ACCURATE DETERMINATION OF END-TIDAL CARBON DIOXIDE DURING ADMINISTRATION OF OXYGEN BY NASAL CANNULAE

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Bowe EA, Boysen PG, Broome JA, Klein EF Jr. Accurate determination of end-tidal carbon dioxide during administration of oxygen by nasal cannulae.

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ABSTRACT. Measurement of end-tidal carbon dioxide tension ($P_{ET}CO_2$) by mass spectrometry or infrared capnometry provides a clinically useful approximation of arterial carbon dioxide tension ($PaCO_2$) in intubated patients. Although several devices have been proposed to sample $P_{ET}CO_2$ during spontaneous breathing (i.e., unintubated patients receiving supplemental oxygen), thus far no reports have documented their efficacy. This article reports the use of an easily constructed modification of simple nasal cannulae that permits accurate sampling of $P_{ET}CO_2$ during oxygen administration to unintubated patients. After amputation of the closed tip, a cap from a syringe was inserted via a slit made at the base into one prong of a pair of nasal cannulae. A capnometer was connected to the syringe cap, and $P_{ET}CO_2$ and $PaCO_2$ were determined simultaneously during the administration of 3 L/min oxygen via nasal cannulae to 21 normocapnic patients. The $PaCO_2 - P_{ET}CO_2$ gradients were calculated and compared with values obtained in the same patients after intubation and mechanical ventilation. No significant difference was found between the calculated gradients with nasal cannulae (2.09 ± 2.18 mm Hg) versus intubation (2.87 ± 2.82 mm Hg). Simultaneous oxygen administration and accurate sampling of $P_{ET}CO_2$ may be achieved in unintubated patients by using this easily constructed modification of nasal cannulae.

KEY WORDS. Measurement techniques: capnography. Monitoring: carbon dioxide. Oxygen: delivery.

Although discrepancies exist between measurements of the partial pressure of carbon dioxide in end-tidal gas ($P_{ET}CO_2$) and arterial blood ($PaCO_2$), $P_{ET}CO_2$ is accepted as a clinically accurate estimate of $PaCO_2$ in the absence of lung disorders [1–4]. Methods have been proposed to allow sampling of end-tidal gases during oxygen administration by nasal cannulae [5,6] and simple oxygen mask [7–9]. It has been suggested, however, that these devices are not adequate for quantitative analysis of exhaled gases [8,10–12]. We have developed and tested a modification of standard nasal cannulae that allows accurate sampling of $P_{ET}CO_2$ during oxygen administration via nasal cannulae.

SUBJECTS AND METHODS

To monitor $P_{ET}CO_2$ during the administration of oxygen through nasal cannulae, a set of nasal prongs (model 1103, Hudson Oxygen Therapy Sales Co, Temecula, CA) was modified to permit the insufflation of oxygen into one nostril while exhaled gases are monitored from the other. This was accomplished by first cutting the solid tip off a plastic syringe cap provided on a needleless Becton-Dickinson syringe, models W11844 or

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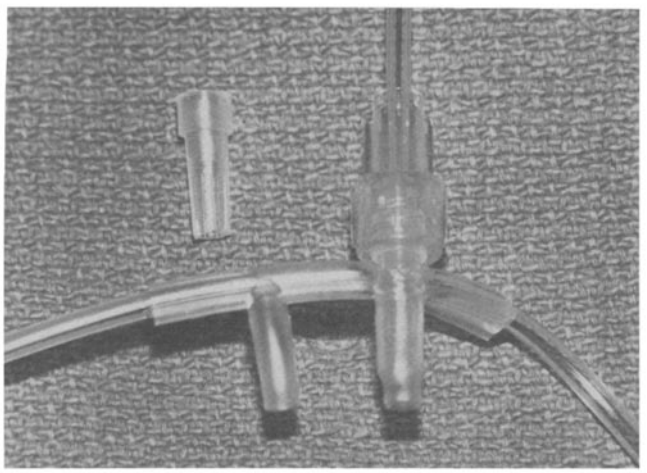

Fig 1. Syringe cap with tip removed (left). Modified nasal cannula with syringe cap inserted and sampling line attached (right). The Luer is part of the sampling line.

W11626 (Becton-Dickinson Co, Rutherford, NJ). The syringe cap was then inserted through a small hole made with a needle at the base of one of the nasal cannula prongs (Fig 1). The syringe cap was fully advanced into the nasal prong to obtain complete occlusion of the prong by the syringe cap. The sampling line from an infrared capnometer (SARACAP, PPG Biomedical Systems, Lenexa, KS) was then connected directly to the syringe cap. Capnometer calibration was performed according to manufacturer's recommendations using a known sample gas containing 5% carbon dioxide, 40% nitrous oxide, and 55% oxygen.

After review of the protocol by our institutional review board, 21 consecutive patients, 35 to 80 years old (mean, 67 years), scheduled to undergo elective cardiac operations were included in the study. Premedicated patients were transported to the operating room, where oxygen (3 L/min) was administered via a set of nasal cannulae modified as already described. A SARACAP capnometer with a sampling flow rate set at 230 cc/min was connected to the modified nasal cannulae at the syringe cap. Blood was drawn from an indwelling arterial catheter for blood gas determination 5 to 10 minutes after the modified nasal cannulae were in place. Simultaneous printout of the current capnometer screen permitted determination of $P_{ET}CO_2$. The digitally displayed value of $P_{ET}CO_2$ was used in subsequent calculations. (SARACAP uses a complex algorithm that evaluates two successive waveforms and the valley between them. Under most circumstances the value reported as $P_{ET}CO_2$ is the maximum value achieved during the first waveform.) After induction of anesthesia, tracheal intubation was performed and the patient was mechanically ventilated (tidal volume = 9 to 12 cc/kg, respiratory frequency = 7 to 10 breaths/min, inspired oxygen fraction = 1.0, no positive end-expiratory pressure). Approximately 10 minutes after mechanical ventilation was instituted, determinations of $PaCO_2$ and $P_{ET}CO_2$ were again performed as described. For all samples, blood gas determinations were performed immediately using an ABL II Acid-Base Laboratory blood gas analyzer (Radiometer America Inc, Orlando, FL) that self-calibrates at regular intervals with a known gas mixture.

The means and standard deviations were calculated for all determinations and for the arterial–to–end-tidal differences ($PaCO_2 - P_{ET}CO_2$) for both modified nasal cannulae and endotracheal tubes. Student's *t* test for paired data was used to compare values obtained for $PaCO_2$ and $PaCO_2 - P_{ET}CO_2$ with both sampling devices. Confidence intervals for the $PaCO_2 - P_{ET}CO_2$ gradient for each sampling device were calculated with the *t* statistic. In addition, the *t* statistic was used to calculate the confidence interval for the difference in gradients obtained with the two devices. Correlation coefficients and regression lines were determined for $PaCO_2$ versus $P_{ET}CO_2$ for both the modified nasal cannulae and endotracheal tube.

RESULTS

No attempt was made to alter spontaneous ventilation in 19 of 21 patients. However, sampling with modified nasal cannulae produced $P_{ET}CO_2$ readings that were clearly spuriously low in 2 patients ($P_{ET}CO_2$ = 15 to 20 mm Hg in somnolent patients). Both patients were predominantly mouth-breathing. When these patients were asked to breathe with their mouths closed, the $P_{ET}CO_2$ increased immediately to values in excess of 30 mm Hg. These subsequent values were used in the calculations. Although other patients had some component of mouth-breathing during sampling with modified nasal cannulae, values that were clearly aberrant were observed only in these 2 patients.

Values for the mean and standard deviation for $PaCO_2$, $P_{ET}CO_2$, and $PaCO_2 - P_{ET}CO_2$ for both sampling devices are presented in Table 1. Figure 2 presents the data for $PaCO_2$ and $P_{ET}CO_2$. During sampling with the modified nasal cannulae, $PaCO_2$ ranged from 29.9 to 44.5 mm Hg (mean ± SD = 38.6 ± 3.84 mm Hg). End-tidal values obtained via modified nasal cannulae with oxygen insufflation rates of 3 L/min ranged from 28.5 to 44.4 mm Hg (mean ± SD = 36.5 ± 4.68 mm Hg). After the institution of mechanical ventilation, $PaCO_2$ ranged from 26.5 to 44.4 mm Hg (mean ± SD = 36.8 ± 4.74 mm Hg). Sampling via an endotracheal

Table 1. Arterial Carbon Dioxide Tension, End-Tidal Carbon Dioxide Tension, and $PaCO_2$ − $PETCO_2$ with Modified Nasal Cannulae and Endotracheal Tube

Variable	Nasal Cannulae[a]	Endotracheal Tube[a]
$PaCO_2$	38.6 ± 3.84	36.8 ± 4.74[b]
$PETCO_2$	36.5 ± 4.68	33.7 ± 5.28[c]
$PaCO_2$ − $PETCO_2$[d]	2.09 ± 2.18	2.87 ± 2.82[b]

[a] Values are means ± SD in mm Hg.
[b] Not significantly different from nasal cannulae values.
[c] Significance not tested.
[d] $PaCO_2$ versus $PETCO_2$: r = 0.89 for nasal cannulae and 0.85 for endotracheal tube.

$PaCO_2$ = arterial carbon dioxide tension; $PETCO_2$ = end-tidal carbon dioxide tension.

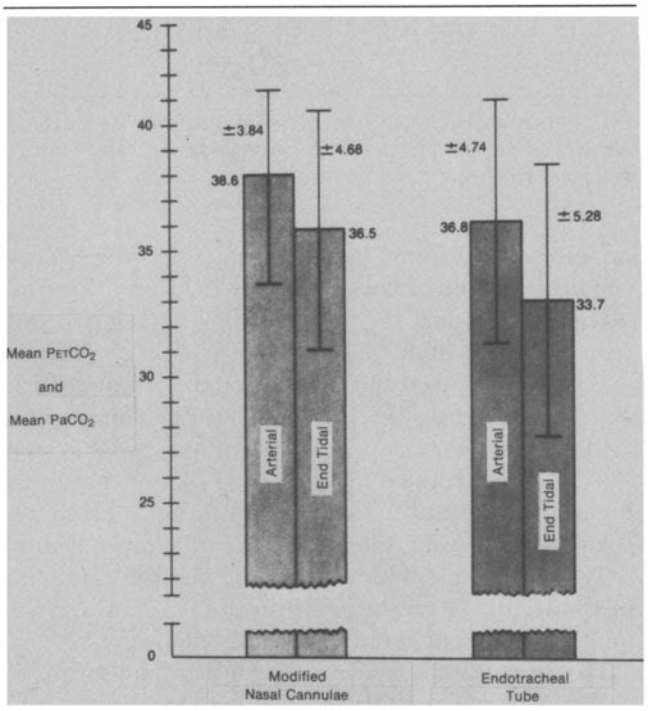

Fig 2. Arterial ($PaCO_2$) and end-tidal ($PETCO_2$) carbon dioxide tensions (in mm Hg) with modified nasal cannulae and endotracheal tube.

tube produced values for $PETCO_2$ that ranged from 25.8 to 45.7 mm Hg (mean ± SD = 33.7 ± 5.28 mm Hg). There was no significant difference between either the $PaCO_2$ or $PaCO_2$ − $PETCO_2$ values obtained with the two different devices. Waveforms obtained with both sampling devices (Fig 3) displayed characteristics of a normal capnogram: rapid increase, nearly horizontal plateau, and rapid decrease to zero.

Confidence intervals are presented in Table 2. $PETCO_2$ was significantly less than $PaCO_2$ ($P < 0.01$)

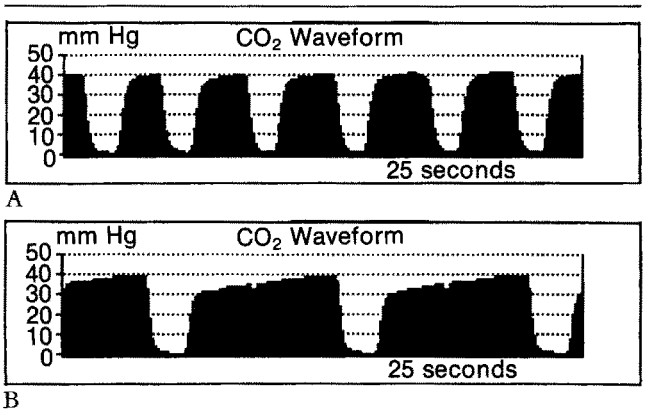

Fig 3. Capnogram waveforms. Actual carbon dioxide (CO_2) waveforms obtained on 1 patient during sampling via modified nasal cannulae (A) and endotracheal tube (B). Simultaneous values for arterial carbon dioxide tension were 40.5 and 39.3 mm Hg, respectively.

Table 2. Arterial Carbon Dioxide Tension/End-Tidal Carbon Dioxide Tension Confidence Intervals with Modified Nasal Cannulae and Endotracheal Tube

Confidence Interval: Sampling Technique	$PaCO_2$ − $PETCO_2$ (mm Hg)
99%	
Endotracheal tube	1.09–4.65
Nasal cannulae	0.74–3.44
95%	
Endotracheal tube minus nasal cannulae differences	−0.80–2.35

$PaCO_2$ = arterial carbon dioxide tension; $PETCO_2$ = end-tidal carbon dioxide tension.

with both sampling techniques. Sampling with modified nasal cannulae produced 99% confidence intervals for $PaCO_2$ − $PETCO_2$ of 0.74 to 3.44 mm Hg. Sampling via an endotracheal tube produced 99% confidence intervals for $PaCO_2$ − $PETCO_2$ of 1.09 to 4.65 mm Hg. On the basis of the calculated confidence intervals, there was no significant difference in the magnitude of $PaCO_2$ − $PETCO_2$ whether sampling was performed via an endotracheal tube or modified nasal cannulae. The 95% confidence intervals for the difference between endotracheal tube and nasal cannulae $PaCO_2$ − $PETCO_2$ were −0.80 to +2.35 mm Hg.

Figures 4 and 5 represent the pairs of data obtained for each patient in each condition. The correlation coefficient was 0.89 with the modified nasal cannulae and was 0.85 following intubation. The regression equation for measurement with nasal cannulae was: $PETCO_2 = 0.73\ PaCO_2 + 12.01$. For measurement via an endotracheal tube, the regression equation was: $PETCO_2 = 0.74\ PaCO_2 + 11.51$.

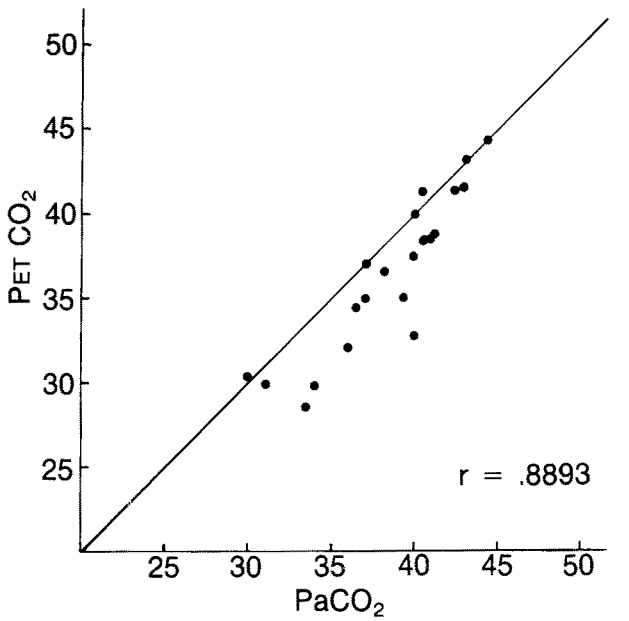

Fig 4. Arterial ($PaCO_2$) versus end-tidal ($P_{ET}CO_2$) carbon dioxide tensions (in mm Hg) obtained with modified nasal cannulae. Each plot point represents 1 patient.

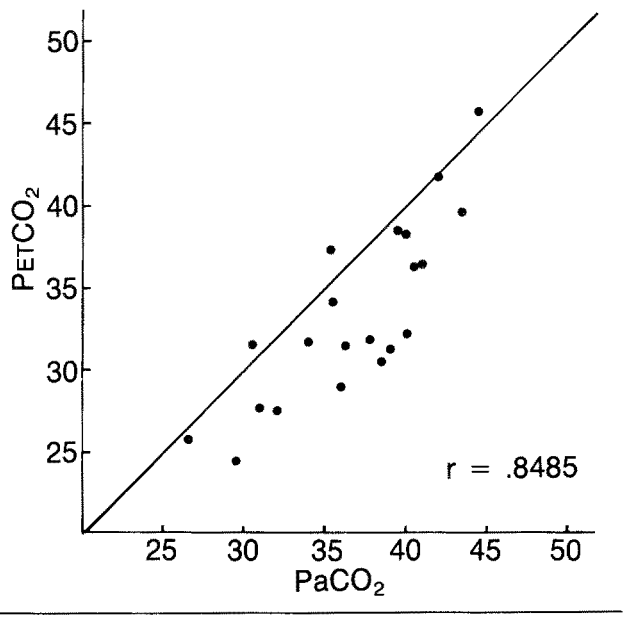

Fig 5. Arterial ($PaCO_2$) versus end-tidal ($P_{ET}CO_2$) carbon dioxide tensions (in mm Hg) obtained with endotracheal tube. Each plot point represents 1 patient.

DISCUSSION

Monitoring of $P_{ET}CO_2$ by infrared capnometry or mass spectometry provides a clinically useful approximation of $PaCO_2$ in intubated patients [1–4]. Monitoring of $P_{ET}CO_2$ in spontaneously breathing, unintubated patients is also potentially useful, especially for sedated patients during regional or local anesthesia or for patients in the recovery room receiving supplemental oxygen during emergence from residual general anesthesia. Previously proposed devices, while allowing the detection of carbon dioxide in exhaled gas (and therefore determination of apnea), have not allowed the quantitative analysis of exhaled gases. Consequently, the magnitude of respiratory depression could not be determined.

This study appears to be the first controlled evaluation of a simple oxygen administration device intended to permit oxygen insufflation while allowing simultaneous, quantitative sampling of exhaled gases. The modified nasal cannulae used in our investigation have provided measurements of $P_{ET}CO_2$ that produce $PaCO_2 - P_{ET}CO_2$ gradients quantitatively similar to those previously reported in intubated patients [2–4]. $P_{ET}CO_2$ measurement always underestimates $PaCO_2$ because gas from lung units that are ventilated but not perfused (alveolar dead space or high ventilation–perfusion ratio units) contains little or no carbon dioxide. When this gas mixes with that from "normal" lung units, the resultant concentration of carbon dioxide is reduced. This phenomenon accounts for the fact that $P_{ET}CO_2$ is lower than $PaCO_2$ in both conditions.

Positive-pressure ventilation produces an increase in alveolar dead space [13,14]; this increase is then associated with an increase in the magnitude of $PaCO_2 - P_{ET}CO_2$. In our study, the mean $PaCO_2 - P_{ET}CO_2$ was higher, though not statistically significant, during mechanical than during spontaneous ventilation. A statistically significant difference between the two sampling methods may have been demonstrable had a larger number of patients been included in the study.

No attempt was made to modify respiration in 19 (90%) of the 21 patients. Mouth-breathing produced a clearly spurious value for $P_{ET}CO_2$ in 2 patients. When these patients breathed with their mouths closed, $P_{ET}CO_2$ values in excess of 30 mm Hg were obtained almost immediately. The rapidity of the increase and the subsequent stability of $P_{ET}CO_2$ indicate that the low values obtained for these 2 patients probably were due to contamination of the aspirated sample by room air. In several other patients, a component of mouth-breathing was noted, but values for $P_{ET}CO_2$ obtained using modified nasal cannulae were in excess of 25 mm Hg. It is conceivable that coaching all patients to breathe through closed mouths would have produced a closer correlation between $PaCO_2$ and $P_{ET}CO_2$ sampled with modified nasal cannulae. Alternatively, as will be de-

scribed, use of a lower sampling flow rate may also have reduced the $PaCO_2 - PETCO_2$ gradient obtained in these patients.

Although the only problem with sampling accuracy encountered in this study occurred in the 2 patients who were predominantly mouth-breathing, other inaccuracies have been predicted. Failure to isolate insufflated oxygen from exhaled gases (which should produce a falsely low value for $PETCO_2$) may occur in the presence of a perforated nasal septum. Complete obstruction of the sampling catheter or of the sampling nostril (e.g., by blood or secretions) should produce a complete absence of carbon dioxide from the measured gases. Similarly, although not affecting the accuracy of measured $PETCO_2$, complete obstruction of the nostril used for insufflation of oxygen undoubtedly would diminish the alveolar oxygen tension.

Hypoventilation or mouth-breathing may cause diminished expiratory gas flow rates through the measuring nostril. In this situation, use of high gas sampling flow rates by the capnometer may produce entrainment of room air, which produces an erroneously low value for $PETCO_2$, during sample aspiration. This study was undertaken using a sampling flow rate of 230 ml/min. According to an informal survey of the manufacturers, the nominal sampling flow rates of nineteen currently available mass spectrometers or capnometers range from 17 to 300 ml/min, with several models having two different aspiration rates that are user-selectable. With one exception, no capnometer has a high sampling flow rate greater than 250 ml/min. If the lower aspiration rate is selected on each model, the sampling flow rates of all devices can be set to 150 ml/min or less. These lower flow rates may produce more accurate determinations for patients whose expiratory gas flow rates may be inadequate to prevent contamination of the sample by air entrainment.

The highest $PaCO_2$ in any of our patients during spontaneous ventilation and sampling with the modified nasal cannulae was 44.5 mm Hg. In this patient, $PaCO_2 - PETCO_2$ was 0.1 mm Hg, less than the mean difference of 2.09 mm Hg obtained with this sampling device. The ability of the modified nasal cannulae to accurately sample end-tidal gas during marked hypoventilation has not been evaluated in the present study. The increase in $PaCO_2$ during pharmacologic sedation is due to decreased alveolar ventilation. In its most extreme condition (apnea), no end-tidal gas is available for sampling. If sedation produces expiratory flow rates through the nostril used for sampling that are less than the aspiration flow rate of the sampling device, room air will be entrained, producing an increase in $PaCO_2 - PETCO_2$.

The efficacy of nasal prongs for oxygen administration in mouth-breathing patients has been explained by describing the nasopharynx as a reservoir filled with oxygen from which gas is entrained during spontaneous inspiration [15]. Therefore we see no reason why an amount of oxygen administered through one nostril should produce an inspired oxygen fraction different from that produced when an amount of oxygen is administered through both nostrils. The effect of changing to single-nostril oxygen administration was not, however, tested in the present study. The administration of 3 L/min of oxygen through one nostril will also have a drying effect on that nostril equivalent to the administration of 6 L/min through both nasal prongs. Although we observed no difficulty with crusting of nasal secretions or drying of nasal mucosa in this study or in patients undergoing monitoring for longer periods during regional anesthesia, these complications have been reported to occur with oxygen flow rates in excess of 6 L/min (two patent prongs) on a long-term basis [15].

Other devices have been proposed for measuring $PETCO_2$ during simple oxygen administration. Goldman [6] and Ibarra and Lees [5] constructed devices similar to ours by attempting to obstruct one prong of a set of nasal cannulae with a 16-gauge intravenous catheter [6] or with a mass spectrometer sampling catheter that had the connector removed [5]. No patient data were presented in either article. Although Ibarra and Lees reported that the sampling catheter successfully obstructed the nasal prong, we were unable to achieve this with the materials available. Similarly, our initial attempts at obstructing one nasal prong with a 14-gauge catheter were unsuccessful. While a carbon dioxide waveform was obtained in our initial trials with both devices, the waveforms were markedly attenuated from normal and the $PaCO_2 - PETCO_2$ was excessive. Immersing either modified nasal prong in water produced a continuous stream of bubbles even at oxygen flow rates as low as 1 L/min, confirming incomplete obstruction of the nasal prong. Incomplete obstruction allowed oxygen to be insufflated around the sampling catheter, thereby contaminating the exhaled gas sample and producing a spuriously low value for $PETCO_2$.

This leak of insufflated oxygen apparently was responsible for the reports of Norman et al [8] and Urmey [10], in which the devices proposed by Ibarra and Lees [5] and Goldman [6] were described as "unsatisfactory" [8] or as producing "artifactually low" values for $PETCO_2$ [10]. Norman et al [8] proposed suturing the tip of a sampling catheter, again with the connector removed, 1 cm from the pharyngeal end of a nasal airway. Using the devices proposed by Ibarra and Lees [5]

and their own devices, Norman et al [8] conducted patient trials and found $P_{ET}CO_2$ monitoring was less reliable than when the standard connection was used with an endotracheal tube. Although no data were presented, the nasal airway device was noted to produce a more consistently satisfactory carbon dioxide curve than did the partially obstructed nasal prong [8]. Dunphy [11] attempted to measure $P_{ET}CO_2$ during oxygen administration by face mask using a capnograph sampling catheter attached to a nasopharyngeal airway, apparently in a manner similar to that described by Norman et al [8]. Comparing $PaCO_2$ with $P_{ET}CO_2$ sampled in this manner, they calculated a correlation coefficient of 0.59.

Pressman [9] and Huntington and King [7] have advocated taping a 14-gauge intravenous catheter inside an oxygen mask at a point "close to, but not irritating" [7] the patient's nose. Huntington and King reported obtaining satisfactory estimations of $P_{ET}CO_2$ in awake and sedated patients, but no data were presented and no statistical comparisons made. When evaluating the ability of this configuration to determine respiratory rate, Pressman [9] reported highly satisfactory results in almost all cases. Although no data were presented, the values for $P_{ET}CO_2$ obtained under these circumstances were noted to be less accurate than when monitoring via an endotracheal tube [9]. Given the fact that insufflation of oxygen into the mask is continuous, some dilution of exhaled carbon dioxide would be expected with this sampling technique.

Thus far, sampling via the modified nasal cannulae used in our investigation has provided measurements that are remarkably consistent with the previously accepted difference seen in intubated patients [4]. In addition, the mean $PaCO_2 - P_{ET}CO_2$ difference observed with modified nasal cannulae compares favorably with the mean $PaCO_2 - P_{ET}CO_2$ difference observed when the same patients were intubated. Although we have not conducted a formal study with other patient populations, use of this device in patients undergoing cataract operations or other relatively short procedures under regional anesthesia has permitted clinically useful $P_{ET}CO_2$ measurements.

Measurement of $P_{ET}CO_2$ as an approximation of $PaCO_2$ is clinically useful in many patient populations, but has not previously been available for spontaneously breathing, unintubated patients who are receiving supplemental oxygen. Although the device described in the present report is not currently manufactured, it is easily constructed of materials readily available in most operating rooms and provides a reliable method of sampling exhaled gases for analysis by infrared capnometry or mass spectrometry.

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The apparatus and method described herein are covered by U.S. Patent Application S.N. 181,814: Method and Apparatus for Inhalation of Treating Gas for Quantitative Analysis. Filed April 15, 1988—in the name of Edwin A. Bowe, et al.

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