Impact of Three-Dimensional Echocardiography on Classification of the Severity of Aortic Stenosis

Jayant S. Jainandunsing, MD, Feroze Mahmood, MD, Robina Matyal, MD, Omair Shakil, MD, Philip E. Hess, MD, Justin Lee, MD, Peter J. Panzica, MD, and Kamal R. Khabbaz, MD

Department of Anesthesiology, University Medical Center Groningen, Groningen, Netherlands; and Department of Anesthesia, Critical Care, and Pain Medicine, and Department of Surgery, and Division of Cardiac Surgery, Beth Israel Deaconess Medical Center, Boston, Massachusetts

Background. Owing to its elliptical shape, the left ventricle outflow tract (LVOT) area is underestimated by two-dimensional (2D) diameter-based calculations which assume a circular shape. This results in overestimation of aortic stenosis (AS) by the continuity equation. In cases of moderate to severe AS, this overestimation can affect intraoperative clinical decision making (expectant management versus replacement). The purpose of this intraoperative study was to compare the aortic valve area calculated by 2D diameter based and three-dimensional (3D) derived LVOT area via transesophageal echocardiography (TEE) and its impact on severity of AS.

Methods. The LVOT area was calculated using intraoperative 2D and 3D TEE data from patients undergoing aortic valve replacement (AVR) and coronary artery bypass graft (CABG) surgery using the 2D diameter (RADIUS), 3D planimetry (PLANE), and 3D biplane (π · x · y) measurement (ELLIPSE) methods. For each method, the LVOT area was used to determine the aortic valve area by the continuity equation and the severity of AS categorized as mild, moderate, or severe.

Results. A total of 66 patients completed the study. The RADIUS method (3.5 ± 0.9 cm²) underestimated LVOT area by 21% (p < 0.05) compared with the PLANE method (4.1 ± 0.1 cm²) and by 18% (p < 0.05) compared with the ELLIPSE method (4.0 ± 0.9 cm²). There was no significant difference between the two 3D methods, namely, PLANE and ELLIPSE. Seven AVR patients (18%) and 1 CABG surgery patient (6%) who had originally been classified as severe AS by the 2D method were reclassified as moderate AS by the 3D methods (p < 0.001).

Conclusions. Three-dimensional echocardiography has the potential to impact surgical decision making in cases of moderate to severe AS.


An accurate measurement of the left ventricle outflow tract (LVOT) diameter is integral to derivation of aortic valve area (AVA) by the continuity equation [1]. The LVOT area estimation (π · x · y) in this calculation is based on the assumption that the LVOT is circular in shape. However, recent evidence from three-dimensional (3D) data suggests that the LVOT is actually elliptical with major and minor axes [2–5]. The calculation of the LVOT area by transthoracic/transesophageal echocardiography (TEE) is based on measurement of the minor axis of the LVOT (parasternal long-axis view and midesophageal long-axis view) [6]. Area estimation based on minor axis diameter with assumption of a circular shape therefore leads to significant underestimation of the LVOT area and subsequently of the AVA [4, 7]. Hence, AVA derived from continuity equation with two-dimensional (2D) echocardiography potentially overestimates the degree of aortic stenosis (AS) [7]. Given the recent trend of expectant management for mild to moderate AS such errors in AVA calculation can have significant clinical consequences [8].

Computed tomography (CT) and magnetic resonance imaging (MRI) of the aortic root has established the elliptical shape of the LVOT [5, 9]. The presence of major and minor axes of LVOT has also been confirmed by 3D TEE imaging of the aortic root [2, 10]. The 3D data allow the generation of an en-face view of the LVOT, which can be traced to obtain its perimeter with clearly defined edges without any geometric assumptions (Fig 1). Planimetry of an en-face view yields a relatively larger LVOT area than estimations based on measurement of minor axis with 2D echocardiography [10]. Hence, of all the methods, 2D echocardiography yields the smallest LVOT area [11], which results in “overestimation” of AS by the continuity equation. Accurate estimation of AVA is one factor that guides surgical decision making in cases of mild to moderate AS during coronary artery bypass graft (CABG) surgery. Owing to lack of geometric
assumptions, 3D data provide a more accurate estimate of AVA. Particularly during cases of mild to moderate AS during CABG surgery, provision of these data can potentially modify surgical decision making. In this context we studied the LVOT geometry of patients who had undergone elective aortic valve replacement (AVR) at our institution. Specifically, we used the planimetered LVOT area obtained with 3D echocardiography to recalculate the AVA and compare it with the 2D-acquired AVA as calculated intraoperatively with the continuity equation.

Material and Methods
Routinely collected intraoperative echocardiographic data (2D and 3D) of patients undergoing elective cardiac surgery were analyzed for this study. The chairman of the Institutional Review Board approved this study with waiver of informed consent. We used acquired echocardiographic data from patients who had undergone elective AVR and CABG surgery with intraoperative 3D TEE between March 2011 and February 2012. We excluded patients who underwent emergency procedures, concomitant procedures with AVR (CABG, mitral and tricuspid valve, ascending aorta) as well as patients who did not have intraoperative 3D TEE.

Several operators collected the intraoperative 3D echocardiographic data. The geometric reconstruction and analysis of the LVOT was performed post hoc in our laboratory by investigators who were blinded to the intraoperative values of the AVA as well as to the values obtained by each other. The reliability of the assessment comparing intra and interobserver correlation was 0.91 and 0.84, respectively (p < 0.01 for both).

The TEE examinations were performed with a Philips iE-33 ultrasound system and an X7-2t probe (Philips Medical Systems Andover, MA) after induction of general anesthesia before institution of cardiopulmonary bypass. A comprehensive 2D examination was performed according to the guidelines. The AVA was calculated by the continuity equation using LVOT area measured using three different methods, as described below.

In method 1, the 2D diameter method (RADIUS), the LVOT diameter was measured in the 2D midesophageal long-axis view utilizing the zoom function 1 cm from the insertion of the aortic leaflets in midsystole (Fig 1). The machine software automatically derived the LVOT area (\(A\)). The velocity time integrals through the LVOT (pulse wave Doppler) and aortic valve (continuous wave...
Doppler) were obtained and traced in the deep transgastric window with optimal Doppler alignment.

In method 2, the 3D planimetry method (PLANE), the LVOT area was obtained by direct planimetry of the enface view of the LVOT obtained by 3D imaging. The 3D imaging of the LVOT was performed using R-wave gated imaging over two to four 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 were immediately accessed in the on-cart 3D geometric quantification software Q-Lab version 8.1.2 (Advanced Ultrasound Quantification Software; Philips Medical Systems, Andover, MA) and analyzed. Briefly, the multiplanar reformatting planes were aligned to display the three orthogonal views (sagittal, coronal, and transverse) of the LVOT and the aortic valve in the mid-systolic position (Fig 1). The gain and brightness setting were adjusted to clearly delineate the edges of the LVOT, which was then planimetrized in the enface view. The LVOT area thus obtained was used to calculate the AVA by the continuity equation (Fig 1).

In method 3, the 3D biplane measurement method (ELLIPSE), the major axis (y) and minor axis (x) of the LVOT were measured in the en-face view obtained with 3D data and multiplanar reformatting planes (Fig 1). The LVOT area was calculated using the ellipsoid formula \( \pi \cdot x \cdot y \) and used for AVA calculation by continuity equation.

### Statistical Analysis

All data were entered into Microsoft Excel (Microsoft Corporation, Redmond, WA), and analyzed with SPSS 20.0.0 (IBM, Armonk, NY). We assessed the data for a normal distribution using the Shapiro-Wilk test. Comparison of calculated LVOT area was made using the repeated measures analysis of variance with Greenhouse-Geisser correction; post-hoc Bonferroni test was used to compare individual values. Agreement among the measurement methods to determine the size of the LVOT was performed using Pearson correlation, and Bland-Altman plots were generated. Comparison between the AVR and CABG patients was performed using the \( t \) test and Fisher’s exact test. Any \( p \) value of 0.05 or less was considered to be statistically significant. Data are presented as mean ± SD or percentage of group, as appropriate.

### Results

We recruited a total of 66 patients that included 46 AVR patients and 20 CABG patients (Table 1). Mean LVOT area (n = 66) was 3.5 cm\(^2\) ± 0.9 cm\(^2\), 4.1 cm\(^2\) ± 0.1 cm\(^2\), and 4.0 cm\(^2\) ± 0.9 cm\(^2\) according to the RADIUS, PLANE, and ELLIPSE methods, respectively (Table 2). There was significant correlation among all three methods of LVOT area measurement as demonstrated by the Bland-Altman plots (Fig 2). The RADIUS method underestimated LVOT area by 21% and 18% when compared with the PLANE and ELLIPSE methods, respectively (\( p < 0.001 \) for both). Of note, there was no significant difference between the two 3D methods, namely, the PLANE and ELLIPSE methods (\( p > 0.05 \)).

### Table 1. Patient Demographics

<table>
<thead>
<tr>
<th>Demographics</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of patients</td>
<td>66</td>
</tr>
<tr>
<td>Age, years, average</td>
<td>72.5</td>
</tr>
<tr>
<td>Aortic valve replacement</td>
<td>46</td>
</tr>
<tr>
<td>Coronary artery bypass graft surgery</td>
<td>18</td>
</tr>
<tr>
<td>Male:female</td>
<td>2:1</td>
</tr>
<tr>
<td>Beta-blocker</td>
<td>67%</td>
</tr>
<tr>
<td>Diabetes mellitus</td>
<td>61%</td>
</tr>
<tr>
<td>Hypertension</td>
<td>85%</td>
</tr>
</tbody>
</table>

When comparing AVR patients (n = 46) with patients who underwent CABG surgery (n = 20), we found no significant differences in RADIUS area (3.7 cm\(^2\) ± 1.0 cm\(^2\) versus 3.4 ± 0.7 cm\(^2\), \( p = 0.22 \)), PLANE area (4.3 cm\(^2\) ± 1.1 cm\(^2\) versus 4.1 cm\(^2\) ± 0.8 cm\(^2\), \( p = 0.48 \)), or ELLIPSE area (4.1 cm\(^2\) ± 0.9 cm\(^2\) versus 4.0 cm\(^2\) ± 0.8 cm\(^2\), \( p = 0.72 \)), between the two groups. Likewise, the percent differences between measures were similar between types of surgery (\( p > 0.05 \) for all; Table 2).

The severity of AS (mild, moderate, and severe) was calculated for AVR patients and was found to be different when comparing the 2D method RADIUS with the 3D methods PLANE and ELLIPSE (\( p < 0.001 \); Table 3). Of significance, 7 of the 38 patients (18%) who had been categorized with severe AS by the 2D methods were reclassified as mild or moderate stenosis by the 3D methods (\( p < 0.001 \)). Among patients who underwent CABG surgery, velocity time integrals measurements were inadequate in 2 patients because of suboptimal Doppler alignment, so the AVA was recalculated for the remaining 18 patients. Among these, 1 patient (6%) who had originally been classified as having severe AS by the 2D method was reclassified as moderate AS by the 3D methods (\( p < 0.001 \); Table 4).

### Comment

The results of our study demonstrate that LVOT area is significantly underestimated by 2D minor axis measurements as compared with 3D data (Table 2). This underestimation of the LVOT area manifested as an overestimation of AS in 18% of patients in the AVR group.

### Table 2. The Calculated Area of the Left Ventricular Outflow Tract

<table>
<thead>
<tr>
<th>Methoda</th>
<th>LVOT Area</th>
<th>Correlation Valuesb</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>To PLANE</td>
</tr>
<tr>
<td>RADIUS</td>
<td>3.5 cm(^2) ± 0.9 cm(^2)</td>
<td>( r = 0.80 )</td>
</tr>
<tr>
<td>PLANE</td>
<td>4.1 cm(^2) ± 0.1 cm(^2)</td>
<td>( p \leq 0.001 )</td>
</tr>
<tr>
<td>ELLIPSE</td>
<td>4.0 cm(^2) ± 0.9 cm(^2)</td>
<td>...</td>
</tr>
</tbody>
</table>

\( ^a \) See Methods for definition of measurements using the three methods.

\( ^b \) Correlation values describe the Pearson correlation between measurements of left ventricular outflow tract (LVOT) area.
Therefore, 3D echocardiography has the potential to significantly impact surgical decision-making. In our study, both the PLANE and ELLIPSE methods were based on 3D geometric data and their corresponding AVAs were larger than that calculated using the 2D RADIUS method (Table 2). Because it is devoid of geometric assumptions and takes into account the elliptical shape of the LVOT, the 3D data derived LVOT area should be considered more accurate. In our study, the differences in LVOT area measurements were also observed in patients without any aortic valve pathology, namely, patients undergoing CABG surgery, implying that the LVOT is elliptical in shape in the majority of cases and LVOT and AVA determinations based on assumptions of circular shape ($r^2$) with 2D echocardiography are prone to error. Owing to a narrow range of AVAs for severity grading, this degree of area underestimation can have consequences for clinical decision making.

With percutaneous AVR becoming a popular option, the anatomy of the aortic root has been extensively investigated with CT and MRI [10, 12–15] and the elliptical/oval shape of the LVOT is now well established [5, 16, 17]. Underestimation of LVOT area with 2D diameter-derived calculation and consequent overestimation of the degree of AS has also been acknowledged [2, 4, 17, 18]. The intraoperative use of 3D data in cases with unanticipated mild to moderate AS has shown the potential to impact surgical decision making [19]. Of the various methods (continuity versus Gorlin equation), continuity equation based on 2D LVOT diameter measures the smallest AVA [11]. This discordance has been attributed to methodologic differences [11, 20–22]. During a standard 2D TTE and TEE examination, the minor axis is measured as the diameter of the circular LVOT and configured into the continuity equation to calculate the AVA. It is quite possible that the use of the minor axis for diameter-based LVOT area calculation results in the overestimation of the severity of AS and the observed discordance between different methods.

Approximately 2.4% of the patients referred for CABG have echocardiographic evidence of AS [23]. An accurate estimation of AVA is necessary to determine the need for a prophylactic AVR in this patient population [24, 25]. Unanticipated AS and aortic valve abnormalities during CABG surgery are well-known phenomena. In such situations, an accurate AVA calculation determines the need for an AVR. Single diameter-based AVA calculations are commonly the source of erroneous AVA calculation. Among the CAGB patients in our study, 1 patient underwent an unanticipated AVR for severe AS that was downgraded to moderate in severity by 3D data (Table 4). Although the decision to operate for moderate AS is contextual, our results demonstrate the potential impact of utilizing 3D data for estimation of severity AS.

Routine use of 3D methods to diagnose and grade AS has the potential to revise our established practice in a significant number of patients undergoing cardiac surgery. Importantly, the elliptical shape of the LVOT was also observed in the patients undergoing CABG without

### Table 3. Classification of Aortic Stenosis Severity in Aortic Valve Replacement Patients by Two-Dimensional and Three-Dimensional Methods

<table>
<thead>
<tr>
<th>Aortic Stenosis Classification (n = 46)</th>
<th>2D Method, n</th>
<th>3D Method, n</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;1.0 cm</td>
<td>38</td>
<td>31</td>
</tr>
<tr>
<td>1.0–1.5 cm</td>
<td>7</td>
<td>12</td>
</tr>
<tr>
<td>&gt;1.5 cm</td>
<td>1</td>
<td>3</td>
</tr>
</tbody>
</table>

$p < 0.001$.

2D = two-dimensional; 3D = three-dimensional.

### Table 4. Classification of Aortic Stenosis Severity in Coronary Artery Bypass Graft Patients by Two-Dimensional and Three-Dimensional Methods

<table>
<thead>
<tr>
<th>Aortic Stenosis Classification (n = 18)</th>
<th>2D Method, n</th>
<th>3D Method, n</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;1.0 cm</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>1.0–1.5 cm</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>&gt;1.5 cm</td>
<td>15</td>
<td>17</td>
</tr>
</tbody>
</table>

$p < 0.001$.

2D = two-dimensional; 3D = three-dimensional.
any anatomic abnormalities of the LVOT or the aortic valve. Accurate estimation of LVOT area is an integral component of the continuity equation and the greatest source of error in AVA calculation [1]. An AVA calculated with 3D planimetered LVOT area is more accurate and has also shown better agreement with AVA measured invasively [26, 27]. Therefore, use of the 3D-derived LVOT area, which is devoid of geometric assumptions, can have a significant impact on the diagnosis as well as the severity assessment of AS. Because echocardiography is most commonly used for diagnosing AS, 3D echocardiography offers a practical alternative to CT and MRI for imaging of the LVOT [10] for accurate AVA calculation. This application of this knowledge could be particularly useful for unanticipated intraoperative situation of mild to moderate AS or when there is discordance between various methods.

We can identify certain limitations of our study. We did not have any CT or MRI data to compare the 3D data derived AVA's. However, the degree of underestimation of LVOT area in our study is similar to that of the earlier investigations using CT and MRI data [2, 7, 17, 18]. Additionally, demonstration of the ellipsoid nature of the LVOT area and its impact on AVA and severity of stenosis has been established previously. The continuity equation based calculation of the AVA is "flow corrected," in other words, it is not affected by the hemodynamic variations and the greatest source of error is the assumption of the circular shape of LVOT, as was demonstrated in our study. Therefore, we are confident of the validity of our findings. We also do not have complete data on the methodology used to diagnose AS in our patients. However, our aim was to assess the impact of the three different methods of LVOT area estimation on severity grade for patients already diagnosed with AS. We were able to demonstrate this consistently in our study. Routine use and application of this methodology and clinical impact would require further study.

In conclusion, 3D TEE showed that the LVOT was elliptical in shape in most cases and its area can be measured with direct planimetry as well as with the ellipsoid formula. Compared with 3D echocardiography, 2D imaging underestimated the LVOT area, which consequently resulted in overestimation of the degree of stenosis. Incorporation of this information resulted in revision of the severity grades of AS in a significant number of patients. We conclude that 3D TEE has the potential to impact intraoperative surgical decision-making in patients with AS.

References
3. Halpern EF, Mallya R, Sewell M, Shulman M, Zwas DR. Differences in aortic valve area measured with CT planimetry and echocardiography (continuity equation) are related to divergent estimates of left ventricular outflow tract area. AJR Am J Roentgenol 2009;192:1668–73.
20. Garcia D, Dumesnil JG, Durand L-G, Kadem L, Pibarot P. Discrepancies between catheter and Doppler estimates of valve effective orifice area can be predicted from the pressure recovery phenomenon: practical implications with regard to
ABTS Requirements for the 10-Year Milestone for Maintenance of Certification

Diplomates of the American Board of Thoracic Surgery (ABTS) who plan to participate in the 10-Year Milestone for the Maintenance of Certification (MOC) process as Certified-Active must hold an unrestricted medical license in the locale of their practice and privileges in a hospital accredited by the JCAHO (or other organization recognized by the ABTS). In addition, a valid ABTS certificate is an absolute requirement for entrance into the MOC process. If your certificate has expired, the only pathway for renewal of a certificate is to take and pass the Part I (written) and the Part II (oral) certifying examinations.

The CME requirements are 150 Category I credits over a five-year period. At least half of these CME hours need to be in the broad area of thoracic surgery. Category II credits are not accepted. Interested individuals should refer to the Board’s website (www.abts.org) for a complete description of acceptable CME credits.

Diplomates will be required to take and pass a secured exam after their application has been approved. Taking SESATS in lieu of the secured exam is not an option. The secured exam is administered over a two-week period in September of every year at Pearson Vue Testing Centers, which are located nationwide. Diplomates will have the opportunity to select the day and location of their exam. For the dates of the next MOC exam, visit the Board’s web site at www.abts.org.

Starting on July 1, 2014, the ABTS will require its Diplomates to participate in an outcomes database as fulfillment of Part IV (Performance in Practice) for the 10-year Milestone of Maintenance of Certification (MOC). For a list of approved outcomes databases or for more information on how to have a database approved by the Board, visit the Board’s website at www.abts.org. Participation in the Professional Portfolio will no longer be accepted as fulfillment of MOC Part IV after July 1, 2014.

Diplomates may apply for MOC in the year their certificate expires or, if they wish to do so, they may apply up to two years before it expires. However, the new certificate will be dated 10 years from the date of expiration of their original certificate or most recent MOC certificate. In other words, going through the MOC process early does not alter the 10-year validation. Diplomates certified prior to 1976 (the year that time-limited certificates were initiated) are also required to participate in MOC if they wish to maintain valid certificates.

The deadline for submitting an application for 10-year Milestone of MOC is March 15 of every year. Information outlining the rules, requirements, and dates for MOC in thoracic surgery is available on the Board’s website at www.abts.org. For additional information, please contact the American Board of Thoracic Surgery, 633 N St. Clair St, Ste 2320, Chicago, IL 60611; telephone (312) 202-5900; fax (312) 202-5960; e-mail: info@abts.org.