2011

Agreement between arterial partial pressure of carbon dioxide and saturation of hemoglobin with oxygen values obtained by direct arterial blood measurements versus noninvasive methods in conscious healthy and ill foals

David M. Wong
Iowa State University, dwong@iastate.edu

Cody J. Alcott
Iowa State University, cjalcott@iastate.edu

Chong Wang
Iowa State University, chwang@iastate.edu

Jennifer L. Bornkamp
Iowa State University, bornkamp@iastate.edu

Jessica L. Young
Iowa State University

Agreement between arterial partial pressure of carbon dioxide and saturation of hemoglobin with oxygen values obtained by direct arterial blood measurements versus noninvasive methods in conscious healthy and ill foals

Abstract

Objective—To determine agreement between indirect measurements of end-tidal partial pressure of carbon dioxide (Petco2) and saturation of hemoglobin with oxygen as measured by pulse oximetry (Spo2) with direct measurements of Paco2 and calculated saturation of hemoglobin with oxygen in arterial blood (Sao2) in conscious healthy and ill foals. Design—Validation study. Animals—10 healthy and 21 ill neonatal foals. Procedures—Arterial blood gas analysis was performed on healthy and ill foals examined at a veterinary teaching hospital to determine direct measurements of Paco2 and Pao2 along with Sao2. Concurrently, Petco2 was measured with a capnograph inserted into a naris, and Spo2 was measured with a reflectance probe placed at the base of the tail. Paired values were compared by use of Pearson correlation coefficients, and level of agreement was assessed with the Bland-Altman method. Results—Mean ± SD difference between Paco2 and Petco2 was 0.1 ± 5.0 mm Hg. There was significant strong correlation (r = 0.779) and good agreement between Paco2 and Petco2. Mean ± SD difference between Sao2 and Spo2 was 2.5 ± 3.5%. There was significant moderate correlation (r = 0.499) and acceptable agreement between Sao2 and Spo2. Conclusions and Clinical Relevance—Both Petco2 obtained by use of nasal capnography and Spo2 obtained with a reflectance probe are clinically applicable and accurate indirect methods of estimating and monitoring Paco2 and Sao2 in neonatal foals. Indirect methods should not replace periodic direct measurement of corresponding parameters.

Comments

This article is from *Journal of the American Veterinary Medical Association* 239 (2011): 1341, doi: 10.2460/javma.239.10.1341. Posted with permission.

Authors

David M. Wong, Cody J. Alcott, Chong Wang, Jennifer L. Bornkamp, Jessica L. Young, and Brett A. Sponseller

Agreement between arterial partial pressure of carbon dioxide and saturation of hemoglobin with oxygen values obtained by direct arterial blood measurements versus noninvasive methods in conscious healthy and ill foals

David M. Wong, DVM, MS, DACVIM, DACVECC; Cody J. Alcott, DVM, DACVIM; Chong Wang, PhD; Jennifer L. Bornkamp, DVM; Jessica L. Young, DVM; Brett A. Sponseller, DVM, PhD, DACVIM

Objective—To determine agreement between indirect measurements of end-tidal partial pressure of carbon dioxide (P_{ETCO_2}) and saturation of hemoglobin with oxygen as measured by pulse oximetry (Spo_2) with direct measurements of $Paco_2$ and calculated saturation of hemoglobin with oxygen in arterial blood (Sao_2) in conscious healthy and ill foals.

Design—Validation study.

Animals—10 healthy and 21 ill neonatal foals.

Procedures—Arterial blood gas analysis was performed on healthy and ill foals examined at a veterinary teaching hospital to determine direct measurements of $Paco_2$ and Pao_2 along with Sao_2. Concurrently, P_{ETCO_2} was measured with a capnograph inserted into a naris, and Spo_2 was measured with a reflectance probe placed at the base of the tail. Paired values were compared by use of Pearson correlation coefficients, and level of agreement was assessed with the Bland-Altman method.

Results—Mean ± SD difference between $Paco_2$ and P_{ETCO_2} was 0.1 ± 5.0 mm Hg. There was significant strong correlation (r = 0.779) and good agreement between $Paco_2$ and P_{ETCO_2}. Mean ± SD difference between Sao_2 and Spo_2 was 2.5 ± 3.5%. There was significant moderate correlation (r = 0.499) and acceptable agreement between Sao_2 and Spo_2.

Conclusions and Clinical Relevance—Both P_{ETCO_2} obtained by use of nasal capnography and Spo_2 obtained with a reflectance probe are clinically applicable and accurate indirect methods of estimating and monitoring $Paco_2$ and Sao_2 in neonatal foals. Indirect methods should not replace periodic direct measurement of corresponding parameters. (*J Am Vet Med Assoc* 2011;239:1341–1347)

Ill foals presented for veterinary care often require assessment of blood oxygenation and evaluation of the status of patient ventilation.[1] Arterial blood gas analysis remains the gold standard for evaluation of these variables and is commonly used for this purpose to define and monitor arterial blood oxygenation and pulmonary function in ill foals. However, it can be difficult to collect arterial blood samples from foals, particularly foals with hypovolemia or in a state of circulatory shock. Other limitations and disadvantages of arteriopuncture include inadvertent collection of venous blood, hematoma formation, and poor patient cooperation. Furthermore, repeated arterial blood sample collection can result in pain and stress in foals along with vascular trauma and added client expense. In humans, capnography and pulse oximetry are noninvasive methods of assessing the $Paco_2$ and the Sao_2, respectively, as indirect measures of ventilation and oxygenation.[2]

From the Lloyd Veterinary Medical Center, Department of Veterinary Clinical Sciences (Wong, Alcott, Bornkamp, Young, Sponseller), and the Department of Production Animal Medicine (Wang), College of Veterinary Medicine, Iowa State University, Ames, IA 50011.
Address correspondence to Dr. Wong (dwong@iastate.edu).

Abbreviations

P_{ETCO_2}	End-tidal partial pressure of carbon dioxide
Sao_2	Calculated saturation of hemoglobin with oxygen in arterial blood
Spo_2	Saturation of hemoglobin with oxygen as measured by use of pulse oximetry

In general, the P_{ETCO_2} is lower than arterial values because of intrapulmonary dead-space ventilation, physiologic shunting, and variation in ventilation-to-perfusion ratios.[3–6] In healthy people and small animal species, the difference between $Paco_2$ and P_{ETCO_2}, also known as the $Paco_2$–P_{ETCO_2} gradient, is < 5 mm Hg.[5,7,8] The correlation between P_{ETCO_2} and $Paco_2$ has been good in awake, nonintubated people and dogs.[5,6,9–11] However, neither the correlation between P_{ETCO_2} and $Paco_2$ nor the evaluation of the $Paco_2$–P_{ETCO_2} gradient in conscious neonatal foals has been investigated. Similarly, numerous studies[2,12] on infants have demonstrated good to excellent accuracy and reliability of Sao_2 measured by use of pulse oximetry, compared with the accuracy and reliability calculated by use of arterial blood gas analysis, in the neonatal critical care setting.

One study[13] on foals concluded that pulse oximetry is a valuable method for assessing Sa_{O_2} in anesthetized foals. However, investigation into the usefulness and accuracy of pulse oximetry in conscious healthy and ill foals, compared with measurements calculated from arterial blood gas analysis, has not been performed.

If adequate agreement between direct and indirect measurements of Pa_{CO_2} and Sa_{O_2} exists, indirect assessment of these variables in conscious foals may be helpful in the therapeutic management of ill foals and may provide a less invasive, continuous, and more affordable means of patient monitoring. Therefore, the purpose of the study reported here was to evaluate the agreement between Pa_{CO_2} and P_{ETCO_2} in healthy and ill spontaneously breathing nonintubated foals. In addition, the agreement between the Sp_{O_2} and Sa_{O_2} was determined. A further objective was to determine whether respiratory rate, heart rate, or rectal temperature was associated with the accuracy of capnography or pulse oximetry. We hypothesized that there would be good agreement between both Pa_{CO_2} and P_{ETCO_2} as well as between Sp_{O_2} and Sa_{O_2}.

Materials and Methods

Animals—This prospective study included all neonatal foals (≤ 10 days of age) admitted to or born at the Lloyd Veterinary Medical Center at Iowa State University between January and May 2010, in which an arterial blood gas analysis was performed as part of their diagnostic evaluation. This included healthy foals born from mares admitted for monitoring and facilitation of parturition, healthy and ill foals born from mares with placentitis, and ill foals admitted for various medical disorders. Foals were considered healthy on the basis of physical examination, adequate transfer of maternal antibodies, and historical absence of maternal disorders during gestation or parturition. Definitive diagnosis in ill foals was based on clinical and diagnostic evaluation, which may have included a CBC, serum biochemical analysis, aerobic and anaerobic bacterial culture of blood samples, evaluation of serum immunoglobulin concentration, and ancillary diagnostic tests such as radiography and ultrasonography. Not all diagnostic testing was performed on all ill foals but was left to the discretion of the attending clinician. The experimental protocol was approved by the Institutional Animal Care and Use Committee of Iowa State University.

Procedures—Arterial blood samples were collected anaerobically into heparinized syringes from the dorsal metatarsal artery in all foals while in lateral recumbency at different times throughout hospitalization. All samples were analyzed within 5 minutes by use of a blood gas analyzer[a]; blood gas measurements (Pa_{CO_2} and Pa_{O_2}) were corrected to the foal's rectal temperature but not for the elevation at which the experiment was conducted (280.4 m [920 feet]). The Sa_{O_2} was obtained from measured Pa_{O_2} by use of a dissociation curve described for equine hemoglobin.[14] The blood gas analyzer was calibrated with reagent packs and gas standards prior to and every hour of each day during experimentation. Within 2 minutes after collection of arterial blood, and while foals were still in lateral recumbency, a reflectance transducer[b] was positioned over the coccygeal artery until a strong and consistent signal was detected, then was secured to the tail base with adhesive tape for indirect measurement of Sp_{O_2} by use of a commercial patient monitor.[c] Consecutive measurements of Sp_{O_2} data were continuously recorded over a 2-minute period. Values of Sp_{O_2} were recorded only if the pulse rate displayed on the oximeter was equal to the heart rate indicated by thoracic auscultation. Additionally, to obtain a sample of gas from the nasopharynx, a modified nasal tube (endotracheal tube with a 7-mm outer diameter cut to 4 cm in length) was connected to a side-stream capnograph and then inserted deep into a naris of the foal. Consecutive measurements of respiratory rate and P_{ETCO_2} were continuously monitored and recorded for 2 minutes by use of a commercially available capnograph.[c] The capnograph was calibrated prior to experimental use by means of manufacturer-supplied gas. The Sp_{O_2} and P_{ETCO_2} values were subsequently averaged with the mean value used for subsequent analysis.

Statistical analysis—Sample mean ± SD values were calculated for all variables. The association between P_{ETCO_2} and Pa_{CO_2} was assessed by use of Pearson correlation coefficients and tested for significance. Similarly, the association between Sp_{O_2} and Sa_{O_2} was assessed by use of Pearson correlation coefficients and tested for significance.

To assess levels of agreement, differences were calculated and summarized by use of mean ± SD values between the paired values of P_{ETCO_2} and Pa_{CO_2} and between the paired values of Sa_{O_2} and Sp_{O_2}. The 95% limits of agreement were calculated as mean difference ± 2 SD of the difference.[15] A paired *t* test was applied to test the difference of the mean value for each of the pairs. The association between paired differences and the variables respiratory rate, heart rate, and rectal temperature was assessed by use of Pearson correlation coefficients. The association between paired differences and health status (healthy or ill) was assessed by use of a 2-sample *t* test. Values of $P \leq 0.05$ were considered significant. Correlation coefficients were interpreted as weak (< 0.4), moderate (0.4 to 0.7), or strong (> 0.7).[5]

Results

Thirty-one neonatal foals were evaluated during the study period; breeds included Quarter Horse (n = 13), Thoroughbred (9), Paint (6), Percheron (1), Appaloosa (1), and Standardbred (1). Foals had a mean age of 4.1 days (range, 1 to 10 days) and a mean body weight of 52.7 kg (115.9 lb; range, 38 to 68 kg [83.6 to 149.6 lb]). Various coat colors were represented including bay and sorrel. There were 13 fillies and 18 colts, of which 10 were healthy and 21 were ill. Medical disorders of ill foals included failure of passive transfer of maternal antibodies, septicemia, enteritis and colitis, neonatal encephalopathy, patent urachus, neonatal isoerythrolysis, musculoskeletal disorders, congenital aganglionosis, and intussusception; some ill foals had > 1 concurrent disorder. The mean ± SD rectal temperature, heart rate, and respiratory rate were 38.2 ±

0.6°C (100.7 ± 1.0°F), 99 ± 19.8 beats/min, and 36 ± 18 breaths/min, respectively.

Regarding CO_2 values, the mean ± SD measurements of $Paco_2$ and $Petco_2$ for healthy foals were 49.2 ± 3.7 mm Hg and 48.5 ± 6.0 mm Hg, respectively, whereas mean measurements for ill foals were 48.3 ± 9.1 mm Hg and 48.5 ± 8.6 mm Hg, respectively. There was no significant difference in the mean values of $Paco_2$ or $Petco_2$ between the 2 groups; therefore, all individual measurements from healthy and ill foals were pooled, yielding a mean ± SD $Paco_2$ and $Petco_2$ of 48.6 ± 7.8 mm Hg (range, 42.8 to 67.1 mm Hg) and 48.5 ± 7.7 mm Hg (range, 33.4 to 66.3 mm Hg), respectively. There was a strong and significant linear correlation (r = 0.792; $P < 0.001$) between $Paco_2$ and $Petco_2$ with the calculated 95% limits of agreement of –9.9 to 10.1 mm Hg (**Figures 1 and 2**). The mean ± SD $Paco_2$–$Petco_2$ gradient was 0.7 ± 4.4 mm Hg for healthy foals and –0.2 ± 5.3 mm Hg for ill foals, with no significant difference between the means; therefore, the values of healthy and ill foals were pooled, yielding a mean ± SD $Paco_2$–$Petco_2$ gradient of 0.1 ± 5.0 mm Hg. Individual $Petco_2$ measurements were within ± 2 mm Hg of $Paco_2$ in 13 of 31 foals, within ± 5 mm Hg of $Paco_2$ in 24 of 31 foals, and within ± 10 mm Hg of $Paco_2$ in 26 of 31 foals. There was no significant correlation between the mean $Paco_2$–$Petco_2$ gradient and respiratory rate, heart rate, or rectal temperature. As noted, the difference between the mean ± SD $Paco_2$ and $Petco_2$ in all foals (ie, the $Paco_2$–$Petco_2$ gradient) was 0.1 mm Hg.

The reflectance transducer, placed at the base of the tail, provided a reliable pulse rate comparable with that obtained via thoracic auscultation in all foals. The mean ± SD Sao_2 and Spo_2 for healthy foals were 96.2 ± 1.4% and 93.2 ± 3.5%, respectively, whereas mean measurements for ill foals were 95.3 ± 2.5% and 93.1 ± 4.1%, respectively. There was no significant difference in the mean values of Sao_2 or Spo_2 between healthy and ill foals; therefore, individual measurements from healthy and ill foals were pooled, yielding a mean ± SD Sao_2 and Spo_2 of 95.6 ± 2.2% (range, 88.9% to 97.8%) and 93.1 ± 3.9% (range, 85.3% to 100.0%), respectively. The mean value of Sao_2 was significantly ($P < 0.001$) higher than that of Spo_2. There was a moderate and significant linear correlation (r = 0.450; P = 0.011) between Sao_2 and Spo_2 (**Figure 3**). Calculated 95% limits of agreement were –4.5% to 9.5% (**Figure 4**). The mean ± SD difference between reported Sao_2 and Spo_2 was 3.0 ± 3.4% for healthy foals and 2.3 ± 3.6% for ill foals, with no significant difference between the means; therefore, the values of healthy and ill foals were pooled, yielding a mean ± SD difference between Sao_2 and Spo_2 of 2.5 ± 3.5%. Individual Sao_2 values were within ± 2% of Spo_2 values in 10 of 31 foals, within ± 5% in 22 of

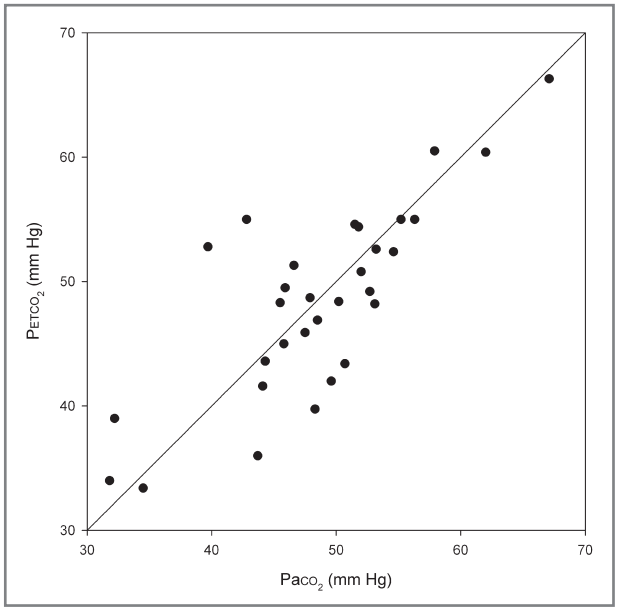

Figure 1—Scatterplot of paired measurements of $Petco_2$ and $Paco_2$ for 31 conscious neonatal foals (10 healthy and 21 ill). The solid line represents the line of identity.

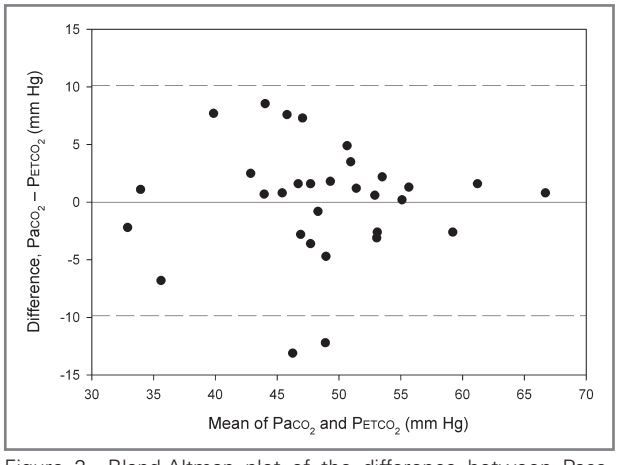

Figure 2—Bland-Altman plot of the difference between $Paco_2$ and $Petco_2$ versus the mean of $Paco_2$ and $Petco_2$. Paired measurements of $Paco_2$ and $Petco_2$ were used to determine the partial pressure of CO_2 in 31 conscious neonatal foals (10 healthy and 21 ill). Dashed horizontal lines represent the 95% limits of agreement (ie, mean difference ± 2 SD).

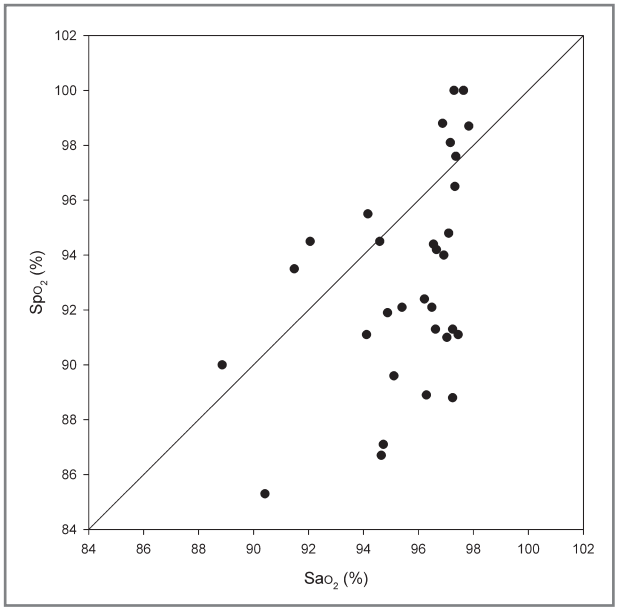

Figure 3—Scatterplot of paired measurements of Spo_2 and Sao_2 for 31 conscious neonatal foals (10 healthy and 21 ill). The solid line represents the line of identity.

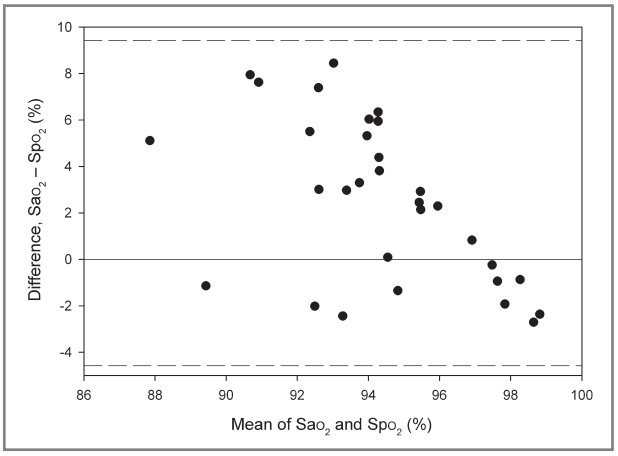

Figure 4—Bland-Altman plot of the difference between Sao_2 and Spo_2 versus the mean of Sao_2 and Spo_2. Paired measurements of Sao_2 and Spo_2 were used to determine the saturation of hemoglobin with oxygen in 31 conscious neonatal foals (10 healthy and 21 ill). Dashed horizontal lines represent the 95% limits of agreement (ie, mean difference ± 2 SD).

31 foals, and within ± 10% in 31 of 31 foals. In addition, there was no significant correlation between the mean Sao_2 and Spo_2 difference and respiratory rate, heart rate, or rectal temperature.

Discussion

Both hypercapnia and hypocapnia can be detrimental to neonatal foals. Hypercapnia results in respiratory acidemia and cerebral vasodilation, which can subsequently increase cerebral blood flow and intracranial pressure; these changes can consequently result in intracranial hemorrhage.[16,17] Conversely, hypocapnia can increase the risk for cerebral injury as a result of decreased blood flow to the brain, leading to ischemia of the white matter.[16,17] Thus, maintaining the $Paco_2$ concentration within the range observed in healthy individuals is an important goal in the care of critical patients. One particular situation in which foals can become substantially hypercapnic is with the clinical syndrome of neonatal encephalopathy.[18,19] A noninvasive method of estimating $Paco_2$ and detecting hypercapnia or hypocapnia would improve clinical evaluation and monitoring of ill foals with underlying ventilatory or pulmonary disorders and would guide treatment while avoiding frequent arteriopuncture. Results of this study support the use of $Petco_2$ monitoring as an estimate of $Paco_2$ in ill neonatal foals on the basis of a significant and strong correlation and relatively good agreement between the 2 measurements.

Although $Petco_2$ was strongly correlated with $Paco_2$ in this study (r = 0.792), correlation is a measure of association between 2 measurements, rather than agreement between 2 measurements. Perfect correlation exists between 2 methods when pairs of measurements approximate a straight line. However, interpretation of correlation can be deceiving; for example, if 2 different rectal thermometers always differ by 10°C (50°F), the 2 thermometers are strongly correlated but their level of agreement is low. Perfect agreement exists between 2 methods when pairs of measurements lie along a line of unity with a slope of 1 and an intercept of 0.[15] Therefore, it is agreement, rather than correlation, that determines whether one method of measurement can replace another.[20] The 95% limits of agreement between $Paco_2$ and $Petco_2$ in this study were –9.9 to 10.1 mm Hg, indicating that 95% of $Petco_2$ measurements were from 10.1 mm Hg less than to 9.9 mm Hg greater than measured $Paco_2$. This range can be subjectively interpreted in different ways. In an analogous study[5] evaluating the agreement between $Paco_2$ and $Petco_2$ in dogs, the 95% limits of agreement (–5.7 to 14.1 mm Hg) were similar to those documented in the study presented here.[5] The authors of the aforementioned study in dogs concluded that $Petco_2$ was a clinically useful method of monitoring ventilation in ill dogs. Conversely, the 95% limits of agreement in a comparable study[6] in children were –12.9 to 5.5 mm Hg; in that study, the authors concluded that this range was clinically too imprecise to replace $Paco_2$. In the present study, we consider the 95% limits of agreement between $Petco_2$ and $Paco_2$ as an acceptable adjunctive method of estimating and monitoring changes in $Paco_2$, especially considering that 77.4% of $Petco_2$ measurements were within 5 mm Hg of paired $Paco_2$ measurements. Additionally, the limits of agreement in the present study (10.1 mm Hg) were better than those in the aforementioned studies in dogs (14.07 mm Hg)[5] and children (12.88 mm Hg),[6] as the present study was smaller in magnitude than those previous studies. Moreover, the mean $Paco_2$–$Petco_2$ gradient was only 0.1 mm Hg, indicating little bias in the use of $Petco_2$ to approximate $Paco_2$. Together, this information suggests that $Petco_2$ can be used to estimate $Paco_2$ and monitor ventilatory status in conscious, spontaneously breathing neonatal foals. In the present study, there was no correlation between the mean $Paco_2$–$Petco_2$ gradient nor mean difference between Sao_2 and Spo_2 and respiratory rate, heart rate, or rectal temperature, suggesting that variations in these variables such as tachypnea, tachycardia, or fever, which are commonly observed in ill foals, do not significantly alter the association between direct and indirect measured values of $Paco_2$ or Sao_2. As with any indirect clinicopathologic measurements, periodic direct measurement of $Paco_2$ is a prudent approach to monitor patients, especially when drastic changes are observed in indirect measurements.

Previous studies[3,21–23] have evaluated the use of capnography ($Petco_2$) to monitor $Paco_2$ in anesthetized adult horses and foals. In 1 study[22] involving anesthetized adult horses, there was a significant correlation (r = 0.805; $P < 0.001$) between $Petco_2$ and $Paco_2$, with a mean ± SD $Paco_2$–$Petco_2$ gradient of 11.9 ± 8.1 mm Hg for halothane anesthesia. Those authors concluded that $Petco_2$ monitoring was an acceptable means of monitoring respiratory acid-base balance. Alternatively, authors of another study[23] did not recommend capnography as a method of evaluating $Paco_2$ on the basis of poor limits of agreement between $Petco_2$ and $Paco_2$ (–20.1 to 8.7 mm Hg) in anesthetized adult horses. In a study[3] involving anesthetized foals, the mean ± SD $Paco_2$–$Petco_2$ gradient was 7 ± 5 mm Hg (5 to 60 minutes after induction). This difference significantly increased to 13 ± 5 mm Hg 65 to 90 minutes after induction. The authors concluded that $Petco_2$ was useful in predict-

ing changes in $Paco_2$ during the early (< 60 minutes) anesthetic period, but also stated that the margin for error in predicting $Paco_2$ from $Petco_2$ was unacceptable for making clinical judgments about ventilatory status in anesthetized foals.[3] In previous equine studies[3,22,23] comparing $Paco_2$ and $Petco_2$, it is clear that anesthesia negatively impacts the association between these variables because of the effects of general anesthesia and prolonged recumbency resulting in hypoventilation, increased respiratory dead space, and ventilation-perfusion mismatch.[3,22,23] Although the difference between $Paco_2$ and $Petco_2$ in the study reported here was much less than that reported for anesthetized animals, direct comparisons between studies are not possible, as the population of our study consisted of conscious foals.

There was no significant difference in the $Paco_2$–$Petco_2$ gradient between healthy and ill foals in the present study; thus, values obtained from both healthy and ill neonatal foals were combined, resulting in the reported $Paco_2$–$Petco_2$ gradient of 0.1 ± 5.0 mm Hg. A number of equine studies have also evaluated the $Paco_2$–$Petco_2$ gradient in anesthetized horses and foals, but to the authors' knowledge, this is the first evaluation of the $Paco_2$–$Petco_2$ gradient in conscious foals. As noted in the previous study[3] on foals, the mean $Paco_2$–$Petco_2$ gradients were 7 and 13 mm Hg at 5 to 60 minutes and 65 to 90 minutes, respectively, after anesthetic induction.[3] Other studies[3,4,21,22] in anesthetized adult horses also reflect a higher $Paco_2$–$Petco_2$ gradient in anesthetized horses, and this fact has been attributed to increased physiologic dead space, increased ventilation-perfusion ratio, and hypoventilation, among other factors.[3,4,21,22] Clinically, the $Paco_2$–$Petco_2$ gradient can be used to document and monitor a variety of respiratory or cardiac conditions.[24–28] For example, neonatal infants with pulmonary disorders such as persistent pulmonary hypertension, respiratory distress syndrome, pneumonia, or meconium aspiration had a significantly higher $Paco_2$–$Petco_2$ gradient (7.4 ± 3.3 mm Hg) when compared with aged-matched healthy controls (3.0 ± 2.4 mm Hg).[25] The $Paco_2$–$Petco_2$ gradient has also been used to support the diagnosis of pulmonary thromboembolism as well as to monitor efficacy of thrombolysis in patients with pulmonary thromboembolism.[27,28] Therefore, the $Paco_2$–$Petco_2$ gradient can be used to evaluate or monitor progression of various pulmonary or cardiovascular diseases.

In the study reported here, there were instances in which the $Petco_2$ was higher than the $Paco_2$ (Figures 1 and 2). In theory, this should not occur, but this finding has been reported in similar studies[5,6,9,23,29,30] on people, horses, and dogs. This detail may have contributed to the small $Paco_2$–$Petco_2$ gradient documented in our study. The exact reason for the occurrence in the present study is unknown, but possible reasons include the temporal delay between collection and measurement of $Paco_2$ and measurement of $Petco_2$, errors in calibration of the capnograph or blood gas analyzer, overestimation of $Petco_2$ from interference of water vapor in the capnograph's sampling chamber, or trapping of CO_2 within the nasopharynx because of increased expiratory resistance from nasopharyngeal obstruction or presence of the measuring chamber.[31] The fact that $Paco_2$ was measured at a single time point whereas the $Petco_2$ was the mean measurement obtained over 2 minutes may have also impacted results. Other proposed causes of a higher $Petco_2$, compared with $Paco_2$, include excessive CO_2 production coupled with low inspired volume or high cardiac output, CO_2 displacement from hemoglobin as a result of high inspired O_2 content, low functional residual capacity, and alveoli with low ventilation-to-perfusion ratios.[32,33]

Just as hypercapnia or hypocapnia can be detrimental to the health of foals, hypoxemia can be equally harmful. Pulse oximetry is a monitoring technique that provides immediate information about the patient's pulse rate and oxygenation status and has been investigated in anesthetized horses and foals.[13,23,34–37] A previous study[13] in neonatal foals documented a significant and strong correlation between Sao_2 and Spo_2 ($r = 0.93$; $P < 0.001$) with a reflectance probe in anesthetized foals; in that study, Spo_2 underestimated Sao_2, with a mean difference between Sao_2 and Spo_2 of 5.3%.[13] Results of the present study are the first to report comparisons between Sao_2 and Spo_2 in conscious neonatal foals and suggest that Spo_2 measured with a reflectance probe[c] placed at the base of the tail is a feasible method of monitoring Sao_2.

In the present study, Spo_2 tended to underestimate Sao_2, with a mean difference of 2.5%. Interestingly, other studies[13,23,36,37] on horses have also documented that Spo_2 generally underestimates Sao_2. In the study reported here, the limits of agreement were –4.5% to 9.5%, indicating that 95% of Spo_2 measurements were from 9.5% less than to 4.5% greater than Sao_2. Manufacturers report pulse oximetry accuracy to 1 SD of < ± 3% when arterial oxygen saturation is ≥ 70%.[12] To incorporate the 95% confidence interval, this number is doubled (eg, < ± 6%). Thus, the manufacturer's reported accuracy is open to interpretation. Overall, pulse oximetry appears to provide a good estimate of Sao_2 and allows clinicians to monitor changes in pulse and hemoglobin saturation in conscious neonatal foals. Even though 71% of Spo_2 values were within 5% of Sao_2, the authors believe that the limits of agreement in the study reported here are large enough to indicate that Spo_2 cannot supplant precise determination of Sao_2 via arterial blood gas analysis. Additionally, although the correlation between Sao_2 and Spo_2 in the present study was significant, the actual correlation ($r = 0.499$) was moderate at best. Therefore, arterial blood gas analysis should be used to confirm and monitor Spo_2 changes (ie, desaturation of hemoglobin).

Transmittance probes use a phototransmitter on one side of a tissue bed while the photodetector is on the other side of the tissue bed, thus requiring a thin extremity (eg, ear or finger) or body structure (eg, lip or tongue) to be isolated or clamped between the phototransmitter and photodetector. A reflectance probe, in which both the phototransmitter and photodetector are on the same side of the tissue bed, was selected for the present study because, in the authors' clinical experience, transmittance probes have an inconsistent ability to detect a pulse in foals. This observation is supported by equine studies[34,36] that failed to detect the pulse with transmittance probes placed on a nostril, a lip, or the

vulva. Furthermore, some transmittance probes do not work consistently on darkly pigmented tissue.[34,36] Of note, consistent detection of the pulse has been documented when the transmittance probe is placed on the tongue[13,23,34,36,37]; however, this site is not particularly feasible in conscious foals. In the study reported here, the reflectance probe was always able to detect the foal's pulse and provide an Spo_2 reading, regardless of skin pigmentation. Considering the ease of placement and maintenance of the reflectance probe in proper position on the ventral aspect of the tail base, the ability to consistently detect a pulse, and the relatively good agreement with Sao_2 measurements, the authors suggest that placement of a reflectance probe at this site is an ideal method of monitoring pulse rate and Sao_2 in foals, particularly if the foal is recumbent for prolonged periods because of illness. In turn, real-time and continuous assessment of the pulse and Spo_2 on a moment-to-moment basis will facilitate patient monitoring as well as response to therapeutic interventions. However, the authors would like to reiterate that Spo_2 cannot completely supplant arterial blood gas analysis on the basis of the findings in the present study.

There are several limitations of this study that should be considered. First, simultaneous determination of measurements, such as $Paco_2$ and $Petco_2$, was not possible; therefore, the gap in time (2 to 5 minutes) between measurements could have resulted in temporal differences between direct and indirect measurements. Another limitation is the fact that clinical patients were studied; therefore, deliberate hypercapnia or hypocapnia and hypoxemia could not be induced. The $Paco_2$ in this study ranged from 42.8 to 67.1 mm Hg; thus, correlations between extremely low or high $Paco_2$ values and $Petco_2$ were not investigated. Similarly, Sao_2 in this study ranged from 88.9% to 97.8%; thus, correlation between Sao_2 and Spo_2 cannot be made with lower (eg, < 80%) Sao_2 values. A prior study[13] in which foals were anesthetized allowed manipulation of the Pao_2 and Sao_2. In that study,[13] the authors concluded that poor precision of Spo_2 occurred when Sao_2 values were < 80%. However, the authors also stated that the reflectance probe performed more consistently over various ranges of Sao_2 than did other transmittance probes.[13] Other studies[36,37] in anesthetized adult horses have also documented increased variability in the difference between Sao_2 and Spo_2 as well as limits of agreement when Sao_2 values were < 80%. Additionally, in the ideal situation, Spo_2 should have been compared with Sao_2 values determined by use of a co-oximeter rather than with a calculated value; however, this instrument was not available to the investigators of the present study. Therefore, it is possible that some error in accuracy may occur owing to the use of a calculated, rather than measured, Sao_2 via co-oximetry.

Finally, although the benefits of the noninvasive and continuous ability to monitor $Petco_2$ and Spo_2 are clear, the inherent limitations of the actual instruments (ie, the capnograph and pulse oximeter) must be recognized. Sidestream capnography slightly increases airway resistance and also draws 125 to 500 mL of gas/min from the patient, but these factors would be negligible in most foals.[38] Pulse oximetry has technical limitations, including a limited ability of the instrument to detect an arterial pulse in patients with impaired arterial perfusion from shock, hypothermia, or hypovolemia. Motion artifact in conscious foals is also a common limitation. Clinicians must realize that accuracy of the instrument deteriorates when Sao_2 is < 80% and that dyshemoglobinemias (ie, carboxyhemoglobin and methemoglobin) and the use of diagnostic dyes (ie, methylene blue) will provide erroneous results.[2,12,13] Furthermore, Sao_2 is an estimate of Pao_2, and because of the sigmoid shape of the oxygen dissociation curve, large changes in Pao_2 may occur at the upper portions of the curve whereas minimal changes are observed in Sao_2. Thus, a patient, especially one receiving supplemental oxygen, may have a dramatic decrease in Pao_2 with only a minimal decrease in Spo_2. The oxygen dissociation curve may also shift as a result of increases or decreases in pH or $Paco_2$; thus, Spo_2 should be interpreted in light of the patient's blood pH and $Paco_2$.

End-tidal partial pressure of carbon dioxide and Spo_2 have been used as adequate methods of estimating and monitoring $Paco_2$ and blood oxygenation, respectively, in infants and adults.[2,11,39,40] Results of the study reported here suggested that $Petco_2$ can also be used in neonatal foals when assessment and monitoring of $Paco_2$ is necessary. Determination of pulse rate with a reflectance probe was reliable in this study, and Spo_2 measurements had acceptable limits of agreement with Sao_2. However, pulse oximetry underestimated Sao_2 in this study. Clinicians should realize the limitations of this study and be advised that $Petco_2$ and Spo_2 should not replace the judicious use of direct measurement of $Paco_2$ and Pao_2 via arterial blood gas analysis, especially when marked changes in $Petco_2$ or Spo_2 are observed.

a. Rapidlab, Bayer Heatlhcare, Rarrytown, NY.
b. Oxisensor II RS10, Tyco Healthcare Group, Pleasanton, Calif.
c. Passport2, Datascope Patient Monitoring, Mahwah, NJ.

References

1. Palmer JE. Ventilatory support of the critically ill foal. *Vet Clin North Am Equine Pract* 2005;21:457–486.
2. Soubani AO. Noninvasive monitoring of oxygen and carbon dioxide. *Am J Emerg Med* 2001;19:141–146.
3. Geiser DR, Rohrbach BW. Use of end-tidal CO_2 tension to predict arterial CO_2 values in isoflurane-anesthetized equine neonates. *Am J Vet Res* 1992;53:1617–1621.
4. Hopkins SR, Bayly WM, Slocombe RF, et al. Effect of prolonged heavy exercise on pulmonary gas exchange in horses. *J Appl Physiol* 1998;84:1723–1730.
5. Kelmer E, Scanson LC, Reed A, et al. Agreement between values for arterial and end-tidal partial pressures of carbon dioxide in spontaneously breathing, critically ill dogs. *J Am Vet Med Assoc* 2009;235:1314–1318.
6. Moses JM, Alexander JL, Agus MS. The correlation and level of agreement between end-tidal and blood gas Pco_2 in children with respiratory distress: a retrospective analysis. *BMC Pediatr* [serial online] 2009;9:20. Available at: www.biomedcentral.com/1471-2431/9/20. Accessed Aug 10, 2010.
7. Schmitz BD, Shapiro BA. Capnography. *Respir Care Clin North Am* 1995;1:107–117.
8. Raffe M. Oximetry and capnography In: Wingfield W, Raffe M, eds. *The veterinary ICU book*. Jackson, WY: Teton NewMedia, 2002;86–95.
9. Amuchou Singh S, Singhal N. Does end-tidal carbon dioxide measurement correlate with arterial carbon dioxide in extreme-

ly low birth weight infants in the first week of life? *Indian Pediatr* 2006;43:20–25.
10. Barton CW, Wang ES. Correlation of end-tidal CO_2 measurements to arterial $Paco_2$ in nonintubated patients. *Ann Emerg Med* 1994;23:560–563.
11. Cheng KI, Tang CS, Tsai EM, et al. Correlation of arterial and end-tidal carbon dioxide in spontaneously breathing patients during ambulatory gynecologic laparoscopy. *J Formos Med Assoc* 1999;98:814–819.
12. Sinex JE. Pulse oximetry: principles and limitations. *Am J Emerg Med* 1999;17:59–67.
13. Chaffin MK, Matthews NS, Cohen ND, et al. Evaluation of pulse oximetry in anaesthetised foals using multiple combinations of transducer type and transducer attachment site. *Equine Vet J* 1996;28:437–445.
14. Smale K, Anderson LS, Butler PJ. An algorithm to describe the oxygen equilibrium curve for the Thoroughbred racehorse. *Equine Vet J* 1994;26:500–502.
15. Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet* 1986;1:307–310.
16. Ambalavanan N, Carlo WA. Hypocapnia and hypercapnia in respiratory management of newborn infants. *Clin Perinatol* 2001;28:517–531.
17. Jankov RP, Tanswell AK. Hypercapnia and the neonate. *Acta Paediatr* 2008;97:1502–1509.
18. Giguere S, Slade JK, Sanchez LC. Retrospective comparison of caffeine and doxapram for the treatment of hypercapnia in foals with hypoxic-ischemic encephalopathy. *J Vet Intern Med* 2008;22:401–405.
19. Vaala WE. Peripartum asphyxia. *Vet Clin North Am Equine Pract* 1994;10:187–218.
20. Bland JM, Altman DG. Measuring agreement in method comparison studies. *Stat Methods Med Res* 1999;8:135–160.
21. Meyer RE, Short CE. Arterial to end-tidal CO_2 tension and alveolar dead space in halothane- or isoflurane-anesthetized ponies. *Am J Vet Res* 1985;46:597–599.
22. Cribb PH. Capnographic monitoring during anesthesia with controlled ventilation in the horse. *Vet Surg* 1988;17:48–52.
23. Koenig J, McDonell W, Valverde A. Accuracy of pulse oximetry and capnography in healthy and compromised horses during spontaneous and controlled ventilation. *Can J Vet Res* 2003;67:169–174.
24. Choudhury M, Kiran U, Choudhary SK, et al. Arterial-to-end-tidal carbon dioxide tension difference in children with congenital heart disease. *J Cardiothorac Vasc Anesth* 2006;20:196–201.
25. Hagerty JJ, Kleinman ME, Zurakowski D, et al. Accuracy of a new low-flow sidestream capnography technology in newborns: a pilot study. *J Perinatol* 2002;22:219–225.
26. Short JA, Paris ST, Booker PD, et al. Arterial to end-tidal carbon dioxide tension difference in children with congenital heart disease. *Br J Anaesth* 2001;86:349–353.
27. Taniguchi S, Irita K, Sakaguchi Y, et al. Arterial to end-tidal CO_2 gradient as an indicator of silent pulmonary embolism. *Lancet* 1996;348:1451.
28. Thys F, Elamly A, Marion E, et al. $Paco(2)/Etco(2)$ gradient: early indicator of thrombolysis efficacy in a massive pulmonary embolism. *Resuscitation* 2001;49:105–108.
29. McNulty SE, Roy J, Torjman M, et al. Relationship between arterial carbon dioxide and end-tidal carbon dioxide when a nasal sampling port is used. *J Clin Monit* 1990;6:93–98.
30. Takano Y, Sakamoto O, Kiyofuji C, et al. A comparison of the end-tidal CO_2 measured by portable capnometer and the arterial P_{CO_2} in spontaneously breathing patients. *Respir Med* 2003;97:476–481.
31. Severinghaus JW. Water vapor calibration errors in some capnometers: respiratory conventions misunderstood by manufacturers? *Anesthesiology* 1989;70:996–998.
32. Fletcher R, Jonson B, Cumming G, et al. The concept of dead-space with special reference to the single breath test for carbon dioxide. *Br J Anaesth* 1981;53:77–88.
33. Marino PL. Oximetry and capnography In: Marino PL, ed. *The ICU book*. Philadelphia: Lippincott Williams & Wilkins, 1998;355–370.
34. Matthews NS, Hartke S, Allen JC Jr. An evaluation of pulse oximeters in dogs, cats and horses. *Vet Anaesth Analg* 2003;30:3–14.
35. Watney GC, Norman WM, Schumacher JP, et al. Accuracy of a reflectance pulse oximeter in anesthetized horses. *Am J Vet Res* 1993;54:497–501.
36. Whitehair KJ, Watney GC, Leith DE, et al. Pulse oximetry in horses. *Vet Surg* 1990;19:243–248.
37. Matthews NS, Hartsfield SM, Sanders EA, et al. Evaluation of pulse oximetry in horses surgically treated for colic. *Equine Vet J* 1994;26:114–116.
38. Hackett TB. Pulse oximetry and end tidal carbon dioxide monitoring. *Vet Clin North Am Small Anim Pract* 2002;32:1021–1029.
39. Casati A, Gallioli G, Passaretta R, et al. End tidal carbon dioxide monitoring in spontaneously breathing, nonintubated patients. A clinical comparison between conventional sidestream and microstream capnometers. *Minerva Anestesiol* 2001;67:161–164.
40. Keogh BF, Kopotic RJ. Recent findings in the use of reflectance oximetry: a critical review. *Curr Opin Anaesthesiol* 2005;18:649–654.