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

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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.

Disciplines
Large or Food Animal and Equine Medicine | Veterinary Anatomy | Veterinary Physiology

Comments
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Design—Validation study.

Animals—10 healthy and 21 ill neonatal foals.

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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 ± 3.6%. 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. (J Am Vet Med Assoc 2011;239:1341–1347)

Abbreviations

| Petco2 | End-tidal partial pressure of carbon dioxide |
|------------------------|
| SaO2 | Calculated saturation of hemoglobin with oxygen in arterial blood |
| Spo2 | Saturation of hemoglobin with oxygen as measured by use of pulse oximetry |

In general, the Petco2 is lower than arterial values because of intrapulmonary dead-space ventilation, physiologic shunting, and variation in ventilation-to-perfusion ratios.1–4 In healthy people and small animal species, the difference between Paco2 and Petco2, also known as the Paco2–Petco2 gradient, is < 5 mm Hg.5,7,8 The correlation between Petco2 and Paco2 has been good in awake, nonintubated people and dogs.5,8–11 However, neither the correlation between Petco2 and Paco2 nor the evaluation of the Paco2–Petco2 gradient in conscious neonatal foals has been investigated. Similarly, numerous studies2,12 on infants have demonstrated good to excellent accuracy and reliability of SaO2 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.

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One study on foals concluded that pulse oximetry is a valuable method for assessing \( \text{SaO}_2 \) 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 \( \text{Paco}_2 \) and \( \text{SaO}_2 \) 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 \( \text{PaCO}_2 \) and \( \text{PetcO}_2 \), in healthy and ill spontaneously breathing nonintubated foals. In addition, the agreement between the \( \text{SpO}_2 \) and \( \text{SaO}_2 \) 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 \( \text{Paco}_2 \) and \( \text{PetcO}_2 \) as well as between \( \text{SpO}_2 \) and \( \text{SaO}_2 \).

**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; blood gas measurements (\( \text{Paco}_2 \) and \( \text{Pao}_2 \)) 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 \( \text{SaO}_2 \) was obtained from measured \( \text{Pao}_2 \) by use of a dissociation curve described for equine hemoglobin. 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 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 \( \text{SpetO}_2 \) by use of a commercial patient monitor. Consecutive measurements of \( \text{SpetO}_2 \) data were continuously recorded over a 2-minute period. Values of \( \text{SpO}_2 \) 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 \( \text{PetcO}_2 \) were continuously monitored and recorded for 2 minutes by use of a commercially available capnograph. The capnograph was calibrated prior to experimental use by means of manufacturer-supplied gas. The \( \text{SpO}_2 \) and \( \text{PetcO}_2 \) 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 \( \text{PetcO}_2 \) and \( \text{Paco}_2 \) was assessed by use of Pearson correlation coefficients and tested for significance. Similarly, the association between \( \text{SpO}_2 \) and \( \text{SaO}_2 \) 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 \( \text{PetcO}_2 \) and \( \text{Paco}_2 \) and between the paired values of \( \text{SaO}_2 \) and \( \text{SpO}_2 \). The 95% limits of agreement were calculated as mean difference ± 2 SD of the difference. 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 \( P ≤ 0.05 \) were considered significant. Correlation coefficients were interpreted as weak (\( < 0.4 \)), moderate (\( 0.4 \) to 0.7), or strong (\( > 0.7 \)).

**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 CO₂ values, the mean ± SD measurements of \( \text{Paco}_2 \) and \( \text{Petco}_2 \) 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 \( \text{Paco}_2 \) or \( \text{Petco}_2 \) between the 2 groups; therefore, all individual measurements from healthy and ill foals were pooled, yielding a mean ± SD \( \text{Paco}_2–\text{Petco}_2 \) gradient of 0.1 ± 3.0 mm Hg. Individual \( \text{Paco}_2–\text{Petco}_2 \) measurements were within ± 2 mm Hg of \( \text{Paco}_2 \) in 13 of 31 foals, within ± 5 mm Hg of \( \text{Paco}_2 \) in 24 of 31 foals, and within ± 10 mm Hg of \( \text{Paco}_2 \) in 26 of 31 foals. There was no significant correlation between the mean \( \text{Paco}_2–\text{Petco}_2 \) gradient and respiratory rate, heart rate, or rectal temperature. As noted, the difference between the mean \( \text{Paco}_2–\text{Petco}_2 \) 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 \( \text{Paco}_2–\text{Petco}_2 \) gradient of 0.1 ± 3.0 mm Hg. Individual \( \text{Paco}_2–\text{Petco}_2 \) measurements were within ± 2 mm Hg of \( \text{Paco}_2 \) in 13 of 31 foals, within ± 5 mm Hg of \( \text{Paco}_2 \) in 24 of 31 foals, and within ± 10 mm Hg of \( \text{Paco}_2 \) in 26 of 31 foals.

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 \( \text{Sao}_2 \) and \( \text{Spo}_2 \) for healthy foals were 96.2 ± 1.4% and 93.2 ± 3.3%, respectively, whereas mean measurements for ill foals were 93.3 ± 2.5% and 93.1 ± 4.1%, respectively. There was no significant difference in the mean values of \( \text{Sao}_2 \) or \( \text{Spo}_2 \) between healthy and ill foals; therefore, individual measurements from healthy and ill foals were pooled, yielding a mean ± SD \( \text{Sao}_2 \) and \( \text{Spo}_2 \) 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 \( \text{Sao}_2 \) was significantly (\( P < 0.001 \)) higher than that of \( \text{Spo}_2 \). There was a moderate and significant linear correlation (\( r = 0.450; P = 0.011 \)) between \( \text{Sao}_2 \) and \( \text{Spo}_2 \) (Figure 3). Calculated 95% limits of agreement were −4.5% to 9.5% (Figure 4). The mean ± SD difference between reported \( \text{Sao}_2 \) and \( \text{Spo}_2 \) 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 \( \text{Sao}_2 \) and \( \text{Spo}_2 \) of 2.5 ± 3.5%. Individual \( \text{Sao}_2 \) values were within ± 2% of \( \text{Spo}_2 \) values in 10 of 31 foals, within ± 5% in 22 of
Figure 4—Bland-Altman plot of the difference between SaO\textsubscript{2} and SpO\textsubscript{2} versus the mean of SaO\textsubscript{2} and SpO\textsubscript{2}. Paired measurements of SaO\textsubscript{2} and SpO\textsubscript{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. The 95% lines were –10.1 to 10.1 mm Hg (5 to 60 minutes after induction). This range can be subjectively interpreted in different ways. In an analogous study evaluating the agreement between PACO\textsubscript{2} and PETCO\textsubscript{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. The authors of the aforementioned study in dogs concluded that PETCO\textsubscript{2} was a clinically useful method of monitoring ventilation in ill dogs. Conversely, the 95% limits of agreement in a comparable study 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\textsubscript{2}. In the present study, we consider the 95% limits of agreement between PETCO\textsubscript{2} and PACO\textsubscript{2} as an acceptable adjunctive method of estimating and monitoring changes in PACO\textsubscript{2}, especially considering that 77.4% of PETCO\textsubscript{2} measurements were within 5 mm Hg of paired PACO\textsubscript{2} measurements. Additionally, the 95% 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\textsuperscript{3} and children (12.88 mm Hg),\textsuperscript{6} as the present study was smaller in magnitude than those previous studies. Moreover, the mean PACO\textsubscript{2}–PETCO\textsubscript{2} gradient was only 0.1 mm Hg, indicating little bias in the use of PETCO\textsubscript{2} to approximate PACO\textsubscript{2}. Together, this information suggests that PETCO\textsubscript{2} can be used to estimate PACO\textsubscript{2} and monitor ventilatory status in conscious, spontaneously breathing neonatal foals. In the present study, there was no correlation between the mean PACO\textsubscript{2}–PETCO\textsubscript{2} gradient nor mean difference between SaO\textsubscript{2} and SpO\textsubscript{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\textsubscript{2} or SaO\textsubscript{2}. As with any indirect clinical measurements, periodic direct measurement of PACO\textsubscript{2} is a prudent approach to monitor patients, especially when drastic changes are observed in indirect measurements.

Previous studies\textsuperscript{13,14,20} have evaluated the use of capnography (PETCO\textsubscript{2}) to monitor PACO\textsubscript{2} in anesthetized adult horses and foals. In 1 study\textsuperscript{22} involving anesthetized adult horses, there was a significant correlation (r = 0.805; P < 0.001) between PETCO\textsubscript{2} and PACO\textsubscript{2} with a mean ± SD PACO\textsubscript{2}–PETCO\textsubscript{2} gradient of 11.9 ± 8.1 mm Hg for halothane anaesthesia. Those authors concluded that PETCO\textsubscript{2} monitoring was an acceptable means of monitoring respiratory acid-base balance. Alternatively, authors of another study\textsuperscript{23} did not recommend capnography as a method of evaluating PACO\textsubscript{2} on the basis of poor limits of agreement between PETCO\textsubscript{2} and PACO\textsubscript{2} (–20.1 to 8.7 mm Hg) in anesthetized adult horses. In a study involving anesthetized foals, the mean ± SD PACO\textsubscript{2}–PETCO\textsubscript{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\textsubscript{2} was useful in predict-
ing changes in Paco2, during the early (< 60 minutes) anesthetic period, but also stated that the margin for error in predicting Paco2 from Petco2 was unacceptable for making clinical judgments about ventilatory status in anesthetized foals.3 In previous equine studies2,22,23 comparing Paco2 and Petco2, it is clear that anesthesia negatively impacts the association between these variables because of the effects of general anesthesia and prolonged recency resulting in hyperventilation, increased respiratory dead space, and ventilation-perfusion mismatch.2,22,23 Although the difference between Paco2 and Petco2 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 Paco2–Petco2 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 Paco2–Petco2 gradient of 0.1 ± 5.0 mm Hg. A number of equine studies have also evaluated the Paco2–Petco2 gradient in anesthetized horses and foals, but to the authors’ knowledge, this is the first evaluation of the Paco2–Petco2 gradient in conscious foals. As noted in the previous study3 on foals, the mean Paco2–Petco2 gradients were 7 and 13 mm Hg at 5 to 60 minutes and 65 to 90 minutes, respectively, after anesthetic induction.3 Other studies3,22,23 in anesthetized adult horses also reflect a higher Paco2–Petco2 gradient in anesthetized horses, and this fact has been attributed to increased physiologic dead space, increased ventilation-perfusion ratio, and hyperventilation, among other factors.2,22–24 Clinically, the Paco2–Petco2 gradient can be utilized to document and monitor a variety of respiratory or cardiac conditions.24–27 For example, neonatal infants with pulmonary disorders such as persistent pulmonary hypertension, respiratory distress syndrome, pneumonia, or meconium aspiration had a significantly higher Paco2–Petco2 gradient (7.4 ± 3.3 mm Hg) when compared with aged-matched healthy controls (3.0 ± 2.4 mm Hg).25 The Paco2–Petco2 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 Paco2–Petco2 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 Petco2 was higher than the Paco2 (Figures 1 and 2). In theory, this should not occur, but this finding has been reported in similar studies2,6,9,23,29,30 on people, horses, and dogs. This detail may have contributed to the small Paco2–Petco2 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 Paco2 and measurement of Petco2, errors in calibration of the capnograph or blood gas analyzer, overestimation of Petco2 from interference of water vapor in the capnograph’s sampling chamber, or trapping of CO2 within the nasopharynx because of increased expiratory resistance from nasopharyngeal obstruction or presence of the measuring chamber.31 The fact that Paco2 was measured at a single time point whereas the Petco2 was the mean measurement obtained over 2 minutes may have also impacted results. Other proposed causes of a higher Petco2, compared with Paco2, include excessive CO2 production coupled with low inspired volume or high cardiac output, CO2 displacement from hemoglobin as a result of high inspired O2 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.13,23,30–37 A previous study13 in neonatal foals documented a significant and strong correlation between SaO2 and Spo2 (r = 0.93; P < 0.001) with a reflectance probe in anesthetized foals; in that study, Spo2 underestimated SaO2, with a mean difference between SaO2 and Spo2 of 5.3%.13 Results of the present study are the first to report comparisons between SaO2 and Spo2 in conscious neonatal foals and suggest that Spo2 measured with a reflectance probe placed at the base of the tail is a feasible method of monitoring SaO2.

In the present study, Spo2 tended to underestimate SaO2, with a mean difference of 2.9%. Interestingly, other studies13,23,30–37 on horses have also documented that Spo2 generally underestimates SaO2. In the study reported here, the limits of agreement were –4.5% to 9.5%, indicating that 95% of Spo2 measurements were from 9.5% less than to 4.5% greater than SaO2. Manufacturers report pulse oximetry accuracy to 1 SD of < ± 3% when arterial oxygen saturation is ≥ 70%.13 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 SaO2, and allows clinicians to monitor changes in pulse and hemoglobin saturation in conscious neonatal foals. Even though 71% of Spo2 values were within 5% of SaO2, the authors believe that the limits of agreement in the study reported here are large enough to indicate that Spo2 cannot supplant precise determination of SaO2 via arterial blood gas analysis. Additionally, although the correlation between SaO2 and Spo2 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 Spo2 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 other 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 studies34,35 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.\textsuperscript{34,36} Of note, consistent detection of the pulse has been documented when the transmittance probe is placed on the tongue\textsuperscript{12,23,34,36,37}; 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 \( Sp_o \), 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 \( Sa_o \), measurements, the authors suggest that placement of a reflectance probe at this site is an ideal method of monitoring pulse rate and \( Sa_o \) 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 \( Sp_o \) 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 \( Sp_o \) 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 \( Pae_CO_2 \) and \( PECO_2 \), 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 \( Pae_CO_2 \) in this study ranged from 42.8 to 67.1 mm Hg; thus, correlations between extremely low or high \( Pae_CO_2 \) values and \( PECO_2 \) were not investigated. Similarly, \( Sa_o \), in this study ranged from 88.9% to 97.8%; thus, correlation between \( Sa_o \) and \( Sp_o \) cannot be made with lower (eg, < 80%) \( Sa_o \) values. A prior study\textsuperscript{13} in which foals were anesthetized allowed manipulation of the \( Pao_2 \) and \( Sa_o \). In that study,\textsuperscript{13} the authors concluded that poor precision of \( Sp_o \) occurred when \( Sa_o \) values were < 80%. However, the authors also stated that the reflectance probe performed more consistently over various ranges of \( Sa_o \) than did other transmittance probes.\textsuperscript{13} Other studies\textsuperscript{46,37} in anesthetized adult horses have also documented increased variability in the difference between \( Sa_o \) and \( Sp_o \) as well as limits of agreement when \( Sa_o \), values were < 80%. Additionally, in the ideal situation, \( Sp_o \) should be compared with \( Sa_o \) 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, \( Sa_o \) via co-oximetry.

Finally, although the benefits of the noninvasive and continuous ability to monitor \( PECO_2 \) and \( Sp_o \) 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 300 mL of gas/min from the patient, but these factors would be negligible in most foals.\textsuperscript{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 \( Sa_o \) is < 80% and that dyshemoglobinemias (ie, carboxyhemoglobin and methemoglobin) and the use of diagnostic dyes (ie, methylene blue) will provide erroneous results.\textsuperscript{2,12,13} Furthermore, \( Sa_o \) 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 \( Sa_o \). Thus, a patient, especially one receiving supplemental oxygen, may have a dramatic decrease in \( Pao_2 \), with only a minimal decrease in \( Sp_o \). The oxygen dissociation curve may also shift as a result of increases or decreases in \( pH \) or \( Pae_CO_2 \); thus, \( Sp_o \) should be interpreted in light of the patient’s blood \( pH \) and \( Pae_CO_2 \).

End-tidal partial pressure of carbon dioxide and \( Sp_o \) have been used as adequate methods of estimating and monitoring \( Pae_CO_2 \) and blood oxygenation, respectively, in infants and adults.\textsuperscript{7} Results of the study reported here suggested that \( PECO_2 \) can also be used in neonatal foals when assessment and monitoring of \( Pae_CO_2 \) is necessary. Determination of pulse rate with a reflectance probe was reliable in this study, and \( Sp_o \) measurements had acceptable limits of agreement with \( Sa_o \). However, pulse oximetry underestimated \( Sa_o \) in this study. Clinicians should realize the limitations of this study and be advised that \( PECO_2 \) and \( Sp_o \) should not replace the judicious use of direct measurement of \( Pae_CO_2 \) and \( Pao_2 \) via arterial blood gas analysis, especially when marked changes in \( PECO_2 \) or \( Sp_o \) are observed.

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