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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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 PacO₂ along with SaO₂. Concurrently, PetCO₂ was measured with a capnograph inserted into a nares, 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 ± 3.6%. 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)

Ill foals presented for veterinary care often require assessment of blood oxygenation and evaluation of the status of patient ventilation. 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 PacO₂ and the SaO₂, respectively, as indirect measures of ventilation and oxygenation.

Abbreviations

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<th>Abbreviation</th>
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<tr>
<td>PacO₂</td>
<td>End-tidal partial pressure of carbon dioxide</td>
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<tr>
<td>SaO₂</td>
<td>Calculated saturation of hemoglobin with oxygen in arterial blood</td>
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<td>Spo₂</td>
<td>Saturation of hemoglobin with oxygen as measured by use of pulse oximetry</td>
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In general, the PetCO₂ is lower than arterial values because of intrapulmonary dead-space ventilation, physiologic shunting, and variation in ventilation-to-perfusion ratios. In healthy people and small animal species, the difference between PacO₂ and PetCO₂, also known as the PacO₂–PetCO₂ gradient, is < 5 mm Hg. The correlation between PetCO₂ and PacO₂ has been good in awake, nonintubated people and dogs. 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 studies 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.
One study on foals concluded that pulse oximetry is a valuable method for assessing $Sao_2$ 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.

The agreement between direct and indirect measurements of $Paco_2$ and $Sao_2$ 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 capability of pulse oximetry in conscious healthy and ill spontaneously breathing nonintubated foals. In addition, the agreement between the $Sp_o_2$ and $Sao_2$ 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 $Paco_2$ and $Peta_2$ as well as between $Sp_o_2$ and $Sao_2$.

**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 ($Paco_2$ and $PaO_2$) 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 $Sao_2$ was obtained from measured $PaO_2$ 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 $SpO_2$ by use of a commercial patient monitor. Consecutive measurements of $SpO_2$ data were continuously recorded over a 2-minute period. Values of $SpO_2$ 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 $Peta_2$ 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 $SpO_2$ and $Peta_2$ 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 $Peta_2$ and $Paco_2$ was assessed by use of Pearson correlation coefficients and tested for significance. Similarly, the association between $SpO_2$ and $Sao_2$ 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 $Peta_2$ and $Paco_2$ and between the paired values of $Sao_2$ and $SpO_2$. 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 $P \leq 0.05$ 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 ±
Regarding CO\textsubscript{2} values, the mean ± SD measurements of Pa\textsubscript{co} and Pet\textsubscript{co} 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 Pa\textsubscript{co} or Pet\textsubscript{co} between the 2 groups; therefore, all individual measurements from healthy and ill foals were pooled, yielding a mean ± SD Pa\textsubscript{co} 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 Pa\textsubscript{co} and Pet\textsubscript{co} with the calculated 95% limits of agreement of –9.9 to 10.1 mm Hg (Figures 1 and 2). The mean ± SD Pa\textsubscript{co}–Pet\textsubscript{co} 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 Pa\textsubscript{co}–Pet\textsubscript{co} gradient of 0.1 ± 3.0 mm Hg. Individual Pet\textsubscript{co} measurements were within ± 2 mm Hg of Pa\textsubscript{co} in 13 of 31 foals, within ± 5 mm Hg of Pa\textsubscript{co} in 24 of 31 foals, and within ± 10 mm Hg of Pa\textsubscript{co} in 26 of 31 foals. There was no significant correlation between the mean Pa\textsubscript{co}–Pet\textsubscript{co} gradient and respiratory rate, heart rate, or rectal temperature. As noted, the difference between the mean ± SD Pa\textsubscript{co} and Pet\textsubscript{co} in all foals (ie, the Pa\textsubscript{co}–Pet\textsubscript{co} 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 Sa\textsubscript{o2} and Sp\textsubscript{o2} 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 Sa\textsubscript{o2} or Sp\textsubscript{o2} between healthy and ill foals; therefore, individual measurements from healthy and ill foals were pooled, yielding a mean ± SD Sa\textsubscript{o2} and Sp\textsubscript{o2} 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 Sa\textsubscript{o2} was significantly (P < 0.001) higher than that of Sp\textsubscript{o2}. There was a moderate and significant linear correlation (r = 0.450; P = 0.011) between Sa\textsubscript{o2} and Sp\textsubscript{o2} (Figure 3). Calculated 95% limits of agreement were –4.5% to 9.1% (Figure 4). The mean ± SD difference between reported Sa\textsubscript{o2} and Sp\textsubscript{o2} 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 Sa\textsubscript{o2} and Sp\textsubscript{o2} of 2.5 ± 3.5%. Individual Sa\textsubscript{o2} values were within ± 2% of Sp\textsubscript{o2} values in 10 of 31 foals, within ± 5% in 22 of

![Figure 1](https://example.com/figure1.png)  
*Figure 1—Scatterplot of paired measurements of Pet\textsubscript{co} and Pa\textsubscript{co} for 31 conscious neonatal foals (10 healthy and 21 ill). The solid line represents the line of identity.*

![Figure 2](https://example.com/figure2.png)  
*Figure 2—Bland-Altman plot of the difference between Pa\textsubscript{co} and Pet\textsubscript{co} versus the mean of Pa\textsubscript{co} and Pet\textsubscript{co}. Paired measurements of Pa\textsubscript{co} and Pet\textsubscript{co} were used to determine the partial pressure of CO\textsubscript{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](https://example.com/figure3.png)  
*Figure 3—Scatterplot of paired measurements of Sp\textsubscript{o2} and Sa\textsubscript{o2} for 31 conscious neonatal foals (10 healthy and 21 ill). The solid line represents the line of identity.*
31 foals, and within ± 10% in 31 of 31 foals. In addition, there was no significant correlation between the mean SaO₂ and SpO₂ 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. 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. Thus, maintaining the Paco₂ 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. A noninvasive method of estimating Paco₂ 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 arterio-venous blood sampling. Results of this study support the use of Petco₂ monitoring as an estimate of Paco₂ in ill neonatal foals on the basis of a significant and strong correlation and relatively good agreement between the 2 measurements.

Although Petco₂ was strongly correlated with Paco₂ 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. Therefore, it is agreement, rather than correlation, that determines whether one method of measurement can replace another. The 95% limits of agreement between Paco₂ and Petco₂ in this study were –9.9 to 10.1 mm Hg, indicating that 95% of Petco₂ measurements were from 10.1 mm Hg less than to 9.9 mm Hg greater than measured Paco₂. This range can be subjectively interpreted in different ways. In an analogous study evaluating the agreement between Paco₂ and Petco₂ 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 Petco₂ 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 Paco₂. In the present study, we consider the 95% limits of agreement between Petco₂ and Paco₂ as an acceptable adjunctive method of estimating and monitoring changes in Paco₂, especially considering that 77.4% of Petco₂ measurements were within 5 mm Hg of paired Paco₂ 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) and children (12.88 mm Hg), as the present study was smaller in magnitude than those previous studies. Moreover, the mean Paco₂–Petco₂ gradient was only 0.1 mm Hg, indicating little bias in the use of Petco₂ to approximate Paco₂. Together, this information suggests that Petco₂ can be used to estimate Paco₂ and monitor ventilatory status in conscious, spontaneously breathing neonatal foals. In the present study, there was no correlation between the mean Paco₂–Petco₂ gradient or mean difference between SaO₂ and SpO₂ 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 Paco₂ or SaO₂. As with any indirect clinico-pathologic measurements, periodic direct measurement of Paco₂ is a prudent approach to monitor patients, especially when drastic changes are observed in indirect measurements.

Previous studies have evaluated the use of capnography (Petco₂) to monitor Paco₂ in anesthetized adult horses and foals. In 1 study involving anesthetized adult horses, there was a significant correlation (r = 0.805; P < 0.001) between Petco₂ and Paco₂, with a mean ± SD Paco₂–Petco₂ gradient of 11.9 ± 8.1 mm Hg for halothane anesthesia. Those authors concluded that Petco₂ monitoring was an acceptable means of monitoring respiratory acid-base balance. Alternatively, authors of another study did not recommend capnography as a method of evaluating Paco₂ on the basis of poor limits of agreement between Petco₂ and Paco₂ (–20.1 to 8.7 mm Hg) in anesthetized adult horses. In a study involving anesthetized foals, the mean ± SD Paco₂–Petco₂ 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 Petco₂ was useful in predict-
ing changes in $\text{Paco}_2$ during the early (< 60 minutes) anesthetic period, but also stated that the margin for error in predicting $\text{Paco}_2$ from $\text{Petco}_2$ was unacceptable for making clinical judgments about ventilatory status in anesthetized foals. In previous equine studies comparing $\text{Paco}_2$ and $\text{Petco}_2$, 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. Although the difference between $\text{Paco}_2$ and $\text{Petco}_2$ 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 $\text{Paco}_2$–$\text{Petco}_2$ 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 $\text{Paco}_2$–$\text{Petco}_2$ gradient of 0.1 ± 3.0 mm Hg. A number of equine studies have also evaluated the $\text{Paco}_2$–$\text{Petco}_2$ gradient in anesthetized horses and foals, but to the authors’ knowledge, this is the first evaluation of the $\text{Paco}_2$–$\text{Petco}_2$ gradient in conscious foals. As noted in the previous study on foals, the mean $\text{Paco}_2$–$\text{Petco}_2$ gradients were 7 and 13 mm Hg at 5 to 60 minutes and 65 to 90 minutes, respectively, after anesthetic induction. Other studies in anesthetized adult horses also reflect a higher $\text{Paco}_2$–$\text{Petco}_2$ gradient in anesthetized horses, and this fact has been attributed to increased physiologic dead space, increased ventilation-perfusion ratio, and hyperventilation, among other factors. Clinically, the $\text{Paco}_2$–$\text{Petco}_2$ gradient can be used to document and monitor a variety of respiratory or cardiac conditions. For example, neonatal infants with pulmonary disorders such as persistent pulmonary hypertension, respiratory distress syndrome, pneumonia, or meconium aspiration had a significantly higher $\text{Paco}_2$–$\text{Petco}_2$ gradient (7.4 ± 3.3 mm Hg) when compared with aged-matched healthy controls (3.0 ± 2.4 mm Hg). The $\text{Paco}_2$–$\text{Petco}_2$ 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. Therefore, the $\text{Paco}_2$–$\text{Petco}_2$ 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 $\text{Petco}_2$ was higher than the $\text{Paco}_2$ (Figures 1 and 2). In theory, this should not occur, but this finding has been reported in similar studies on people, horses, and dogs. This detail may have contributed to the small $\text{Paco}_2$–$\text{Petco}_2$ 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 $\text{Paco}_2$ and measurement of $\text{Petco}_2$, errors in calibration of the capnograph or blood gas analyzer, overestimation of $\text{Petco}_2$ from interference of water vapor in the capnograph’s sampling chamber, or trapping of $\text{CO}_2$ within the nasopharynx because of increased respiratory resistance from nasopharyngeal obstruction or presence of the measuring chamber. The fact that $\text{Paco}_2$ was measured at a single time point whereas the $\text{Petco}_2$ was the mean measurement obtained over 2 minutes may have also impacted results. Other proposed causes of a higher $\text{Petco}_2$ compared with $\text{Paco}_2$ include excessive $\text{CO}_2$ production coupled with low inspired volume or high cardiac output, $\text{CO}_2$ displacement from hemoglobin as a result of high inspired $\text{O}_2$ content, low functional residual capacity, and alveoli with low ventilation-to-perfusion ratios.

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. A previous study documented a significant and strong correlation between Sa$_\text{O}_2$ and Sp$_\text{O}_2$ ($r = 0.93; P < 0.001$) with a reflectance probe in anesthetized foals; in that study, Sp$_\text{O}_2$ underestimated Sa$_\text{O}_2$, with a mean difference between Sa$_\text{O}_2$ and Sp$_\text{O}_2$ of 5.3%. Results of the present study are the first to report comparisons between Sa$_\text{O}_2$ and Sp$_\text{O}_2$ in conscious neonatal foals and suggest that Sp$_\text{O}_2$, measured with a reflectance probe placed at the base of the tail is a feasible method of monitoring Sa$_\text{O}_2$.

In the present study, Sp$_\text{O}_2$ tended to underestimate Sa$_\text{O}_2$, with a mean difference of 2.3%. Interestingly, other studies on horses have also documented that Sp$_\text{O}_2$ generally underestimates Sa$_\text{O}_2$. In the study reported here, the limits of agreement were −4.5% to 9.3%, indicating that 95% of Sp$_\text{O}_2$ measurements were from 9.3% less than to 4.3% greater than Sa$_\text{O}_2$. Manufacturers report pulse oximetry accuracy to ±3% when arterial oxygen saturation is ≥70%. 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 Sa$_\text{O}_2$, and allows clinicians to monitor changes in pulse and hemoglobin saturation in conscious neonatal foals. Even though 71% of Sp$_\text{O}_2$ values were within 5% of Sa$_\text{O}_2$, the authors believe that the limits of agreement in the study reported here are large enough to indicate that Sp$_\text{O}_2$ cannot supplant precise determination of Sa$_\text{O}_2$ via arterial blood gas analysis. Additionally, although the correlation between Sa$_\text{O}_2$ and Sp$_\text{O}_2$ 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 Sp$_\text{O}_2$ 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 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 tongue13,34,36,37; 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 SpO2 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 SaO2 measurements, the authors suggest that placement of a reflectance probe at this site is an ideal method of monitoring pulse rate and SaO2 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 SpO2 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 SpO2 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 PaCO2 and PetCO2, 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 PaCO2 in this study ranged from 42.8 to 67.1 mm Hg; thus, correlations between extremely low or high PaCO2 values and PetCO2 were not investigated. Similarly, SaO2 in this study ranged from 88.9% to 97.8%; thus, correlation between SaO2 and SpO2 cannot be made with lower (eg, < 80%) SaO2 values. A prior study13 in which foals were anesthetized allowed manipulation of the PaCO2 and SaO2. In that study,13 the authors concluded that poor precision of SpO2 occurred when SaO2 values were < 80%. However, the authors also stated that the reflectance probe performed more consistently over various ranges of SaO2 than did other transmittance probes.13 Other studies36,37 in anesthetized adult horses have also documented increased variability in the difference between SaO2 and SpO2 as well as limits of agreement when SaO2 values were < 80%. Additionally, in the ideal situation, SpO2 should have been compared with SaO2 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, SaO2 via co-oximetry.

Finally, although the benefits of the noninvasive and continuous ability to monitor PetCO2, and SpO2 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.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 SaO2 is < 80% and that dyshemoglobinemias (ie, carboxyhemoglobin and methemoglobin) and the use of diagnostic dyes (ie, methylene blue) will provide erroneous results.2,13,15 Furthermore, SaO2 is an estimate of PaO2, and because of the sigmoid shape of the oxygen dissociation curve, large changes in PaO2 may occur at the upper portions of the curve whereas minimal changes are observed in SaO2. Thus, a patient, especially one receiving supplemental oxygen, may have a dramatic decrease in PaO2 with only a minimal decrease in SpO2. The oxygen dissociation curve may also shift as a result of increases or decreases in pH or PaCO2; thus, SpO2 should be interpreted in light of the patient’s blood pH and PaCO2.

End-tidal partial pressure of carbon dioxide and SpO2 have been used as adequate methods of estimating and monitoring PaCO2 and blood oxygenation, respectively, in infants and adults.2,4,5 Results of the study reported here suggested that PetCO2 can also be used in neonatal foals when assessment and monitoring of PaCO2 is necessary. Determination of pulse rate with a reflectance probe was reliable in this study, and SpO2 measurements had acceptable limits of agreement with SaO2. However, pulse oximetry underestimated SaO2 in this study. Clinicians should realize the limitations of this study and be advised that PetCO2 and SpO2 should not replace the judicious use of direct measurement of PaCO2 and PaO2 via arterial blood gas analysis, especially when marked changes in PetCO2 or SpO2 are observed.

References

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