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CARDIAC INDEX MEASUREMENTS BY TRANSCUTANEOUS DOPPLER ULTRASOUND AND TRANSTHORACIC ECHOCARDIOGRAPHY IN ADULT AND PEDIATRIC EMERGENCY PATIENTS

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ABSTRACT. Introduction. Non-invasive hemodynamic monitoring may facilitate resuscitation in critically ill patients. Validation studies examining a transcutaneous Doppler ultrasound technology, USCOM-1A, using pulmonary artery catheter as the reference standard showed varying results. In this study, we compared non-invasive cardiac index (CI) measurements by USCOM-1A with transthoracic echocardiography (TTE). **Methods.** This study was a prospective, observational cohort study at a university tertiary-care emergency department, enrolling a convenience sample of adult and pediatric patients. Paired measures of CI, stroke volume index (SVI), aortic outflow tract diameter (OTD), velocity time integral (VTI) were obtained using USCOM-1A and TTE. Pearson's correlation and Bland–Altman analyses were performed. **Results.** One-hundred and sixteen subjects were enrolled, with obtainable USCOM-1A CI measurements for 99 subjects (55 adults age 50 ± 20 years and 44 children age 11 ± 4 years) in the final analysis. Cardiac, gastrointestinal and infectious illnesses were the most common presenting diagnostic categories. The reference standard TTE measurements of CI, SVI, OTD, and VTI in all subjects were 3.08 ± 1.18 L/min/m^2, 37.10 ± 10.91 mL/m^2, 1.92 ± 0.36 cm, and 20.36 ± 4.53 cm, respectively. Intra-operator reliability of USCOM-1A CI measurements showed a correlation coefficient of $r = 0.79$, with $11 \pm 22\%$ difference between repeated measures. The bias and limits of agreement of USCOM-1A compared to TTE CI were 0.58 (-1.48 to 2.63) L/min/m^2. The percent difference in CI measurements with USCOM-1A was $31 \pm 28\%$ relative to TTE measurements. **Conclusions.** The USCOM-1A hemodynamic monitoring technology showed poor correlation and agreement to standard transthoracic echocardiography measures of cardiac function. The utility of USCOM-1A in the management of critically ill patients remains to be determined.

KEY WORDS. cardiac index, non-invasive hemodynamic monitoring, USCOM-1A, transcutaneous Doppler ultrasound, transthoracic echocardiography.

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INTRODUCTION

Hemodynamic monitoring is paramount in the management of critically ill patients. While the invasive determination of cardiac output (CO) using pulmonary artery catheterization and the thermodilution technique remains the traditional standard, controversies exist regarding its utility and safety [1]. A variety of minimally invasive hemodynamic monitoring technologies have been developed, which become attractive as alternative methods of

measuring cardiac output. These technologies include thoracic electrical impedance, transpulmonary thermodilution, lithium dilution, pulse contour analysis, echocardiography and esophageal Doppler ultrasound [2].

Recently, a non-invasive method of transcutaneous, continuous-wave Doppler ultrasound measurement of cardiac output was developed, USCOM-1A (Ultrasonic Cardiac Output Monitor, USCOM Ltd, Sydney, Australia). This technology utilizes transaortic or transpulmonary Doppler ultrasound flow tracing to calculate cardiac output as the product of stroke volume and heart rate. Stroke volume is calculated from a proprietary algorithm applying ultrasound principles of blood velocity–time integral measurements in the ventricular aortic outflow tract. Previous studies comparing USCOM-1A measurements of cardiac output to those obtained by standard thermodilution technique have shown mixed results [3–6]. However, in the clinical setting, the USCOM-1A technology has been used to assess cardiac side effects from chemotherapy drugs for the treatment of breast cancer [7], to assess fluid loading during spinal anesthesia prior to cesarean delivery [8], and to measure cardiac output and assess fluid and vasopressor therapy in hemodynamically unstable patients during air rescue [9].

With the increasing emphasis on early intervention for the critically ill patients, especially in the emergency department (ED), the utility of an easy-to-use, non-invasive hemodynamic monitoring technology becomes obvious [10]. Previously we have shown that the USCOM-1A technology has acceptable inter-rater *reliability* when used in the ED setting [11, 12]. To our knowledge, no study has examined the *accuracy* of this technology in the ED patients. In this study, we aim to compare cardiac index (cardiac output adjusted to body surface area) measurements by USCOM-1A to those obtained from transthoracic echocardiography (TTE) in adult and pediatric patients presenting to the ED.

METHODS AND MATERIALS

Study design

This was a prospective observational cohort study performed over a 3-month period, from February 1 to April 30, 2006, at an academic ED with approximately 65,000 annual patient visits. The study was approved by the Institutional Review Board (IRB) at our institution and was considered to be minimal risk to the subjects.

Inclusion criteria

A convenience sample of ED subjects greater than 1-year old was enrolled. Enrollment occurred 2 days per week when the study team was available. Subjects were approached by the investigator and the purpose of the study was explained. Verbal *consent* was obtained from adult subjects, greater than 18 years old, whereas verbal *assent* was obtained from pediatric subjects. Subjects unable to give verbal consent or assent, such as those with altered mental status, comatose, or sedated on mechanical ventilation, were enrolled with IRB approved waiver of consent and assent if an authorized representative was not available. Since we aimed to enroll subjects with a wide range of clinical presentations and cardiac output, no other inclusion criteria was necessary.

Exclusion criteria

Subjects with a medical history of congenital heart disease, or unable to tolerate the supine position for the duration of the study procedures were excluded from the study.

Study protocol and data measurements

After subject enrollment, the first set of hemodynamic parameters (USCOM-1A $_{\text{pre-TTE}}$) including cardiac index (CI), stroke volume index (SVI), aortic outflow tract diameter (OTD), velocity time integral (VTI) and heart rate (HR) were recorded by a trained operator. The same hemodynamic parameters were then measured with TTE by a certified echocardiographer within 15 min after the USCOM-1A measurements. TTE measurements were then verified by a cardiologist (RB). The average of three TTE measurements was recorded for data analysis. Both the echocardiographer and cardiologist were blinded to the USCOM-1A measurements. To evaluate the reproducibility (or intra-operator reliability) of USCOM-1A measurements, a second set of hemodynamic parameters (USCOM-1A $_{\text{post-TTE}}$) were then obtained by the same USCOM-1A operator within 15 min of the TTE measurements. The mean of pre-TTE and post-TTE USCOM-1A measurements was calculated for comparison with the (average of three) TTE measurements. All measurements were obtained with the subject in supine position.

Training of the USCOM-1A operator included operating the USCOM-1A device, obtaining measurements with the Doppler ultrasound probe placed at the subject's suprasternal notch, and recognition of an acceptable aortic cardiac profile. We utilized a previously defined set of

criteria for acceptable cardiac profiles obtained with the USCOM-1A [11, 13].

Cardiac index and stroke volume index

CI was calculated by the following equations:

1. CI = SVI × HR
2. SVI = stroke volume (SV)/body surface area
3. SV = aortic outflow tract area (πr^2) × stroke distance, or
4. SV = $\pi \times (OTD/2)^2 \times VTI$, where OTD is the aortic outflow tract diameter and VTI is the velocity time integral.

Outflow tract diameter

The USCOM-1A technology provided estimations of the aortic outflow tract diameter based on the patient's height and a proprietary nomogram (USCOM Ltd, Sydney, Australia). For TTE measurements, the aortic OTD was the diameter at the aortic valve annulus, measured directly by the echocardiographer via the parasternal long-axis view in *zoomed* mode.

Velocity time integral

Velocity time integral (VTI) was used to estimate the distance that a column of blood travels in one systolic stroke (or stroke distance) as measured by Doppler ultrasound signal. VTI measurements by the USCOM-1A technology were obtained using the continuous-wave technique, whereas VTI was obtained using the pulse-wave technique by TTE.

Heart rate

Heart rate (HR) measurements were obtained by USCOM-1A and TTE, rather than from physical exam or bedside telemetry monitor.

Measuring cardiac function with USCOM-1A

The USCOM-1A device includes a display monitor with touchscreen capability. The system also contains a central processing unit (CPU), a 20-gigabyte hard drive memory and a 2-h battery life (Figure 1). Connected to the monitor is a 2.2 MHz transducer with a diameter of 1.0 cm for acquisition of Doppler flow cardiac profiles in adults, pediatrics, infants and neonates. The monitor displays real-time, beat-to-beat data including 20 different cardiac parameters. For the purpose of this study, CI, SVI, VTI and HR are recorded and examined.

Fig. 1. The Ultrasonic Cardiac Output Monitor (USCOM-1A) with dimensions 3.1 cm height, 3.5 cm width, and 1.8 cm depth. The monitor weighs 5.4 kg, with a touchscreen interface display screen. Cardiac parameters measured by the system include peak velocity (Vpk), velocity time integral (VTI), heart rate (HR), minute distance (MD), ejection time percent (ET%), stroke volume (SV), stroke volume index (SVI), stroke volume variability (SVV), cardiac output (CO), cardiac index (CI), systemic vascular resistance (SVR), systemic vascular resistance index (SVRI), mean pressure gradient (Pmn), flow time (FT), flow time corrected (FTc), stroke work (SW), cardiac power (CPO), oxygen saturation (SpO_2), oxygen delivery (DO_2), and stroke volume saturation (SVS).

A cardiac profile is obtained by the operator placing the transducer at the subject's suprasternal notch, aiming the Doppler beam inferiorly and posterior to the sternum, and interrogating for transaortic flow across the aortic valve to measure left-sided cardiac parameters. Ultrasound transmission gel (Aquasonic 100, Parker Laboratories, Inc., Fairfield, New Jersey) is applied to the subject's skin prior to placing the transducer. Right-sided cardiac function can also be measured with the transducer placed on the parasternal border, and directing the beam across the pulmonary valve. In this study, we chose to only obtain left-sided cardiac measurements due to the ease of locating aortic flow at the sternal notch.

An acceptable cardiac profile must (1) be triangular shape, (2) display clear start and completion of systole, (3) have the highest and sharpest peak achievable, and (4) show signal filling in of the profile. Once the operator is

satisfied with the signal, three cardiac profiles are selected from the display for averaging by the internal USCOM-1A software to obtain one set of measurements.

Statistical analysis

Data were analyzed for all subjects, and also separately for adult and pediatric subgroups. As proposed by Critchley et al. for reporting results comparing cardiac output measurement techniques, the USCOM-1A and TTE paired measurements of CI, SVI, OTD, VTI and HR were compared using Bland–Altman (bias and limits of agreement) and percent difference analyses [14]. Percent difference was calculated by taking the absolute value of the difference between USCOM-1A and TTE measurements and dividing by the TTE measurement. The intra-operator reliability of the USCOM-1A measurements (USCOM-1A $_{\text{pre-TTE}}$ versus USCOM-1A $_{\text{post-TTE}}$) was also examined applying Pearson's correlation. All statistical analyses were performed using GraphPad Prism 4.0 or SPSS 13.0.

RESULTS

During the study period, 116 subjects were enrolled. In 17 subjects (6 adult and 11 pediatric), USCOM-1A measurements could not be obtained due to thick sternum, atrial fibrillation, or subject discomfort during placement of the Doppler ultrasound probe at the suprasternal notch. These subjects were excluded, and 99 subjects with age 33 ± 24 years were included in the final data analysis, resulting in an applicability of 85%. Fifty-five subjects were adult with age 50 ± 20 years, and 44 pediatric with age 11 ± 4 years. The most common diagnostic categories among the subjects were cardiac (21%), gastrointestinal (17%), and infectious (14%) related illnesses (Table 1).

Using TTE measurements as the reference standard, CI, SVI, OTD, and VTI in all subjects were 3.08 ± 1.18 L/min/m^2, 37.10 ± 10.91 mL/m^2, 1.92 ± 0.36 cm, and 20.36 ± 4.53 cm, respectively (Table 2). No patient had aortic valve disease as confirmed by pulse-wave TTE imaging.

The time interval between USCOM-1A measurements (USCOM-1A $_{\text{pre-TTE}}$ versus USCOM-1A $_{\text{post-TTE}}$) by the same operator in all subjects was 11 ± 10 min. USCOM-1A measurements of CI were 11 ± 22% different with Pearson's correlation of $r = 0.79$ when obtained by the same operator before and after TTE measurements (Table 2).

The bias (and limits of agreement) for CI measurements was 0.58 (−1.48 to 2.63) in all subjects; in adult and pediatrics, bias and limits of agreement were 0.27 (−1.21 to 1.76) and 0.96 (−1.46 to 3.37) L/min/m^2, respectively. Bland–Altman analyses for SVI, OTD, VTI and HR are further illustrated in Table 2 and Figure 2.

The percent difference in CI measurements with USCOM-1A was 31 ± 28% relative to TTE measurements;

Table 1. Subject characteristics

	Adult	Pediatric	All
No. subjects	55	44	99
Age (years)	50 ± 20	11 ± 4	33 ± 24
Height (cm)	169 ± 22	141 ± 30	157 ± 29
Weight (kg)	86 ± 30	44 ± 22	68 ± 34
MAP (mm Hg)	91 ± 16	85 ± 13	88 ± 15
Body surface area (m^2)	1.94 ± 0.35	1.29 ± 0.45	1.65 ± 0.51
Diagnostic category (%)			
Cardiac	18	3	21
Gastrointestinal	11	6	17
Infectious	2	12	14
Trauma	8	5	13
Neurologic	7	6	13
Respiratory	4	3	7
Hematologic	1	2	3
Metabolic	1	1	2
Other	5	6	11

MAP mean arterial pressure.

Table 2. USCOM-1A reliability and accuracy analyses with transthoracic echocardiogram (TTE) as reference standard

	Adult	Pediatric	All
CI (L/min/m^2)			
USCOM-1A	2.99 ± 1.13	4.50 ± 1.63	3.66 ± 1.56
TTE	2.72 ± 0.92	3.54 ± 1.32	3.08 ± 1.18
P value	<0.01	<0.01	<0.01
SVI (mL/m^2)			
USCOM-1A	40.94 ± 15.06	49.33 ± 12.69	44.67 ± 14.60
TTE	35.56 ± 11.25	39.02 ± 10.28	37.10 ± 10.91
P value	<0.01	<0.01	<0.01
OTD (cm)			
USCOM-1A	2.02 ± 0.13	1.71 ± 0.27	1.88 ± 0.25
TTE	2.11 ± 0.21	1.67 ± 0.36	1.92 ± 0.36
P value	<0.01	0.23	0.17
VTI (cm)			
USCOM-1A	23.68 ± 7.10	26.27 ± 6.24	24.81 ± 6.83
TTE	19.00 ± 3.92	22.11 ± 4.69	20.36 ± 4.53
P value	<0.01	<0.01	<0.01
Heart rate (bpm)			
USCOM-1A	75 ± 16	92 ± 23	82 ± 21
TTE	76 ± 15	88 ± 23	80 ± 19
P value	0.67	0.82	0.89
Intra-operator reliability of USCOM-1A CI measurements (pre- vs. post-TTE measurement)			
ΔTime (min)	11 ± 11	13 ± 6	11 ± 10
ΔCI (% difference)	9 ± 20	22 ± 24	11 ± 22
Pearson's *r*-value	0.84	0.70	0.79
Bland–Altman analysis, bias (limits of agreement)			
CI (L/min/m^2)	0.27 (−1.21 to 1.76)	0.96 (−1.46 to 3.37)	0.58 (−1.48 to 2.63)
SVI (mL/m^2)	5.38 (−16.10 to 26.86)	10.31 (−14.31 to 34.92)	7.57 (−15.74 to 30.88)
OTD (cm)	−0.09 (−0.44 to 0.26)	0.05 (−0.43 to 0.52)	−0.03 (−0.46 to 0.40)
VTI (cm)	4.95 (−6.09 to 16.0)	4.16 (−4.29 to 12.61)	4.60 (−5.37 to 14.58)
HR (bpm)	−0.22 (−17.78 to 17.34)	0.42 (−17.74 to 18.58)	−0.01 (−17.66 to 17.64)
Percent difference (%)			
CI	25 ± 22	41 ± 33	31 ± 28
SVI	28 ± 28	38 ± 30	32 ± 29
OTD	9 ± 13	10 ± 9	10 ± 12
VTI	31 ± 24	24 ± 16	28 ± 21
HR	8 ± 7	6 ± 8	7 ± 8

in adults and pediatrics, percent difference was 25 ± 22% and 41 ± 33%, respectively. CI measurements with USCOM-1A were consistently higher than TTE measurements (Table 2; Figure 3).

DISCUSSION

A patient presenting to the ED may not appear unstable based on his or her initial vital signs, such as heart rate and blood pressure [15]. Thus, a rapid and accurate method to measure hemodynamic parameters such as cardiac index can facilitate the early identification and resuscitation of critically ill patients in the ED. Several non-invasive to minimally invasive technologies have been introduced to meet this growing need. Identifying which technology provides efficient and reliable clinical data presents a tremendous challenge. Our study investigated the accuracy of a transcutaneous Doppler ultrasound technology, USCOM-1A, in measuring cardiac index compared to that obtained by the TTE technique. As a non-invasive hemodynamic monitoring technology, USCOM-1A has

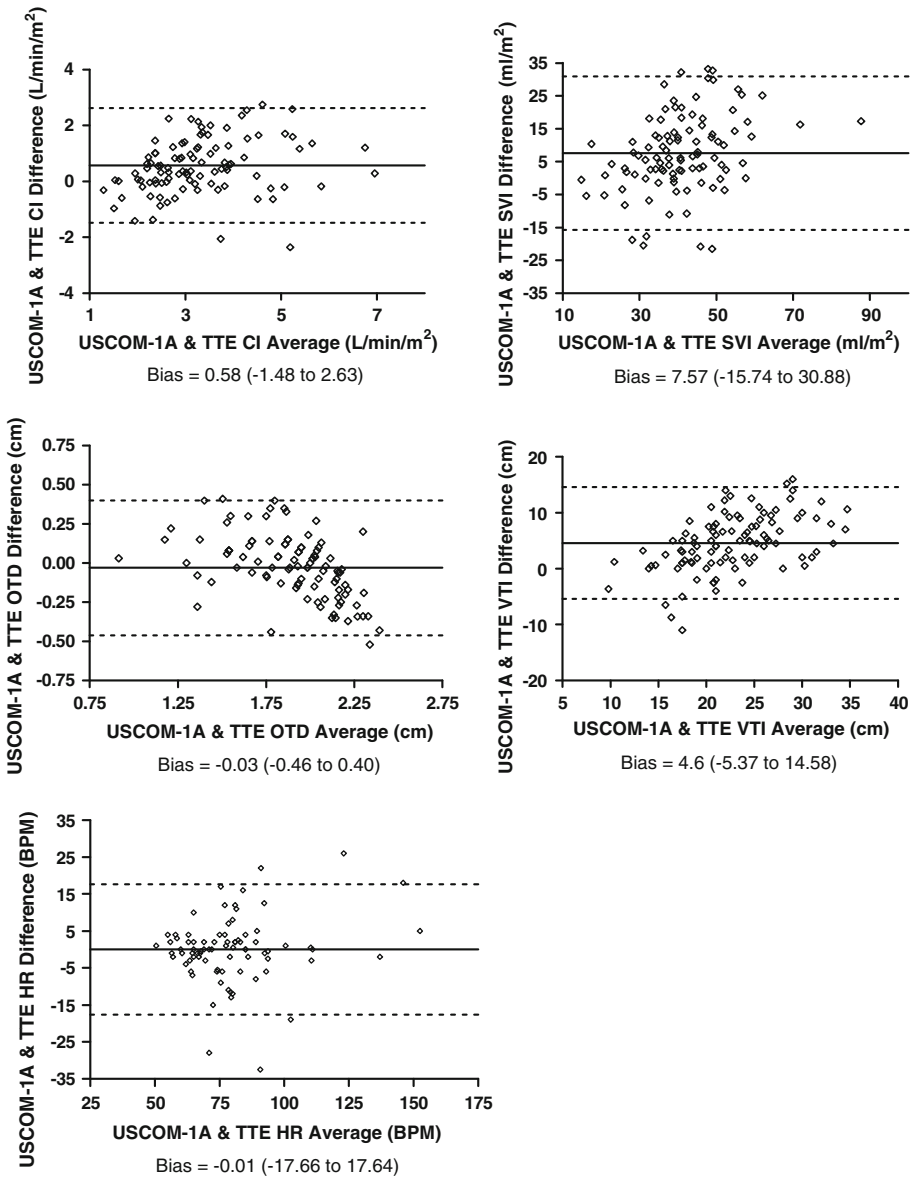

Fig. 2. Bland–Altman plots for cardiac index (CI), stroke volume index (SVI), aortic outflow tract diameter (OTD), velocity time integral (VTI), and heart rate (HR).

been applied in a variety of clinical settings with almost no risk to patients [8, 9, 16, 17]. A previous study showed that ED physicians having no prior ultrasonographic experience would require training with 20 patient assessments in order to obtain reliable USCOM-1A measurements [13]. In a busy clinical environment such as the ED or intensive care unit, nurses may possibly assist physicians by measuring cardiac index with USCOM-1A in approximately 10 min [18].

Our decision to use TTE as the reference standard to validate the USCOM-1A measurements was unique when compared to other studies that have relied on thermodilution to evaluate the accuracy of a new hemodynamic monitoring technology. However, the use of right heart catheterization and thermodilution technique as a reference standard has well known risks and complications that limit its applicability in the ED and in this study. Furthermore, comparison of left-sided cardiac

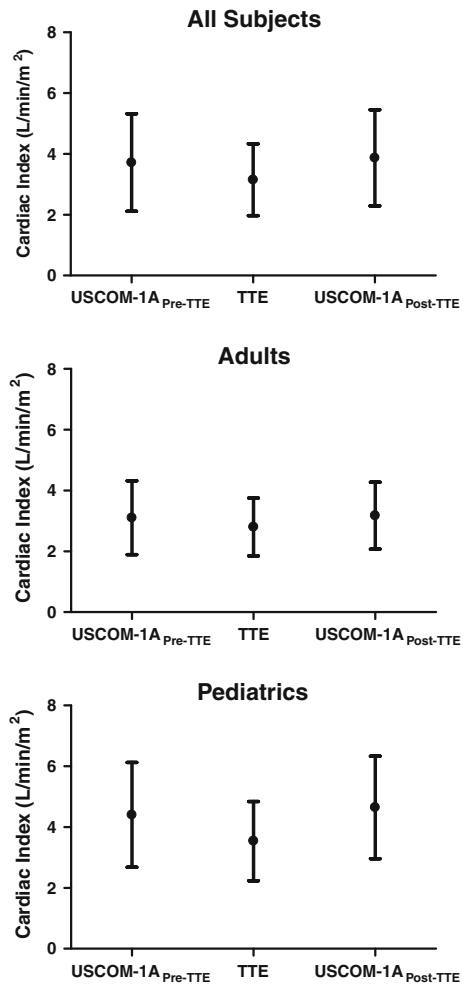

Fig. 3. Comparison of USCOM-1A cardiac index obtained pre- and post-transthoracic echocardiography (TTE) measurements. Data are plotted as mean ± standard deviation.

output derived from Doppler ultrasound measures of aortic flow against right heart indices provided by thermodilution has obvious inherent limitations, such as in patients with tricuspid regurgitation from pulmonary hypertension or end-stage left heart failure. Another potential reference standard is transesophageal echocardiography cardiac index measurement, which has previously been shown to have acceptable correlation and agreement when compared to thermodilution cardiac index [19]. However, transesophageal echocardiography is also not readily available in our ED setting, and not without associated risks and complications. Thus, our approach of comparing USCOM-1A transcutaneous Doppler ultrasound with TTE allowed us to validate left heart cardiac index in a feasible and practical manner.

Our results showed that cardiac index measurements from the USCOM-1A technology have moderate variability when compared to TTE measurements in both adult and pediatric subjects. Values obtained with USCOM-1A appeared to be higher than those measured with TTE. We also performed a simple PubMed search for studies validating the USCOM-1A technology, using the search term ''USCOM''. We identified thirty-seven articles meeting this search criterion. Two of the investigators (HBN and DPB) then reviewed the articles and selected those studies that compared USCOM-1A with a reference standard hemodynamic monitoring technology. Fifteen studies published from 2005 to April 1, 2010 were identified (Table 3). These studies compared USCOM-1A with thermodilution, orthotopic artificial heart, inert gas rebreathing, transesophageal echocardiography, ultrasonic flow probe, or cardiac magnetic resonance imaging in a variety of clinical settings including the animal lab. The *applicability* (or percent of subjects with successful USCOM-1A measurements obtainable in the study population) ranged from 77 to 100%. All studies included Bland–Altman analyses, showing a wide range of bias and limits of agreement (Figure 4). Percent difference in cardiac output (or cardiac index) measured by USCOM-1A compared to a reference standard ranged from 0.3 to 36%. Comparison of USCOM-1A with TTE cardiac index measurements in our current study of the ED setting should be evaluated in the context of these previous studies utilizing other modalities as the reference standard.

Our results and the results of previous studies suggest that the use of Doppler ultrasound to determine cardiac index has several inherent technological limitations. Potential sources of variation exist in the estimation of aortic outflow tract area, the determination of velocity–time integral as well as the variability with operator-dependent measurements. These limitations may discourage widespread use of this noninvasive method of CO determination. However, understanding the limitations may explain some of the results in our study. Cardiac index is calculated as the product of stroke volume index and heart rate. Stroke volume index is determined by measurement of the aortic outflow tract area and stroke distance. Using TTE, the aortic outflow tract area is determined by direct 2-dimensional measurement of the aortic outflow tract diameter performed by the echocardiographer. With USCOM-1A, the aortic outflow tract area is not directly measured, but calculated from a proprietary anthropometric algorithm based on the subject's body height [20]. Stroke distance is simply the distance a red blood cell travels per systolic stroke. This can be easily measured as the velocity time integral (VTI) of the Doppler flow profile of each systolic stroke. Thus, the accuracy of the USCOM-1A technology depends on obtaining accurate, reproducible VTI values. A precise VTI measurement requires a good flow signal and its

Table 3. Previous studies examining the accuracy of USCOM-1A compared to a reference standard

Study	Subjects/Setting	No. subjects	No. measurements	Applicability	Measure	Reference method	Bias (LOA)	% difference
Current study	Emergency department	99	99	85%	CI	Transthoracic echocardiogram	0.58 L/min/m^2 (−1.48 to 2.63)	31%
Trinkmann [30]	Heart disease	56	45	80%	CO	Cardiac magnetic resonance imaging	0.6 L/min (0.5 to 1.7)	21%
Thom [31]	Intensive care	89	250	95%	CO	Thermodilution	−0.09 L/min (−3.01 to 2.83)	19%
Corley [18]	Heart failure or pulm HTN	24	60	80%	CO	Themodilution	−0.34 L/min (−1.4 to 0.7)	9%
Phillips [32]	Heart failure	7	18	100%	CO	CardioWest (orthotopic artificial heart)	−0.01 L/min (−0.47 to 0.45)	0.3%
Van Lelyveld-Haas [6]	Medical and surgical intensive care	25	263	96%	CO	Thermodilution	−9% (−43 to 24)	17%
Saur [33]	Heart disease	63	63	86%	CO	Inert gas rebreathing	0.4 L/min (−0.6 to 1.4)	9%
Su [34]	Intraoperative liver transplantation	10	290	77%	CO	Thermodilution	−0.02 L/min (−1.06 to 1.10)	13%
Wong [4]	Intraoperative liver transplantation	12	71	86%	CO	Thermodilution	0.39 L/min (−1.47 to 2.25)	5%
Knirsch [3]	Pediatric patients with congenital heart disease	24	24	DNA	CO	Thermodilution	−0.13 L/min (−1.47 to 1.21)	36%
Van den Oever [35]	Cardiac surgery	22	22	95%	CO	Transesophageal echocardiogram	−0.79 L/min (−3.66 to 2.08)	DNA
Chan [5]	Post cardiac surgery	26	34	87%	CI	Thermodilution	0.22 L/min/m^2 (−1.17 to 1.62)	8%
Chand [36]	Post cardiac surgery	40	40	80%	CO	Thermodilution	−0.14 L/min (−0.39 to 0.11)	DNA
Tan [37]	Post cardiac surgery	22	40	92%	CO	Thermodilution	0.18 L/min (−1.43 to 1.78)	DNA
Knoblock [38]	Post cardiac surgery	36	180	DNA	CO	Thermodilution	−0.23 L/min (−2.52–1.79)	5%
Critchley [39]	Dogs	6	319	DNA	CO	Ultrasonic flow probe	−0.01 L/min (−0.34 to 0.31)	13%

Applicability represents the percent of subjects with successful USCOM-1A measurements obtainable in the study population. *CO* cardiac output, *CI* cardiac index, *OTD* outflow tract diameter, *LOA* limits of agreement, *DNA* data not available.

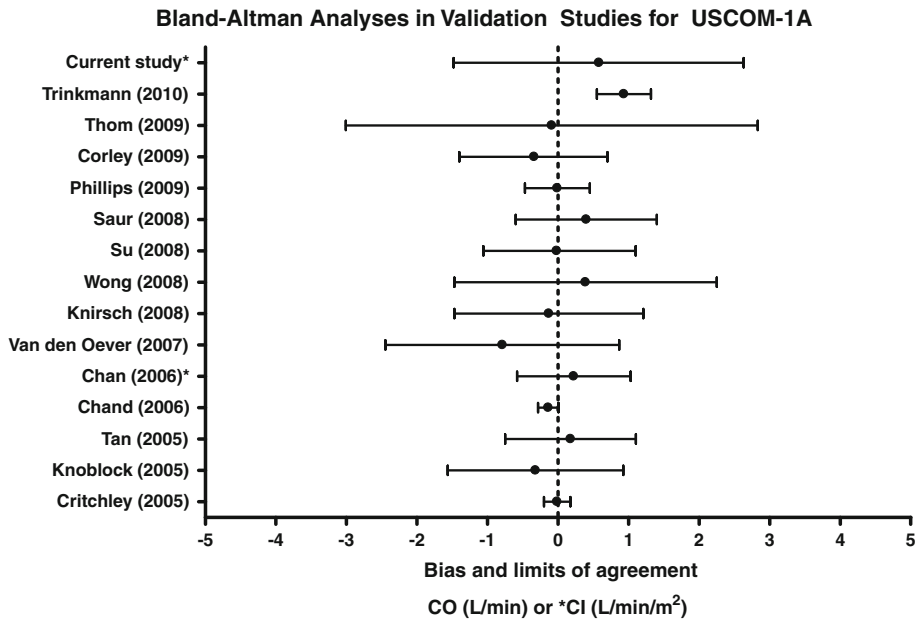

Fig. 4. Bias and limits of agreement determined by Bland–Altman analyses performed by previous authors comparing USCOM-1A to a reference standard.

correct interpretation, both of which are heavily dependent on the subject and the operator. An improper technique of poor Doppler ultrasound beam alignment with blood flow at the aortic outflow tract will lead to suboptimal VTI measurement. The current study and our previous study examining the inter-rater reliability of the USCOM-1A technology showed that 85% of subjects enrolled had acceptable Doppler signal for calculation of CI [11].

Patient positioning has also been shown to influence Doppler signal quality obtained by USCOM-1A [21]. The sitting position was found to be the least suitable and least reliable position in which to perform cardiac output measurements compared with the supine, Trendelenburg (20 degrees), left lateral tilt (20 degrees) and right lateral tilt (20 degrees) positions. Our study attempted to control for subject position-dependent Doppler signal quality by performing all USCOM-1A measurements in the supine position.

Operator variability is another potential source for the poor agreement in measurements between USCOM-1A and TTE. Both of these technologies are dependent on operator training and technical skill. We attempted to limit intra-operator variability by recording the average of three TTE values for each set of measurements performed by the echocardiographer. While we did not examine the intra-operator reliability of TTE measurements, the reproducibility of cardiac output measurements performed by TTE has been studied, with variability from 5 to 9% [22, 23]. For USCOM-1A measurements, we obtained two values (pre-TTE and post-TEE) for each set of measurements. To our surprise, the correlation between repeated USCOM-1A measurements by the same operator was less than desirable ($r = 0.79$), with 11% difference between 2 CI measurements obtained at a mean interval of 11 min apart.

Considering multiple sources of variability in measurements as discussed above, our USCOM-1A measurements of CI are higher than the reference TTE measurements, with an overall 31% difference. Critchley et al. utilized an error-gram to propose a difference of 30% or less in CI measurements as acceptable when comparing a new hemodynamic monitoring technique with the reference standard of thermodilution [14]. This 30% threshold for acceptability assumed 20% error in the test method and a similar 20% error in the reference standard. Assuming our reference TTE measurements had 10% error as suggested by previous studies, the USCOM-1A measurements would have an approximate 28% error, based on the error-gram proposed by Critchley et al. [14, 22, 23].

Our results showing that both pre-TTE and post-TTE USCOM-1A measurements are higher than TTE suggest that the difference between the two methods of measuring CI is due to their inherent technological differences, rather than operator variability or dynamic physiologic alterations in CI. The question then is: clinically, does this difference matter? Multiple authors have advocated the utility of *functional* hemodynamic monitoring in which changes in cardiac function in response to treatments are more important than single static measurements [24–26]. As such

the utility of USCOM-1A in various clinical settings examining CO responsiveness to fluid loading, drug therapy, cardiac resynchronization, and exercise has been studied [8, 9, 17, 27–29]. For example, Teoh et al. utilized USCOM-1A to examine the effect of colloid loading during spinal anesthesia [8]. They showed that intravascular expansion with hydroxyethyl starch given as preload, but not at the time of cerebrospinal fluid identification, increased maternal CO. Knobloch et al. also applied USCOM-1A during air rescue, showing that the technology can guide emergency physicians in assessing CO responsiveness after fluid and vasopressor therapies [9].

In conclusion, our study contributes to the body of literature comparing USCOM-1A to other methods of cardiac index measurements. We showed that USCOM-1A measures of cardiac index do not agree well with those obtained by standard transthoracic echocardiography. Several factors may explain these findings including variable Doppler measurements of velocity time integral, the geometric assumptions of aortic outflow tract area and operator technique variability. The utility of USCOM-1A in the management of critically ill patients remains to be determined.

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