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 (CSA_{LVOT}). 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.

Measurements and Main Results: The area of the LVOT differed significantly between methods, being significantly larger in the 3D method (3.57 ± 0.70 cm^2 *v* 3.98 ± 0.93 cm^2) . This resulted in a 10% lower CO with the 2D method of LVOT area estimation.

Conclusions: LVOT area is underestimated with the single-axis 2D method when compared with 3D planimetered area. This results in a CO that is approximately 10% lower with the 2D method.

KEY WORDS: *cardiac output, left ventricular outflow tract, stroke volume, transesophageal echocardiography, 2D vs 3D*

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 (CSA_{LVOT}) 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, CSA_{LVOT} 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[1] 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 either 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_{LVOT} because of the use of a single 2D diameter has been found to introduce errors in estimation of aortic valve area (AVA).[2]

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.[3–5] As a result, it is now established that the use of the 2D-obtained minor axis diameter alone leads to underestimation of true CSA_{LVOT}.[6,7] Subsequently, this underestimation of CSA_{LVOT} leads to overestimation of the severity of aortic stenosis (AS) by the continuity equation.[8,9] 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 echocardiographic data and multiplanar reformatting 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_{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.[8]

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.[10] 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 ME-LAX 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 (πr^2). 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 × 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 planimetered 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 $p \leq 0.05$ 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 ($p = 0.11$).

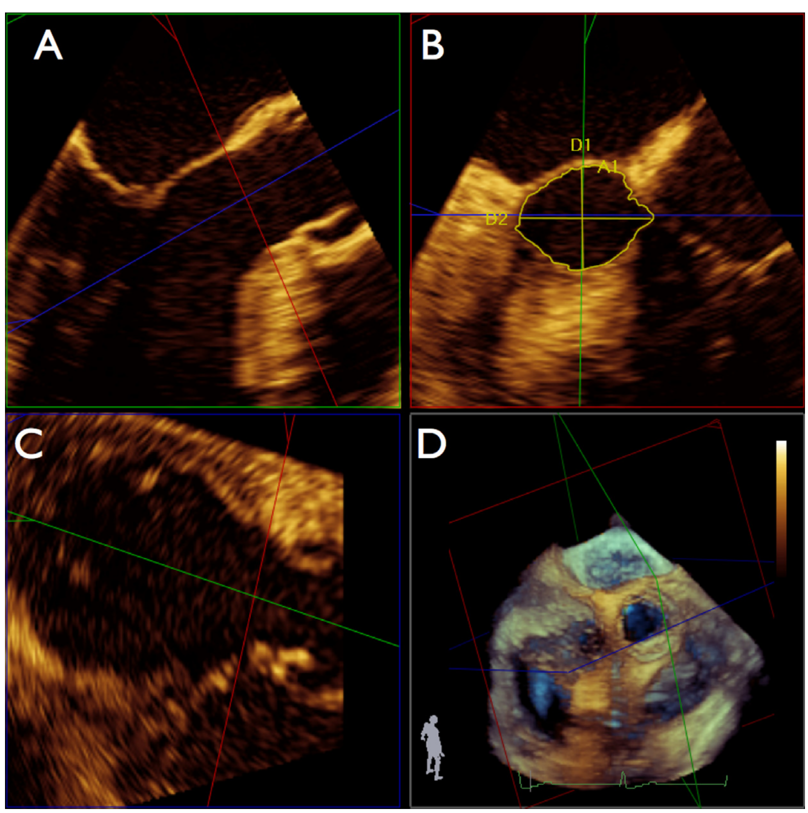

Fig 1. Multiplanar reformatting planes are aligned orthogonally to each other to obtain an accurate *en face* view of the left ventricular outflow tract. In this case, the left ventricular outflow tract possesses an elliptical shape. D1, Minor axis diameter; D2, major axis diameter; A1, area tracing.