

# Evaluation of a transcutaneous blood gas monitoring system in critically ill dogs

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## Abstract

**Objectives** – To describe the use of a transcutaneous blood gas monitoring system in critically ill dogs, determine if transcutaneous and arterial blood gas values have good agreement, and verify if clinical or laboratory variables are correlated with differences between transcutaneous and arterial blood gas measurements.

**Design** – Prospective observational study.

**Setting** – University teaching hospital ICU.

**Animals** – Twenty-three client-owned dogs.

**Interventions** – In critically ill dogs undergoing arterial blood gas monitoring, a transcutaneous blood gas monitor was used to measure transcutaneous partial pressure of carbon dioxide (PtcCO<sub>2</sub>) and transcutaneous partial pressure of oxygen (PtcO<sub>2</sub>) values 30 minutes after sensor placement, which were compared to PaCO<sub>2</sub> and PaO<sub>2</sub> values measured simultaneously. Clinical and laboratory variables were concurrently recorded to determine if they were correlated with the difference between transcutaneous and arterial blood gas measurements.

**Measurements and Main Results** – Bland-Altman analysis revealed a mean bias of 4.6 ± 26.3 mm Hg (limits of agreement [LOA]: –46.9/+56.1 mm Hg) between PtcO<sub>2</sub> and PaO<sub>2</sub> and a mean bias of 9.3 ± 8.5 mm Hg (LOA: –7.5/+26.0 mm Hg) between PtcCO<sub>2</sub> and PaCO<sub>2</sub>. The difference between PtcCO<sub>2</sub>–PaCO<sub>2</sub> was strongly negatively correlated with HCO<sub>3</sub><sup>–</sup> ( $r^2 = 0.52, P < 0.001$ ) and PaCO<sub>2</sub> ( $r^2 = 0.58, P < 0.001$ ) and weakly positively correlated with diastolic blood pressure ( $r^2 = 0.21, P = 0.044$ ), whereas the difference between PtcCO<sub>2</sub>–PaCO<sub>2</sub> was moderately negatively correlated with diastolic blood pressure ( $r^2 = 0.33, P = 0.008$ ).

**Conclusions** – Agreement between transcutaneous and arterial PO<sub>2</sub> and PCO<sub>2</sub> measurements in these critically ill dogs was inferior to that reported in similar adult and pediatric human studies. The transcutaneous monitor consistently over-estimated PaO<sub>2</sub> and PaCO<sub>2</sub> and should not be used to replace arterial blood gas measurements in critically ill dogs requiring blood gas interpretation.

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**Keywords:** blood pressure, hemoglobin, hypotension, PO<sub>2</sub>, PCO<sub>2</sub>

## Introduction

Repeated blood gas measurements are often required to assess ventilation and oxygenation in critically ill patients to assist clinicians in designing appropriate treatment plans. Unfortunately, frequent blood sampling

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The transcutaneous blood gas monitor used in this study was provided by Radiometer Canada for a trial period.

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## Abbreviations

AARC	American Association for Respiratory Care
BE	base excess
DAP	diastolic arterial pressure
ETCO <sub>2</sub>	end-tidal carbon dioxide
Hgb	hemoglobin
HR	heart rate
MAP	mean arterial pressure
PtcCO <sub>2</sub>	transcutaneous PCO <sub>2</sub>
PtcO <sub>2</sub>	transcutaneous PO <sub>2</sub>
SAP	systolic arterial pressure
TPP	total plasma protein

from small human patients causes iatrogenic anemia, which likely also occurs in small veterinary patients undergoing repeated blood sampling. Blood sampling

for repeated blood gas analysis is also stressful and uncomfortable for human patients requiring multiple punctures if indwelling catheters are not placed.<sup>2</sup> Likewise, arterial blood sampling is technically challenging or impossible in very small or young animals and complications related to arterial puncture are reported in small dogs.<sup>3</sup> Because PO<sub>2</sub> and PCO<sub>2</sub> measurements are required to make decisions regarding the need for oxygen supplementation or mechanical ventilation, a reliable method to measure these variables in small animals is essential. Transcutaneous blood gas monitoring enables noninvasive measurement of PO<sub>2</sub> and PCO<sub>2</sub> and avoids the issues and costs associated with arterial blood sample collection.<sup>4</sup> Additionally, continuous monitoring of PCO<sub>2</sub> and PO<sub>2</sub> using transcutaneous monitors can detect changes in respiratory status earlier than blood gas analysis, allowing clinicians to respond more quickly.<sup>5–8</sup>

Transcutaneous blood gas monitors are widely used in human medicine, especially in neonatal or other patients without arterial access, to obtain noninvasive and continuous blood gas measurements during mechanical ventilation, bronchoscopy, and sleep apnea or pulmonary function studies.<sup>9–12</sup> They enable the assessment of adequacy of ventilation and oxygenation, tissue perfusion, and the viability of skin flaps or ischemic limbs.<sup>9–12</sup> Studies comparing end-tidal carbon dioxide (ETCO<sub>2</sub>) and transcutaneous PCO<sub>2</sub> (PtcCO<sub>2</sub>) measurements in neonates, infants, and children receiving mechanical ventilation for respiratory failure reveal that PtcCO<sub>2</sub> is more accurate than ETCO<sub>2</sub>.<sup>13,14</sup> Similarly, transcutaneous blood gas monitors have recently become more reliable and when used in adult human patients also estimate PaCO<sub>2</sub> more accurately than ETCO<sub>2</sub>.<sup>12,15,16</sup> However, the accuracy of transcutaneous blood gas monitors in people is affected by several factors including variations in skin thickness,<sup>17</sup> presence of peripheral edema, low cardiac output causing tissue hypoperfusion, peripheral vasoconstriction, administration of vasoconstricting drugs,<sup>18</sup> as well as ventilation and oxygenation status.<sup>9,10,15,19</sup> For example, PtcCO<sub>2</sub> is more accurate at normal and increased PaCO<sub>2</sub> values compared to lower PaCO<sub>2</sub> values (ie, during hyperventilation).<sup>20</sup> Additionally, the reliability of transcutaneous PO<sub>2</sub> (PtcO<sub>2</sub>) is decreased during hypoxemia and hyperoxemia in adult and neonatal human patients and studies show that, in general, PtcO<sub>2</sub> monitoring is less accurate compared to PtcCO<sub>2</sub> monitoring.<sup>10,21,22</sup>

There is limited information in the veterinary literature pertaining to transcutaneous blood gas monitoring in dogs. A study investigating PtcCO<sub>2</sub> measurements in 8 adult healthy dogs undergoing nonemergency orthopedic surgery found that PtcCO<sub>2</sub> over-estimated PaCO<sub>2</sub> by an average of 10.6 mm Hg and lagged behind changes in PaCO<sub>2</sub> during progression from normal ventilation

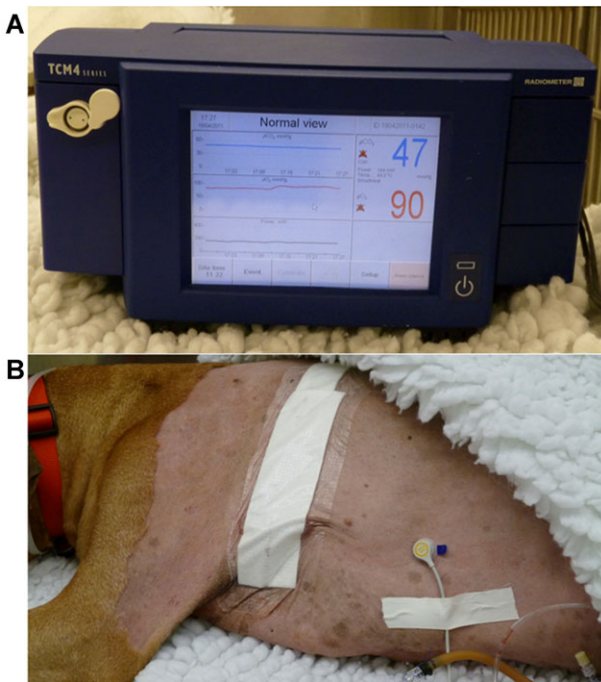
to hyperventilation (ie, induction of hypocapnia) by approximately 6 minutes.<sup>23</sup> The authors concluded that the PtcCO<sub>2</sub> monitor might be useful for detecting changes or trends in PaCO<sub>2</sub>, but was not accurate enough to be used as a surrogate measurement of PaCO<sub>2</sub>.<sup>23</sup> An experimental study using anesthetized dogs demonstrated that PtcO<sub>2</sub> became less accurate compared to PaO<sub>2</sub> as the cardiac output decreased during induced hemorrhage, but the accuracy of PtcO<sub>2</sub> improved after fluid resuscitation.<sup>24</sup> PtcO<sub>2</sub> and PtcCO<sub>2</sub> measurements have also been used for the evaluation of skin graft viability in dogs in experimental settings.<sup>25,26</sup> To the authors' knowledge, there are no published reports describing the utility of the PtcO<sub>2</sub> and PtcCO<sub>2</sub> monitoring in hospitalized critically ill dogs.

The objectives of the present study were to describe the use of a transcutaneous blood gas monitoring system in critically ill dogs, determine if transcutaneous and arterial blood gas values have good agreement, and verify if clinical or laboratory variables are correlated with differences between transcutaneous and arterial blood gas measurements.

### Materials and Methods

A commercial transcutaneous blood gas monitoring system<sup>a</sup> was obtained for a trial period in the ICU of our institution between February and March 2011. During that time period, any critically ill dogs hospitalized in the ICU that already had an indwelling arterial catheter and arterial blood gas measurements planned at the discretion of the attending clinician as a part of his/her diagnostic plan were included in this observational study. Because American Association for Respiratory Care (AARC) clinical practice guidelines<sup>10</sup> state that PaO<sub>2</sub> > 100 mm Hg can result in falsely increased or decreased PtcO<sub>2</sub> and PtcCO<sub>2</sub> values, respectively, any dogs with a PaO<sub>2</sub> > 100 mm Hg were excluded from analysis.

The transcutaneous monitor was calibrated according to the manufacturer's specifications before application of the sensor probe to each dog and the sensor probe temperature was set to 44°C. The sensor probe was attached to the skin of the abdomen or thorax where the hair was already clipped, or after clipping the dog's hair approximately 2 × 2 cm. The application site was cleaned with an alcohol swab and an adhesive plastic ring was attached to the skin. Contact gel was applied to the skin and the sensor probe was attached to the ring (Figure 1). The manufacturer's recommended minimum equilibration and physiological stabilization time after sensor probe placement was 5–10 minutes for a PtcCO<sub>2</sub> measurement and 10–20 minutes for a PtcO<sub>2</sub> measurement; therefore, PtcCO<sub>2</sub> and PtcO<sub>2</sub> were recorded 30 minutes after probe application. The sensor probe was not left in the same



**Figure 1:** (A) Transcutaneous PCO<sub>2</sub> and PO<sub>2</sub> monitor and (B) sensor probe attached to the thorax of a dog recovering from a lateral thoracotomy.

position for more than 8 hours, to prevent thermal injuries secondary to the sensor probe heat.

An arterial blood sample was collected from the indwelling arterial catheter 30 minutes after sensor placement and blood gas analysis was performed with a commercial blood gas analyzer.<sup>b</sup> Because of a 30-second delay between the monitor and transcutaneous sensor, 30-minute PtcCO<sub>2</sub> and PO<sub>2</sub> values were recorded 30 seconds after arterial blood sampling. At the time of arterial blood sampling, the following variables were also recorded: body weight, rectal temperature, heart rate (HR), systolic arterial pressure (SAP), diastolic arterial pressure (DAP), and mean arterial pressure (MAP). Blood pressure was recorded using an oscillometric device.<sup>c</sup> Additionally, PCV, hemoglobin (Hgb), total plasma protein (TPP), pH, HCO<sub>3</sub><sup>-</sup>, base excess (BE), and lactate were concurrently recorded from results measured using the arterial blood sample.

### Statistical analyses

A Shapiro-Wilk test was used to determine standard normal distribution of the data. Data with standard normal distribution were presented as mean  $\pm$  SD and data not normally distributed were presented as median (range). PtcO<sub>2</sub> and PtcCO<sub>2</sub> were compared with PaO<sub>2</sub> and PaCO<sub>2</sub> by performing Bland-Altman analysis.<sup>27</sup> Precision was

defined as  $\pm 2$  SD of the mean bias in the Bland-Altman analysis. Depending on standard normal distribution, Pearson's or Spearman's correlation coefficient was performed to determine if PtcO<sub>2</sub> and PtcCO<sub>2</sub> were significantly correlated with PaO<sub>2</sub> and PaCO<sub>2</sub>, respectively, and if the recorded clinical (body weight, temperature, HR, SAP, DAP, MAP) and laboratory (PCV, Hgb, TPP, pH, HCO<sub>3</sub><sup>-</sup>, BE, lactate, PaO<sub>2</sub>, PaCO<sub>2</sub>) variables were significantly correlated with the difference between the transcutaneous and arterial blood gas measurements (PtcO<sub>2</sub> – PaO<sub>2</sub> and PtcCO<sub>2</sub> – PaCO<sub>2</sub>). A  $P < 0.05$  was considered to indicate statistical significance for all comparisons. Commercial statistical software<sup>d</sup> was used for all statistical analyses and commercial graphing software<sup>e</sup> was used to generate the figures.

### Results

Data were initially recorded from 26 dogs including 18 male dogs (2 intact, 16 neutered) and 8 female dogs (1 intact, 7 neutered). However, 3 dogs (2 neutered males, 1 neutered female) with a PaO<sub>2</sub> > 100 mm Hg were excluded from the analysis. The median (range) age of the 23 included dogs was 9 (1–10) years and the mean  $\pm$  SD body weight was 33.1  $\pm$  13.4 kg. Recorded clinical variables are summarized in Table 1. Most dogs ( $n = 20/23$ , 87%) had an arterial catheter placed for direct blood pressure monitoring or arterial blood sampling during anesthesia. Reasons for anesthesia in those dogs included gastrointestinal mass resection or foreign body removal ( $n = 7$ ), oral mass resection ( $n = 2$ ), extremity mass resection ( $n = 2$ ), and laryngeal mass resection, lung mass resection, exploratory thoracotomy, cataract surgery, stifle surgery, hemilaminectomy, rhinotomy, amplatzer occlusion, and advanced imaging ( $n = 1$  for each). The remaining dogs ( $n = 3/23$ , 13%) had an arterial catheter placed specifically for invasive blood pressure monitoring or repeated arterial blood gas analysis in the ICU for conditions including pulmonary contusions, aspiration pneumonia, and atrial fibrillation ( $n = 1$  for each). Two dogs were receiving oxygen supplementation at the time of data collection including 1 dog with a nasal cannula placed after an exploratory thoracotomy for spontaneous pneumothorax and another dog that was endotracheally intubated and undergoing mechanical ventilation for aspiration pneumonia. That same dog was in septic shock and being administered dobutamine<sup>f</sup> at the time of data collection.

The transcutaneous monitor sensor probe was attached to the lateral aspect of the abdomen ( $n = 13$ ) or thorax ( $n = 6$ ), ventral abdomen ( $n = 2$ ), or ventrolaterally on the thorax ( $n = 2$ ). There were no dermal or other complications noted in any of the dogs after the sensor probe and adhesive ring were removed from the

**Table 1:** Clinical, laboratory, and transcutaneous monitor variables recorded in critically ill dogs

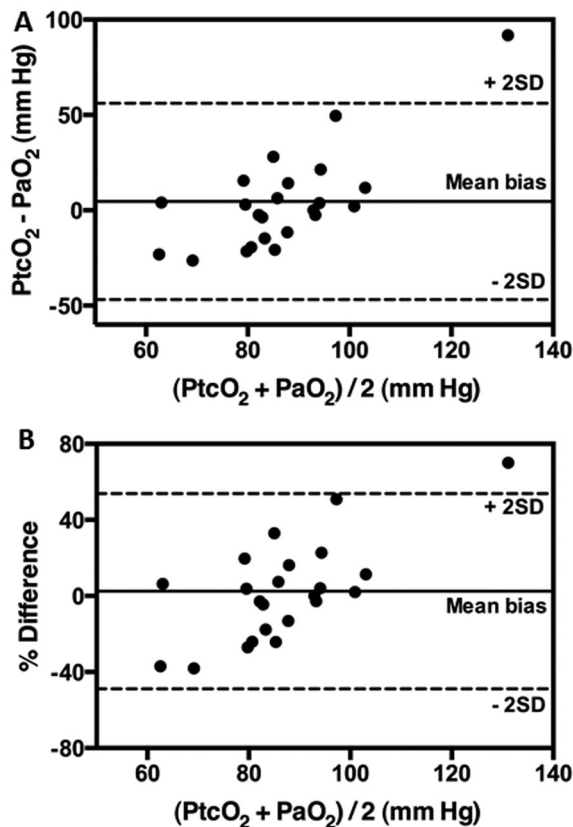
Variable	N	Measurement
Heart rate (per min)	23	80 (46–157)
Rectal temperature (°C)	23	37.3 ± 0.8
Rectal temperature (°F)	23	99.1 ± 0.6
Systolic arterial pressure (mm Hg)	20	143 ± 21
Diastolic arterial pressure (mm Hg)	20	84 ± 23
Mean arterial pressure (mm Hg)	20	107 ± 24
PCV (%)	23	36.2 ± 6.9
Hemoglobin (g/L)	23	122 ± 27
Hemoglobin (g/dL)	23	12.2 ± 2.7
Total plasma protein (g/L)	23	52 ± 8
Total plasma protein (g/dL)	23	5.2 ± 0.8
pH	23	7.40 ± 0.04
HCO <sub>3</sub> <sup>-</sup> (mmol/L, mEq/L)	23	21.7 ± 2.4
Base excess (mmol/L, mEq/L)	23	-2.4 ± 2.3
Lactate (mmol/L)	23	1.3 (0.5–3.5)
PaO <sub>2</sub> (mm Hg)	23	84.7 ± 9.9
PtcO <sub>2</sub> (mm Hg)	23	87 (55–177)
PtcO <sub>2</sub> - PaO <sub>2</sub> (mm Hg)	23	2.1 (-26.3–91.8)
PaCO <sub>2</sub> (mm Hg)	23	36.0 ± 5.5
PtcCO <sub>2</sub> (mm Hg)	23	46 (33–57)
PtcCO <sub>2</sub> - PaCO <sub>2</sub> (mm Hg)	23	11.9 (-11.2–24.3)

Values with standard normal distribution are expressed as mean ± SD and values without standard normal distribution are expressed as median (range).

HCO<sub>3</sub><sup>-</sup>, bicarbonate; PtcCO<sub>2</sub>, transcutaneous PCO<sub>2</sub>; PtcO<sub>2</sub>, transcutaneous PO<sub>2</sub>.

application site. Transcutaneous and arterial PO<sub>2</sub> and PCO<sub>2</sub> measurements are listed in Table 1. PtcO<sub>2</sub> and PaO<sub>2</sub> measurements ( $r^2 = 0.03$ ,  $P = 0.398$ ) were not correlated, nor were PtcCO<sub>2</sub> and PaCO<sub>2</sub> measurements ( $r^2 = 0.02$ ,  $P = 0.561$ ). Bland-Altman analyses revealed a mean bias of  $4.6 \pm 26.3$  mm Hg between PtcO<sub>2</sub> and PaO<sub>2</sub> with wide limits of agreement (LOA;  $-46.9/+56.1$  mm Hg; Figure 2A), as well as a mean percentage difference of  $2.5 \pm 26.2\%$  (LOA  $-48.9/+53.8\%$ ; Figure 2B). Likewise, there was a mean bias of  $9.3 \pm 8.5$  mm Hg between PtcCO<sub>2</sub> and PaCO<sub>2</sub> with wide LOA  $-7.5/+26.0$  mm Hg (Figure 3A), as well as a mean percentage difference of  $22.9 \pm 21.7\%$  (LOA  $-19.6/+65.3\%$ ; Figure 3B).

Correlations between the differences between transcutaneous and arterial blood gas measurements and recorded clinical and laboratory variables are included in Table 2. The PtcCO<sub>2</sub> - PaCO<sub>2</sub> difference was negatively correlated with HCO<sub>3</sub><sup>-</sup> ( $r^2 = 0.52$ ,  $P < 0.001$ ; Figure 4A) and PaCO<sub>2</sub> ( $r^2 = 0.58$ ,  $P < 0.001$ ; Figure 4B), and positively correlated with DAP ( $r^2 = 0.21$ ,  $P = 0.044$ ; Figure 5A). The PtcO<sub>2</sub> - PaO<sub>2</sub> difference was negatively correlated with DAP ( $r^2 = 0.33$ ,  $P = 0.008$ ; Figure 5B). Correlations were not identified between PtcO<sub>2</sub> - PaO<sub>2</sub> or PtcCO<sub>2</sub> - PaCO<sub>2</sub> and other measured clinical and laboratory variables (Table 2).



**Figure 2:** Bland-Altman analyses comparing transcutaneous PO<sub>2</sub> (PtcO<sub>2</sub>) and PaO<sub>2</sub> measured in 23 critically ill dogs.

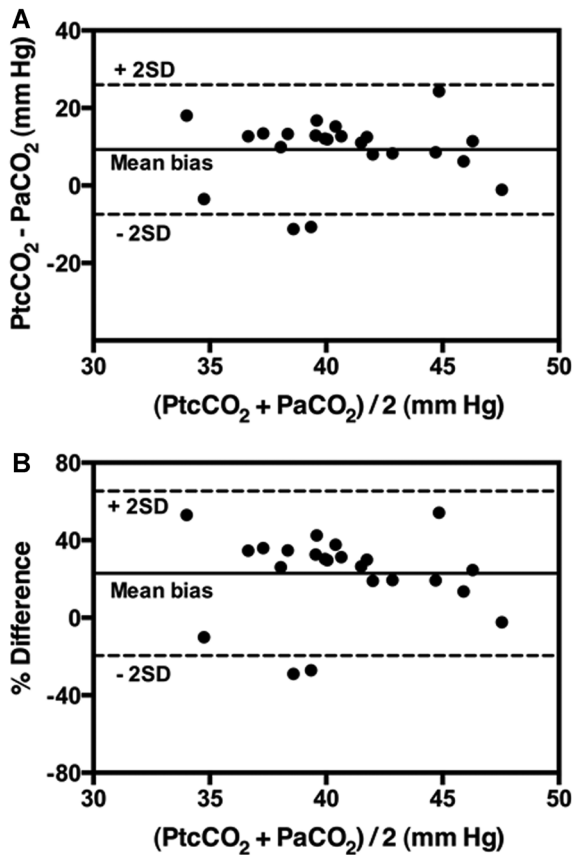
**Table 2:** Correlations between the difference between transcutaneous and arterial blood gas measurements and clinical and laboratory variables in 23 critically ill dogs

Variable	PtcO <sub>2</sub> - PaO <sub>2</sub>			PtcCO <sub>2</sub> - PaCO <sub>2</sub>		
	R	r <sup>2</sup>	P-Value	r	r <sup>2</sup>	P-Value
SAP	0.44	0.19	0.055	0.08	<0.01	0.746
DAP	<b>-0.58</b>	<b>0.33</b>	<b>0.008</b>	<b>0.45</b>	<b>0.21</b>	<b>0.044</b>
MAP	0.13	0.02	0.572	-0.12	0.01	0.621
TPP	0.39	0.15	0.065	0.07	<0.01	0.737
pH	0.12	0.01	0.600	0.34	0.12	0.112
HCO <sub>3</sub> <sup>-</sup>	0.15	0.02	0.494	<b>-0.72</b>	<b>0.52</b>	<b>&lt;0.001</b>
BE	-0.03	<0.01	0.894	-0.22	0.05	0.322
Lactate	<-0.01	<0.01	0.988	0.07	<0.01	0.734
PaO <sub>2</sub>	-0.26	0.07	0.223	0.15	0.02	0.500
PaCO <sub>2</sub>	<0.01	<0.01	0.995	<b>-0.76</b>	<b>0.58</b>	<b>&lt;0.001</b>

SAP, systolic arterial pressure; DAP, diastolic arterial pressure; MAP, mean arterial pressure; TPP, total plasma protein; BE, base excess; HCO<sub>3</sub><sup>-</sup>, bicarbonate; PtcCO<sub>2</sub>, transcutaneous PCO<sub>2</sub>; PtcO<sub>2</sub>, transcutaneous PO<sub>2</sub>. Measurements in bold represent significant findings ( $P < 0.05$ ).

### Discussion

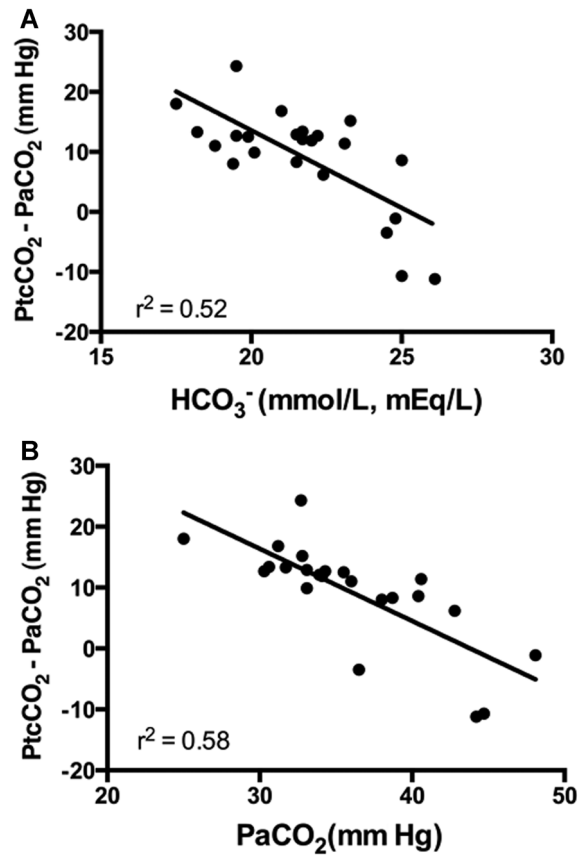
The present study investigated the utility of a transcutaneous blood gas monitor, designed for use in



**Figure 3:** Bland-Altman analyses comparing transcutaneous PCO<sub>2</sub> (PtcCO<sub>2</sub>) and PaCO<sub>2</sub> measured in 23 critically ill dogs.

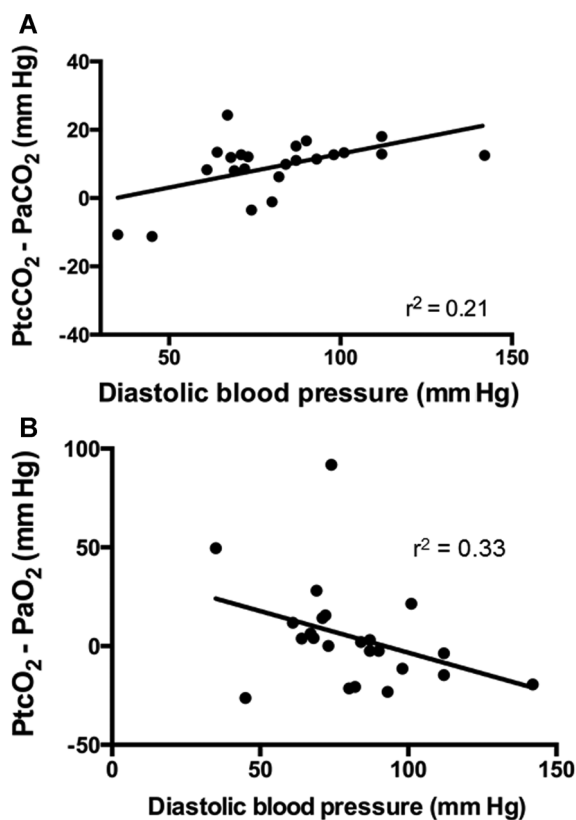
people, in a small group of hospitalized critically ill dogs. The monitor features a combination PtcO<sub>2</sub> and PtcCO<sub>2</sub> sensor and has been available for use since 2010. The monitor performs PtcO<sub>2</sub> measurements using a Clark sensor, whereas a Stowe-Severinghaus electrode is used for the PtcCO<sub>2</sub> measurements. The monitor was easy to use in terms of its calibration and application of the sensor probe, which took approximately 5 minutes each. Measurements were visible on the monitor screen by about 5 minutes after probe placement, but because the manufacturer recommends waiting 10–20 minutes for stabilization, arterial blood gas measurements were not taken for comparison until 30 minutes after sensor probe placement. The temperature probe was heated to 44°C as per the manufacturer's recommendation, to enhance blood flow to the application site and improve the diffusion of gases across the skin, thereby improving the accuracy of the monitor.<sup>9,12,15</sup>

Despite following all of the manufacturer's recommendations for calibration and sensor probe fixation, concurrent transcutaneous and arterial blood gas measurements did not have good correlation in this group of critically ill dogs. Given that correlation



**Figure 4:** Correlations between (A) bicarbonate (HCO<sub>3</sub><sup>-</sup>) and (B) PaCO<sub>2</sub> and the difference between transcutaneous CO<sub>2</sub> and PaCO<sub>2</sub> (PtcCO<sub>2</sub> – PaCO<sub>2</sub>) measured in 23 critically ill dogs.

analyses alone are not recommended for assessment of agreement between 2 diagnostic tests, Bland-Altman analysis was used since the results more reliably indicate the accuracy of the diagnostic test.<sup>28</sup> Bland-Altman analyses revealed that the transcutaneous blood gas measurements had moderate agreement with arterial blood gas measurements. The mean bias (difference) between the measurements was relatively small with PtcO<sub>2</sub> over-estimating PaO<sub>2</sub> by an average of approximately 5 mm Hg, whereas PtcCO<sub>2</sub> over-estimated PaCO<sub>2</sub> by an average of approximately 9 mm Hg. However, the LOA were extremely wide, indicating that the transcutaneous measurements were often very different from the arterial blood gas measurements. The AARC clinical practice guidelines state that while PtcCO<sub>2</sub> typically over-estimates PaCO<sub>2</sub>, "...the acceptable clinical range of agreement for PtcCO<sub>2</sub> is ± 7.5 mm Hg."<sup>10</sup> Therefore, the PtcCO<sub>2</sub> measurements from the present study would not be considered clinically acceptable by AARC standards. In comparison with human studies, agreement between transcutaneous and arterial PO<sub>2</sub> and PCO<sub>2</sub> measurements



**Figure 5:** Correlations between diastolic arterial pressure and the difference between (A) transcutaneous PO<sub>2</sub> and PaO<sub>2</sub> (PtcO<sub>2</sub> - PaO<sub>2</sub>) and (B) transcutaneous PCO<sub>2</sub> and PaCO<sub>2</sub> (PtcCO<sub>2</sub> - PaCO<sub>2</sub>) measured in 23 critically ill dogs.

was inferior in the present study, as most human studies show mean differences of < 5 mm Hg.<sup>29–34</sup>

Inaccuracies in transcutaneous blood gas measurements can occur for many technical reasons including inappropriate heating of the sensor probe, improper calibration, trapped air bubbles underneath the sensor probe, leaks in the fixation device, or damaged sensor probe membranes.<sup>9,12,15</sup> Likewise, some clinical situations can result in falsely increased or decreased transcutaneous blood gas values. For example, falsely decreased PtcO<sub>2</sub> and PtcCO<sub>2</sub> measurements can occur with hypoperfusion or vasoactive drug administration, peripheral edema or increased thickness of the skin or subcutaneous tissue, and placement of the sensor on distal extremities with limited blood flow.<sup>9,12,15</sup> Attempts to limit clinical reasons for the transcutaneous monitor's inaccuracies were made including placement of the sensor probe on the dog's body, rather than its extremities, and avoidance of application of the sensor probe to areas of peripheral edema. Unfortunately, the exact location of the sensor probe application site was not standardized in the present study, which might have affected the

accuracy of the results. The preferred location to obtain transcutaneous measurements in neonates and small pediatric patients is the upper chest.<sup>10</sup> Other locations more commonly used in adults include the lateral abdomen, chest, buttock, upper thigh, forearm, ear lobe, cheek, or forehead.<sup>10</sup> Given the authors' limited experience with the transcutaneous blood gas monitoring device, it is possible that some of the values did not agree with arterial blood gas measurements because of technical issues with sensor probe placement.

Although the authors also followed AARC guidelines by not comparing PaO<sub>2</sub> to transcutaneous measurements in dogs with PaO<sub>2</sub> > 100 mm Hg, PtcO<sub>2</sub> is even considered less accurate in human patients with a PaO<sub>2</sub> > 80 mm Hg.<sup>21</sup> The mean PaO<sub>2</sub> measured in dogs in the present study was approximately 85 mm Hg and 3 dogs with PaO<sub>2</sub> over 100 mm Hg were excluded from analysis because of the decreased accuracy of transcutaneous blood gas measurements in patients with hyperoxemia. An experimental study evaluating the accuracy of a PtcO<sub>2</sub> monitor in healthy anesthetized cats revealed that PtcO<sub>2</sub> closely matched PaO<sub>2</sub> during normoxemia and hypoxemia, but was significantly lower than PaO<sub>2</sub> during hyperoxemia.<sup>35</sup> Conversely, falsely increased PtcO<sub>2</sub> measurements occur with improper sensor probe application or increased capillary blood flow due to patient movement.<sup>9,12,15</sup> Therefore, these factors might have affected the results in the present study as well.

PtcO<sub>2</sub> measurements are also affected by altered blood flow to the probe application site during hypoperfusion.<sup>9,12,15</sup> This has limited the use of PtcO<sub>2</sub> monitoring in neonates and adults, especially those with severe systemic illness, given that PtcO<sub>2</sub> monitoring in those patients tends to reflect perfusion rather than oxygenation.<sup>9,12,15</sup> An experimental study showed that the difference between PtcO<sub>2</sub> and PaO<sub>2</sub> measurements in dogs with induced hemorrhage increased as the cardiac output decreased.<sup>24</sup> This difference decreased after the dogs received appropriate fluid resuscitation, suggesting improved accuracy of the monitor when perfusion was restored.<sup>24</sup> In other words, PtcO<sub>2</sub> appears to correlate better with mixed venous rather than arterial PO<sub>2</sub> during low cardiac output states. In the present study, the difference between PtcO<sub>2</sub> and PaO<sub>2</sub> measurements was moderately negatively correlated with DAP; however, other measurements of perfusion (eg, MAP, lactate) were not correlated. It is possible that the difference between PtcO<sub>2</sub> and PaO<sub>2</sub> measurements in this group of critically ill dogs was affected by the decrease in DAP and subsequent decrease in oxygen delivery to the sensor probe site. PtcO<sub>2</sub> measurements are also influenced by skin thickness, which influences local oxygenation.<sup>17,36</sup> The oxygen consumption of the skin is increased in thicker skin, which increases the difference

between PtcO<sub>2</sub> and PaO<sub>2</sub> in older infants and children.<sup>37</sup> Differences in skin thickness might have also influenced the PtcO<sub>2</sub> measurements in dogs in the present study, given that the sensor probe application site was not standardized.

In human patients, PtcCO<sub>2</sub> measurements are more accurate in comparison to PtcO<sub>2</sub> measurements,<sup>21</sup> giving rise to the recent development of combination PtcCO<sub>2</sub> and pulse oximetry (rather than PtcO<sub>2</sub>) sensors. In the present study, PtcCO<sub>2</sub> measurements averaged approximately 20% (9 mm Hg) higher than PaCO<sub>2</sub> measurements. There are very few published studies investigating the use of transcutaneous blood gas monitoring in dogs; however, a study investigating 8 adult dogs anesthetized for orthopedic surgery found a mean ± SD difference between PtcCO<sub>2</sub> and PaCO<sub>2</sub> of 8.9 ± 12 mm Hg 10 minutes after sensor application.<sup>23</sup> Thus, that transcutaneous blood gas monitor also over-estimated PaCO<sub>2</sub> in that group of dogs and had unacceptably large variability in the measurements. However, the monitor had an acceptable lag time (6.2 min) during the adjustment from normal to hyperventilation.<sup>23</sup> Therefore, the authors cautioned against the use of the monitor to replace PaCO<sub>2</sub> measurements, but recommended that it instead be used to trend PCO<sub>2</sub> values.

Interestingly, the difference between PtcCO<sub>2</sub> and PaCO<sub>2</sub> was moderately negatively correlated with HCO<sub>3</sub><sup>-</sup> and weakly positively correlated with DAP. The reason for these conflicting findings is unclear. Typically, decreased HCO<sub>3</sub><sup>-</sup> would be considered a reflection of poor perfusion, which normally falsely decreases PtcCO<sub>2</sub> measurements. However, a study investigating PtcCO<sub>2</sub> monitoring in the early 1980s found that PtcCO<sub>2</sub> values became falsely increased during low cardiac output states in adult human patients during surgery or ICU hospitalization.<sup>22</sup> Unfortunately, that does not explain the positive correlation between the PtcCO<sub>2</sub> – PaCO<sub>2</sub> difference and DAP, which is generally increased with improved perfusion. Local blood and tissue production of CO<sub>2</sub> is very dependent upon blood flow to the site, which is why it is common practice for monitors to apply a correction factor to PtcCO<sub>2</sub> measurements, so that they more closely reflect the PaCO<sub>2</sub> value. It is possible that the increased DAP improved blood flow to the sensor probe site, such that local CO<sub>2</sub> production increased, thereby increasing the difference between the PtcCO<sub>2</sub> and PaO<sub>2</sub> values.

The present study also found that the difference between PtcCO<sub>2</sub> – PaCO<sub>2</sub> was strongly negatively correlated with PaCO<sub>2</sub>, suggesting that the accuracy of the transcutaneous monitor decreased during hypocapnia (hyperventilation). In human studies, PtcCO<sub>2</sub> is more accurate during normal and hypoventilation compared

to hyperventilation, as evidenced by difficulty detecting PtcCO<sub>2</sub> at a lower PaCO<sub>2</sub>.<sup>19,20</sup> Likewise, a study investigating 6 healthy anesthetized cats found that the difference between PtcCO<sub>2</sub> and PaCO<sub>2</sub> was also wider during hypocapnia, compared to normo- or hypercapnia.<sup>35</sup> Similarly, the study using 8 anesthetized dogs found that the difference between PtcCO<sub>2</sub> – PaCO<sub>2</sub> decreased during hypercapnia.<sup>23</sup> Therefore, in patients with unstable or changing ventilatory patterns, especially hyperventilation that might lead to hypocapnia, PtcCO<sub>2</sub> measurements might not be accurate. This inaccuracy is hypothesized to occur due to a reflex vasoconstriction and alterations in blood flow to the sensor probe site and subsequent decreased diffusion of CO<sub>2</sub> across the skin.<sup>19,20</sup>

It is likely that species differences exist with regards to the transcutaneous monitor's ability to accurately measure PCO<sub>2</sub>. The transcutaneous monitor used in the present study has a pH-sensitive glass electrode covered in a CO<sub>2</sub>-permeable Teflon membrane, which allows CO<sub>2</sub> to diffuse across and combine with water to form carbonic acid. The carbonic acid dissociates to HCO<sub>3</sub><sup>-</sup> and H<sup>+</sup>, which causes pH changes that result in electrical output calibrated to be linearly associated with changes in CO<sub>2</sub>.<sup>38</sup> The Severinghaus method is then used to analyze the electrical output from the electrode and calculate the transcutaneous blood gas values based on formulas taking into account skin metabolism and local production of CO<sub>2</sub>. These monitors and the formulas they use are calibrated for people,<sup>8</sup> but not dogs that have a different skin thickness and likely different skin metabolism and local CO<sub>2</sub> production compared to people. To the authors' knowledge, no such formula has been derived for use in dogs, and all published studies investigating the use of transcutaneous monitors in veterinary patients use this same technology and human calibration formulas.

Aside from the inherent limitations of using a monitor designed and calibrated for humans, there are other limitations of the present study that might have affected the results and warrant discussion. Only a small number of dogs with relatively normal blood gas values were included in the study, and an arterial blood gas was only sampled once at 30 minutes after sensor probe placement. While the authors attempted to perform blood sampling and record data when the dog's condition was stable, ongoing changes in blood pressure, oxygenation, or ventilation might have affected the accuracy of the PCO<sub>2</sub> and PO<sub>2</sub> measurement. There was also 1 dog included that was administered dobutamine, which might have resulted in alterations in peripheral blood flow and the accuracy of the transcutaneous monitor.<sup>9,15,18</sup> Unfortunately, because only 1 dog received vasoactive medications, this precluded the ability to perform

statistical analysis to determine whether the vasoactive medications were associated with a larger difference between the transcutaneous and arterial blood gas measurements. Additionally, the site of the sensor probe application was not standardized in terms of the exact location on the thorax or abdomen. Future studies should ensure that a consistent site is used for sensor probe fixation, to avoid alterations in skin thickness in different parts of the body affecting results. Finally, relatively stable hospitalized patients were included; therefore, extreme variations in PCO<sub>2</sub> or PO<sub>2</sub> that would be expected in other critically ill dogs were not investigated in the present study.

### Conclusions

Agreement between transcutaneous and arterial PO<sub>2</sub> and PCO<sub>2</sub> measurements in the present study was inferior to that reported in similar adult and pediatric human studies. Therefore, the transcutaneous monitor studied was not considered reliable in estimating PaO<sub>2</sub> or PaCO<sub>2</sub> in this group of critically ill dogs. Although the monitor might be considered for noninvasively trending blood gas measurements, it should not be used alone, without intermittent measurement of arterial blood gas values. Differences between transcutaneous and arterial blood gas measurements were increased in dogs with hypocapnia or hypoperfusion; therefore, transcutaneous measurements might over-estimate arterial blood gas values during those situations. As such, transcutaneous blood gas measurements should always be verified with arterial blood gas results. Further studies investigating a larger population of critically ill dogs are needed to fully determine the clinical utility of this and other transcutaneous blood gas monitors.

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### Footnotes

- <sup>a</sup> TCM CombiM monitoring system; Radiometer Medical ApS, Bronshøj, Denmark.
- <sup>b</sup> ABL800 FLEX analyzer; Radiometer Medical ApS.
- <sup>c</sup> Cardell Veterinary Monitor, 9401 BP; Sharn Veterinary Inc, Tampa, FL.
- <sup>d</sup> SAS/STAT v 9.2, SAS Institute, Cary, NC.
- <sup>e</sup> GraphPad Prism 6; GraphPad Software, San Diego, CA.
- <sup>f</sup> Dobutamine Injection, Abbott Laboratories Ltd, Saint-Laurent, QC, Canada.
- <sup>g</sup> TCM TOSCA/CombiM monitoring systems, Operator's manual from software version 3.0, Radiometer Medical ApS.

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