Agreement between values for arterial and end-tidal partial pressures of carbon dioxide in spontaneously breathing, critically ill dogs

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Objective—To determine agreement between arterial partial pressures of carbon dioxide ($Paco_2$) and end-tidal partial pressures of carbon dioxide ($Petco_2$) measured with a nasal catheter in spontaneously breathing, critically ill dogs.

Design—Validation study.

Animals—26 client-owned dogs admitted to an intensive care unit for various conditions.

Procedures—$Paco_2$ was measured with a commercial blood gas analyzer, and $Petco_2$ was measured with a sidestream capnograph attached to a nasal catheter. Measurements were obtained twice (ie, with and without supplemental oxygen). Paired values were compared by means of the Pearson correlation method. Level of agreement was assessed by means of the Bland-Altman method.

Results—Mean difference between $Paco_2$ and $Petco_2$ when dogs did not receive supplemental oxygen (mean ± SD, 3.95 ± 4.92 mm Hg) was significantly lower than mean difference when dogs did receive supplemental oxygen (6.87 ± 6.42 mm Hg). Mean difference in dogs with a condition affecting the respiratory system (8.55 ± 5.43 mm Hg) was significantly higher than mean difference in dogs without respiratory tract disease (3.28 ± 3.23 mm Hg). There was a significant linear correlation and good agreement between measured values of $Paco_2$ and $Petco_2$. Catheter size, ventilatory status, and outcome were not significantly associated with mean difference between $Paco_2$ and $Petco_2$.

Conclusions and Clinical Relevance—Results suggested that nasal capnography is a clinically relevant method of estimating $Paco_2$ in spontaneously breathing, critically ill dogs, but that values should be interpreted with caution in dogs receiving supplemental oxygen and in dogs with conditions affecting the respiratory system. (*J Am Vet Med Assoc* 2009;235:1314–1318)

Capnography is a useful, noninvasive diagnostic tool that provides important information regarding the ventilatory status of patients and is considered a standard method of monitoring ventilation during general anesthesia.[1] In mammals without any clinically important ventilation-perfusion mismatch, end-tidal partial pressures of carbon dioxide ($Petco_2$) are typically approximately 5 mm Hg lower than corresponding arterial partial pressures of carbon dioxide ($Paco_2$) because of the physiologic dead space.[2]

An important limitation of capnography is the requirement for endotracheal intubation to obtain reliable values. This limits the use of capnography to anesthetized and intubated patients, precluding its use in most patients in ICUs. In such patients, arterial blood gas analysis is the gold-standard method for evaluat-

ABBREVIATION	
ICU	Intensive care unit

ing ventilation, but sample collection can be technically challenging in patients that are small, obese, or hypotensive and in patients with peripheral edema or thrombosis.[3,4] In addition, arterial blood sample collection can be associated with various adverse effects, including transient or permanent artery occlusion, bleeding, hematoma formation, infection, and patient discomfort.[3,4]

Many dogs hospitalized in an ICU have hypoventilation (eg, because of cervical myelopathy, head trauma, upper airway obstruction, or administration of various drugs) or hyperventilation (eg, because of pain, anxiety, hypoxia, or pulmonary thromboembolism). Therefore, a simple technique for monitoring the ventilatory status of critically ill, spontaneously breathing dogs would be beneficial.

Nasal catheters are frequently inserted in dogs hospitalized in an ICU as a means of providing supplemental oxygen because administration of oxygen via a nasal catheter has been shown to be an effective method of increasing the fraction of inspired oxygen.[5] Most commonly, a red rubber catheter is advanced from the nostril through the ventral meatus to the nasophar-

ynx. In people, similar nasal cannulas have been used to measure $PETCO_2$, and various studies[6–11] have shown that the technique is simple and noninvasive and, for the most part, provides accurate results. Factors that influenced accuracy in humans were high respiratory rate (> 20 breaths/min), low tidal volume (< 500 mL),[8] airway obstruction, cyanosis, mouth breathing, oxygen supplementation,[12] and physical characteristics of the cannula.[8]

To our knowledge, only 2 previous studies[13,14] have evaluated the use of capnometry in spontaneously breathing animals. The first[13] found an acceptable correlation between nasal and arterial CO_2 partial pressures in 43 dogs and cats recovering from anesthesia; however, none of the animals in that study had conditions affecting the respiratory system, and none were receiving oxygen supplementation. The second[14] found an acceptable correlation between $PETCO_2$ measured via a nasal catheter and $PaCO_2$; however, the study involved only 6 healthy research dogs of the same breed and a narrow weight range. The present study, therefore, was designed to determine whether nasal capnography would be a clinically reliable method of monitoring ventilation among a diverse population of spontaneously breathing, critically ill dogs. Specifically, the purposes of the study reported here were to determine agreement between $PaCO_2$ and $PETCO_2$ measured with a nasal catheter in spontaneously breathing, critically ill dogs and to determine whether ventilatory status, body weight, nasal catheter size, or outcome was associated with the accuracy of nasal capnography. We hypothesized that in the absence of any clinically relevant ventilation-perfusion mismatching, $PETCO_2$ measured via a nasal catheter would correlate with $PaCO_2$.

Materials and Methods

The study protocol was approved by the University of Tennessee Institutional Animal Care and Use Committee. Dogs admitted to the veterinary teaching hospital's ICU with a nasal oxygen catheter and an arterial catheter in place were eligible for inclusion in the study. In addition, dogs admitted to the ICU were eligible for inclusion in the study if a nasal catheter was in place and arterial blood samples were collected as dictated by the dog's condition. Because previous studies[8,14] have shown that nasal capnography is inaccurate in dogs that are panting and in people that are tachypneic, dogs were excluded if they were panting.[8,14]

For dogs included in the study, the nasal catheter was connected to a side-stream capnograph.[a] Following a calibration period, 30 consecutive measurements of $PETCO_2$ were recorded for 1 minute while the dog was breathing spontaneously; values were averaged, with the average value used for all subsequent analyses. Concurrently, an arterial blood sample was collected, and $PaCO_2$ was measured with a commercial blood gas analyzer.[b] All values were obtained twice: once while dogs were not receiving supplemental oxygen and once while dogs were receiving supplemental oxygen via a face mask with the oxygen flow rate adjusted to the lowest rate that did not result in inspired CO_2. For oxygen-dependent dogs, values were obtained only while dogs were receiving supplemental oxygen.

Signalment, underlying disease, type and size of nasal catheter, and vital parameters were recorded for each dog, and the primary investigator made a determination as to whether the dog had a primary condition that was affecting the respiratory system. The alveolar-arterial difference in partial pressure of oxygen (PAO_2 – PaO_2) was calculated on the basis of results of blood gas analyses of arterial blood samples obtained when dogs were not receiving supplemental oxygen. In addition, the ventilation-to-perfusion ratio was calculated by use of the following formula: $(150 – 1.2 [PaCO_2])$ $– PaO_2$. Reference range for the ventilation-to-perfusion ratio was < 10 mm Hg.

Statistical analysis—Data were summarized as mean ± SD. Paired values for $PaCO_2$ and $PETCO_2$, taken when dogs were and were not receiving supplemental oxygen, were compared by means of the Pearson correlation method, and correlation coefficients were interpreted as weak (< 0.4), moderate (0.4 to 0.7), or strong (> 0.7). Level of agreement was assessed by means of the Bland-Altman method[15] for each oxygen treatment. The 95% limits of agreement were calculated as the mean difference between $PaCO_2$ and $PETCO_2$ ± 2 SD.

The Pearson correlation method was also used to asses the relationship between dog weight and the difference between $PaCO_2$ and $PETCO_2$ ($PaCO_2$ – $PETCO_2$) when supplemental oxygen was and was not being administered. A repeated-measures ANOVA was used to determine whether there was a significant effect of oxygen treatment on the difference between $PaCO_2$ and $PETCO_2$ and to test the difference between $PaCO_2$ and $PETCO_2$ in dogs in which PAO_2 – PaO_2 was high and dogs in which PAO_2 – PaO_2 was within reference limits. Two-way ANOVA and multiple independent-samples t tests with a Bonferroni correction were used to test for differences in mean difference when dogs were grouped on the basis of other factors of interest. Because of small samples, differences between $PaCO_2$ and $PETCO_2$ were averaged across oxygen treatments for t test comparisons. Continuous variables were assessed for normality by means of the Shapiro-Wilk test. The Levene F test was used to evaluate homogeneity of variance. When 1 or both assumptions were violated, logarithmically transformed data were used for means testing. All analyses were performed with standard software.[c] Values of $P < 0.05$ were considered significant.

Results

Twenty-nine dogs met the inclusion criteria for this study, but 3 were later excluded. Two dogs were excluded because of failure to obtain a reliable alveolar plateau when the nasal catheter was connected to the capnograph. One of these dogs was whining during measurements; the other was a small brachiocephalic dog that had crust in its nostrils and in which a 5-F red rubber nasal catheter had been inserted. The third dog was excluded because of an artifactually low $PaCO_2$ value (ie, the $PETCO_2$ value was higher than the $PaCO_2$ value) that most likely was a result of an air bubble over the CO_2 sensor.

The remaining 26 dogs completed the study. This included 14 spayed females, 1 sexually intact female,

and 11 neutered males. Mean and median ages of dogs that completed the study were 6.3 and 6 years, respectively (range, 1 to 12 years). Mean and median body weights were 28.6 and 28.7 kg (62.9 and 63.14 lb), respectively (range, 5 to 50 kg [11 to 110 lb]).

Paired measurements for $Paco_2$ and $Petco_2$ were obtained from 25 dogs that received supplemental oxygen. Paired measurements could only be obtained from 21 dogs while dogs were not receiving supplemental oxygen. Five dogs were oxygen dependent, and measurements were not obtained without oxygen supplementation in these dogs. In 1 dog, measurements were obtained only without oxygen supplementation because of technical difficulties associated with obtaining an arterial blood sample.

Mean difference between $Paco_2$ and $Petco_2$ when supplemental oxygen was not administered (mean ± SD, 3.95 ± 4.92 mm Hg) was significantly ($P = 0.016$) lower than mean difference when supplemental oxygen was given (6.87 ± 6.42 mm Hg). The mean difference between $Paco_2$ and $Petco_2$ was significantly higher ($P = 0.027$) in dogs with a condition affecting the respiratory system (8.55 ± 5.43 mm Hg) than in dogs without a condition affecting the respiratory system (3.28 ± 3.23 mm Hg). Mean difference in dogs in which Pao_2 – Pao_2 was high (5.27 ± 4.63 mm Hg; n = 11) was not significantly ($P = 0.778$) different from mean difference in dogs in which Pao_2 – Pao_2 was within reference limits (4.39 ± 3.92 mm Hg; 9).

There was a strong significant ($r = 0.833$; $P < 0.001$) linear correlation between $Paco_2$ and $Petco_2$ values obtained when dogs did not receive supplemental oxygen (**Figure 1**). Calculated 95% limits of agreement were –5.72 to 14.07 mm Hg (**Figure 2**). Similarly, there was a strong significant ($r = 0.707$; $P < 0.001$) linear correlation between $Paco_2$ and $Petco_2$ values obtained when supplemental oxygen was administered (**Figure 3**). Calculated 95% limits of agreement were –7.25 to 19.97 mm Hg (**Figure 4**).

Body weight and mean $Paco_2$ – $Petco_2$ difference were not significantly correlated regardless of whether dogs were ($r = 0.042$; $P = 0.840$) or were not ($r = 0.188$; $P = 0.414$) receiving supplemental oxygen.

Nine dogs were either hyperventilating or hypoventilating while receiving supplemental oxygen, but were identified as having normal ventilation when oxygen was not administered. Eight other dogs had normal ventilation with supplemental oxygen, but were identified as having a ventilation problem when supplemental oxygen was not administered. Paired measurements from 4 dogs that were hyperventilating both with and without supplemental oxygen treatment were excluded from the analysis. There was no significant ($P = 0.587$) effect of the interaction between oxygen supplementation and ventilation status on the mean difference between $Paco_2$ and $Petco_2$ for the 17 dogs included in this analysis. Also, mean difference between $Paco_2$ and $Petco_2$ did not differ significantly ($P = 0.439$) between hypoventilating and hyperventilating dogs.

Six of the 7 dogs with the highest difference between $Paco_2$ and $Petco_2$ (> 10 mm Hg) had pleural space disease, and all 6 of these dogs underwent thoracotomy for various conditions, including spontaneous
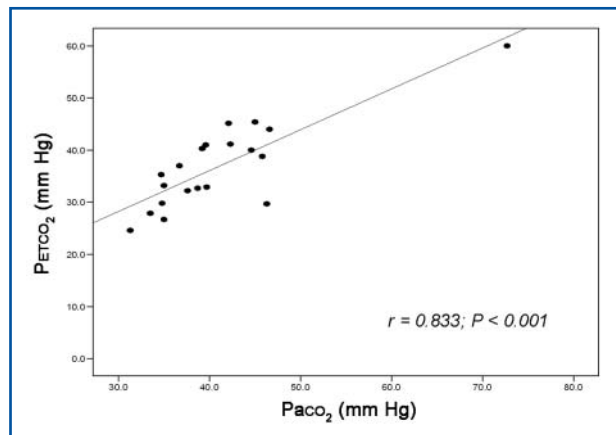

Figure 1—Scatterplot of paired measurements of $Paco_2$ and $Petco_2$ (obtained by means of nasal capnography) in 21 dogs; dogs were not receiving supplemental oxygen at the time measurements were obtained. The solid line represents the linear correlation.
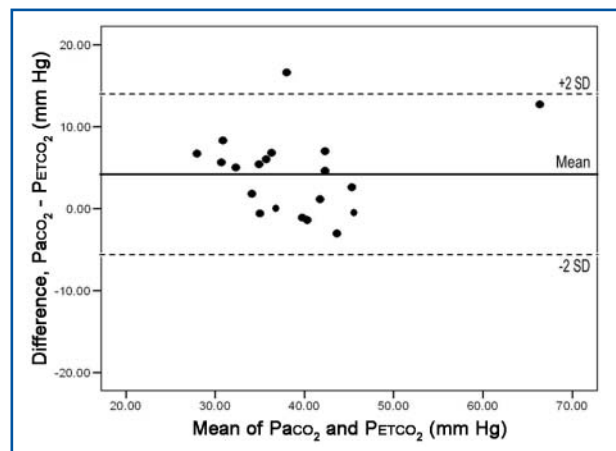

Figure 2—Bland-Altman plot of paired measurements of $Paco_2$ and $Petco_2$ (determined by means of nasal capnography) in 21 dogs; dogs were not receiving supplemental oxygen at the time measurements were obtained. The solid horizontal line represents the mean difference between $Paco_2$ and $Petco_2$; dotted horizontal lines represent the 95% limits of agreement (ie, mean difference ± 2 SD).
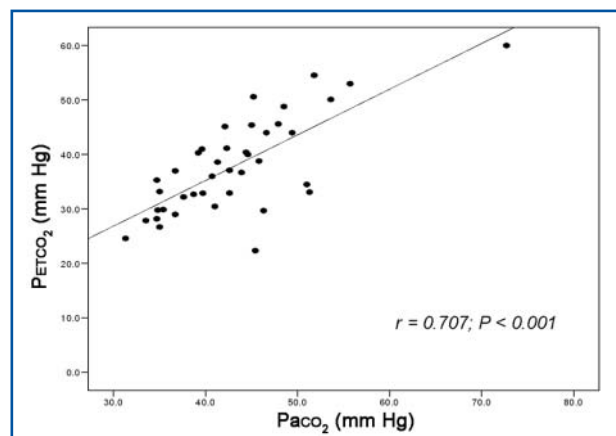

Figure 3—Scatterplot of paired measurements of $Paco_2$ and $Petco_2$ (obtained by means of nasal capnography) in 25 dogs; dogs were receiving supplemental oxygen at the time measurements were obtained. The solid line represents the linear correlation.
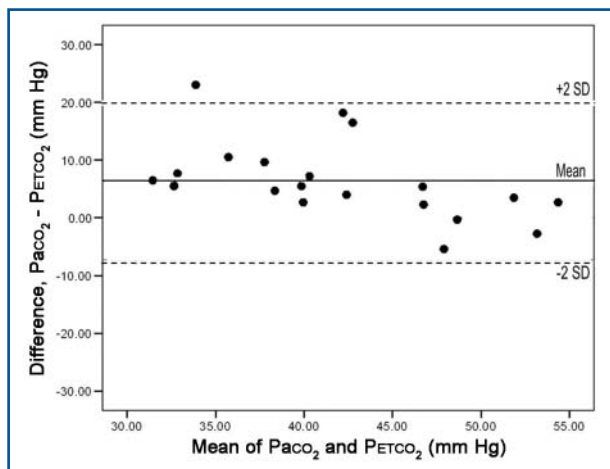
Figure 4—Bland-Altman plot of paired measurements of $Paco_2$ and $PETCO_2$ (determined by means of nasal capnography) in 25 dogs; dogs were receiving supplemental oxygen at the time measurements were obtained. The solid horizontal line represents the mean difference between $Paco_2$ and $PETCO_2$; dotted horizontal lines represent the 95% limits of agreement (ie, mean difference ± 2 SD).

pneumothorax, pericardioperitoneal diaphragmatic hernia, pacemaker placement secondary to sick sinus syndrome, and removal of a thymoma. The seventh dog had substantial hypoventilation ($Paco_2$ 72 mm Hg) and was slow to recover from anesthesia because of a neck bandage that had been placed following removal of a large cervical mass. Although measured $PETCO_2$ in this dog (60 mm Hg) was indicative of hypoventilation, $PETCO_2$ substantially underestimated $Paco_2$. Once the bandage was removed and the patient was positioned in sternal recumbency, the difference between $Paco_2$ and $PETCO_2$ decreased to 5.4 mm Hg and the patient's condition improved.

Paired values for $Paco_2$ and $PETCO_2$ were obtained from 12 dogs with an 8-F red rubber nasal catheter and from 9 dogs with a 10-F nasal catheter. Measurements obtained from dogs with a 5-F nasal catheter were excluded from this analysis. There was no significant ($P = 1.0$) effect of nasal catheter size on the mean of the average difference between $Paco_2$ and $PETCO_2$. Finally, 16 dogs were classified as alive at discharge and 10 were classified as having died during treatment or having been euthanatized within 3 weeks after discharge as a result of the underlying disease. Mean average difference between $Paco_2$ and $PETCO_2$ did not differ significantly ($P = 0.788$) between these 2 outcome groups.

Ten of the 21 (47%) dogs from which measurements were obtained when supplemental oxygen was not being administered were hypoxemic ($Pao_2 < 80$ mm Hg). Three of these 10 dogs were not considered to have a primary condition affecting the respiratory system, and oxygen supplementation had not been included in the treatment plan. For all 3 of these dogs, measurements were obtained during the immediate postoperative period; 1 dog had undergone portosystemic shunt ligation, 1 had undergone intestinal resection and anastomosis secondary to a jejunal foreign body, and 1 had undergone removal of a large cervical mass. In all 3 dogs, Pao_2 increased with oxygen supplementation.

Discussion

Results of the present study suggested that measurement of $PETCO_2$ via a nasal catheter was a feasible and clinically useful method of monitoring ventilation in spontaneously breathing, critically ill dogs admitted to an ICU. As expected, agreement between $PETCO_2$ measured via this method and $Paco_2$ was highest for dogs without respiratory tract disease that were not receiving oxygen supplementation. On the other hand, although mean difference between $Paco_2$ and $PETCO_2$ was significantly higher when dogs were receiving supplemental oxygen (mean ± SD, 6.87 ± 6.42 mm Hg) than when they were not (3.95 ± 4.92 mm Hg), we believe that this difference is likely not clinically important, in that a 5-mm Hg difference is expected between arterial and alveolar partial pressures of carbon dioxide because of physiologic dead space. A 6.87-mm Hg difference between arterial and alveolar partial pressures of carbon dioxide would still allow clinicians to obtain useful information regarding their patients' ventilatory status and would be unlikely to result in clinical errors detrimental to the patients. Nevertheless, this value represents the mean, and results of nasal capnography should be interpreted more cautiously in dogs receiving supplemental oxygen.

In the present study, the presence of a clinical condition affecting the respiratory system was associated with a significant increase in the mean difference between $Paco_2$ and $PETCO_2$. These findings were expected because parenchymal lung disease and pleural space disease both increase intrapulmonary shunting, causing areas of ventilation-perfusion mismatching within the lungs and thereby decreasing the accuracy and precision of capnography in patients with these conditions. The presence of a high Pao_2 – Pao_2 value was not associated with a higher mean difference between $Paco_2$ and $PETCO_2$. This unexpected finding was most likely a result of the small sample population for which Pao_2 – Pao_2 could be calculated and the high SD within this population.

Results of the present study are in general agreement with results of 2 previous studies[13,14] investigating the use of nasal capnography in dogs. The first study[13] involved dogs without pulmonary disease that were not panting and not receiving supplemental oxygen and reported a mean difference between $Paco_2$ and $PETCO_2$ of 3.2 mm Hg. The second[14] reported a clinically acceptable correlation between $Paco_2$ and $PETCO_2$ in healthy large-breed dogs. As in the present study, oxygen insufflation mildly increased the mean difference between $Paco_2$ and $PETCO_2$.

A previous study[8] in people found that tube size may influence the accuracy of nasal capnography measurements. In contrast, in the present study, mean difference between $Paco_2$ and $PETCO_2$ was not significantly associated with nasal catheter size. However, the range of nasal catheter sizes used in the present study was limited. Similarly, mean difference between $Paco_2$ and $PETCO_2$ was not associated with body weight, ventilatory status, or patient outcome in the present study.

Three of 10 dogs in the present study that were not considered to have a primary condition affecting the respiratory system were determined to be hypox-

emic (ie, $Pa_{O_2} < 80$ mm Hg). Oxygen supplementation was not initially part of the treatment plan in these dogs, but was instituted on the basis of results of arterial blood gas analyses, and in all 3, the Pa_{O_2} improved with oxygen supplementation. Findings in these dogs illustrate the importance of assessing oxygenation status in critically ill dogs and providing appropriate treatment if hypoxemia is identified, particularly during the postoperative period and even if the underlying condition does not involve the respiratory system.

Ultimately, monitoring ventilation with the use of nasal capnography is not necessary in all ICU patients. We believe it would be most beneficial for monitoring patients during the perioperative period, including patients at risk for hypoventilation, such as those with upper airway obstruction or conditions affecting the cervical region; critically ill patients, particularly those that are recumbent; and patients being weaned off mechanical ventilation. If the nasal catheter is being used for oxygen administration, the oxygen line can be temporarily disconnected to allow measurement of P_{ETCO_2} and replaced by flow-by oxygen administration in patients that are sedated or recumbent. Alternatively, 2 nasal catheters can be placed, 1 for oxygen administration and 1 for continuous capnography.

The present study had several important limitations. First, only 6 small dogs (< 10 kg) and no cats were enrolled. Collection of arterial blood samples and insertion of arterial catheters are technically challenging in small patients; therefore, there may have been a bias toward including large-breed dogs. Second, although 15 measurements were obtained from hypoventilating dogs, only 1 of these was from a dog that had severe hypoventilation (Pa_{CO_2}, 72 mm Hg). In this dog, the measured P_{ETCO_2} significantly underestimated the degree of hypoventilation. Studies involving more dogs with severe hypoventilation ($Pa_{CO_2} > 60$ mm Hg) are needed to determine the clinical applicability of nasal capnography in monitoring dogs with severe hypoventilation. A previous study[16] revealed that capnography is less reliable for monitoring severe hypoventilation in anesthetized, mechanically ventilated, healthy dogs, which could be the case for nasal capnography as well.

It is important to remember that arterial blood gas analysis remains the gold-standard method for assessing ventilation. Although the present and previous studies have revealed a clinically applicable correlation between results of nasal capnography and Pa_{CO_2}, we still recommend that arterial blood gas analysis be intermittently performed on a case-by-case basis.

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