Original Contribution

Measuring cardiac index with a focused cardiac ultrasound examination in the ED☆☆☆

Vi Am Dinh MDa, H. Samuel Ko MD, MBAa, Rajiv Rao BSD, Ramesh C. Bansal MD, FASEC, Dustin D. Smith MDa, Tae Eung Kim MDa, H. Bryant Nguyen MD, MSa,b,*

aDepartment of Emergency Medicine, Loma Linda University, Loma Linda, CA 92354, USA
bDepartment of Medicine, Division of Pulmonary and Critical Care, Loma Linda University, Loma Linda, CA 92354, USA
cDepartment of Medicine, Division of Cardiology, Loma Linda University, Loma Linda, CA 92354, USA
dSchool of Medicine, Loma Linda University, Loma Linda, CA 92354, USA

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Abstract
Objectives: Noninvasive technology may assist the emergency department (ED) physician in determining the hemodynamic status in critically ill patients. The objective of our study was to show that ED physicians can accurately measure cardiac index (CI) by performing a bedside focused cardiac ultrasound examination.

Methods: A convenience sample of adult subjects were prospectively enrolled. Cardiac index, left ventricular outflow tract (LVOT) diameter, velocity time integral (VTI), stroke volume index, and heart rate were obtained by trained ED physicians and a certified cardiac sonographer. The primary outcome was percent of optimal LVOT diameter and VTI measurements as verified by an expert cardiologist.

Results: One hundred patients were enrolled, with obtainable CI measurements in 97 patients. Cardiac index, LVOT diameter, VTI, stroke volume index, and heart rate measurements by ED physician were $2.42 \pm 0.70 \text{ L min}^{-1} \text{ m}^{-2}$, $2.07 \pm 0.22 \text{ cm}$, $18.30 \pm 3.71 \text{ cm}$, $32.34 \pm 7.92 \text{ mL beat}^{-1} \text{ m}^{-2}$, and $75.32 \pm 13.45 \text{ beats/min}$, respectively. Measurements of LVOT diameter by ED physicians and sonographer were optimal in 90.0% (95% confidence interval, 82.6%-94.5) and 91.3% (73.2%-97.6%) of patients, respectively. Optimal VTI measurements were obtained in 78.4% (69.2%-85.4%) and 78.3% (58.1%-90.3%) of patients, respectively. In 23 patients, the correlation ($r$) for CI between ED physician and sonographer was 0.82 (0.60-0.92), with bias and limits of agreement of $-0.11 \text{ L min}^{-1} \text{ m}^{-2}$ and percent difference of 12.4% ± 10.1%.

Conclusions: Emergency department ED physicians can accurately measure CI using standard bedside ultrasound. A focused ultrasound cardiac examination to derive CI has potential use in the management of critical ill patients in the ED.

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1. Introduction

Hemodynamic monitoring can facilitate the resuscitation of critically ill patients in the emergency department (ED) [1]. Clinically, however, ED physicians are often inaccurate
in determining the hemodynamic status of acutely ill patients [2]. The use of advanced hemodynamic monitoring can change physician assessment of patient hemodynamics and treatment [3]. In applying any hemodynamic monitoring technique, cardiac index (CI) is considered the reference standard parameter for targeting organ perfusion and oxygen delivery in shock [4]. Insertion of a pulmonary artery catheter (Swan-Ganz) is traditionally required to calculate CI by thermodilution [5]. Besides being invasive, potential complications of pulmonary artery catheter placement include infection, arterial puncture, arrhythmias, pneumothorax, hemothorax, and pulmonary artery rupture [6,7]. Recently, there has been an increased interest in the development of noninvasive to minimally invasive technologies to measure CI, such as the use of pulse contour analysis, lithium dye dilution, electrical bioimpedance, and transesophageal and transthoracic echocardiography with pulsed or continuous wave Doppler ultrasound [8]. Many of these technologies are expensive and unavailable in most EDs. However, bedside transthoracic echocardiography with pulsed-wave Doppler ultrasound, or focused cardiac ultrasound, is noninvasive, commonly available, and emerging as a promising noninvasive technique for measuring hemodynamic parameters [9,10].

Emergency department physicians are able to effectively perform bedside focused cardiac ultrasound to assess pericardial effusion, left ventricular function, and cardiac standstill [11-13]. A review of the cardiology literature shows that echocardiography is a reliable method for measuring CI [14-17]. To our knowledge, no previous study has examined the ability of ED physicians in measuring CI using echocardiography. The objective of our study was to determine the accuracy of CI measurements by ED physicians performing a bedside focused cardiac ultrasound examination with technology available in the ED.

2. Methods

2.1. Study design and setting

This was a prospective observational cohort study performed during a 5-month period, February 1 to June 30, 2011, at an academic ED with approximately 63,000 annual patient visits. The study was approved by the institutional review board at our institution and was considered to present minimal risk to the subjects.

2.2. Training

Before study enrollment, 2 ED physicians (V.A.D., H.S.K.) were trained to measure CI using the ultrasound system Z. One Ultra, equipped with the 4-MHz phased-array probe P4-1c (Zonare Medical Systems, Inc, Mountainview, CA). Training of each ED physician included 20 total hours of hands-on instructions by a certified cardiac sonographer. Training involved acquiring adequate images with parasternal long-axis and apical 5-chamber views. The ED physicians also learned how to use the cardiac software on the Z. One Ultra system to measure left ventricular outflow tract (LVOT) diameter and velocity time integral (VTI). These are necessary parameters to calculate CI (see later).

2.3. Patient selection

A convenience sample of ED patients older than 18 years were enrolled. Enrollment occurred approximately 5 days per month when the study team was available. Patients were approached by an investigator, and the purpose of the study was explained. An informed consent was obtained, with written consent provided by a legal representative for patients unable to give consent, such as those with altered mental status, comatose, or sedated on mechanical ventilation. Patients with a medical history of congenital heart disease, aortic valvular disease, inability to lie supine, or inability to lie in the left lateral decubitus position throughout the duration of the study procedure were excluded.

2.4. Study protocol and data measurements

After patient enrollment, physiologic and clinical data were recorded, including weight, height, and chief concern. A set of hemodynamic parameters was then obtained by a trained ED physician using cardiac ultrasound. Parameters included were LVOT diameter, VTI, and heart rate (HR). For a selected number of patients, the sonographer obtained the same set of hemodynamic parameters directly following and

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Rating of ultrasound images to measure LVOT diameter and VTI: optimal, suboptimal, and unobtainable</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Optimal LVOT</strong></td>
<td>Horizontally lined image with clear definition of anterior and posterior limits of LVOT with correct placement of the caliper points</td>
</tr>
<tr>
<td><strong>Suboptimal LVOT</strong></td>
<td>Image may be angulated or anterior, and posterior limits of LVOT are not completely clear. However, measurements were still usable.</td>
</tr>
<tr>
<td><strong>Unobtainable LVOT</strong></td>
<td>Completely unobtainable images of parasternal long-axis view with unmeasurable LVOT</td>
</tr>
<tr>
<td><strong>Optimal VTI</strong></td>
<td>Clear apical 5-chamber view with proper alignment of the pulse Doppler sample volume parallel to the aortic flow with minimal spectral broadening</td>
</tr>
<tr>
<td><strong>Suboptimal VTI</strong></td>
<td>Pulse Doppler sample volume not completely parallel to flow but within 20°-30° or with excessive spectral broadening</td>
</tr>
<tr>
<td><strong>Unobtainable VTI</strong></td>
<td>Completely unobtainable images of apical 5-chamber view or extremely large pulsed-wave Doppler angle to flow</td>
</tr>
</tbody>
</table>
blinded to the ED physician measurements. All ultrasound images obtained by the ED physician and sonographer were stored and then verified by a cardiologist (R.C.B.) using a scale to rate the acceptability of the ultrasound measurements (Table 1).

2.5. Cardiac index calculation by focused cardiac ultrasound

The 2 parameters required to calculate CI are the LVOT diameter and the VTI. The LVOT diameter is the diameter of the aortic outflow tract, which can be calculated by obtaining a parasternal long-axis view (Fig. 1). The measurement is obtained by measuring the distance from the inner edge to inner edge, where the right aortic valve coronary cusp meets the interventricular septum to where the noncoronary cusp meets the anterior mitral valve leaflet, in a line parallel to the aortic annulus. Velocity time integral is an estimation of the distance that a column of blood travels in 1 systolic stroke, or stroke distance. Using ultrasound, the VTI can be measured by obtaining an apical 5-chamber view and then placing a pulsed-wave Doppler cursor near the aortic valve annulus (Fig. 2). The Doppler signal is then traced using the cardiac software to calculate VTI.

After obtaining the LVOT diameter and VTI, CI can be calculated from the following equation: 

\[ CI = \frac{SVI \times HR}{\text{body surface area}} \]

where \( SVI = \frac{SV}{\text{body surface area}} \) and \( SV = \frac{\pi \times (LVOT \text{ diameter}/2)^2 \times VTI}{\text{stroke distance}} \). Heart rate is calculated by the ultrasound cardiac software during the VTI measurements, rather than from physical examination or bedside telemetry monitor.

2.6. Outcome

The primary outcome measured was percentage of optimal LVOT diameter and VTI measurements as verified by an expert cardiologist to confirm the technical adequacy of the calculated CI measurements. Table 1 illustrates our ratings of optimal, suboptimal, and unobtainable LVOT diameter and VTI measurements. The secondary outcome was interrater variability of CI between the ED physician and sonographer.

2.7. Statistical analysis

Descriptive analysis was performed for all subjects. The interrater reliability of ultrasound measurements by the emergency physicians and sonographer was calculated using percent difference, \( \kappa \), Pearson correlation, and Bland-Altman analysis. For determining \( \kappa \), normal CI was defined as 2.5 to 4.0 \( \text{L min}^{-1} \text{m}^{-2} \), with values outside this range being abnormal. Data are presented as mean ± SD or with 95% confidence intervals. All analyses were performed using R-statistics (v2.13.1, R Development Core Team, R Foundation, Vienna, Austria).

3. Results

One hundred patients were enrolled in the study, with ages of 51 ± 20 years and 50% being female. The most...
common diagnostic categories, with respect to chief concern, were cardiac (30%), gastrointestinal (18%), musculoskeletal (16%), and neurologic (9%) (Table 2).

All patients had LVOT diameter measurable by ED physician; however, VTI measurements were unobtainable in 3 patients due to body habitus or because the patient did not tolerate the examination. Twenty-three patients had LVOT diameter and VTI measurements performed by the sonographer within 10 minutes after the ED physician had completed the examination. Verification from the expert cardiologist showed optimal LVOT diameter measurements in 90.0% and 91.3% of patients by ED physician and sonographer, respectively (Table 3). Optimal VTI measurements by ED physician and sonographer were 78.4% and 78.3%, respectively. There was no statistical difference in cardiologist rating of LVOT diameter or VTI measurements between ED physician and sonographer.

Cardiac index, LVOT diameter, VTI, SVI, and HR measurements by ED physician were $2.42 \pm 0.70 \text{ L min}^{-1} \text{ m}^{-2}$, $2.07 \pm 0.22 \text{ cm}$, $18.30 \pm 3.71 \text{ cm}$, $32.34 \pm 7.92 \text{ mL beat}^{-1} \text{ m}^{-2}$, and $75.32 \pm 13.45 \text{ beats/min}$, respectively (Table 4). The percent difference between ED physician and sonographer for CI measurements was $12.4\% \pm 10.1\%$, with $\kappa = 0.56$ and correlation coefficient of $r = 0.82$ ($P < .01$; Fig. 3). The bias and limits of agreement for CI between ED physician and sonographer was $-0.11 (-1.06$ to $0.83)$ L min$^{-1}$ m$^{-2}$ (Fig. 4).

4. Discussion

Our study shows that CI can be measured by ED physicians using standard available ultrasound technology. After a training period of 20 hours, there was no statistical difference between the ability of the ED physicians to obtain LVOT diameter and VTI measurements as compared with a certified cardiac sonographer. Our training protocol is comparable with other studies examining focused cardiac ultrasound in the ED [11-13]. However, we specifically showed that ED physicians with limited ultrasound training can accurately measure CI.

We were unable to calculate CI in 3 patients due to unobtainable VTI measurements, resulting in an applicability of 97% with ultrasound CI measurements performed by ED physicians. The cardiologist (R.C.B.), who verified the measurements by both ED physicians and sonographer, has significant expertise in echocardiography having developed one of the first protocols for 2-dimensional echocardiographic examination [18]. Thus, we believe that our results are highly valid with respect to the accuracy of our measurements.

Our study also showed that CI measurements between ED physicians and a sonographer had acceptable correlation. Measurements of LVOT diameter and VTI had similar intrarater reliability compared with the reliability of cardiac dimensions measured by other trained sonographers [19]. The measurements by the ED physician slightly underestimated CI relative to sonographer measurements with no statistical difference. However, the percent difference in SVI measurements between ED physician and sonographer is similar to the variability in stroke volume obtained by 2

### Table 2 Patient characteristics

<table>
<thead>
<tr>
<th>Total no. of subjects</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (y)</td>
<td>$51 \pm 20$</td>
</tr>
<tr>
<td>Male/Female, no.</td>
<td>50:50</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>$170 \pm 11$</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>$81 \pm 45$</td>
</tr>
<tr>
<td>BMI (kg/m$^2$)</td>
<td>$17.7 \pm 5.9$</td>
</tr>
<tr>
<td>BSA (m$^2$)</td>
<td>$1.92 \pm 0.28$</td>
</tr>
<tr>
<td>Diagnostic category, no, % (95% CI)</td>
<td></td>
</tr>
<tr>
<td>Cardiac</td>
<td>30, 30.0 (21.9-39.6)</td>
</tr>
<tr>
<td>Gastrointestinal</td>
<td>18, 18.0 (11.7-26.7)</td>
</tr>
<tr>
<td>Respiratory</td>
<td>7, 7.0 (3.4-13.8)</td>
</tr>
<tr>
<td>Neurologic</td>
<td>9, 9.0 (4.8-16.2)</td>
</tr>
<tr>
<td>Endocrine</td>
<td>3, 3.0 (1.0-8.5)</td>
</tr>
<tr>
<td>Musculoskeletal</td>
<td>16, 16.0 (10.1-24.4)</td>
</tr>
<tr>
<td>Infectious</td>
<td>8, 8.0 (4.1-15.0)</td>
</tr>
<tr>
<td>Hematologic</td>
<td>3, 3.0 (1.0-8.5)</td>
</tr>
<tr>
<td>Other</td>
<td>6, 6.0 (2.8-12.5)</td>
</tr>
</tbody>
</table>

Data are presented as mean ± SD or as proportion with 95% CI. BMI, body mass index; BSA, body surface area; CI, confidence interval.

### Table 3 Expert cardiologist rating of cardiac ultrasound images, obtained by ED physician and sonographer, required to compute CI, including LVOT and VTI

<table>
<thead>
<tr>
<th>Operator</th>
<th>Cardiologist rating</th>
<th>Total no. of subjects</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No. of subjects, % (95% confidence interval)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Optimal</td>
<td>Suboptimal</td>
</tr>
<tr>
<td>ED physician</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LVOT</td>
<td>90, 90.0 (82.6-94.5)</td>
<td>7, 7.0 (3.4-13.8)</td>
</tr>
<tr>
<td>VTI</td>
<td>76, 78.4 (69.2-85.4)</td>
<td>15, 15.5 (9.6-24.0)</td>
</tr>
<tr>
<td>Sonographer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LVOT</td>
<td>21, 91.3 (73.2-97.6)</td>
<td>0, 0.0 (0.0-14.3)</td>
</tr>
<tr>
<td>VTI</td>
<td>18, 78.3 (58.1-90.3)</td>
<td>4, 17.4 (7.0-37.1)</td>
</tr>
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</table>
independent cardiologists [20]. Variability in CI measurements based on VTI has also been described because VTI measurement itself is dependent on the operator angle of the pulsed-wave Doppler [21-22]. In addition, CI variability may be affected by the physiologic fluctuations in stroke volume rather than solely by technical differences between operators.

A number of studies since the 1980s have shown that CI measurements by transthoracic echocardiography have a high correlation with thermodilution CI measurements obtained by pulmonary artery catheterization, with a correlation coefficient up to 0.96 [23-27]. Cardiac index determined by the LVOT A number of studies have shown a high correlation between CI measurements obtained by transthoracic echocardiography and thermodilution CI measurements obtained by pulmonary artery catheterization.

### Table 4: Hemodynamic measurements of all patients obtained by ED physician and paired measurements obtained by both ED physician and sonographer

<table>
<thead>
<tr>
<th>All patients (N = 97), ED physician</th>
<th>Patients with paired measurements by both ED physician and sonographer (n = 23)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>ED physician</td>
</tr>
<tr>
<td>CI (L min^{-1} m^{-2})</td>
<td>2.42 ± 0.70</td>
</tr>
<tr>
<td>LVOT (cm)</td>
<td>2.07 ± 0.22</td>
</tr>
<tr>
<td>VTI (cm)</td>
<td>18.30 ± 3.71</td>
</tr>
<tr>
<td>SVI (mL beat^{-1} m^{-2})</td>
<td>32.34 ± 7.92</td>
</tr>
<tr>
<td>HR (beats/min)</td>
<td>75.32 ± 13.45</td>
</tr>
</tbody>
</table>

LOA: limits of agreement.
Doppler ultrasound method has been shown to be both sensitive and specific in identifying the cause of shock in critically ill patients [28]. We observed that the limiting factor in our ultrasound image acquisition was obtaining the apical 5-chamber view, required to measure VTI. Accordingly, our results showed a lower percentage of optimal VTI images compared with optimal LVOT images obtained by either ED physician or sonographer.

Important to shock resuscitation is an end point that will reflect fluid responsiveness. This end point will guide the decision to administer more fluids or, alternatively, initiate vasoactive therapy to maintain blood pressure and organ perfusion. Traditionally, an increase in CI of greater than 15% after a fluid challenge has been considered the optimal end point reflecting fluid responsiveness. When CI does not increase in response to fluid therapy aimed at increasing preload, cardiac contractility has reached a plateau and further fluid resuscitation can be deleterious, resulting in volume overload and pulmonary edema. This fundamental tenet of shock resuscitation is based on Starling’s [29] law of the heart. Thus, a change in CI after a fluid bolus is often used as the reference standard when validating other indicators of fluid responsiveness, such as central venous pressure, stroke volume variation, passive leg raise, and inferior vena caval index [30-33]. Among these, the caval index, or the change in the inferior vena cava diameter with inspiration, observed by ultrasound has been advocated as a noninvasive indicator of volume status [34]. However, the caval index is a surrogate for central venous pressure, which numerous studies already have shown not to be a reliable measure of fluid responsiveness [30,35]. Other cardiac function parameters obtainable from ultrasound include ejection fraction, fractional shortening, and E-point septal separation; but none of these have been validated as a measure of fluid responsiveness or end point of resuscitation [10]. The ability to measure CI as a guide to resuscitation is ideal because it is the reference standard that other volume indicators are based on [4].

Clinicians commonly use mean arterial pressure (MAP) as an end point for fluid resuscitation. However, MAP is proportional to the product of cardiac output and systemic vascular resistance (SVR), MAP = cardiac output × SVR. In shock, MAP may be normal due to the increase in SVR by endogenous mechanisms to compensate for the decreased preload. Targeting a normal MAP during resuscitation may result in CI still being suboptimal and persistent organ hypoperfusion. For example, in a hemorrhagic shock model, blood loss up to 30% can maintain normal blood pressure. Beyond this point, the compensatory increase in SVR is exhausted and the fall in blood pressure is accelerated, resulting in rapid cardiovascular collapse and death [36]. Furthermore, knowing CI may assist the ED physician in determining the etiology of shock. For example, if CI is low and MAP is low, then cardiogenic shock may have occurred with an elevated vascular resistance. Many patients, of course, will fall into an indeterminate category in which trending CI measurements, in conjunction with other hemodynamic monitoring methods, may be additionally valuable in the diagnosis and resuscitation of shock.

There are inherent disadvantages of using ultrasound to measure CI. The equation to calculate CI with ultrasound assumes that LVOT is a circle. Anatomically, however, LVOT varies in shape by each individual. In addition, VTI measurement is dependent on the angle at which the pulse Doppler waveform is obtained. Lastly, adequate cardiac views may be difficult to obtain in daily practice due to patient body habitus and position. Our results showed that despite these limitations, CI measurements were similar between ED physicians and sonographer, with a significant number of measurements determined as optimal by the cardiologist.

The availability of the sonographer was limited, and we were only able to compare ED physician and sonographer CI measurements in 24% of the patients. However, we believe that this number of patients is an adequate representation of the ED physicians’ ability to reliably measure CI, especially with the cardiologist verifying the measurements performed in all patients by both the ED physicians and sonographer. Our study was performed in an academic institution with a formal ultrasound training curriculum; thus, the results may not yet be generalizable to other settings. We examined the ability to measure CI by 2 motivated ED physicians after 20 hours of training; thus, we do not know if our results in a convenience sample can be reproducible by other ED physicians in our group or at other institutions. However, our experience will be precedence for further studies examining ED physician measurements of CI by a focused cardiac ultrasound examination.

As hospital overcrowding continues to worsen, critically ill patients will remain longer in the ED. Thus, it is becoming more important that the ED physician has the adequate tools to recognize and intervene early in those patients who are potentially hemodynamically compromised. Echocardiography has been used for hemodynamic monitoring for years by cardiologists. The use of bedside cardiac ultrasound as a hemodynamic monitoring device by noncardiologists is continuing to evolve [9]. Our study showed that CI can be measured by ED physicians with ultrasound technology available in the ED and can, therefore, potentially be used in the management of critically ill patients.

**Acknowledgment**

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References

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