Cardiac Output Calculation and Three-Dimensional Echocardiography

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Objective: To compare the determination of stroke volume (SV) and cardiac output (CO) using 2-dimensional (2D) versus 3-dimensional (3D) transesophageal echocardiography (TEE).

Design: Prospective observational study.

Setting: Tertiary care university hospital.

Participants: 35 patients without structural valve abnormalities undergoing isolated coronary artery bypass grafting.

Interventions: Left ventricular outflow tract (LVOT) diameter determined with 2D TEE was used to estimate LVOT cross-sectional area (CSALVOT). LVOT area was measured directly with 3D TEE by planimetry on an en face view. SV and CO were calculated for both methods using the continuity equation.

TRANSESOPHAGEAL ECHOCARDIOGRAPHY (TEE) can be used to calculate cardiac output (CO) in the perioperative setting. An accurate measurement of the left ventricular outflow tract (LVOT) diameter is integral to this calculation. In the first step, a multiple of the cross-sectional area (CSA) of the LVOT (CSALVOT) and velocity time integral (VTI) of the LVOT is used to estimate the stroke volume (SV). This is then multiplied with the patient’s heart rate (HR) to estimate the CO. Intraoperatively, using 2-dimensional (2D) echocardiography, CSALVOT is estimated by measuring the LVOT diameter in the midesophageal long-axis view (ME-LAX). This calculation is based on the assumption of a circular shape of the LVOT and that a single diameter can be used to provide an accurate estimate of its area. It is now established that the LVOT is not circular but elliptical in a significant proportion of patients, with major and minor axes. Depending on which single diameter is used (ie, major or minor), LVOT area estimation possibly can be under- or overestimated. During 2D TEE examination, the ME-LAX view displays the minor axis of the LVOT. Therefore, LVOT area calculations based on the minor axis potentially can lead to underestimation of LVOT area and are, therefore, the source of most errors. The underestimation of CSA of the LVOT because of the use of a single 2D diameter has been found to introduce errors in estimation of aortic valve area (AVA).  

Because of the popularity of percutaneous aortic valve replacement, the anatomy of the LVOT and aortic root has been studied extensively with 3-dimensional (3D) imaging. As a result, it is now established that the use of the 2D-obtained minor axis diameter alone leads to underestimation of true CSA of the LVOT. Subsequently, this underestimation of CSA of the LVOT leads to overestimation of the severity of aortic stenosis (AS) by the continuity equation. Because the calculation of CO by echocardiography is based on the same principle, it is quite possible that estimation of CO also is affected by the erroneous assumption of the circular shape of the LVOT. Clinical availability of 3D echoangiographic data and multiplanar reformating have made it feasible to incorporate the quantitative aspects of these data into hemodynamic calculations. Because they are devoid of geometric assumptions, it is also possible that use of 3D quantitative data would improve accuracy of hemodynamic calculations. Therefore, the authors' main objective was to measure and compare the CO calculated with CSA of the LVOT derived from 2D-obtained diameter of the LVOT with 3D planimetered LVOT area using real-time 3D TEE in patients undergoing cardiac surgery.

MATERIAL AND METHODS

The study was conducted as part of an ongoing Institutional Review Board (IRB) protocol of intraoperative echocardiographic data collection with waiver of informed consent. Routinely collected intraoperative echocardiographic data (2D and 3D) of patients undergoing elective cardiac surgery were analyzed for this study. The authors used echocardiographic data from patients who had undergone isolated coronary artery bypass graft (CABG) surgery with intraoperative 3D TEE between March 2011 and February 2012. Patients who underwent emergency procedures, combined procedures (eg, CABG and mitral and tricuspid valve repair or replacement, aortic valve, or ascending aortic surgery), as well as those who did not have an intraoperative 3D TEE, were excluded from the study.

A single experienced echocardiographer (FM) collected all the intraoperative 3D data. The geometric reconstruction and analysis of the LVOT was performed post hoc in the echocardiography laboratory by an investigator (MM) who was blinded to the intraoperative values. The authors previously have noted good reliability of multiple assessments comparing both intra- and interobserver correlation. Intraoperative TEE examinations were performed with a Philips iE-33 ultrasound system and an X7-2t probe (Philips Healthcare, Andover, MA) after induction of general anesthesia and before institution of cardiopulmonary bypass. A comprehensive 2D exam

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was performed according to the guidelines. Stroke volume calculation was performed using CSA_{LVOT} \times VTI_{LVOT}. CSA_{LVOT} was calculated with 2D and 3D images.

In the 2D method, the LVOT diameter was measured in the 2D MELAX view using the zoom function 1 cm from the insertion of the aortic leaflets in mid-systole. The machine software automatically derived the LVOT area (m²). The velocity time integral (VTI) through the LVOT was obtained and traced using pulse-wave Doppler in the deep transgastric window with optimal Doppler alignment and the sample volume located in a similar position to the one used for LVOT diameter measurement. SV was calculated as VTI_{LVOT} \times CSA_{LVOT}, and CO as SV \times HR. The heart rate was noted to use the same value for the 3D method calculations.

In the 3D method, imaging of the LVOT was obtained using R-wave gated imaging over 2 to 4 heartbeats during a brief period of apnea and absence of electrical or motion interference to achieve the highest spatial and temporal resolution. The acquired 3D data later were accessed on 3D geometric quantification software (Q-Lab Version 8.1.2 Advanced Ultrasound Quantification Software, Philips Healthcare, Andover, MA) and analyzed. Briefly, the multiplanar reformatting planes were aligned to display the three geometrically orthogonal views (sagittal, coronal, and transverse) of the LVOT and the aortic valve in the mid-systolic position (Fig 1). The gain and brightness settings were adjusted to clearly delineate the edges of the LVOT, which was then planimeted in the en face view 1 cm proximal to the insertion of the aortic valve leaflets. The CSA_{LVOT} thus obtained was used to calculate SV and CO by the continuity equation.

All data were entered into Microsoft Excel for Mac (Microsoft Corporation, Redmond, WA) and analyzed with SPSS 20.0.0 (IBM Corp., Armonk, NY). Data are presented as mean ± standard deviation (SD) or percentage of a group where applicable. The Shapiro-Wilk test was used to assess the data for a normal distribution. Comparison of the LVOT estimates with each method was compared using paired t-test. Correlation between 2D and 3D methods was performed using Pearson correlation. Bland-Altman analysis was performed comparing the cardiac output calculations using the LVOT from both methods. A one-sample t-test was performed to determine the significance of the mean values of the difference. Linear regression was performed to assess for proportional bias. Significance was determined at the p ≤ 0.05 level (Fig 2).

## RESULTS

A total of 35 patients were analyzed. The mean age was 67.12 ± 10.45 years, with 77% male (n = 27) and 23% female (n = 8). The data were found to be consistent with a normal distribution (p > 0.10 for all). The LVOT area was larger in the 3D than in the 2D method (3.98 ± 0.93 v 3.6 ± 0.7; p = 0.001). Stroke volume was 64.8 ± 19.3 mL in the 2D method and 72.18 ± 23.91 mL in the 3D method (p < 0.001). CO was underestimated in the 2D (4.2 ± 1.5 L/min) versus the 3D (4.6 ± 1.6 L/min) methods. Other comparative values of the 2D and 3D measurements are found in Table 1. The authors found good correlation between the 2D and 3D calculations of cardiac output (r = 0.91, p < 0.001). Using Bland-Altman analysis (Fig 3), the CO calculated by the 2 techniques showed poor agreement with a fixed bias (mean difference 0.45 ± 0.68 L/min, p < 0.001), and no proportional bias (p = 0.11).

Fig 1. Multiplanar reformatting planes are aligned orthogonally to each other to obtain an accurate en face view of the left ventricular outflow tract. In this case, the left ventricular outflow tract possesses an elliptical shape. D1, Minor axis diameter; D2, major axis diameter; A1, area tracing.
DISCUSSION

The results of this study indicated that the underestimation of CSA\textsubscript{LVOT} with 2D echocardiography based on a single axis diameter influences the calculation of CO. As compared with 3D planimetered LVOT area, using 2D-derived CSA\textsubscript{LVOT} during calculation of CO leads to a 10% underestimation of CO. An assumption of a circular shape of the LVOT seems to introduce this error in estimation of CSA\textsubscript{LVOT}. The results of this study were consistent with earlier reports of the effect of the elliptical shape of the LVOT on AVA calculation and corroborate observations. The 2D minor axis–based CSA\textsubscript{LVOT} consistently underestimates the area in comparison with the 3D planimetered area. This study also demonstrated the feasibility of clinical use of the quantitative aspects of 3D data and the potential effect this can have on clinical decision-making. With multiplanar reformatting of 3D data, exact orthogonal imaging planes can be dissected to make accurate linear measures. An en face view of the LVOT readily can be obtained and its area can be planimetered directly without any geometric assumptions. Hence, underestimation of CSA\textsubscript{LVOT} by the 2D method affects the accuracy of CO calculation. These results can be extrapolated to an accurate echocardiographic calculation of CO beyond the periooperative arena (eg, intensive care unit, emergency room).

A circular LVOT and accurate calculation of CSA\textsubscript{LVOT} by measuring its diameter are the 2 integral assumptions of the continuity equation. Other assumptions include parallel alignment of the Doppler beam and placement of the sample volume at the exact site of LVOT diameter measurement. Of these, LVOT diameter is the source of significant error in the equation because the diameter is halved to radius and then squared, leading to amplification of the error. With ready availability of 3D data, the lack of any geometric assumptions during 3D imaging has highlighted the limitations of 2D-derived calculations. In the ME-LAX view, of the 2, the minor axis of the LVOT is visualized and measured, leading to underestimation of the area.\textsuperscript{11,13} The acquisition of an en face view of the LVOT eliminates the assumption of circularity and is presumably more accurate. Larger LVOT areas also are obtained with the ellipsoid method than the minor axis–based method, prompting further questions regarding the accuracy of the traditional method.\textsuperscript{8} Therefore, 3D echocardiography not only highlights the limitations of 2D but also provides more accurate information, which potentially can affect decision-making in the operating room. One interesting aspect of these results was that in some cases CSA\textsubscript{LVOT} was higher with the 2D method. This finding may be explained by a slightly oblique angle of the scan plane when the image was obtained.

This study was limited to a small number of patients and needs to be further validated in larger populations and perhaps against CO measured by pulmonary artery catheterization. Another limitation lay in the offline analysis of data, but the software needed for this is already available on most ultrasound systems and, therefore, routinely can be used in the perioperative setting. Furthermore, the authors studied normal LVOT geometry, but the effect of LVOT calcification and other abnormalities (eg, septal hypertrophy) on its elliptical shape

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<tr>
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<th>2D Method</th>
<th>3D Method</th>
<th>p Value</th>
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<tbody>
<tr>
<td>LVOT diameter (cm)</td>
<td>2.1 ± 0.2</td>
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<tr>
<td>LVOT area (cm\textsuperscript{2})</td>
<td>3.6 ± 0.7</td>
<td>3.98 ± 0.93</td>
<td>0.001</td>
</tr>
<tr>
<td>Stroke volume (mL)</td>
<td>64.8 ± 19.3</td>
<td>72.18 ± 23.91</td>
<td>&lt;0.001</td>
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<tr>
<td>Cardiac output (L/min)</td>
<td>4.2 ± 1.5</td>
<td>4.6 ± 1.6</td>
<td>0.001</td>
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NOTE: p values calculated using paired t-test.
Abbreviations: 2D, 2-dimensional; 3D, 3-dimensional; LVOT, left ventricular outflow tract.
need to be further investigated. Quite possibly, the 2D method of LVOT area may be even more accurate under these circumstances.

In conclusion, the authors have demonstrated the limitation of 2D imaging for measuring an accurate CO because of the elliptical shape of the LVOT. The use of the minor axis alone for CSA_{LVOT} calculation leads to lower SV and CO when compared with values obtained using 3D planimetry. Routine use of intraoperative 3D echocardiography can improve the accuracy of this hemodynamic calculation.

REFERENCES