Evaluation of a combined transcutaneous carbon dioxide pressure and pulse oximetry sensor in adult sheep and dogs

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Objective—To evaluate a combined transcutaneous carbon dioxide pressure (tcP\textsubscript{CO\textsubscript{2}}) and pulse oximetry sensor in sheep and dogs.

Animals—13 adult sheep and 11 adult dogs.

Procedures—During inhalation anesthesia, for the first 10 minutes following sensor placement, arterial blood gas was analyzed and tcP\textsubscript{CO\textsubscript{2}} was recorded every 2 minutes. Subsequently, the animals were hyper-, normo-, and hypoventilated. The simultaneously obtained tcP\textsubscript{CO\textsubscript{2}} and Paco\textsubscript{2} values were analyzed by use of Bland-Altman statistical analysis.

Results—Mean ± SD overall difference between tcP\textsubscript{CO\textsubscript{2}} and Paco\textsubscript{2} 10 minutes after sensor application was 13.3 ± 8.4 mm Hg in sheep and 8.9 ± 12 mm Hg in dogs. During hyper-, normo-, and hypoventilation, mean difference (bias) and precision (limits of agreement [bias ± 2 SD]) between tcP\textsubscript{CO\textsubscript{2}} and Paco\textsubscript{2} values were 13.2 ± 10.4 mm Hg (limits of agreement, −7.1 and 33.5 mm Hg) in sheep and 10.6 ± 10.5 mm Hg (limits of agreement, −9.9 and 31.2 mm Hg) in dogs, respectively. Changes in Paco\textsubscript{2} induced by different ventilation settings were detected by the tcP\textsubscript{CO\textsubscript{2}} sensor with a lag (response) time of 4.9 ± 3.5 minutes for sheep and 6.2 ± 3.6 minutes for dogs.

Conclusions and Clinical Relevance—The tcP\textsubscript{CO\textsubscript{2}} sensor overestimated Paco\textsubscript{2} in sheep and dogs and followed changes in Paco\textsubscript{2} with a considerable lag time. The tcP\textsubscript{CO\textsubscript{2}} sensor might be useful for noninvasive monitoring of changes but cannot be used as a surrogate measure for Paco\textsubscript{2}. (Am J Vet Res 2007;68:265–270)

Pulse oximetry used for determination of Spo\textsubscript{2}, a standard noninvasive technique used in veterinary anesthesia, provides continuous information regarding the patient’s SaO\textsubscript{2}. A disadvantage of the sole use of pulse oximetry is the lack of information regarding CO\textsubscript{2} status. Knowledge of SaO\textsubscript{2} and Paco\textsubscript{2} in a patient is essential for determination of the adequacy of ventilation and oxygenation. Presently, periodic blood sampling is still required to assess Paco\textsubscript{2}, so a single noninvasive sensor, yielding continuous information on both oxygenation and ventilation, is highly desirable. The use of a combined Spo\textsubscript{2} and tcP\textsubscript{CO\textsubscript{2}} sensor was first reported in 1999. The digital sensor combines the basic elements of a Severinghaus-type tcP\textsubscript{CO\textsubscript{2}} sensor and those of a reflectance pulse oximeter sensor. A built-in mixed-signal microcontroller located in the sensor head amplifies, digitizes, and analyzes the measured signals at the measurement site and sends the processed digital signal to the main monitor unit. The P\textsubscript{CO\textsubscript{2}} is measured potentiometrically by determining the pH of an electrolyte solution. This electrolyte solution is separated from the skin by a membrane that is highly permeable to CO\textsubscript{2}. The measured changes in pH of the electrolyte solution are proportional to the logarithm of the changes in P\textsubscript{CO\textsubscript{2}}. The sensor is warmed to a surface temperature of 41°C to enhance CO\textsubscript{2} diffusion and blood perfusion locally. The Spo\textsubscript{2} and the pulse frequency are derived through digital signal processing of the photoplethysmogram. In the present study, the objective was to evaluate the digital sensor in sheep and dogs by determination of the sensor time to steady state and the ability to monitor arterial blood gas changes during different stages of mechanical ventilation.

Materials and Methods

Animals and instrumentation—Thirteen adult sheep and 11 adult dogs were used in this study. The sheep (2 rams and 11 ewes) were a variety of Swiss breeds, weighed (mean ± SD) 76 ± 9 kg, and were 3.5 ± 1.2 years old. The dogs (7 males and 4 females) were a variety of breeds, weighed (mean ± SD) 17 ± 5 kg, and were 3.5 ± 1.2 years old. The animals were randomly assigned to the different ventilation settings.
were of mixed breeds or of a variety of pure breeds, weighed 33 ± 10 kg, and were 6.2 ± 4.3 years old. All animals were client-owned and were classified as completely healthy or having mild systemic disease and underwent nonemergency orthopedic surgery (eg, repair of cruciate ligaments). The study was performed according to Swiss Federal Law concerning animal welfare. In all animals, food was withheld for 12 hours before surgery. For preanaesthetic medication, the sheep were given buprenorphine (10 µg/kg, IM) and xylazine (0.1 mg/kg, IM) and the dogs received buprenorphine (7 µg/kg, IM) and acepromazine (0.03 mg/kg, IM) half an hour prior to induction. Anesthesia was induced with ketamine (2 mg/kg, IV) and diazepam (0.1 mg/kg, IV) in sheep and propofol (4 mg/kg, IV) in dogs. Following endotracheal intubation, the animals were connected to a circle anesthetic circuit. Balanced anesthesia was maintained with isoflurane in 100% oxygen (10 mL/kg/min) and ketamine (10 µg/kg/min, IV) in sheep and fentanyl (10 µg/kg/h, IV) in dogs. Mechanical ventilation was performed with a tidal volume of 6 to 11 mL/kg and a respiration rate (6 to 22 breaths/min) according to the study protocol to achieve the desired EtCO₂ for normoventilation (35 to 50 mm Hg), hypoventilation (50 to 90 mm Hg), and hyperventilation (20 to 30 mm Hg).

For arterial blood sampling and invasive blood pressure monitoring, an arterial catheter was placed in the auricularis caudalis artery (sheep) or the metatarsalis lateralis artery (dogs). Blood gas samples were collected with a self-filling arterial sampler, capped, placed on ice, and analyzed within 60 minutes with a conventional blood gas analyzer. The analyzer was calibrated automatically and checked once daily.

The combined tcPCO₂ and SpO₂ sensor was applied to the animal’s ear. For this purpose, the inside proximal third of the ear was razor-shaved and a special sticky clip was mounted and additionally secured with cyanoacrylate to maintain the sensor’s airtight cutaneous seal. The sensor was attached to the clip after placing a drop of sensor gel on the sensor membrane. The electrolyte and membrane of the sensor were replaced every 10 days. Before every use, automatic calibration was triggered by taking the sensor out and placing it back into the docking station.

Anesthesia of all sheep and dogs was routinely monitored via temperature (nasal [in sheep] and esophageal [in dogs]), ECG, invasive blood pressure monitoring, pulse oximetry, heart rate, EtCO₂, spirometry, and anesthetic gas analysis continuously with a patient monitor. Recordings were made every 5 minutes unless specified (ie, 2 minutes).

Nasal or esophageal temperature, mean arterial pressure, EtCO₂, heart rate derived from the ECG, tcPCO₂, SpO₂ derived from the sensor, and pulse frequency derived from the plethysmogram were recorded at every measurement point. The analog signal outputs of the sensor docking station (tcPCO₂, SpO₂ derived from the sensor, and pulse frequency derived from the plethysmogram of the sensor) were recorded every 2 seconds with an analog digital signal-processing circuit and a personal computer.

Experimental protocol—After anesthetic induction, the animals were mechanically ventilated and normoventilation (EtCO₂, 35 to 45 mm Hg) was achieved by controlling the ventilator’s respiration rate. The following baseline values were recorded: Pao₂, PacO₂, Sao₂, EtCO₂, heart rate derived from the ECG, mean arterial blood pressure, and temperature. After 15 minutes of normoventilation, a second set of baseline values was obtained. When EtCO₂ was from 35 to 45 mm Hg, EtCO₂ values varied <4 mm Hg during the last 15 minutes, temperature was >36°C, and mean arterial blood pressure was >60 mm Hg, the experiment was started. In the first study cycle, the initial time following sensor placement required for the sensor to accurately estimate Pao₂ (time to steady state) was investigated. For this measurement, the transcutaneous sensor was mounted in the previously attached clip. Sensor output (SpO₂ derived from the sensor, tcPCO₂, and pulse frequency derived from the plethysmogram of the sensor) and the physiologic variables measured with the monitor (EtCO₂, heart rate derived from the ECG, mean arterial blood pressure, and temperature) were recorded, and blood gas samples were collected at 2-minute intervals for 10 minutes.

Following the first study sequence, the animals were successively hyper-, normo-, and hyperventilated to achieve Pao₂ from 20 to 30 mm Hg, 35 to 50 mm Hg, and 50 to 90 mm Hg, respectively. Tidal volume was kept constant, the respiratory frequency was changed to achieve the desired EtCO₂, and each ventilation setting was continued for 15 minutes. At 5-minute intervals, blood gas samples were collected and sensor output (SpO₂ derived from the sensor, tcPCO₂, and pulse frequency derived from the plethysmogram of the sensor) and the physiologic variables measured with the monitor were simultaneously obtained.

After finishing each experimental sequence, the quality of the pulse oximetry and transcutaneous signal outputs from the sensor were recorded as good or poor (on the basis of the measured plethysmographic signal amplitude) and a note was made of signal consistency or any signal disturbances.

Statistical analysis—Descriptive statistics were applied to analyze the biometric and clinical data. The time to steady state and delay (response time) of the sensor were investigated with curve-fitting calculations. Sensor time to steady state for tcPCO₂ was defined as the time until the tcPCO₂ value was approximately 90% of its steady-state plateau value after sensor application. For this purpose, all tcPCO₂ values of each animal during the first part of the study were curve-fitted with the function:

\[ f = A(1 - e^{-X/T}) \]

where A is the value of the horizontal asymptote of the function, X is time, and T is the time constant. The time constant multiplied by 2.3 is equivalent to 90% of the constant A. The mean of all individual time constant values was calculated and multiplied by 2.3 to obtain the desired mean sensor time to steady state for tcPCO₂ in the sheep and dogs.
Mean sensor response time (ie, the delay in detection of changes in $P_{CO_2}$) was calculated by measuring the time shift between the tc$P_{CO_2}$ curve (from the data record, measured at 2-second intervals) and the Pa$P_{CO_2}$ curve (polynomial of fifth degree function through the 5-minute interval arterial blood gas values).

The $P_{CO_2}$ bias (mean values of tc$P_{CO_2}$ – Pa$P_{CO_2}$) was calculated by use of measurement data from the end points of each 15-minute ventilation setting. Paired Student $t$ tests and Bland-Altman statistics were used to compare the degree of agreement between results of arterial blood gas analyses and the noninvasive tc$P_{CO_2}$ measurements. The Bland-Altman analysis was used for comparison between tc$P_{CO_2}$ and Pa$P_{CO_2}$. This analysis overcomes the limitations of traditional linear regression analysis, which reveals correlations but not interchangeability of the 2 coincident methods of measurement. Mean ± SD values are reported. For all analyses, $P < 0.05$ was considered significant.

## Results

The sensor was evaluated in 13 sheep, although 3 sheep were excluded from the data set. One was excluded because of a sensor fault and the other 2 because of problems unrelated to the study. The sensor was evaluated in 11 dogs. Two dogs had to be excluded completely from the study because the surgeon was leaning on the sensor, which caused high sensor contact pressure and substantial signal drift. In 1 dog, the second part of the experimental protocol was not performed. For the purpose of statistical analysis, the study included 10 sheep for each experimental setting, 9 dogs for evaluation of sensor time to steady state, and 8 dogs for evaluation of sensor accuracy.

Relevant biometric data were determined (Table 1). Among all measurements, continual measurements of tc$P_{CO_2}$ were obtained in 92% of sheep measurements and 100% of dog measurements.

After the initial sensor application, the tc$P_{CO_2}$ value of the sensor began to increase and required some time to reach the steady-state plateau value. In both species, the sensor occasionally overestimated tc$P_{CO_2}$, compared with Pa$P_{CO_2}$. Ten minutes after sensor application, the overall difference between tc$P_{CO_2}$ and Pa$P_{CO_2}$ was 13.3 ± 8.4 mm Hg in sheep and 8.9 ± 12 mm Hg in dogs. This difference was significant ($P = 0.007$) in sheep and not significant ($P = 0.039$) in dogs.

The sensor's tc$P_{CO_2}$ time to steady state was calculated from the data obtained after application of the sensor until the tc$P_{CO_2}$ measurement reached the steady-state plateau value during anesthesia with normocapnia (Et$CO_2$, 35 to 45 mm Hg), normal temperature (>36°C), and normal blood pressure (mean arterial blood pressure > 60 mm Hg). The sensor mean tc$P_{CO_2}$ time to steady state was 4.3 ± 2.3 minutes in sheep and 7 ± 6.5 minutes in dogs, respectively (Figure 1).

During hyperventilation in sheep, mean Pa$P_{CO_2}$ of 29.5 ± 3 mm Hg and mean tc$P_{CO_2}$ of 47.7 ± 10 mm Hg were measured. During hyperventilation in dogs, Pa$P_{CO_2}$ of 29.3 ± 4 mm Hg and tc$P_{CO_2}$ of 42.7 ± 9 mm Hg were measured. During normoventilation, the Pa$P_{CO_2}$ in sheep was 42.6 ± 4 mm Hg and the tc$P_{CO_2}$ was 56.9 ± 10 mm Hg. In dogs, the Pa$P_{CO_2}$ was 41 ± 5 mm Hg and the tc$P_{CO_2}$ was 49.8 ± 12 mm Hg. During hyperventilation, the Pa$P_{CO_2}$ was 63.3 ± 9 mm Hg in sheep and 55.2 ± 7 in dogs and the tc$P_{CO_2}$ was 70.9 ± 11 mm Hg in sheep and 64.7 ± 16 mm Hg in dogs. During hypo-, normo-, and hypercapnia, significant ($P = 0.009$) differences were observed between the tc$P_{CO_2}$ and the Pa$P_{CO_2}$ in sheep. In dogs, significant ($P = 0.04$) differences were detected.

### Table 1—Variables (mean ± SD) measured during anesthesia in 10 sheep and 9 dogs in a study of a combined tc$P_{CO_2}$ and pulse oximetry sensor.

<table>
<thead>
<tr>
<th>Intraoperative variable</th>
<th>Sheep</th>
<th>Dogs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hct (%)</td>
<td>24.6 ± 2.5</td>
<td>28.5 ± 9.8</td>
</tr>
<tr>
<td>Start of study</td>
<td>21.8 ± 3.7</td>
<td>28.5 ± 10.5</td>
</tr>
<tr>
<td>Nasal or esophageal temperature (°C)</td>
<td>37.5 ± 0.5</td>
<td>36.3 ± 0.9</td>
</tr>
<tr>
<td>Nasal or esophageal temperature decrease (°C)</td>
<td>0.7 ± 0.3</td>
<td>0.4 ± 0.6</td>
</tr>
<tr>
<td>Mean arterial blood pressure (mm Hg)</td>
<td>99 ± 10</td>
<td>69 ± 12</td>
</tr>
<tr>
<td>Heart rate (beats/min)</td>
<td>97 ± 16</td>
<td>75 ± 22</td>
</tr>
</tbody>
</table>
between the tcPco2 and Paco2 measurement methods during normocapnia but not during hypo- and hypercapnia (P = 0.06).

Bland-Altman analysis revealed bias (mean ± SD values of tcPco2 – Paco2) and precision (bias ± 2 SD) between tcPco2 and Paco2 of 13.2 ± 10.4 mm Hg and –7.1 to 33.5 mm Hg in sheep and 10.6 ± 10.5 mm Hg and –9.9 to 31.2 mm Hg in dogs, respectively (Figures 2 and 3). The limits of agreement were fairly wide in both species. The difference between tcPco2 and Paco2 reached a maximum of 41.1 mm Hg in 1 sheep. The maximum observed difference between tcPco2 and Paco2 in dogs was 26.9 mm Hg.

Changes in Paco2 induced through different ventilation settings were detected by the tcPco2 sensor after a time lag. When the ventilation was altered from normoventilation (Etco2, 43.4 ± 3.5 mm Hg) to hyperventilation to induce hypocapnia (Etco2, 32.7 ± 8.6 mm Hg), the tcPco2 sensor values followed the Paco2 values with a 4.9 ± 3.5-minute delay in sheep, respectively, from 41.8 ± 6.8 mm Hg to 29.3 ± 4 mm Hg with a 6.2 ± 3.6-minute delay in dogs (Figure 4).

During inhalation anesthesia, calculated Sao2 was 93.2% to 99.9% in sheep and 97.4% to 99.9% in dogs and was considered adequate in all animals. The Spo2 sensor was capable of detecting a continual Spo2 signal in 7 of 13 sheep and in 5 of 10 dogs. An intermittent Spo2 signal was measured in 5 of 13 sheep and 3 of 10 dogs. No Spo2 signal was obtained in 1 sheep and 2 dogs.

**Discussion**

The tcPco2 sensor overestimated Paco2 values but was capable of monitoring changes in Paco2 induced by 15-minute periods of hyper-, normo-, and hypoventilation in adult sheep and dogs. After placement of the sensor on the skin, it took 4.3 ± 2.3 minutes in sheep and 7 ± 6.5 minutes in dogs before the sensor generated a steady-state tcPco2 value. Immediately after this first part of the experimental protocol was completed, the second part commenced. In both species, the sensor had reached steady state before the second part of the experimental protocol started. Therefore, the sensor’s time to reach steady state value did not interfere with the accuracy of measurements in the second part of the experiment.

Ten minutes after sensor placement, with a stable plane of anesthesia and normocapnia, the divergence between tcPco2 and Paco2 exceeded 8 mm Hg in both species. During the alteration of ventilation protocol,
the \( \text{tcPCO}_2 \) values also overestimated \( \text{PaCO}_2 \) by various amounts. Bland-Altman analysis revealed a wide range between the calculated limits of agreement. We concluded, therefore, that the new method cannot be used to assess alterations in \( \text{PaCO}_2 \) in place of intermittent arterial blood gas analysis in adult sheep and dogs.

This study detected a greater difference between \( \text{tcPCO}_2 \) and \( \text{PaCO}_2 \) measurements than that in similar studies,\(^ {14,16} \) in humans. In humans, by use of identical methods, recordings obtained from the sensor evaluated here reveal excellent correlation with \( \text{PaCO}_2 \).\(^ {3,8} \) Therefore, the discrepancy seems to be attributable to species differences. No comparative information is available regarding the anatomic and physiologic aspects of ovine, canine, and human skin. A major factor contributing to the poor correlation of \( \text{tcPCO}_2 \) with \( \text{PaCO}_2 \) may be the thick epidermis and sparse capillary perfusion of canine and ovine ear skin.\(^ {9} \) A potentially vasoconstrictive agent (xylazine) was administered to the sheep. However, because xylazine has a short half-life in sheep (23 minutes)\(^ {10} \) and has only peripheral vasoconstrictive effects at high plasma concentrations,\(^ {9} \) we do not believe that the pharmacologic effects of xylazine affected our results.

The divergence between \( \text{tcPCO}_2 \) and \( \text{PaCO}_2 \) could be explained by the fact that \( \text{tcPCO}_2 \) values represent not only the gas pressure from the vessels but also the \( \text{CO}_2 \) generated by skin metabolism beneath the sensor.\(^ {13} \) Cuvelier et al.\(^ {1} \) found that transcutaneous measurement in human patients did not satisfactorily assess the exact values of \( \text{PaCO}_2 \) when \( \text{PaCO}_2 \) was > 50 mm Hg. Such findings contradict our results, in which differences between \( \text{tcPCO}_2 \) and \( \text{PaCO}_2 \) decreased as \( \text{PaCO}_2 \) increased.

Hazinski and Severinghaus\(^ {11} \) estimated \( \text{tcPCO}_2 \) (at 44°C) to be at least 1.37 times the simultaneously obtained \( \text{PaCO}_2 \), likely because the \( \text{tcPCO}_2 \) sensor detects \( \text{CO}_2 \) from sources other than blood vessels. Therefore, a finding of \( \text{tcPCO}_2 \) values greater than \( \text{PaCO}_2 \) values does not mean that the former were incorrectly measured.\(^ {10} \) Hence, it has been postulated that it is not logical to have a correction factor\(^ {10} \) because \( \text{tcPCO}_2 \) monitoring provides a new variable with its own characteristics.\(^ {13} \)

To understand this new variable, one must consider that a variety of factors, both technical and physiologic, can influence \( \text{tcPCO}_2 \). Technical factors that interfere with \( \text{tcPCO}_2 \) monitoring include stabilization time of the sensor, attainment of an airtight seal between sensor and skin, the sensor’s operating temperature, signal drift, fragility of the sensor membranes, and the need for recalibrations with calibration gases.\(^ {3,13} \)

It is important to allow sufficient time for stabilization of \( \text{tcPCO}_2 \) signal to increase the precision of transcutaneous measurements,\(^ {7} \) and it is important to periodically recalibrate the sensor. Secure attachment of the sensor at the skin site must be maintained. If the sensor becomes detached from the skin, the monitor will measure the \( \text{PCO}_2 \) in air, which is approximately 0 mm Hg.\(^ {13} \)

It is important to note that the \( \text{tcPCO}_2 \) sensor mimics arterial blood at the capillary level at the sensor site by heating the skin to 41°C and then corrects the measured \( \text{CO}_2 \) value to 37°C rather than to the actual body temperature.\(^ {15} \) In the blood gas machine, arterial blood is always analyzed at 37°C. If body temperature is > 37°C, the measured \( \text{PaCO}_2 \) will be lower (approx 2 mm Hg for each 1°C increase) than the actual \( \text{PaCO}_2 \) in the blood and vice versa for body temperature < 37°C. Accordingly, the \( \text{tcPCO}_2 \)-\( \text{PaCO}_2 \) gradient is calculated on the basis of temperature-corrected \( \text{PaCO}_2 \). Therefore, the difference will be less if the body temperature is > 37°C and greater if the temperature is < 37°C.

The \( \text{tcPCO}_2 \)-\( \text{PaCO}_2 \) relationship can be influenced by a number of physiologic effects, including dermal capillary blood flow, tissue \( \text{CO}_2 \) production, and \( \text{CO}_2 \) transmissibility.\(^ {16} \) If the \( \text{tcPCO}_2 \) sensor is at steady state with the skin, the values obtained at the surface of the skin should be equal to tissue values. However, tissue \( \text{PCO}_2 \) values do not have to be identical to the \( \text{PaCO}_2 \).\(^ {16} \) Tissue \( \text{CO}_2 \) concentration can be increased by continued generation of \( \text{CO}_2 \) under conditions of decreased capillary blood flow, cutaneous vasoconstriction (caused by low cardiac output or vasoconstrictive agents), low cardiac output states (hypovolemic, cardiogenic, or hypotensive), local accumulation of lactic acid, and the Haldane effect (\( \text{O}_2 \) release-dependent \( \text{CO}_2 \) absorption of hemoglobin).\(^ {3,16,17} \) Therefore, the \( \text{tcPCO}_2 \)-\( \text{PaCO}_2 \) gradient is dependent on the ratio between the change in tissue \( \text{CO}_2 \) production and \( \text{CO}_2 \) washout.\(^ {16} \)

In dogs, \( \text{tcPCO}_2 \) correlates directly with \( \text{PaCO}_2 \), when the cardiac index is > 1.5 L/min/m² and correlates inversely with cardiac index < 1.5 L/min/m² during hypovolemic shock and resuscitation.\(^ {16} \) This finding was confirmed in human patients in an intensive care unit setting where a good correlation between \( \text{tcPCO}_2 \) and \( \text{PaCO}_2 \) values was observed before cardiac decompensation. During cardiac decompensation, cardiac arrest, and cardiopulmonary resuscitation, the \( \text{tcPCO}_2 \) values correlated inversely with cardiac index.\(^ {14,18} \) The severity of shock could be roughly determined by comparing the \( \text{tcPCO}_2 \) values with arterial \( \text{CO}_2 \) pressures.\(^ {18} \)

Heating of the skin by the sensor influences the \( \text{tcPCO}_2 \)-\( \text{PaCO}_2 \) gradient because heating increases tissue \( \text{CO}_2 \) production and heating capillary blood beneath the sensor increases the \( \text{PCO}_2 \).\(^ {14} \) As the heating element of the sensor increases, the \( \text{CO}_2 \) dissociation curve is shifted to the right and \( \text{tcPCO}_2 \) increases. Transcutaneous \( \text{PCO}_2 \) values are therefore always higher than \( \text{PaCO}_2 \) values.\(^ {13} \)

Despite the difference in absolute values, \( \text{tcPCO}_2 \) values change as \( \text{PaCO}_2 \) values change, as revealed in this study and others.\(^ {3,10,16,18,19} \) For correct interpretation of the transcutaneous values, the time lag associated with this measurement method must be taken into account. The \( \text{tcPCO}_2 \) response time is dependent on the sensor's temperature; increasing the sensor's temperature decreases the sensor's response time.\(^ {17} \) The response time of the sensor (at 41°C) in our study was less than that reported in other studies in which a different type of \( \text{tcPCO}_2 \) sensor (at 44°C) was used (response times, 7 to 10 minutes\(^ {10} \) and 8.7 ± 0.6 minutes\(^ {16} \)). This difference may be attributable to different methods of response time calculations. In addition, \( \text{CO}_2 \) resistance to flow, which depends on the permeability of the skin and the capacitative effect (solubility of gas with tissue el-
ments), determines the tcPCO₂ response time. Resistance to flow of CO₂ through the skin is marginal. The high solubility of CO₂ in the membrane material and in skin and the buffering of CO₂ in the tissues yields the response time. It should be remembered that changes in tissue CO₂ values are delayed in relation to corresponding PCO₂ blood values. 

The accuracy of the pulse oximetry sensor could not be tested over a wide range of SaO₂ values. Therefore, conclusions could not be made about the accuracy, response time, or ability of the sensor to monitor changes in SaO₂. However, in both species, consistent SpO₂ readings were not detected with this sensor, even though the animals were well oxygenated.

To assess clinically important changes in PacO₂, the combined sensor cannot replace arterial blood gas measurements in adult sheep and dogs. Instead, it provides a tool for monitoring changes in tcPCO₂. The sensor is capable of detecting changes in PacO₂ during different ventilation settings but always with a time lag. Measurement of tcPCO₂ has several advantages over periodic arterial blood gas analysis. First, it represents what is occurring at the cellular level rather than at the blood level. Second, it provides continuous information. Third, it is noninvasive. Further studies are required to evaluate the accuracy of the combined sensor with different oxygen saturation concentrations in animals. It may offer particular benefits for continuous monitoring of changes in tcPCO₂.

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b. Pico70, Radiometer GmbH, Thalwil, Switzerland.
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g. MAX186, Maxim, Sunnyvale, Calif.
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k. GraphPad Prism, version 4.00, GraphPad Software Inc, San Diego, Calif.