Evaluation of a commercial ultrasonographic hemodynamic recording system for the measurement of cardiac output in dogs

Brian A. Scansen, DVM, MS; John D. Bonagura, DVM, MS; Karsten E. Schober, Dr med vet, PhD; William W. Muir III, DVM, PhD

Objective—To evaluate the accuracy of a commercial ultrasonographic cardiac output (CO) monitoring system (UCOMS) in anesthetized Beagles as assessed by comparison with thermodilution CO (TDCO).

Animals—8 healthy anesthetized Beagles.

Procedures—Simultaneous UCOMS and TDCO measurements of CO were obtained during 4 hemodynamic states: baseline anesthesia (0.5% to 1.5% isoflurane), a higher depth of anesthesia (2% to 3.5% isoflurane) to yield a ≥ 15% reduction in systolic arterial blood pressure, IV infusion of colloidal solution to a mean right atrial pressure of ≥ 15 mm Hg, and IV infusion of dobutamine at 5 µg/kg/min. Measurements were obtained at 2 probe positions: the subxiphoid region and the right thoracic inlet. Correlation and agreement of results between methods were determined via linear regression analysis and Bland-Altman plots.

Results—A significant positive correlation was detected between UCOMS and TDCO measurements obtained at the subxiphoid ($\rho = 0.86$) and thoracic inlet ($\rho = 0.83$) positions. Bland-Altman plots revealed minimal bias between methods (bias ± SD, –0.03 ± 0.73 L/min and –0.20 ± 0.80 L/min for subxiphoid and thoracic inlet measurements, respectively). However, the percentage error associated with UCOMS measurements made at the 2 positions was > 45%.

Conclusions and Clinical Relevance—When compared with the results of TDCO, CO measured with the UCOMS exceeded commonly accepted limits of error in healthy dogs. The UCOMS was, however, able to track changes in CO across hemodynamic states. Additional research is needed to assess the usefulness of the UCOMS for monitoring CO in critically ill dogs. (*Am J Vet Res* 2009;70:862–868)

Accurate monitoring of a critically ill animal is important for selecting a therapeutic intervention, monitoring the animal's condition, and determining a prognosis. Hemodynamic assessment of these animals involves minimally invasive measurements of arterial blood pressure, central venous pressure, and other variables such as heart rate, capillary refill time, and blood lactate concentration. However, these measurements are reportedly insensitive markers of cardiovascular responsiveness and performance in humans.[1–3] Theoretically, CO should provide a more direct indication of the degree of oxygen delivery to tissues. Furthermore, alterations in CO in response to a therapeutic challenge (such as fluid volumes, positive inotropic medications, or vasopressors) would provide useful information on which to make therapeutic recommendations. However, clinical use of CO monitoring is hindered by the lack of accurate, clinically applicable, noninvasive, and cost-efficient methods. Furthermore, techniques for noninvasive clinical determination of CO in dogs require standardization.

Abbreviations

2-D	2-dimensional
CO	Cardiac output
TDCO	Thermodilution cardiac output
UCOMS	Ultrasonographic cardiac output monitoring system

Right heart catheterization and TDCO have long been the principal methods for hemodynamic monitoring and determination of CO in human critical care but have not been widely adopted in veterinary critical care because of attitudes regarding cost, technical difficulties, complications during catheter placement, and animal tolerance. A noninvasive technique to measure and continuously monitor CO would be of particular benefit in the treatment of dogs receiving intensive care or undergoing anesthesia, so long as monitoring could be achieved at a reasonable cost, in a repeatable and

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From the Department of Veterinary Clinical Sciences, College of Veterinary Medicine, The Ohio State University, Columbus, OH 43210.
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Address correspondence to Dr. Scansen.

clinically feasible manner, and with minimal stress to the dogs. Such a device should also be compact and portable.

Noninvasive or minimally invasive methods of measuring CO have been developed in human medicine in response to concerns about complications from catheter placement and reliability of pulmonary artery catheterization.[4–6] Such techniques include thoracic bioimpedance,[7,8] lithium chloride dilution,[9,10] pulse contour analysis,[11,12] partial carbon dioxide rebreathing,[13,14] echocardiography,[15–17] and use of a nonimaging Doppler ultrasound probe.[18–20] Of these, bioimpedance,[21,22] lithium chloride dilution,[23] partial carbon dioxide rebreathing,[22,24] and transthoracic[25] and transesophageal[22] echocardiography have been used in dogs.

Considerable interest exists in the use of Doppler methods for assessment and monitoring of CO. In humans, this was originally performed with dedicated Doppler probes from a suprasternal probe position or with Doppler transesophageal echocardiography.[26–28] However, these attempts were confounded by variability in aortic diameter, suboptimal signal acquisition, and deviation of the ultrasound angle from the direction of flow. A portable, dedicated UCOMS[a] has been approved by the FDA for continuous CO monitoring in humans. Signal acquisition in humans is performed with the patient in a supine position, with the ultrasound probe directed toward the aortic annulus from the suprasternal notch or toward the pulmonary annulus from the second left intercostal space.

A preliminary study[29] in which UCOMS measurements were compared with those of surgically implanted aortic flow probes revealed that this device offered a reliable estimate of CO in dogs. There are no data on the optimal site for signal acquisition in dogs, nor have there been comparisons to a clinically accepted gold standard in dogs. The purpose of the study reported here was to evaluate the accuracy of a UCOMS in isoflurane-anesthetized Beagles during various hemodynamic conditions, as assessed by comparison of results with those of TDCO. In addition, we sought to identify the optimal body site for signal acquisition.

Materials and Methods

Animals—Eight healthy Beagles (5 male and 3 female) with a mean ± SD body weight of 11.1 ± 0.7 kg (range, 9.7 to 11.9 kg) were used. All dogs were sexually intact and 18 months of age. The study protocol was reviewed and approved by the Animal Care and Use Committee of The Ohio State University, and all dogs were treated in compliance with NIH Guidelines for the Care and Use of Laboratory Animals.

Measurement of cross-sectional area of the aorta—Each dog was sedated via IM administration of morphine[b] (0.4 mg/kg) and acepromazine[c] (0.05 mg/kg). A complete Doppler and 2-D echocardiogram was obtained by use of a digital ultrasound system[d] with a 7-MHz nominal frequency probe. Dogs were first evaluated to ensure they did not have structural heart disease. Then the aortic diameter was determined from a right parasternal, long-axis imaging plane and measured at the hinge point of the aortic valve leaflets when they were parallel in early systole. The mean of 5 to 10 measurements was used to calculate the cross-sectional area ($\pi \times [\text{aortic diameter}/2]^2$).

Instrumentation for measurement of CO—A 20-gauge, 2.8-cm over-the-needle catheter was placed in the right cephalic vein, and anesthesia was induced with propofol[e] (4 mg/kg IV). Each dog was orotracheally intubated, and anesthesia was maintained with 0.5% to 1.0% isoflurane[f] in 100% oxygen. Cefazolin[g] (22 mg/kg, IV) was administered every 2 hours throughout the procedure. Heart rate, blood pressure, rectal temperature, end-tidal carbon dioxide concentration, and oxygen saturation as measured by use of pulse oximetry were monitored throughout anesthesia. Instrumentation included a 20- or 22-gauge over-the-needle catheter placed in the left or right dorsal pedal artery for invasive measurement of arterial blood pressure. The dogs were positioned in left lateral recumbency, the hair over the right jugular vein was clipped, and the skin was aseptically prepared with chlorhexidine[h] and isopropyl alcohol. A 1-cm incision was made over the right jugular vein, and the vein was isolated for controlled access. An 8-F introducer sheath[i] was inserted into the vein and secured to the skin. A 7.5-F, 110-cm thermodilution pulmonary artery catheter[j] was then introduced into the sheath, and fluoroscopy was used to guide advancement of the catheter into the main pulmonary artery such that the proximal port was in the right atrium and the distal thermistor was in the proximal right or left pulmonary artery. A 60-cm sterile shield[k] surrounded the pulmonary artery catheter, allowing for adjustment of the catheter while maintaining sterile technique. The catheter was attached to a hemodynamic data acquisition system[l] for continual monitoring of right atrial and pulmonary arterial blood pressure.

For UCOMS imaging, a 3 × 3-cm area of hair was clipped over the midline of the ventral thorax, just caudal to the xiphoid process; a similar square of hair was clipped over the right thoracic inlet. Preliminary attempts with the UCOMS to insonate pulmonary flow for CO determination resulted in inconsistent data and were abandoned in subsequent experiments. Measurements of aortic blood flow by use of the UCOMS were subsequently made at 2 locations: a subxiphoid position with the probe on the ventral midline and directed cephalad and nearly parallel to the sternum and a right thoracic inlet position with the probe directed caudad just medial to the right humeral head.

Measurement of CO—The TDCO was determined with a commercial CO computer.[m] Briefly, 3-mL volumes of ice-cold 5% dextrose in water were rapidly injected into the right atrium through the proximal port of the pulmonary artery catheter. Four or 5 TDCO estimates were obtained at each measurement period, and the mean of 3 measurements that varied by < 10% was used as the TDCO.

The UCOMS measurements were obtained at each treatment period simultaneously with the TDCO measurements. The UCOMS probe contains a small piezoelectric crystal to insonate flow through the aortic annulus via nonimaging, continuous-wave spectral Doppler ultrasonography. Integration of the resultant velocity profile (velocity-time integral) yields the stroke

distance (cm). Multiplication of the stroke distance by the cross-sectional area of the aortic orifice (cm^2) yields a stroke volume (cm^3). The heart rate multiplied by the stroke volume yields CO (L/min). Proprietary software in the UCOMS unit[a] integrates the velocity curves in real-time and measures an instantaneous heart rate from the time between each subsequent flow tracing. If the software fails to accurately trace the velocity profiles as displayed on the screen, manual correction of the frozen traces can be performed. The aortic cross-sectional area is determined from the aortic diameter measured echocardiographically or inserted from a nomogram, and the computer then yields continuous measurements of stroke volume and CO for each aortic impulse. Values for systemic blood pressure and central venous pressure can also be entered into the system for calculation of systemic vascular resistance.

Optimization of the UCOMS signal involved subtle movements of the transducer probe to obtain the cleanest velocity envelope, maximal velocity, and minimal background noise. An audible Doppler-shift channel assisted signal optimization. Once the signal was optimized, 20 to 30 heartbeats from the subxiphoid position were recorded and averaged to obtain the UCOMS-estimated CO. This was then repeated at the thoracic-inlet probe location.

Hemodynamic interventions—Simultaneous TDCO and UCOMS measurements were obtained during 4 hemodynamic conditions: a baseline depth of anesthesia (0.5% to 1.5% inhaled isoflurane); an increased depth of anesthesia (2.0% to 3.5% isoflurane) to yield a ≥ 15% reduction in systolic arterial blood pressure from the baseline value, which presumably reduced myocardial contractility and systemic vascular resistance; an infusion[n] of colloidal solution[o] to achieve a mean right atrial blood pressure or pulmonary capillary wedge blood pressure of ≥ 15 mm Hg to increase ventricular filling pressure; and a dobutamine[p] infusion of 5 µg/kg/min to increase myocardial contractility. After each desired hemodynamic state was achieved, the next intervention was applied and hemodynamic variables were allowed to stabilize for at least 10 minutes before CO was again measured.

After the final CO measurements were made, furosemide[q] (2 mg/kg) was administered IV, all catheters were removed, the incision in the right jugular vein was closed with 6-0 polypropylene suture material,[r] the skin incision was closed, and a light bandage was placed on the neck and dorsal pedal access site. The dogs were monitored for any adverse signs for 3 days after the procedure.

Statistical analysis—Statistical analyses were performed with commercially available software.[s–u] Descriptive statistics were calculated for all variables measured. Data were evaluated for normality with the Komogrov-Smirnoff test and are reported as mean ± SD when normally distributed or as median (range) when not normally distributed. Results of the 3 methods of CO determination (2 UCOMS positions and TDCO) were then compared by use of the Spearman rank correlation test. Agreement and bias between pairs of methods were determined by use of the Bland-Altman method.[30] A repeated-measures linear regression model was used to assess the influence of individual dog responses on the overall correlation. Values of $P \leq 0.05$ were considered significant for all analyses.

Results

Doppler and 2-D echocardiograms did not reveal any structural cardiac abnormality in any of the 8 dogs. The mean ± SD aortic diameter measured by use of these methods was 1.35 ± 0.16 cm.

Signal acquisition with the UCOMS was possible from subxiphoid and thoracic-inlet probe locations in all dogs during all hemodynamic conditions. When the baseline concentration of isoflurane was used for anesthesia, systolic, mean, and diastolic arterial blood pressures were 90.9 mm Hg, 68.0 mm Hg, and 56.4 mm Hg,

Table 1—Mean ± SD values of hemodynamic variables measured by use of UCOMS and TDCO in 8 healthy Beagles anesthetized with 0.5% to 1.5% inhaled isoflurane (baseline) or 2.0% to 3.5% isoflurane (high isoflurane) or when treated with an IV infusion of a colloidal solution or dobutamine.

Variable	Baseline	High isoflurane	Colloidal solution	Dobutamine
TDCO (L/min)	2.07 ± 0.84*	1.80 ± 0.57	2.87 ± 0.75	6.20 ± 1.20
UCOMS SX (L/min)	2.10 ± 0.74	2.08 ± 0.75	2.94 ± 0.90	5.73 ± 1.73
UCOMS TI (L/min)	1.83 ± 0.82	2.16 ± 0.69	2.48 ± 0.81	5.67 ± 1.79
Heart rate (beats/min)	89 ± 19	92 ± 11*	111 ± 8	166 ± 19
Systolic BP (mm Hg)	90.9 ± 12.5	62.5 ± 10.5	98.5 ± 9.7	79.3 ± 22.2
Mean BP (mm Hg)	68.0 ± 9.4	47.0 ± 4.8	76.4 ± 9.1	60.3 ± 16.5
Diastolic BP (mm Hg)	56.4 ± 10.2	39.3 ± 5.9	65.4 ± 9.4	50.8 ± 14.2
Systolic PAP (mm Hg)	18.5 ± 3.3	16.5 ± 2.8	30.1 ± 2.0*	34.9 ± 6.7
Mean PAP (mm Hg)	10.4 ± 2.6	10.8 ± 2.1	24.8 ± 2.9	26.1 ± 3.8*
Diastolic PAP (mm Hg)	5.0 ± 3.2	6.1 ± 2.6	19.8 ± 3.7	19.6 ± 4.2*
CVP (mm Hg)	1.9 ± 1.6	3.4 ± 2.7*	14.3 ± 4.6*	8.3 ± 3.7
PCWP (mm Hg)	3.8 ±1.8	5.6 ± 1.3*	17.5 ± 2.2	12.5 ± 3.4

*Data were not normally distributed.

SX = Subxiphoid position. TI = Thoracic-inlet position. BP = Arterial blood pressure. PAP = Pulmonary arterial blood pressure. CVP = Mean central venous (right atrial) pressure. PCWP = Mean pulmonary capillary wedge pressure.

For those variables for which data were not normally distributed, the median (interquartile range) values were as follows: baseline TDCO, 1.80 L/min (1.67 to 1.97 L/min); high isoflurane heart rate, 85 beats/min (84 to 103 beats/min); colloidal solution systolic PAP, 30 mm Hg (30 to 31 mm Hg); dobutamine mean PAP, 26 mm Hg (24 to 28 mm Hg); dobutamine diastolic PAP, 20 mm Hg (16.5 to 23.5 mm Hg); high isoflurane CVP, 3 mm Hg (2 to 4 mm Hg); colloidal solution CVP, 17 mm Hg (10 to 17.5 mm Hg); and high isoflurane PCWP, 5 mm Hg (5 to 6.5 mm Hg).

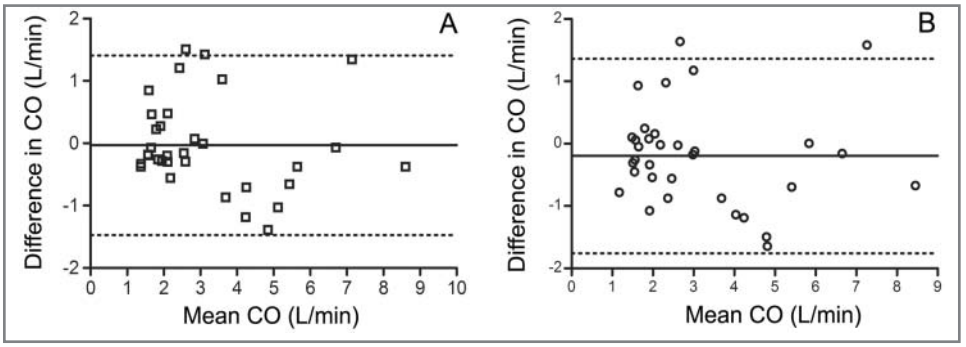

Figure 1—Bland-Altman plots of differences between overall mean CO in 8 healthy Beagles as measured with a UCOMS at 2 anatomic positions (subxiphoid [A] and thoracic inlet [B]) and a TDCO (gold standard) during various hemodynamic conditions. The horizontal line in the center of each graph represents the mean difference in CO (bias) between the methods, and the dashed lines above and below the center line represent the 95% limits of agreement. Bias for UCOMS measurements made at the subxiphoid position was –0.029 L/min (95% limits of agreement, –1.47 L/min to 1.41 L/min). Bias for the UCOMS measurements made at the thoracic-inlet position was –0.197 L/min (95% limits of agreement, –1.76 L/min to 1.36 L/min).

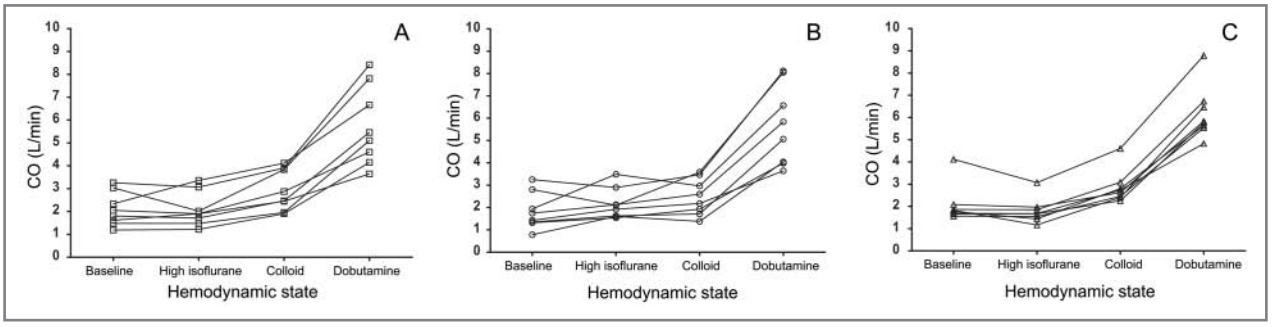

Figure 2—Mean CO in 8 healthy Beagles in 4 hemodynamic conditions (anesthetized with 0.5% to 1.5% inhaled isoflurane [baseline] or 2.0% to 3.5% isoflurane [high isoflurane] or when treated with an IV infusion of a colloidal solution [colloid] or dobutamine), as measured by use of a UCOMS at the subxiphoid probe position (A), a UCOMS at the thoracic-inlet probe position (B), and the TDCO (C).

respectively. These values decreased to 63.5 mm Hg, 47.0 mm Hg, and 39.3 mm Hg, respectively, when the isoflurane concentration was increased. The anesthetic increase yielded minimal changes in central venous pressure and pulmonary capillary wedge pressure, whereas infusion of a colloidal solution or dobutamine resulted in an alteration of hemodynamic values (**Table 1**). The mean (range) volume of colloidal solution infused was 500 mL (42 to 55 mL/kg) over 10 to 20 minutes. Right atrial blood pressure increased from a mean of 2 ± 2 mm Hg (range, 0 to 5 mm Hg) at baseline to 14 ± 5 mm Hg (range, 7 to 18 mm Hg) after infusion of the colloidal solution. Pulmonary capillary wedge pressure increased from a mean of 4 ± 2 mm Hg (range, 1 to 7 mm Hg) at baseline to 18 ± 5 mm Hg (range, 13 to 20 mm Hg) after infusion of the colloidal solution.

The UCOMS values for CO pooled over all treatment periods ranged from 1.19 L/min to 8.41 L/min for the subxiphoid position (mean, 3.18 ± 1.83 L/min) and from 0.78 L/min to 8.12 L/min for the thoracic-inlet position (mean, 3.01 ± 1.87 L/min). The TDCO values ranged from 1.17 L/min to 8.79 L/min (mean, 3.20 ± 1.94 L/min). At high heart rates (typically > 150 beats/min), the flow-tracing algorithm of the UCOMS did not accurately trace the Doppler signal and manual correction of the signal was required.

Measurements obtained by use of the UCOMS at the subxiphoid and thoracic-inlet positions were positively correlated ($\rho = 0.86$ and 0.83, respectively; $P < 0.001$) with TDCO values. The correlation between measurements obtained with the UCOMS at the 2 anatomic positions was also high ($\rho = 0.93$; $P < 0.001$). Results of the repeated-measures linear regression model suggested that the variable dog had little effect on the overall correlation coefficient, with 1 dog accounting for 2.8% of the correlation between the UCOMS subxiphoid position and the TDCO and 1 dog accounting for 1.3% of the correlation between the UCOMS thoracic-inlet position and the TDCO.

Bland-Altman analysis revealed minimal bias between values for CO obtained by use of the 2 UCOMS methods and the TDCO (bias for subxiphoid location, –0.03 ± 0.73 L/min; bias for thoracic-inlet location, –0.20 ± 0.80 L/min), with 95% limits of agreement of –1.47 to 1.41 L/min for measurements obtained at the subxiphoid location and –1.76 to 1.36 L/min for thoracic inlet (**Figure 1**). These limits of agreement correspond to a percentage error of ± 46% for the UCOMS subxiphoid method versus TDCO and ± 53% for the UCOMS thoracic-inlet method versus TDCO (percentage error = ± 2 SD of the bias/mean).[31,32] These values exceeded the 14% to 28% recommended for acceptance of a new CO monitoring method[31,32]; however, the mean CO from each hemodynamic state as measured by use of the UCOMS at subxiphoid and thoracic-inlet probe

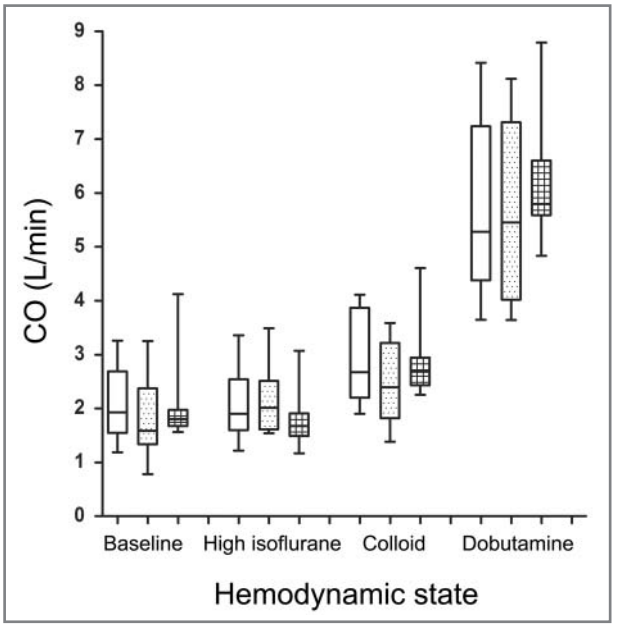

Figure 3—Box-and-whisker plots of CO in 8 healthy Beagles as measured by use of a UCOMS at 2 anatomic positions (subxiphoid [white boxes] and thoracic inlet [dotted boxes]) and a TDCO (gold standard; hatched boxes) in 4 hemodynamic conditions: anesthetized with 0.5% to 1.5% inhaled isoflurane (baseline) or 2.0% to 3.5% isoflurane (high isoflurane) or when treated with an IV infusion of a colloidal solution (colloid) or dobutamine. Boxes represent the interquartile range, the horizontal line within each box represents the median, and whiskers represent the range.

positions closely approximated the values obtained by use of TDCO (**Figures 2 and 3**; Table 1).

Discussion

The results of the present study suggested that a Doppler ultrasound-derived system for measuring CO (UCOMS) could be used in isoflurane-anesthetized dogs to quantify instantaneous blood flow and identify alterations in blood flow associated with changing hemodynamic conditions. However, when the measurements obtained by use of the UCOMS were compared with those of TDCO (gold standard), the percentage error was too high to recommend this device as a substitute for TDCO. Nevertheless, the correlation between the 2 methods was high when comparing all measured values, and the mean CO from each hemodynamic state as measured by use of the UCOMS at subxiphoid and thoracic-inlet probe positions closely approximated the values obtained by use of TDCO. Technologic differences in the manner in which UCOMS and TDCO are performed may be responsible for the discrepancies in absolute calculated CO values (ie, the moderate percentage error); alternatively, there may have been systematic errors that limited agreement between values yielded by the 2 measurement systems.

In Doppler echocardiographic examinations, the suprasternal imaging window provides optimal alignment of the ultrasound waves to ascending aortic blood flow and is used for the estimation of stroke volume in humans.[33] The same imaging window for the thorax of a dog may not be as useful because insonation and optimal Doppler alignment of ascending aortic blood flow in dogs with naturally developing aortic stenosis is best achieved from a subxiphoid imaging window.[34–36] There is also a relative difference in the size of the suprasternal notch in humans and dogs. We evaluated the performance of the UCOMS at the thoracic-inlet and subxiphoid probe positions, and although measurements obtained at both positions were comparable, values of CO obtained at the subxiphoid probe position appeared to have a bias closer to 0 and less wide limits of agreement. If the subxiphoid probe position was indeed superior to the thoracic-inlet position for measuring CO, that superiority may reflect better alignment of the ultrasound waves to aortic blood flow from the subxiphoid position.

Our findings contrast with those of another study[29] involving dogs, in which UCOMS measurements of CO made at the thoracic-inlet probe position were compared with measurements made with an ultrasonic flow probe placed on the ascending aorta. In that study, the 95% limits of agreement between the UCOMS and flow probe measurements were −0.34 L/min to 0.31 L/min (percentage error, ± 13%). This discrepancy may reflect inaccuracies in the TDCO measurements obtained in our study or differences in UCOMS techniques. It is likely that the ultrasonic flow probes of the other study recorded a more accurate CO given the known variability of TDCO. Such discrepancies between TDCO and UCOMS measurements have also been reported for humans in a postoperative critical care setting, with a percentage error of ± 52%.[37] Investigators in that study also concluded that the UCOMS technique could not be used to replace the TDCO in their population of patients; however, whether this lack of agreement was attributable to a failure of thermodilution or inaccuracies in the measurements obtained with the UCOMS remains uncertain.

In the present study, the discrepancy between measurements obtained by use of the UCOMS and TDCO may have reflected differences in the manner in which the 2 systems estimate CO. The TDCO provides a value for mean blood flow over several heart beats, whereas UCOMS measures the instantaneous or beat-to-beat CO. Determination of CO by use of the TDCO can be influenced by changes in lung temperature, rate of indicator injection, indicator temperature or volume, and mixing concerns attributable to the site of indicator injection (ie, right atrium vs right ventricle).[38,39] This is the reason several injections are made at each time point and only values that are within a stated degree of agreement with each other (usually 10% to 20%) are used to determine a mean CO value. The accuracy of the technique is enhanced by visual inspection of the thermodilution washout curve. Similarly, data from several heart beats can be displayed and averaged for each UCOMS measurement. An additional difference between the 2 techniques is the location at which the measurement is obtained. The TDCO measures CO from the right side of the heart, whereas the UCOMS measures CO from the left side of the heart. In stable conditions and over several beats, these 2 values should be equivalent. However, slight variation with respiration, cardiac volume, and relative pulmonary

and systemic vascular resistance may allow for slight variability in CO from both sides of the heart.

The UCOMS device has several potential limitations for use in dogs. All ultrasound-based systems require an adequate imaging window and, for accurate Doppler measurements, alignment of the ultrasound waves to blood flow. Variability in breeds and sizes of dogs may result in variability in the optimal imaging window for individual dogs. However, results of the present study indicated that the subxiphoid and thoracic-inlet imaging windows yielded comparable results in the Beagles evaluated. Additional studies are needed to characterize the optimal probe positions for dogs of various breeds, ages, and sizes. Additionally, use of the UCOMS requires a compliant subject for acquisition of useable signals. This need for compliance is the same for most emergency or intensive care diagnostic procedures, but fractious or unstable animals, particularly those with injury at the site of signal acquisition, may prevent accurate probe position and subsequent CO determination.

Another limitation is that the UCOMS technique requires knowledge of the aortic cross-sectional area to calculate CO. Nomograms based on body surface area are used in humans to estimate cross-sectional area,[40] although such formulae are unlikely to be applicable to dogs. Therefore, in the present study, measurement of the aortic annular diameter was performed in each dog by use of 2-D echocardiography. If nomograms were available for dogs, the need for this step would have been obviated. Formulae that allow determination of aortic diameter from a physical characteristic have been proposed for dogs,[41] but these formulae were based on M-mode echocardiographic measurements, which are unlikely to reflect the true minimal aortic cross-sectional area that is required to estimate CO from an aortic outflow velocity profile. A nomogram based on findings from 2-D echocardiography or postmortem examination is needed for dogs. Alternatively, trends in the stroke distance (area under the aortic velocity curve) may be used to monitor changes in CO because stroke distance correlates directly with left ventricular stroke volume, even if the aortic cross-sectional area and, subsequently, the absolute CO value may not be accurate.

Other means of minimally invasive CO monitoring in dogs have been reported. The lithium chloride dilution method, which is similar in concept to other indicator dilution techniques such as TDCO, is reportedly reliable and comparable to the TDCO method in dogs.[23] However, the lithium chloride dilution method requires arterial access and a blood withdrawal, both of which may be difficult to safely and effectively accomplish in small or hypovolemic dogs. There is also a greater cost associated with the lithium chloride dilution method, both in initial equipment and expendables, compared with the cost of a Doppler-ultrasound method. Bioimpedance as a means of measuring CO in dogs has also been reported.[21,22] That system makes use of an alternating electrical signal to calculate the impedance of blood flow through the thorax, which can be used to estimate stroke volume, CO, and other hemodynamic variables. In dogs, the bioimpedance method is not recommended because it overestimates CO at low values and underestimates CO at high values and has wide limits of agreement.[21,22] Other methods such as partial carbon dioxide rebreathing[22,24] and transthoracic[25] and transesophageal[22] echocardiography can be used to noninvasively measure CO in dogs, but these methods also have disadvantages that limit their clinical usefulness.

The present study had certain limitations. Namely, hemodynamic alterations in an anesthetized dog with normal cardiovascular function in a laboratory setting is not representative of those that would be expected in traumatized, septic, or otherwise impaired dogs in the emergency room, operating theater, or critical care unit. The TDCO was used as the gold standard for comparison in this study but is not 100% accurate.[38,39] The true value of CO at the time of each recording is unknown because measurements obtained by use of either method (UCOMS or TDCO) have potential error and variability.

Whereas the UCOMS cannot be used as a substitute for TDCO on the basis of the results reported here, the UCOMS may be useful, particularly in clinical settings in which TDCO is not commonly performed. Reasons include the noninvasive nature of the UCOMS, the ability to monitor changes in CO in various hemodynamic conditions, the ability to detect and measure beat-to-beat variation in stroke volume and CO, and the relative ease of use. The accuracy of the UCOMS for measurement of CO in dogs may be improved by optimization of the flow-tracing algorithm for the higher heart rate of dogs and inclusion of nomograms for the aortic cross-sectional area in dogs. Additional studies in hemodynamically compromised dogs with naturally occurring disease are needed to evaluate the clinical usefulness of the UCOMS.

a. USCOM Ltd, Sydney, NSW, Australia.
b. Morphine sulfate, Baxter Healthcare Corp, Deerfield, Ill.
c. Acepromazine maleate injection, Boehringer Ingelheim Vetmedica Inc, St Joseph, Mo.
d. GE Vivid 7 Dimension, GE Medical, Milwaukee, Wis.
e. PropoFlo, Abbott Laboratories, North Chicago, Ill.
f. Isoflurane, Abbott Laboratories, North Chicago, Ill.
g. Cefazolin for injection, USP, Sandoz Inc, Broomfield, Colo.
h. ChlorHex-Q, VEDCO, St Joseph, Mo.
i. Fast-Cath Hemostasis Introducer, St. Jude Medical, Minnetonka, Minn.
j. Edwards Swan-Ganz Thermodilution Catheter, Baxter Healthcare Corp, Irvine, Calif.
k. SJM Repositioning Sleeve, St. Jude Medical, Minnetonka, Minn.
l. LifePak 12, Medtronic, Minneapolis, Minn.
m. 9520A Cardiac Output Computer, American Edwards Laboratories, Irvine, Calif.
n. Harvard Apparatus Peristaltic Pump, model HA 66, Instech Laboratories Inc, Plymouth Meeting, Pa.
o. 6% Hetastarch in 0.9% sodium chloride, Hospira Inc, Lake Forest, Ill.
p. Dobutamine hydrochloride, Bedford Laboratories, Bedford, Ohio.
q. Furosemide, IVX Animal Health Inc, St Joseph, Mo.
r. Prolene, Ethicon Inc, Somerville, NJ.
s. Prism 4, GraphPad Software Inc, San Diego, Calif.
t. Sigma Stat, version 3.5, SPSS Inc, Chicago, Ill.
u. Microsoft Office Excel 2003, Microsoft Corp, Redmond, Wash.

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