was judged to be less than optimal, a notation was made as to any associated physiologic abnormalities at the time of sampling. Arterial blood gases were obtained at the end of each of the three 5-minute intervals and analyzed immediately with no correction for body temperature variation from 37°C. Temperature correction of blood gases was not performed for several reasons. Variations in patient temperature would equally affect comparisons made at the various flow rates as well as the peak-to-average $PaCO_2$–$ETCO_2$ differences and so would not significantly affect the results. Further, it might be inappropriate to temperature-correct blood gases without temperature-correcting $ETCO_2$, since the infrared analysis utilized for this study would be similarly affected by a patient (alveolar) temperature at variance with 37°C. Comparisons of $PaCO_2$–$ETCO_2$ differences at various flow rates were statistically analyzed using analysis of variance (ANOVA) with a significance level less than 0.05. Bias and precision were calculated as described by Bland and Altman [11].

RESULTS

Figure 2 plots $PaCO_2$ against peak $ETCO_2$ values. The correlation coefficient was 0.76 ($P < 0.001$). The overall

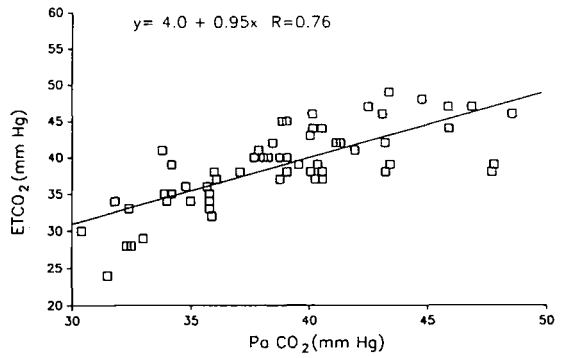

Fig 2. Individual data points for arterial carbon dioxide tension ($PaCO_2$) versus peak end-tidal carbon dioxide ($ETCO_2$) values at combined nasal oxygen flow rates.

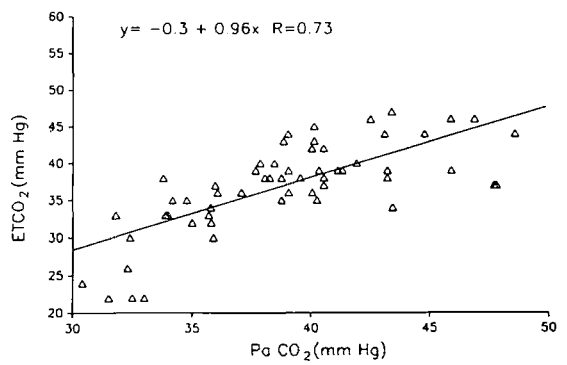

Fig 3. Individual data points for arterial carbon dioxide tension ($PaCO_2$) versus average end-tidal carbon dioxide ($ETCO_2$) values at combined nasal oxygen flow rates.

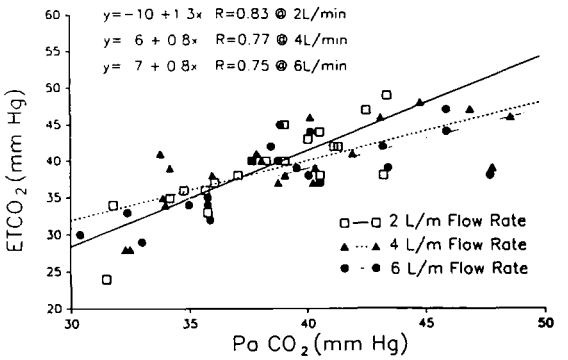

Fig 4. Individual data points for arterial carbon dioxide tension ($PaCO_2$) versus peak end-tidal carbon dioxide ($ETCO_2$) values differentiating the three different nasal oxygen flow rates.

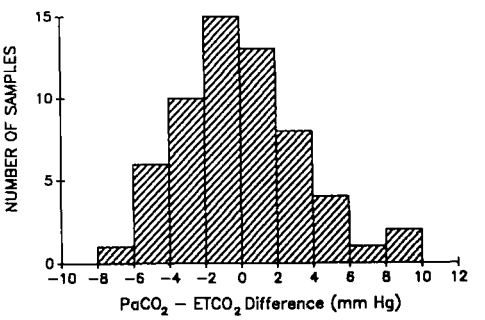

Fig 5. Histogram of the frequency distribution of arterial carbon dioxide tension ($PaCO_2$)–peak end-tidal carbon dioxide ($ETCO_2$) differences at combined nasal oxygen flow rates.

Table 1. Comparison of $PaCO_2$, $ETCO_2$, $PaCO_2$–$ETCO_2$ Bias and Precision and PaO_2 Values (Mean ± SD) at Different Nasal Oxygen Flow Rates

Variable	Flow Rates		
	2 L/min	4 L/min	6 L/min
$PaCO_2$	38.2 ± 3.5	39.2 ± 5.0	39.0 ± 4.6
Peak $ETCO_2$	39.0 ± 5.4	39.4 ± 5.4	38.1 ± 5.0
$PaCO_2$–peak $ETCO_2$ (bias ± precision)	−0.8 ± 3.2	−0.1 ± 3.8	0.8 ± 3.4
$PaCO_2$–average $ETCO_2$ (bias ± precision)	0.6 ± 3.2[a]	1.9 ± 4.0[a]	3.3 ± 4.1[a]
PaO_2	115 ± 30[b]	148 ± 43[b]	182 ± 58[b]

[a] Significantly different ($P < 0.007$) by analysis of variance.
[b] Significantly different ($P < 0.001$) by analysis of variance.
$PaCO_2$ = arterial carbon dioxide tension, $ETCO_2$ = end-tidal carbon dioxide.

mean value (± SD) of $PaCO_2$ was 38.8 mm Hg ± 4.5 and was not significantly different from the peak $ETCO_2$ of 38.8 ± 5.4. Figure 3 plots $PaCO_2$ against average $ETCO_2$ values. Figure 4 illustrates the $PaCO_2$ and peak $ETCO_2$ data plotted with respect to differing nasal cannula oxygen flow rates. There was no significant difference between the groups when compared by ANOVA. Figure 5 is a histogram of the $PaCO_2$–$ETCO_2$ differences. Table 1 lists the means of the grouped data, with comparisons of the $PaCO_2$ and peak $ETCO_2$ values, as well as $PaCO_2$–$ETCO_2$ differences for both peak and average plateau readings at various

Table 2. Comparison of Bias and Precision and Bias Using Peak $ETCO_2$ in Subsets of the Patient Population (Mean ± SD)

Patient Subset	Bias and Precision *vs.* Bias Using Peak $ETCO_2$	
Age ≥ 65 yr	1.8 ± 4.4	NS
RR ≥ 20/min	0.1 ± 3.2	NS
RR ≥ 30/min	5.3 ± 1.9	$P < 0.001$[a]
Average $ETCO_2$	2.0 ± 1.5	$P < 0.001$[b]

[a]Student's *t* test (two-sided, unpaired).
[b]Student's *t* test (paired).
$ETCO_2$ = end-tidal carbon dioxide; NS = not significant; RR = respiratory rate.

flow rates. There was no significant difference between the groups as analyzed by ANOVA. PaO_2 values in Table 1 did show a significant increase with correspondingly higher oxygen flow rates ($P < 0.001$ using ANOVA). Table 2 lists the bias and precision of $PaCO_2$–$ETCO_2$ in the various subgroups and compares these values with the bias and precision of $PaCO_2$–peak $ETCO_2$. Compared with the total population there was a significant difference in patients with respiratory rates of 30/min or greater ($P < 0.001$), as well as a significant difference between the average and peak $PaCO_2$–$ETCO_2$ differences ($P < 0.001$).

DISCUSSION

Our results indicate that there is a correlation between $ETCO_2$ and $PaCO_2$ under the conditions of this study. The most notable factor that influenced the accuracy of correlation was the ability of the observer to differentiate the peak plateau or best expiratory CO_2 waveform from the average of plateau waveforms. The rationale for making this differentiation of waveforms is based on a potential difference in observer technique. Periodic monitoring would more likely result in the selection of a capnogram plateau closer to the average value as determined in this study, whereas continuous monitoring would be required to reliably select the optimum capnogram. Since periodic monitoring more closely approximates the clinical practice, this may be a limiting factor in the application of this monitoring technique when a close relationship between $ETCO_2$ and $PaCO_2$ is important. An on-line graphic display of expired CO_2 waveforms appears to be essential for proper visual interpretation of this continuous information, and a peak/hold processor with numeric display would decrease the need for excessive attention.

Analysis of bias and precision using peak $ETCO_2$ values demonstrated that partial airway obstruction was associated with the greatest $PaCO_2$–$ETCO_2$ differences. The largest negative gradients were associated with sudden increases in $PaCO_2$ produced by sedation, although there was a 5-minute lag between the increase in $PaCO_2$ and the development of the negative gradient. The existence of negative arterial-$ETCO_2$ CO_2 gradients is still somewhat controversial. They are, however, most frequently described in acute hypercapnia, exercise, or the start of rebreathing [12,13]. Overestimation of $ETCO_2$ using an infrared monitoring device may result from both random and nonrandom directional errors produced by the interference of water vapor [14]. It is likely that some of the negative bias as well as the relatively poor precision encountered in this study resulted from the effects of water vapor.

The data also show that the $PaCO_2$–peak $ETCO_2$ difference was not significantly affected by nasal cannula oxygen flow rate ($P > 0.05$). The range of oxygen flow rates used in this study was chosen to represent flow rates likely to be used in clinical practice. The reasons for this finding are not immediately obvious. One hypothesis is that since the catheter itself occupied a considerable portion of the cross-sectional area of a single nasal prong, it could have created enough resistance to oxygen flow to reduce the expected mixing effects in the catheterized nasal passage. Additionally, since the majority of the supplemental oxygen might have flowed to the uncatheterized nasal prong, the oxygen itself could have displaced exhaled gases to the side with the nasal sampling port, thereby yielding a value for $ETCO_2$ that more closely approximated $PaCO_2$ than might otherwise be expected.

It should also be noted that there was a significant oxygen flow rate effect on the $PaCO_2$–average $ETCO_2$ difference ($P < 0.007$). This suggests that as turbulence and obstruction increase, contamination of the sample with fresh gas flow also increases.

A third factor that could have influenced the correlation of $ETCO_2$ with $PaCO_2$ is related to variables affecting dead space ventilation. The differences seen in this study between average and peak $ETCO_2$ values reflect the variation in physiologic dead space relative to the exhaled tidal volume. This is well illustrated in the high-frequency jet ventilation study of Algora-Weber and coworkers [15]. In this study a very poor correlation was found between $PaCO_2$ and $ETCO_2$ during the course of high-frequency jet ventilation in mongrel dogs until an occasional large tidal volume (sigh) was introduced. This maneuver produced a value that more closely reflected $PaCO_2$ ($r = 0.94$, $P < 0.001$). Several variables known to cause either an increase in physiologic dead space, such as age of 65 years or older, or a decrease in exhaled volume, for example by increasing the respiratory rate, were examined. It was determined that only

in the patient subgroup with a respiratory rate of at least 30/min (n = 3) was there a significant increase in the $PaCO_2$–$ETCO_2$ ratio ($P < 0.001$) compared with the overall study population. This suggests relatively accurate sampling of alveolar gas within these physiologic variables. Other factors that may influence physiologic dead space volume, but not evaluated in this study, include body position, breathing pattern, pulmonary disease, pregnancy, and low cardiac output states. In this study all measurements were taken with patients in the supine position, and there were no pregnant patients or patients with low cardiac output states. However, no mechanism was used to prevent respiratory variability, and no attempt was made to exclude patients who may have had mild pulmonary changes. This may have contributed to some of the variability in expiratory CO_2 values [16,17].

The results of the present study show a closer correlation between $PaCO_2$ and $ETCO_2$ than previous studies have shown [10,18]. This discrepancy may have resulted from a combination of procedural differences associated with several possible mechanical difficulties. Assuming the detection of optimal expired CO_2 waveforms in all studies, there are still some important procedural differences to consider. The first difference concerns positioning of the sampling catheter. Louwsma and Silverman placed the sampling catheter 0.5 cm beyond the tip of the nasal cannula and recorded a mean $ETCO_2$–$PaCO_2$ ratio of 0.76 in 13 pre–cardiac surgery patients [10]. Through previous work with this setup, we determined empirically that optimal waveforms were recorded when the tip of the sampling catheter was 1.0 to 1.5 cm distal to the tip of the nasal prong. The exact position of the sampling catheter may be important in minimizing the amount of mixing with fresh gas flow. Other studies have emphasized the importance of the sampling site in obtaining representative samples of end-tidal gas [2]. Another important difference is that the measuring devices used in the various studies were not the same. Specifically, the conversion factors used to convert measured CO_2 to the digital display may be different in different types of capnometers, resulting in one type of capnometer's having a closer correlation between $ETCO_2$ and $PaCO_2$ based on sample processing. Hence, one should be cautious in comparing results from different measuring devices [19].

Several other mechanical problems can occur, such as minuscule leaks in the sampling circuit [20,21] or excessive sedation of the patient with associated partial airway obstruction. Irregular breathing patterns from excessive preanesthestic medication can promote less than adequate capnograms that can skew one's judgment of the appropriate value for $ETCO_2$. Lastly, individuals breathing primarily through the mouth may have an altered nasal CO_2 content. Most patients in our study appeared to be breathing through their nasal passages, but how the patient breathed could not be controlled, and mouth breathing may be a source of error.

In conclusion, it has been shown that $ETCO_2$ values can closely approximate arterial $PaCO_2$ measurements when close observation and selection of optimal waveforms is possible. It is generally assumed that in the clinical setting the best sample of $ETCO_2$ is obtained directly from the distal end of an endotracheal tube, but under circumstances that involve an awake, spontaneously ventilating patient, a reasonably accurate assessment of the patient's arterial $PaCO_2$, under optimal conditions, can be made.

REFERENCES

1. Shankar KB, Moseley H, Kumar Y, Vemula V. Arterial to end tidal carbon dioxide tension difference during caesarean section anesthesia. Anaesthesia 1986;41:698–702
2. 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;66:959–964
3. McEvedy BAB, McLeod ME, Mulera M, et al. End-tidal, transcutaneous, and arterial PCO_2 measurements in critically ill neonates: a comparative study. Anesthesiology 1988;69:112–116
4. Ibarra E, Lees DE. Mass spectrometer monitoring of patients with regional anesthesia. Anesthesiology 1985;63: 572–573
5. Norman EA, Zeig NJ, Ahmad I. Better designs for mass spectrometer monitoring of the awake patient. Anesthesiology 1986;64:664
6. Huntington CT, King HK. A simpler design for mass spectrometer monitoring of the awake patient. Anesthesiology 1986;65:565–566
7. Pressman MA. A simple method of measuring $ETCO_2$ during MAC and major regional anesthesia. Anesth Analg 1988;67:905–906
8. Bowe EA, Boysen PG, Broome JA, Klein EF. Accurate determination of end-tidal carbon dioxide during administration of oxygen by nasal cannula. J Clin Monit 1989;5:105–110
9. Goldman JM. A simple, easy, and inexpensive method for monitoring $ETCO_2$ through the nasal cannula. Anesthesiology 1987;67:606
10. Louwsma DL, Silverman DG. Reproducibility of end tidal CO_2 measurements in sedated patients receiving supplemental O_2 by nasal cannula (abstract). Anesthesiology 1988;69:A268
11. Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. Lancet 1986;1:307–310
12. Fordyce WE, Kanter RK. Arterial-end tidal PCO_2 equilibration in the cat during acute hypercapnia. Respir Physiol 1988;73:257–272
13. Piiper J. Blood-gas equilibrium of carbon dioxide in

lungs; a continuing controversy. J Appl Physiol 1986;60:1–8
14. Severinghaus JW. Water vapor calibration errors in some capnometers: respiratory conventions misunderstood by manufacturers? Anesthesiology 1989;70:996–998
15. Algora-Weber A, Rubio JJ, Dominguez de Villota E, et al. Simple and accurate monitoring of end-tidal carbon dioxide tensions during high-frequency jet ventilation. Crit Care Med 1986;14:895–897
16. Fletcher R. Smoking, age and the artificial-end-tidal PCO_2 difference during anaesthesia and controlled ventilation. Acta Anaesthesiol Scand 1987;31:355–356
17. Whitesell R, Asiddao C, Gollman D, Jablonski J. Relationship between arterial and peak expired carbon dioxide pressure during anesthesia and factors influencing the differences. Anesth Analg 1981;60:508–512
18. Dunphey JA. Accuracy of expired carbon dioxide partial pressure sampled from nasal cannula. II. Anesthesiology 1988;68:960–961
19. From RP, Scamman FL. Ventilatory frequency influences accuracy of end-tidal CO_2 measurements: analysis of seven capnometers. Anesth Analg 1988;67:884–886
20. Zupan J, Martin M, Benumof JL. End-tidal CO_2 excretion waveform and error with gas sampling line leak. Anesth Analg 1988;67:579–581
21. Koebert RF, Munster R. One-way leak in mass spectrometer sampling system. Anesthesiology 1987;67:606–607