Domestic cats respond to anesthesia in a manner that differs from that of other species, especially dogs. Cats are unique with regard to drug distribution and metabolism and cardiovascular depression caused by anesthetic agents, particularly inhalant anesthetics. Studies in which investigators used equipotent doses of halothane revealed that the CO of healthy cats decreased by > 50% in response to the inhalant anesthetic, whereas the change was < 20% in dogs and people. Cardiovascular depression is also evident clinically because severe hypotension is commonly encountered in healthy cats at surgical planes of anesthesia. In 2 studies in which investigators examined morbidity and fatalities in small animal practices, there was a higher mortality rate in cats than in dogs, especially when sick animals were compared. Heightened sensitivity of the feline cardiovascular system to anesthetic agents makes monitoring and management of that system an essential part of anesthetic procedures for cats. Close and detailed monitoring of cardiovascular variables allows early detection of changes in cardiovascular function and improves the ability of clinicians to effectively correct abnormalities. Cardiac output is arguably the most important variable in the evaluation of cardiovascular function because it most closely reflects systemic perfusion.

Several methods can be used for measuring CO. The most common is a thermodilution technique, and it is often considered the standard to which other techniques are compared. The thermodilution technique requires catheterization of the right side of the heart, which has inherent technical difficulties and risks. Moreover, there is some controversy in human medicine whether catheterization of the right side of the heart may be associated with an increase in fatalities. Another disadvantage of the thermodilution technique is that it only provides intermittent measurements, which precludes continuous monitoring of CO. For these reasons, the thermodilution technique and therefore determination of CO are rarely used in feline patients. This results in suboptimal monitoring of the cardiovascular system because measurement of blood

Evaluation of transesophageal echo-Doppler ultrasonography for the measurement of aortic blood flow in anesthetized cats

Marlis L. Rezende, DVM, PhD; Bruno H. Pypendop, DrMedVet, DrVetSci; Jan E. Ilkiw, BVSc, PhD

Objective—To evaluate the use of a transesophageal echo-Doppler ultrasonography (TED) technique for measurement of aortic blood flow (ABF) in relation to cardiac output (CO) measured by use of a thermodilution technique in anesthetized cats.

Animals—6 adult cats (mean ± SD body weight, 5 ± 0.7 kg).

Procedures—Anesthesia was induced and maintained in cats by administration of isoflurane. A thermodilution catheter was placed in a pulmonary artery. The TED probe was positioned in the esophagus in the region where the aorta and esophagus are almost parallel. Five baseline values for ABF and CO were concurrently recorded. Cats were randomly assigned to a high or low CO state (increase or decrease in CO by at least 25% from baseline, respectively). Baseline conditions were restored, and the other CO state was induced, after which baseline conditions were again restored. For each CO state, ABF and CO were measured 5 times at 5-minute intervals. Correlation and agreement between the techniques were determined by use of the Pearson product-moment correlation and Bland-Altman method.

Results—CO ranged from 0.16 to 0.75 L/min and ABF from 0.05 to 0.48 L/min. Overall data analysis revealed a high correlation (r = 0.884) between techniques but poor agreement (limits of agreement, −0.277 to 0.028 L/min). During the low CO state, correlation between techniques was low (r = 0.413).

Conclusions and Clinical Relevance—TED did not accurately measure CO. However, it allowed evaluation of CO patterns and may be useful clinically in anesthetized cats. (Am J Vet Res 2008;69:1135–1140)
pressure becomes the surrogate for measurement of blood flow. However, blood pressure is affected by both CO and vascular resistance, which limits its value in the assessment of cardiovascular function (particularly the flow component).

The TED technique was developed to allow non-invasive, easy-to-use, continuous monitoring of blood flow in the descending aorta.1 The transesophageal probe used in the study reported here consisted of 2 transducers. A pulsed-Doppler transducer estimates mean velocity of ABF; and an M-mode transducer measures the diameter of the aorta in the area in which flow velocity is measured.11-14 The device used this information to calculate blood flow in the descending aorta, which is used as an estimate of CO. Blood flow of the descending aorta constitutes approximately 70% of CO.15

The TED technique also has limitations. Velocity of blood flow is not uniform throughout a cross-sectional area of the aorta, the angle between the Doppler signal and direction of blood flow can only be estimated, and the cross-sectional area of the aorta can vary slightly during the cardiac cycle, all of which may add variability to results for the technique.16

Nevertheless, the TED method has been used in humans to estimate CO during anesthesia or in patients in critical care units, and it could be a good alternative to use of the thermodilution technique in cats. Studies to compare TED and thermodilution techniques for measurement of CO in humans have yielded results that have ranged from poor17 to strong18,19 correlations between the 2 methods.

The objective of the study reported here was to evaluate the TED technique for continuous estimation of CO in anesthetized cats. The study was designed to compare measurements obtained by use of the thermodilution technique with those obtained by use of the thermo- dilution technique during normal, high, and low CO.

Materials and Methods

Animals—Six healthy conditioned domestic adult cats (mean ± SD body weight, 5 ± 0.7 kg) were used in the study. Cats were considered healthy on the basis of results of physical examination. The study protocol was approved by the Animal Use and Care Committee of the University of California, Davis, Calif.

Experimental design—Anesthesia was induced in a chamber by use of 5% isoflurane in oxygen. After induction of anesthesia, cats were orotracheally intubated, and anesthesia was maintained with 2% isoflurane (end-tidal concentration) in oxygen administered via a nonrebreathing circuit with a fresh gas flow of 500 mL/kg/min. Cats breathed spontaneously throughout the study. A catheter was percutaneously placed in a cephalic vein for the administration of lactated Ringer’s solution at a rate of 3 mL/kg/h. A 5-F introducer was placed in the right jugular vein. A 4-F thermodilution catheter8 was inserted via the introducer and positioned by use of fluoroscopic guidance such that the tip and thermistor were located in the pulmonary artery. A lead II ECG was continuously monitored. Inspired and end- tidal concentrations of isoflurane, oxygen, and carbon dioxide were continuously measured by use of a Raven spectrometer.4 Hemoglobin oxygen saturation was continuously determined by use of pulse oximetry.7 Systolic arterial pressure was measured before each CO measurement by use of a Doppler flow detector placed over a branch of the median artery and an occluding cuff attached to a sphygmomanometer. Core body temperature (measured at the level of the pulmonary artery by the thermistor of the thermodilution catheter) was maintained between 38° and 39°C by use of circulating warm water blankets and forced-air heat, as needed.

Cardiac output was determined, in triplicate, by use of a thermodilution technique and a CO computer.1 Three milliliters of ice-cold 5% dextrose in water or saline (0.9% NaCl) solution was injected through the proximal port of the thermodilution catheter for each determination. Mean value of the 3 measurements was then calculated.

Aortic blood flow was continuously measured by use of a TED device.6 A 7-mm probe was introduced into the esophagus through the oral cavity and positioned in the region where the descending aorta and esophagus are almost parallel. Fine adjustments of the probe position were then made by use of the M-mode until both aortic walls could be identified, and the widest aortic diameter was measured. Diameter of the descending aorta was then measured, flow velocity at that location was continuously determined, and ABF was calculated. Aortic blood flow was recorded concurrently with each CO determination.

After instrumentation was completed, 5 baseline measurements were concurrently obtained for CO and ABF at 5-minute intervals. Cats were then randomly assigned to a CO state (ie, high or low CO). High CO was achieved by decreasing the isoflurane concentration by 2% from baseline CO; low CO was achieved by decreasing the isoflurane concentration by 20% and administering a constant rate infusion of dobutamine (5 to 20 µg/kg/min, IV), which was titrated to maintain a SAP of 90% of baseline for each CO state. At 5 minutes after the change of CO state, the aortic blood flow was assessed. Three baseline measurements were obtained, and the mean of the 3 measurements was used as the CO state measurement.

The device used this information to calculate blood flow in the descending aorta, which is used as an estimate of CO. Blood flow of the descending aorta constitutes approximately 70% of CO.15

The device used this information to calculate blood flow in the descending aorta, which is used as an estimate of CO. Blood flow of the descending aorta constitutes approximately 70% of CO.15

Table 1.—Mean ± SD values for physiologic variables during various CO states in 6 anesthetized cats.

<table>
<thead>
<tr>
<th>CO state*</th>
<th>SAP (mm Hg)</th>
<th>PrcO2 (mm Hg)</th>
<th>ESNO (%)</th>
<th>SpO2 (%)</th>
<th>Temperature (°C)†</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline CO</td>
<td>96 ± 13</td>
<td>41 ± 3</td>
<td>2.0 ± 0.2</td>
<td>99 ± 1</td>
<td>38.1 ± 0.4</td>
</tr>
<tr>
<td>High CO</td>
<td>123 ± 34</td>
<td>47 ± 3</td>
<td>1.9 ± 0.1</td>
<td>99 ± 1</td>
<td>38.4 ± 0.4</td>
</tr>
<tr>
<td>Low CO</td>
<td>161 ± 25</td>
<td>41 ± 6</td>
<td>1.0 ± 0.1</td>
<td>—</td>
<td>38.5 ± 0.6</td>
</tr>
</tbody>
</table>

Data were not statistically analyzed.

*High CO was an increase of at least 25% from baseline CO, and low CO was a decrease of at least 25% from baseline CO.1 Represents core body temperature.

**SAP = Systolic arterial pressure. PrcO2 = End-tidal partial pressure of carbon dioxide. ESNO = End-tidal concentration of isoflurane. SpO2 = Hemoglobin saturation as measured by pulse oximetry. — = Unable to obtain a measurement.

AJVR, Vol 69, No. 9, September 2008
to the rate needed to increase CO by at least 25% from the baseline value. Low CO was achieved by decreasing isoflurane concentration by 50% and administering medetomidine\(^\text{1}\) (30 \(\mu\)g/kg, IV) to decrease CO by at least 25% from the baseline value. Isoflurane concentration was then adjusted to maintain a light plane of anesthesia. For each CO state, a stabilization period of 10 minutes was allowed and CO and ABF were measured concurrently (5 measurements obtained at 5-minute intervals). Baseline conditions were then restored by returning isoflurane to the previous concentration and discontinuing dobutamine infusion or administering the medetomidine antagonist atipamezole\(^\text{1}\) (150 \(\mu\)g/kg, IV). After stabilization at baseline conditions for 10 minutes, concurrent CO and ABF measurements were again obtained. Cats were then assigned to the other CO state, which was induced by the aforementioned methods. Measurements were obtained as described previously: Baseline conditions were restored, and after stabilization for 10 minutes, a final set of CO and ABF measurements was obtained. At the end of the experiment, all catheters and monitoring equipment were removed, and the cats were closely observed until extubated and completely recovered from anesthesia.

Statistical analysis—Correlation between results for the 2 techniques was examined by use of the Pearson product-moment correlation for pooled data for all CO states and then separately for each CO state. Agreement was evaluated by use of the Bland-Altman method. Limits of agreement were defined as the mean difference, and limits of agreement represent the bias ± 1.96 SD of the difference. Gross deviation from the normality assumption was excluded on the basis of the elliptical pattern of a scatterplot of the data.\(^\text{19}\) To assess reproducibility of the TED measurements, the coefficient of variation of the measurement was calculated for each cat for each CO state. The coefficient of variation was 6.4 ± 1.0%.

Results
A total of 150 data pairs of CO-ABF values were obtained for the 6 cats in the study. From these 150 data pairs, 90 were obtained at the baseline state, 30 were obtained at the high CO state, and 30 were obtained at the low CO state. Physiologic variables monitored during the various CO states were not statistically analyzed (Table 1). Total duration of anesthesia remained < 4 hours for all cats. Infusion rates of dobutamine required to achieve the targeted high CO state ranged from 5 to 7.5 \(\mu\)g/kg/min. The CO values obtained by use of the thermodilution technique ranged from 0.16 to 0.75 L/min, whereas the ABF values obtained by use of the TED technique ranged from 0.05 to 0.48 L/min (Table 2). By use of the measurements obtained at each CO state, ABF was 73 ± 14% of the CO determined at the baseline state by use of the thermodilution technique. During the high CO state, ABF was 61 ± 5% of CO, whereas during the low CO state, ABF was 54 ± 24%.

The ABF obtained by use of the TED technique had fairly low variability between measurements within each cat and each CO state. The coefficient of variation was 6.4 ± 1.0%.

Table 2—Mean ± SD values for CO and ABF measured concurrently during various CO states in 6 anesthetized cats.

<table>
<thead>
<tr>
<th>CO state*</th>
<th>CO (L/min)</th>
<th>ABF (L/min)</th>
<th>ABF-to-CO ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All CO states</td>
<td>0.27 ± 0.15</td>
<td>0.25 ± 0.10</td>
<td>67 ± 17</td>
</tr>
<tr>
<td>Baseline CO</td>
<td>0.35 ± 0.07</td>
<td>0.25 ± 0.06</td>
<td>73 ± 14</td>
</tr>
<tr>
<td>High CO</td>
<td>0.61 ± 0.10</td>
<td>0.38 ± 0.07</td>
<td>61 ± 5</td>
</tr>
<tr>
<td>Low CO</td>
<td>0.20 ± 0.03</td>
<td>0.11 ± 0.05</td>
<td>54 ± 24</td>
</tr>
</tbody>
</table>

See Table 1 for key.

Figure 1—Linear regression and correlation between CO measured by use of a thermodilution technique (TDCO) and CO obtained by measurement of ABF by use of a TED technique (TEDCO) for baseline CO, high CO, and low CO (ie, all 150 data pairs) in 6 cats anesthetized with isoflurane. High CO was an increase of at least 25% from baseline CO, whereas during the low CO state, ABF was 54 ± 24%.

Table 3—Correlation (95% confidence intervals) for CO (as determined by use of the thermodilution technique) and aortic blood flow (as determined by use of the TED technique) measured simultaneously at different states of CO in 6 anesthetized cats.

<table>
<thead>
<tr>
<th>CO state</th>
<th><strong>r</strong></th>
<th><strong>Bias (L/min)</strong></th>
<th><strong>Limits of agreement (L/min)</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall CO (n=150)</td>
<td>0.884 (0.84 to 0.91)</td>
<td>–0.125</td>
<td>–0.277 to 0.028</td>
</tr>
<tr>
<td>Baseline CO (n=90)</td>
<td>0.834 (0.49 to 0.74)</td>
<td>–0.099</td>
<td>–0.210 to 0.012</td>
</tr>
<tr>
<td>High CO (n=30)</td>
<td>0.888 (0.78 to 0.95)</td>
<td>–0.236</td>
<td>–0.335 to –0.137</td>
</tr>
<tr>
<td>Low CO (n=30)</td>
<td>0.413 (0.06 to 0.67)</td>
<td>–0.091</td>
<td>–0.189 to 0.007</td>
</tr>
</tbody>
</table>

*\(r^*\) represents the mean difference, and limits of agreement represent the bias ± 1.96 SD.
*\(r\) represents the Pearson product-moment correlation coefficient.
\(n\) = Number of pairs of measurements.
Analysis of all data pairs collected during the study (n = 150) revealed a very good correlation between the thermodilution and TED techniques (r = 0.884; Figure 1; Table 3). Analysis of the data pairs on the basis of CO state (90 data pairs at baseline CO, 30 at high CO, and 30 at low CO) indicated that the correlation between techniques was very good at high CO (r = 0.886), less strong at baseline CO (r = 0.634), and weak at low CO (r = 0.413).

Bias and limits of agreement for all data pairs were –0.125 L/min and –0.277 to 0.028 L/min, respectively (Figure 2; Table 3). During high CO, the limits of agreement were –0.167 to –0.069 L/min, whereas the limits of agreement were 0.105 to 0.006 L/min at baseline CO and –0.094 to 0.003 L/min during low CO.

Discussion

Thermodilution is an extensively used and accepted method for determining CO to which other methods for measurement of CO are compared. In cats, thermodilution has been compared with almost all other known methods for measurement of CO and it has provided minimal variability and good reproducibility. Thermodilution is considered a consistent and dependable method for measuring CO in cats and was selected for use in our study as the technique against which the TED technique would be compared. In addition, thermodilution allows repeated measurements to be performed safely, the indicator does not recirculate or accumulate, blood collections are not required, and results are not influenced by peripheral blood flow, all of which are aspects that make this technique appropriate to the study design.

The TED measurement of ABF had good correlation but weak agreement with CO measured by use of the thermodilution method in cats when the 150 data pairs were analyzed (ie, data for all CO states were included). This was expected because ABF is measured in the descending aorta and is therefore not equal to CO. Blood flowing to the brachiocephalic trunk is not measured by the TED technique, and this likely accounted for some of the differences between ABF and CO in the study reported here. Moreover, the proportion of CO reaching the descending aorta depends on the actual CO and is expected to be higher at a high CO than at a low CO because cardiac and cerebral blood flow are better preserved than the blood flow to other organs during low CO states.

Overall analysis of the data pairs obtained in the study revealed a high correlation (r = 0.884) between results for the thermodilution and TED techniques. Comparison of the TED technique with the traditional thermodilution method for measuring CO in humans has revealed variable results that range from poor to strong correlations. The differences in results appear to be related, in part, to the type of device used. Older devices designed to measure ABF in humans calculated ABF on the basis of an estimated aortic diameter derived from a normogram that related a patient’s height, weight, age, and gender, whereas the more recent ABF monitors, such as the one used in the study reported here, actually measure (by use of M-mode ultrasonography) the aortic diameter at the point where velocity of ABF is measured and therefore typically are more accurate.

Analysis of the data pairs on the basis of CO state (ie, baseline CO, high CO, and low CO) revealed considerable variation for the correlation between the 2 techniques. Correlation was very good (r = 0.886) for high CO, less strong (r = 0.634) for baseline CO, and weak (r = 0.413) for low CO. Overestimation of CO by the thermodilution technique during low CO has been reported and could have been the cause of the weak correlation detected during the low CO state, although a decrease in the accuracy of the TED technique cannot be ruled out. It is also possible that the proportion of the CO reaching the descending aorta (where the measurement for the TED technique is obtained) is more variable at low CO than at high CO.

The agreement between techniques in our study was considered poor because the limits of agreement were –0.277 to 0.028 L/min for a mean CO of 0.37 L/min when all data pairs were analyzed and –0.210 to 0.012 L/min, –0.335 to –0.137 L/min, and –0.189 to 0.007 L/min for mean CO of 0.35 L/min, 0.61 L/min, and 0.20 L/min for data pairs obtained for baseline CO, high CO, and low CO, respectively. It has been suggested that changes in the diameter of the descending aorta induced by hemodynamic changes could be responsible for the variability of the limits of agreement reported in several studies. In addition, use of the TED technique reportedly underestimates changes in CO caused by changes in preload and contractility and overestimates changes caused by afterload and its influence on aortic diameter. In our study, even though dobutamine was used to increase CO and medetomidine was used to decrease CO, it is unlikely that the potential changes in aortic diameter caused by these drugs could explain the wide limits of agreement because aortic diameter was measured concurrently with measurement of ABF velocity.

Another aspect to be considered is that the absolute values of CO for a clinically normal adult domestic...
could aid in prompt detection and correction of hemo-
continuous assessment of patterns of CO and therefore
Although this method did not prove suitable to accu-
obtained in a timely and uneventful manner in all cats,
cialized imaging skills. Adequate probe positioning was
is relatively simple to use, and does not require spe-
also explains the increase in systolic arterial pressure
systemic vascular resistance caused by medetomidine.
agonist drugs, such as medetomidine. The increased
was unable to obtain a measurement in any of the cats.
with the technique during periods of hemodynamic instabil-
problem related to the accuracy of the measurement
suggested as a physiologic mechanism.
response of the body favoring blood flow to the head
and heart. An increase in systemic vascular re-
re sistance attributable to adrenergic stimulation has been
suggested as a physiologic mechanism. However, a
problem related to the accuracy of the measurement
tech nique during periods of hemodynamic instabil-
ity cannot be discarded. Similar results have been re-
whereby a decrease in the ABF-to-CO ratio was detected in
CO, and the lowest ratios were obtained with the lowest CO. On the
other hand, a decrease in the ABF-to-CO ratio, even though
less marked, was also detected for the high CO state in
which the CO measured by use of the thermodilution
increase more than did the ABF. An increase in
the ABF-to-CO ratio has been detected after adminis-
abdominal blood flow in critically ill patients with a new
Wodey E, Gai V, Carre F, et al. Accuracy and limitations of con-
References
1. Wilcke JR. Idiosyncracies of drug metabolism in cats. Effects
on pharmacotherapeutics in feline practice. Vet Clin North Am
2. Walker CH. Species differences in microsomal monoxygen-
ase activity and their relationship to biological half-lives. Drug
3. Ingwerson W, Allen DG, Dyson DH, et al. Cardiopulmonary ef-
hects of a halothane/oxygen combination in hypovolemic cats.
4. Dobkin AB, Fedoruk S. Comparison of the cardiovascular, respi-
ratory and metabolic effects of metoxynurane and halothane in
5. Dyson DH, Maxie MG, Schnurr D. Morbidity and mortality as-
sociated with anesthetic management in small animal veterinary
6. Clarke KW, Hall LW. A survey of anaesthesia in small animal prac-
7. Dyson DH, Allen DG, McDonell WN. Comparison of three
8. Matthay MA, Chatterjee K. Bedside catheterization of the pul-
monary artery: risks compared to benefits. Ann Intern Med
of right heart catheterization in the initial care of critically ill
surement of aortic blood flow in critically ill patients with a new
12. Wodey E, Gai V, Carre F, et al. Accuracy and limitations of con-
tinuous esophageal aortic blood flow measurement during
general anaesthesia for children: comparison with transcutane-
blood flow measurement using an intraesophageal probe. Ultra-
14. Muchada R, Cathignol D, Lavandier B. Aortic blood flow mea-
flow and cardiac output: a clinical and experimental study of
continuous esophageal echo-Doppler flowmetry. Acta Anaes-
16. Schuster AH, Nanda NC. Doppler echocardiographic measure-
ment of cardiac output: comparison with a non-golden standard.
17. Schmid ER, Spahn DR, Tornic M. Reliability of a new generation
transoesophageal Doppler device for cardiac output monitoring.
cardiac output in critically ill patients using transesophageal
19. Altman DG. Relation between two continuous variables. In:
Altman DG, ed. Practical statistics for medical research. London:
20. Allen DG, Nymeyer D. A preliminary investigation on the use of
thermodilution and echocardiography as an assessment of car-