Aortic Annular Sizing Using a Novel 3-Dimensional Echocardiographic Method

Use and Comparison With Cardiac Computed Tomography

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Background—Previous studies have shown cross-sectional 3-dimensional (3D) transesophageal echocardiographic (TEE) measurements to severely underestimate multidetector row computed tomographic (MDCT) measurements for the assessment of aortic annulus before transcatheter aortic valve replacement. This study compares annulus measurements from 3D-TEE using off-label use of commercially available software with MDCT measurements and assesses their ability to predict paravalvular regurgitation.

Methods and Results—One hundred patients with severe, symptomatic aortic stenosis who had both contrast MDCT and 3D-TEE for annulus assessment before balloon-expandable transcatheter aortic valve replacement were analyzed. Annulus area, perimeter, and orthogonal maximum and minimum diameters were measured. Receiver operating characteristic analysis was performed with mild or greater paravalvular regurgitation as the classification variable. Three-dimensional TEE and MDCT cross-sectional perimeter and area measurements were strongly correlated (r=0.93–0.94; P<0.0001); however, the small differences (≤1%) were statistically significant (P=0.0002 and 0.0074, respectively). Discriminatory ability for ≥ mild paravalvular regurgitation was good for both MDCT (area under the curve for perimeter and area cover index=0.715 and 0.709, respectively) and 3D-TEE (area under the curve for perimeter and area cover index=0.709 and 0.694, respectively). Differences in receiver operating characteristic analysis between MDCT and 3D-TEE perimeter and area cover indexes were not statistically significant (P=0.15 and 0.35, respectively).

Conclusions—Annulus measurements using a new method for analyzing 3D-TEE images closely approximate those of MDCT. Annulus measurements from both modalities predict mild or greater paravalvular regurgitation with equivalent accuracy. **(*Circ Cardiovasc Imaging*. 2014;7:155-163.)**

Key Words: aortic valve insufficiency ■ aortic valve stenosis ■ echocardiography ■ tomography

Transcatheter aortic valve replacement (TAVR) has emerged as a therapeutic option for patients with symptomatic, severe aortic stenosis and elevated surgical risk.[1,2] The aim of TAVR implantation is to use accurate sizing to optimize valvular hemodynamics while creating a tight seal around the transcatheter heart valve (THV) to minimize paravalvular regurgitation (PVR). Accurate imaging assessment of the aortic valve annulus is critical for THV sizing. Although the traditional measurement of annular diameter has been performed on the 2-dimensional (2D) echocardiographic long-axis view (sagittal plane),[3] multiple studies have demonstrated the oval shape of the annulus,[4–6] with the shortest dimension typically lying in the sagittal plane. Studies across multiple modalities have also shown the advantages of 3-dimensional (3D) assessment of the annulus compared with 2D assessment. Both echocardiography[7–11] and multidetector row computed tomography (MDCT)[5,6,9,12–19] have been used for annular sizing before TAVR and have been shown to be predictive of postimplantation paravalvular aortic regurgitation.[7,8,13,18,20] Because transesophageal echocardiography (TEE) is a relatively safe procedure[21,22] that does not require iodinated contrast and can be used intraprocedurally during TAVR, it is desirable to develop reproducible and accurate 3D-TEE measurements of the aortic valve annulus. Although recent reviews have suggested that 3D-TEE can be used for cross-sectional area and perimeter measurements,[3,23] studies to date have shown clinically significant differences in 3D-TEE and MDCT measurements.[10,11,24,25]

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The goal of the current study is to compare a novel 3D-TEE method for annular assessment with MDCT measurements

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and to compare the predictive value of the 2 modalities for the development of PVR.

Methods

Patient Population and Procedure

This analysis included 100 patients who underwent TAVR with a balloon-expandable Edwards SAPIEN or SAPIEN XT THV (Edwards Lifesciences, Irvine, CA) from November 2011 to January 2013 who also underwent both preprocedural MDCT and intraprocedural TEE. Patients were nonconsecutive because those who had not undergone both MDCT and intraprocedural TEE were excluded. The procedural access route (transfemoral, transapical, or transaortic) was determined by standard protocols. THV sizing was decided at the discretion of the treating physicians with the use of all available imaging modalities (MDCT and 3D-TEE). No patients were excluded from imaging analysis based on image quality. All patients gave informed consent, and the study was approved by the institutional review board for human research.

Image Acquisition

Echocardiography

Patients underwent intraprocedural TEE using commercially available equipment (iE33; Philips Medical Imaging, Andover, MA) according to standard protocols. A full 2D-TEE imaging protocol was performed, including pulsed- and continuous-wave Doppler recordings. User-defined 3D-TEE volumes of the aortic valve complex were acquired (single-beat acquisition) by obtaining long- or short-axis 2D-TEE views from imaging windows, which minimized acoustic shadowing of the annular plane (Movie I in the Data Supplement). The 3D volumes contained the left ventricular outflow tract (LVOT), aortic annulus and valve, and aortic root to the sinotubular junction. Multibeat, spliced images were avoided. Two-dimensional measurements of the annulus were performed from long-axis views with particular attention to avoiding acoustic shadowing of the hinge point of the right coronary cusp; frequently, this required imaging from a deeper esophageal window.

Multidetector Row Computed Tomography

Before the TAVR procedure, patients underwent cardiac computed tomographic angiography using a 320-slice system (Toshiba Medical Systems, Otawara, Japan). The protocol used was specially designed in our institution to minimize iodinated contrast administration while providing cardiac and vascular pre-TAVR assessment during a single contrast bolus administration. During an inspiratory breath-hold, single-volume acquisition was performed with prospective electrocardiographic triggering. Data were acquired with collimation of 240 to 360×0.5 mm and a gantry rotation time of 350 ms. Intravenous injection of 39 to 60 mL of nonionic contrast agent (Iodixanol) was performed at a rate of 3.5 mL/s. The decision on the volume of contrast used was at the discretion of the physician conducting the scan. Tube current and potential were determined by the physician conducting the scan or by software automation according to the patient's body habitus. Real-time bolus tracking with automated peak enhancement detection in the descending aorta was used for timing the scan. Data acquisition was initiated based on a threshold of 180 Hounsfield Units. The 3D data set from the contrast-enhanced scan was reconstructed at 5% increments throughout the cardiac cycle. Images were reconstructed with a slice thickness of 0.5 or 0.25 mm. CT data sets were transmitted to a dedicated workstation and analyzed using 3mensio Valves™ software (version 5.1; Pie Medical Imaging, Maastricht, The Netherlands). Window width and level were optimized by the reader.

Aortic Annulus Measurements and Calculations

The aortic annulus was defined as the plane of the virtual circumferential ring containing the basal attachment points of the 3 aortic valve leaflets.[26] For both echocardiography and CT, the following annular measurements were performed: perimeter, area, and orthogonal maximum and minimum diameters. Average diameter was calculated from perimeter (D_{perim}=perimeter÷π) and area ($D_{area}=2\times\sqrt{[area\div\pi]}$). Mean diameter ($D_{mean}$) was calculated as the average of the maximum diameter (D_{max}) and minimum diameter (D_{min}). Absolute differences (Δ) in nominal THV diameter and measured or calculated annular diameters were determined. Eccentricity index was calculated using the formula maximum diameter/minimum diameter. The cover index (CI) representing the % oversizing of the THV compared with the measured annulus size was calculated separately for mean diameter, perimeter, and area. Diameter CI was calculated as ([nominal THV diameter−measured diameter]/nominal THV diameter)×100%. Perimeter CI was calculated as ([nominal THV perimeter−3D perimeter]/nominal THV perimeter)×100%. Area CI was calculated as ([nominal THV area−3D area]/nominal THV area)×100%. All measurements were performed in midsystole using the most optimal image at or near maximum aortic valve excursion. Initial echocardiographic measurements were performed intraoperatively at the time of THV implant by an echocardiographer experienced in TAVR imaging (R.T.H.). MDCT measurements were performed retrospectively by a CT reader experienced in TAVR imaging (O.K.K.). For each modality, readers were blinded to results of measurements from the other modality. For inter- and intraobserver reproducibility, readers were blinded to the previous measurements.

Echocardiographic Measurements

Two-dimensional TEE annular diameter measurements were performed from the long-axis view that maximally bisected the diameter of the aortic annulus. To ensure optimal selection of this plane, simultaneous biplane imaging was performed or meticulous attention was paid to visualization of the hinge point of the right coronary cusp and the commissure between the left and noncoronary cusps (Figure 1).

Three-dimensional echocardiographic reconstruction for measurement of the aortic annulus was performed by off-label use of commercially available Q-lab MVQ software (version 8.1; Philips Medical Imaging, Andover, MA; Figure 2) as previously described.[27] This allowed for precise identification of the annular plane from orthogonal long-axis views using adjacent anatomy to accurately identify the annular plane, minimizing the effect of acoustic shadowing on measurement of the annulus. Once the plane was defined, the following annular measurements were obtained: area, perimeter, and orthogonal maximum and minimum dimensions.

MDCT Measurements

Commercially available 3mensio Valves™ was used for MDCT annular measurements (Figure 3). The 3mensio Valves™ software requires the user to select a point at the caudal attachment of each aortic valve

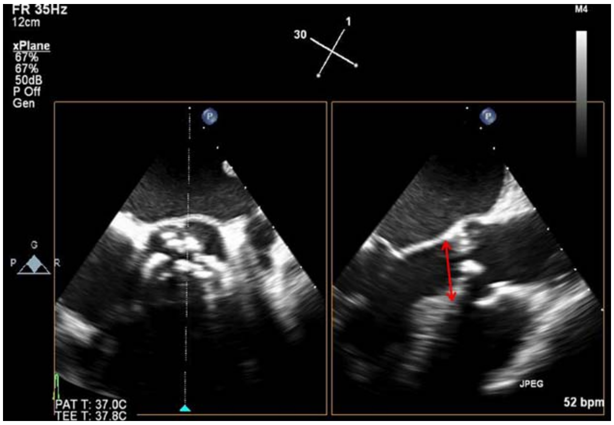

Figure 1. Use of simultaneous multiplane imaging for 2-dimensional transesophageal echocardiographic (2D-TEE) 3-chamber linear annulus measurement. The white line bisecting the midsystolic short-axis image on the 2D-TEE view on the left is used to find a long-axis image that maximally bisects the aortic annulus. The measurement is then performed on the orthogonal long-axis view (red arrow).

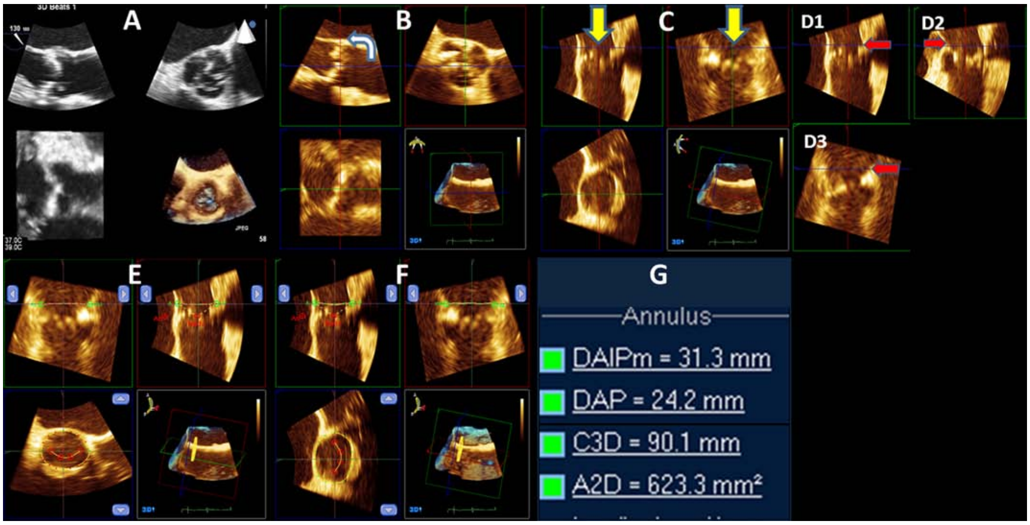

Figure 2. Determination of annulus size by 3-dimensional transesophageal echocardiographic (3D-TEE) MVQ software. **A**, A 3D volume set is acquired from a long-axis 2-dimensional TEE (2D-TEE) view. Acquisition with multiplane 2D visualization is recommended, if available, to ensure minimization of acoustic shadowing of aortic valve hinge points. **B**, After identification of midsystole, the blue panel is used to identify the transverse plane of the annulus by alignment of the 2 orthogonal long-axis views. This can be performed by grabbing the blue line in the sagittal or long-axis plane and rotating the plane ≈90° counterclockwise (white arrow). **C**, The location of the 2 orthogonal long-axis views (in the green and red panels, yellow arrows) can be seen in the transverse plane (blue panel). These orthogonal planes are rotated around the center of the annulus in the transverse plane (blue panel) to confirm that this transverse plane is at the virtual annulus. To confirm this, (**D1**–**D3**) the hinge point of the cusps (red arrows) should be imaged in the orthogonal long-axis views during this rotation. **E**, Once the user has confirmed that the annulus is imaged in the transverse (blue) plane, the initial 4 points, which define 2 orthogonal planes of the annulus, are placed along the maximum and minimum diameters of the annulus in the orthogonal long-axis views. **F**, The user scrolls through a total of 16 points (total of 4 pairs of orthogonal long-axis images in the green and red planes) and confirms that all points lie at the blood–tissue interface and at the annulus. Confirmation of the location of these points will be seen on the transverse plane. The points can be adjusted manually if needed. **G**, Once all points have been confirmed, perimeter, area, and maximum and minimum diameters are then automatically determined by the MVQ package.

leaflet to generate the annular plane (Figure 3A–3C). After generation of the annular plane, a polygonal line was traced circumscribing the annulus, and the perimeter and area were automatically calculated by the software (Figure 3D). Orthogonal maximum and minimum diameters were measured manually by the reader (Figure 3E). The plane was kept at the level of the true virtual basal annulus, regardless of calcification, because avoiding calcification could lead to inaccuracies in measurement. For annular measurements, the annular border was traced outside any visualized calcium. The appearance of partial volume-averaging artifacts (blooming) because of calcification was reduced by adjusting

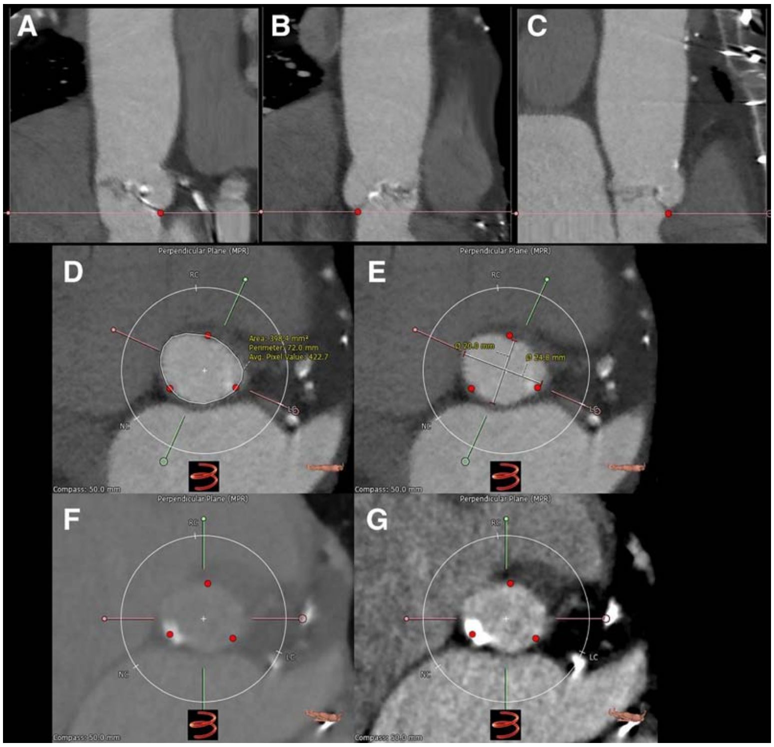

Figure 3. Annulus measurement by multidetector row computed tomography. **A** to **C**, Localization and selection of the 3 aortic valve hinge points are performed to form the annular plane. **D**, The resulting annular plane is shown. A polygonal line is drawn circumscribing the annulus for area and perimeter measurements. **E**, Orthogonal maximum and minimum measurements are performed. **F**, Adjustment of window and level settings is performed to reduce the appearance of partial volume-averaging effects from calcification. The reduced appearance of annulus calcium can be seen in comparison with **G**. **G**, Adjustment of window and level settings is performed to enhance the appearance of intraluminal contrast. The enhanced appearance of intraluminal contrast can be seen in comparison with **F**.

window and level settings (Figure 3F). Images with suboptimal contrast opacification were enhanced by adjusting window and level settings to better delineate the boundaries of the annular lumen (Figure 3G). In cases of both suboptimal contrast opacification and calcified hinge points, window and level settings were adjusted to alternately decrease partial volume averaging or increase lumen/tissue contrast to optimize visualization of the annular boundaries.

Postprocedural Assessment

Assessment of PVR was performed by planimetry of 3D-TEE color Doppler reconstruction with direct planimetry of effective regurgitant orifice area (EROA) (Figure 4) as the method of choice.[28–31] When 3D color Doppler reconstruction was not possible, assessment was performed by a combination of visual estimation of 2D color Doppler imaging and quantitative Doppler assessment of relative stroke volumes across the LVOT and right ventricular outflow tract. In cases where 3D color Doppler was performed, grading of PVR was performed using the following EROA cutoffs: trace, >0 to 4 mm^2; mild, 5 to 9 mm^2; moderate, 10 to 19 mm^2; moderate-severe, 20 to 29 mm^2; and severe, ≥30 mm^2. The need for postdilatation was decided by the treating physicians and was typically based on the immediate postdeployment TEE imaging of more than mild PVR, relying primarily on the short-axis view just apical to the THV stent.

Statistical Analysis

Analyses were performed using SPSS 19.0 (IBM, Armonk, NY), StataSE version 12 (StataCorp LP, College Station, TX), and MedCalc version 12.4.0.0 (MedCalc Software, Ostend, Belgium). Statistical significance was defined as $P<0.05$. Continuous variables are reported as mean±SD. Comparisons between 2 measurements were performed using a paired 2-sided Student *t* test. Normality of distributions for continuous variables was tested using the Kolmogorov–Smirnov test before performing *t* tests. Pearson correlation coefficients were used to assess the correlation between measurements from echocardiography and MDCT. Intraclass correlation coefficients were used to assess interobserver (R.T.H. and O.K.K. for TEE and O.K.K. and J.M.P. for MDCT) and intraobserver (R.T.H. for TEE and O.K.K. for MDCT) variability.[32,33] Receiver operating characteristic curves were generated using ≥ mild PVR as a classification variable by the method of Delong et al.[34] Agreement between measurement methods was displayed with plots using the Bland–Altman method.

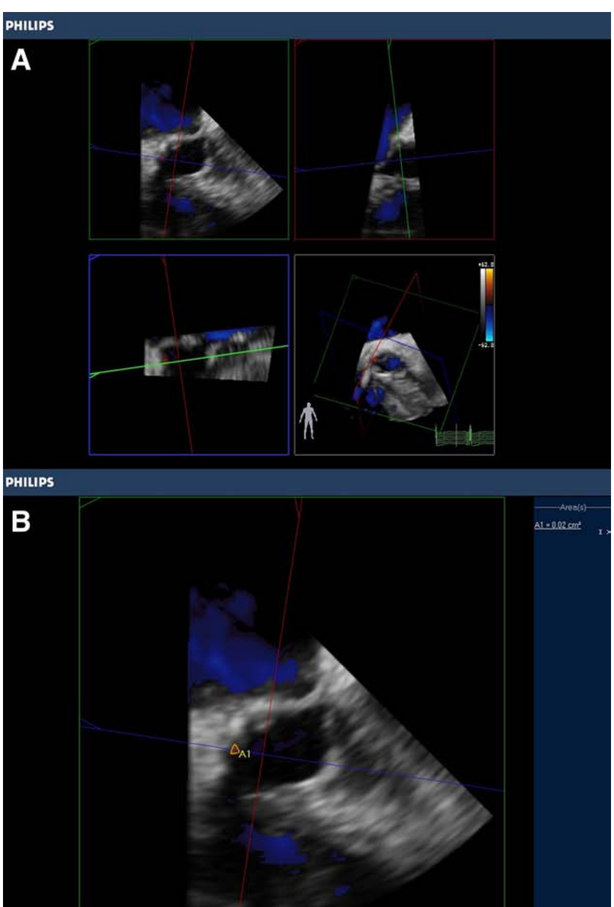

Figure 4. Three-dimensional (3D) transesophageal echocardiographic assessment of paravalvular regurgitation. **A**, Paravalvular regurgitation is localized using 3D color Doppler reconstruction. **B**, An effective regurgitant orifice area is traced on the 3D color Doppler reconstruction.

Results

Study Population

The population consisted of 55 women and 45 men with a mean age of 87.8±8.3 years. Mean pre-TAVR calculated aortic valve area and peak transaortic velocity were 0.67±0.17 cm^2 and 4.1±0.76 m/s, respectively. TAVR was performed in 85 patients via transfemoral access, 9 via transapical access, and 6 via transaortic access. Sixty patients received a SAPIEN THV, and 40 patients received a SAPIEN XT THV. Ten patients received a 29-mm THV, 57 patients received a 26-mm THV, and 33 patients received a 23-mm THV. Balloon postdilatation was performed in 27 patients.

Paravalvular Regurgitation

Immediate postprocedural echocardiographic assessment revealed no PVR in 50 of 100 patients. In the 50 patients with PVR, assessment was performed by 3D color Doppler reconstruction in 43 of 50 patients. In 7 of 50 patients with PVR, assessment was performed by a combination of visual estimation by 2D color Doppler and quantitative Doppler assessment of relative stroke volumes across the LVOT and right ventricular outflow tract. In 6 of these 7 patients, the visual assessment was trace, and the difference between LV and right ventricular stroke volumes was <10 mL; therefore, regurgitation was categorized as trace. In 1 of these 7 patients, the visual assessment was trace-to-mild, and the difference between LV and right ventricular stroke volumes was 29 mL with a regurgitant fraction of 25%, so regurgitation was categorized as mild. At the conclusion of the procedure, 50 patients had no PVR, 28 had trace PVR, 15 had mild PVR, and 7 had moderate PVR. No patient had more than moderate PVR.

Comparison of 2D and 3D Measurements

The mean 2D-TEE sagittal annulus measurement was 23.0±2.0 mm. The sagittal annulus measurement significantly underestimated 3D-TEE and MDCT measurements (Table 1).

Comparison of 3D-TEE and MDCT Measurements

Table 1 compares 3D-TEE and CT annulus measurements. Both area and perimeter measurements showed excellent correlation between the modalities (r=0.93 and 0.94, respectively). Although absolute differences were small (MDCT−3D-TEE for $D_{perimeter}$=0.99±2.9 mm and for D_{area}=0.22±0.78 mm), 3D-TEE measurements were statistically significantly smaller than MDCT measurements (P=0.0002 for perimeter and P=0.0074 for area). Eccentricity index was greater for

Table 1. Comparison Between TEE and MDCT Aortic Annulus Measurements

	3D-TEE Measurement	MDCT Measurement	Δ3D−2D TEE*	ΔMDCT−2D TEE*	ΔMDCT−3D TEE	*R*†	*P* Value†
D_{max}, mm	25.3±2.6	25.6±2.6	2.32±1.54	2.67±1.29	0.34±1.6	0.80	0.03
D_{min}, mm	21.9±2.2	21.7±2.1	−1.07±1.02	−1.25±1.03	−0.20±1.9	0.85	0.10
D_{mean}, mm	23.6±2.3	23.7±2.1	0.63±0.95	0.74±0.92	0.09±1.0	0.90	0.39
Perimeter, mm	74.8±7.0	75.8±6.6	…	…	0.99±2.9	0.93	0.0002
$D_{perimeter}$, mm	23.8±2.2	24.1±2.1	0.85±0.87	1.17±0.95	0.34±0.82	0.93	0.0001
Area, mm²	434.9±81.3	442.8±78.9	…	…	8.0±29.1	0.94	0.0074
D_{area}, mm	23.4±2.2	23.7±2.1	0.47±0.82	−0.70±0.94	0.22±0.78	0.94	0.0045

n=100 for both MDCT and 3D-TEE measurements. Δ2D TEE indicates listed diameter−2-dimensional TEE diameter; 3D, 3-dimensional; D_{area}, average diameter based on area; D_{max}, maximum orthogonal diameter; D_{mean}, $(D_{max}+D_{min})/2$; D_{min}, minimum orthogonal diameter; $D_{perimeter}$, average diameter based on perimeter; MDCT, multidetector row computed tomography; *R*, Pearson correlation coefficient; and TEE, transesophageal echocardiography.

*All with $P<0.0001$ compared with 3D-TEE- or MDCT-based data.

†For 3D TEE vs MDCT.

CT measurements (1.18±0.07 versus 1.16±0.09; $P=0.004$). Figure 5 shows Bland–Altman plots for agreement between methods. For the mean diameter measurement, 3D-TEE measurements were smaller than MDCT measurements with the following mean differences: mean diameter difference=−0.1 mm (range, 1.9 to −2.0 mm), perimeter difference=−1.0 mm (range, 4.0 to −6.0 mm), and area difference=−8.0 mm² (range, 49.1 to −65.0 mm²).

The intraclass correlation coefficients for interobserver variability were 0.86 to 0.95 for 3D-TEE measurements and 0.89 to 0.95 for MDCT measurements. The intraclass correlation coefficients for intraobserver variability were 0.90 to 0.98 for 3D-TEE measurements and 0.91 to 0.98 for MDCT measurements.

Receiver Operating Characteristic Curve Analyses for Predicting PVR

Table 2 summarizes receiver operating characteristic analyses with area under the curve (AUC) values for preprocedural 2D-TEE, 3D-TEE, and MDCT absolute differences (Δ) between THV size and measured annulus diameter, as well as CIs, using ≥ mild PVR as a classification variable. The upper cutoff values for oversizing with the highest combination of sensitivity and specificity are also listed. Discriminatory ability for ≥ mild PVR was good for both MDCT (AUC for perimeter and area CI=0.715 and 0.709, respectively) and 3D-TEE (AUC for perimeter and area CI=0.709 and 0.694, respectively). Figure 6A shows a receiver operating characteristic curve for the 2D-TEE annulus CI using ≥ mild PVR as a classification variable. Figure 6B and 6C shows comparisons of 3D-TEE and MDCT perimeter and area CI, respectively, using ≥ mild PVR as the classification variable. There is no significant difference in AUC values between 3D-TEE and MDCT for perimeter CI or area CI ($P=0.15$ and 0.35, respectively). AUC values for discrimination of ≥ mild PVR for D_{mean} CI between modalities also showed no statistically significant difference ($P=0.45$).

Discussion

The principal findings of this analysis are that (1) novel, off-label use of commercially available software allows 3D-TEE annulus measurements to be made, which closely approximate MDCT measurements; and (2) MDCT and 3D-TEE cross-sectional measurements predict post-TAVR PVR with equivalent accuracy.

MDCT cross-sectional area and perimeter measurements are commonly used for aortic valve annulus sizing before TAVR. Numerous studies have shown the advantages of 3D assessment of the annulus compared with 2D assessment using multiple modalities, including MDCT,[3,5,6,16,20,35,36] 3D-TEE,[7–9,11,28,37] and cardiac MRI.[16] Cross-sectional 3D-TEE annulus measurements have generally been shown to be smaller than MDCT measurements,[11,23,24,38] and a recent study demonstrated that MDCT overestimated whereas 3D-TEE underestimated in vitro phantom annulus diameters.[10] Using a novel, semiautomated 3D-TEE method with widely available software, our study shows excellent correlation between 3D-TEE and MDCT measurements with a small absolute difference (≤1%), with 3D-TEE measurements underestimating MDCT measurements. Although statistically significant, these differences are not clinically relevant. As suggested in the study by Tsang et al,[10] there may be systematic, methodologic reasons for these differences. Three-dimensional TEE and MDCT clearly have different imaging limitations that may lead to the selection of slightly different transverse planes for annulus assessment. In addition, ectopic calcification may introduce significant measurement errors that differ by technique. Finally, the 2 modalities differ in temporal resolution, and thus measurements may be performed in slightly different points in the cardiac cycle.

PVR that is ≥ mild in severity may be associated with increased mortality after TAVR.[39–41] In our analysis, area- and perimeter-based measurements by each modality had statistically similar predictive value for the presence of ≥ mild PVR at the end of the procedure. Jilaihawi et al[11] recently found both MDCT and 3D-TEE cross-sectional measurements to be superior to 2D-TEE annulus for the prediction of PVR. Although not directly compared, the AUC and specificity for prediction of PVR by 3D-TEE cross-sectional measurements were much lower in that study compared with MDCT. This could be explained by several factors: there were fewer PVR events in the 3D-TEE group

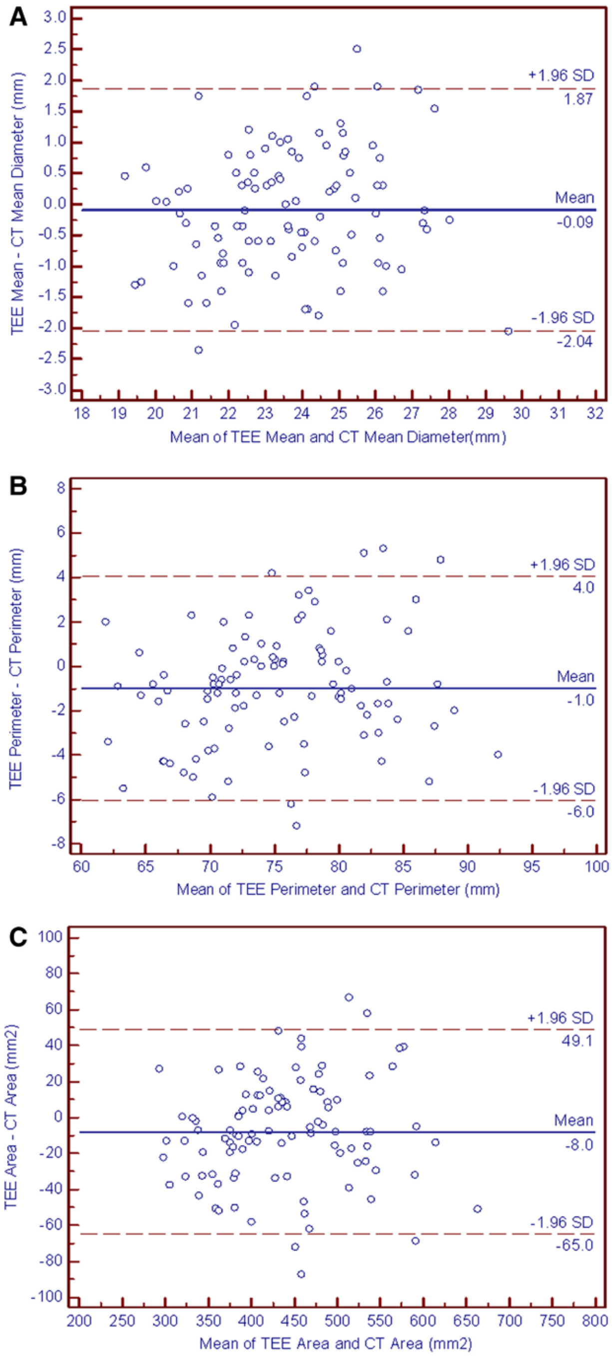

Figure 5. Bland–Altman plots for comparison of 3-dimensional transesophageal echocardiographic (3D-TEE) and multidetector row computed tomographic (MDCT) annulus measurements. Comparison of 3D-TEE vs MDCT annulus mean diameter (**top**), perimeter (**middle**), and area (**bottom**) measurements.

compared with the MDCT group, the technique for cross-sectional 3D-TEE annulus measurement relied on tracing the annulus on a single short-axis view, and MDCT was used to prospectively size the THV with 3D-TEE measurements performed retrospectively. In the patient population used in the current study, treatment decisions were primarily made at the time of implantation using 3D-TEE cross-sectional measurements, and MDCT measurements were performed retrospectively. Our current practice is to use both MDCT and 3D-TEE for sizing and, in the event of a discrepancy, to use the method that provides the best image for data analysis for that individual patient.

Table 2. ROC Analyses for Prediction of ≥ Mild PVR

	AUC	*P* Value	Cutoff	Sensitivity	Specificity
2D TEE					
Δ2D annulus, mm	0.667	0.007	2.3	77.2	56.4
Annulus CI, %	0.669	0.005	9.1	77.3	59.0
3D TEE					
ΔD_{max}, mm	0.689	0.002	0.0	68.2	52.6
ΔD_{min}, mm	0.589	0.24	3.2	59.1	59.0
ΔD_{mean}, mm	0.690	0.001	1.85	72.7	57.7
ΔD_{perim}, mm	0.725	0.001	1.5	77.3	59.0
ΔD_{area}, mm	0.701	0.006	1.4	68.2	69.2
D_{mean} CI, %	0.680	0.003	7.1	72.7	56.4
Perimeter CI, %	0.709	0.0005	5.4	72.7	57.8
Area CI, %	0.694	0.001	12.4	72.7	59.0
MDCT					
ΔD_{max}, mm	0.683	0.001	−0.3	72.7	59.0
ΔD_{min}, mm	0.721	0.0001	3.3	77.3	66.7
ΔD_{mean}, mm	0.717	0.0001	1.4	77.3	59.0
ΔD_{perim}, mm	0.711	0.0003	0.97	77.3	59.0
ΔD_{area}, mm	0.706	0.0005	1.6	77.3	61.5
D_{mean} CI, %	0.722	<0.0001	5.2	77.3	64.0
Perimeter CI, %	0.715	0.0002	3.9	77.3	57.8
Area CI, %	0.709	0.0003	10.7	77.3	60.3

Δ2D annulus indicates nominal THV diameter−2D annulus measurement; 3D, 3-dimensional; AUC, area under the curve; CI, cover index; ΔD_{area}, nominal THV diameter−D_{area}; ΔD_{max}, nominal THV diameter−D_{max}; ΔD_{mean}, nominal THV diameter−D_{mean}; ΔD_{min}, nominal THV diameter−D_{min}; $\Delta D_{perimeter}$, nominal THV diameter−$D_{perimeter}$; MDCT, multidetector row computed tomography; PVR, paravalvular regurgitation; ROC, receiver operating characteristic; and TEE, transesophageal echocardiography.

In our study, the MDCT and 3D-TEE yield comparable measurements of the annulus with equal accuracy in predicting ≥ mild PVR. It is not surprising that the AUC for both modalities is much less than perfect. There are multiple determinants of PVR, including device positioning and LVOT/annulus/leaflet calcification.[41–47] Although the predictive value of annulus sizing is significant, it is unlikely that any method will yield a higher AUC than that shown in this and other studies. In addition, annulus sizing is not the only parameter used to determine THV size; transfemoral access, sinus effacement, sinus height, coronary ostial height, and LVOT anatomy are some of the other important considerations.

Both MDCT and 3D-TEE D_{area} calculations slightly underestimated $D_{perimeter}$. This is likely due, at least in part, to the polygonal line method used in many software packages for annulus tracing (including the 3mensio and MVQ programs used in our study), which creates a disproportionately truncated area compared with perimeter. Although the area CI cutoff would mathematically be expected to be twice the perimeter CI cutoff, the actual area CI cutoff (by either modality) is larger than expected because of a systematic undermeasurement of the true annular area.

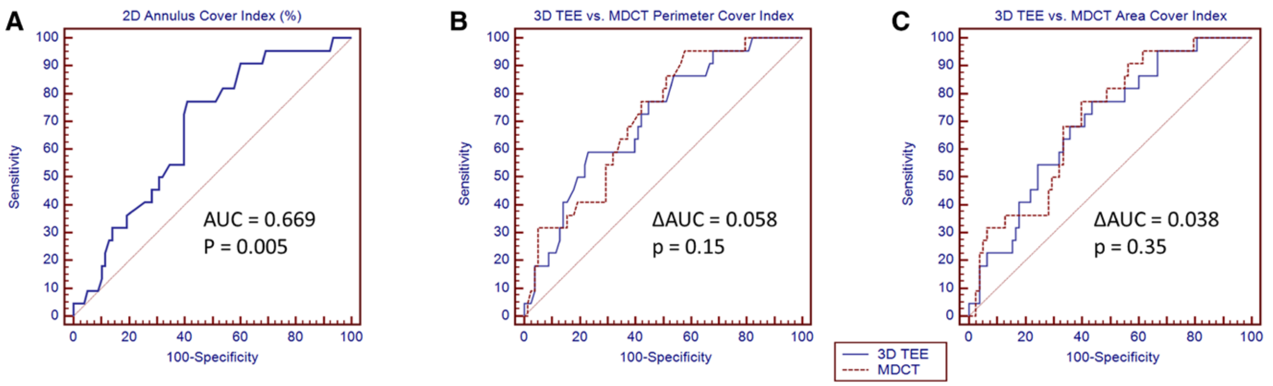

Figure 6. Receiver operating characteristic (ROC) analysis curves for prediction of mild or greater paravalvular regurgitation. **A**, ROC analysis for the 2-dimensional transesophageal echocardiographic (TEE) annulus cover index measurement with the associated area under the curve (AUC)[34] and *P* value. **B**, A comparison of 3-dimensional (3D) TEE vs multidetector row computed tomographic (MDCT) perimeter cover index measurements with the difference in AUC values and *P* value for the difference. **C**, A comparison of 3D-TEE vs MDCT area cover index measurements with the difference in AUC values and *P* value for the difference.

Recent studies[10,11,24] have shown a severe underestimation of 3D-TEE of annulus cross-sectional measurements compared with MDCT measurements. An error in the 10% range that was found in these previous reports is clinically significant and potentially devastating for the patient. The current study also shows smaller measurements by 3D-TEE than by MDCT; however, the difference between 3D-TEE and MDCT measurements is ≤1%, which is much smaller than that observed in studies by Jilaihawi et al,[11] Tsang et al,[10] Husser et al,[25] or Ng et al.[24] Possible reasons for the stronger correlation between 3D-TEE and MDCT measurements in the current study include the novel, off-label use of 3D-TEE software and improvements in MDCT 3D software. Particularly limiting in these previous studies was that the 3D echocardiographic analysis was performed with manual measurements on a single short-axis 3D plane. Given the significant echocardiographic artifacts that may occur (such as acoustic shadowing and side-lobe artifacts), the technique described in the current report allows a more accurate identification of and thus measurement of the annulus. The method does not rely only on the transverse plane of the annulus for this measurement but uses the adjacent structures in the orthogonal long-axis views as an additional guide. We have shown 3D-TEE to be a reliable alternative to MDCT for the assessment of aortic valve annulus. This may allow for critical assessment of the annulus in cases where MDCT angiography is not feasible or desirable, such as in the setting of significant renal insufficiency. Furthermore, if TAVR is used in younger populations in the future, radiation from MDCT will become an increasingly important issue.

Certainly, 3D-TEE and MDCT have distinct strengths and weaknesses. Three-dimensional TEE has superior temporal resolution, which often allows for differentiation of the basal aortic valve hinge point attachments on the basis of visualized separation of calcium, provides physiological information, and essentially eliminates motion-based artifacts. However, 3D-TEE is hampered by suboptimal lateral resolution in the coronal plane, which reduces the ability to measure the blood/tissue interface in this plane. On the contrary, MDCT typically provides superior tissue/lumen contrast but may be limited by artifacts because of partial volume-averaging effects (blooming), heart/lung motion, patient motion (especially in this elderly group of patients who may have difficulty remaining still or holding their breath even for brief periods), and arrhythmias. Both modalities are user dependent, and optimal image acquisition and analysis are always paramount for adequate annular assessment. Given these differences, we think that echocardiography and MDCT are best thought of as complementary imaging modalities. The current study suggests that these 2 modalities are equally accurate and highly correlative.

Limitations

The limitations of 3D-TEE and MDCT imaging have been previously discussed. All measurements were performed by experienced readers. In addition, the acquisition protocol for the 3D-TEE volume sets was also refined to acquire images with the least amount of acoustic shadowing of the annulus. The high reproducibility of these measurements is likely dependent on training and experience, and thus our findings cannot necessarily be generalized to less-experienced readers. Automation of the process for both modalities would be useful. Finally, this analysis included only patients receiving a balloon-expandable Edwards THV, and results about PVR should not be generalized to other valve platforms. Given the mismatch between the SAPIEN and SAPIEN XT patients in our study, we did not analyze these separately. Although studies to date have shown similar short-term PVR and hemodynamic performance data using the SAPIEN and SAPIEN XT valves,[48,49] potential differences between them require further study.

Conclusions

Aortic annulus mean diameter, perimeter, and area can be accurately and reproducibly measured by 3D-TEE. MDCT and 3D-TEE measurements are equally predictive of ≥ mild PVR. Because more automated use-specific software algorithms become commercially available for 3D echocardiography, widespread use will become more feasible.

Disclosures

Dr Williams has received consultant fees from Edwards Lifesciences. Dr Kodali has received consulting fees from Edwards Lifesciences and Medtronic and is a member of the Scientific

Advisory Board of Thubrikar Aortic Valve, Inc., the Medical Advisory Board of Paieon Medical, and the TAVI Advisory Board of St. Jude Medical. Dr Einstein has received grants for other research from GE Healthcare and Philips Healthcare and owns stock in Medtronic. Dr Leon is a nonpaid member of the Scientific Advisory Board of Edwards Lifesciences and Medtronic Vascular. The other authors report no conflicts.

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CLINICAL PERSPECTIVE

Accurate determination of aortic annulus size is essential for the success of transcatheter aortic valve replacement for the treatment of severe, symptomatic aortic stenosis. Multidetector computed tomography (MDCT) has been successfully used for the determination of aortic annulus size. There have not been clinically useful alternatives that provide similar, accurate cross-sectional measurements. The use of iodinated contrast is not ideal for those patients with chronic kidney disease. Furthermore, as with all imaging modalities, MDCT has technical limitations such as motion artifacts, poor temporal resolution, and blooming artifacts. Previous articles have compared MDCT with 3-dimensional transesophageal echocardiography for the measurement of aortic annulus and have found 3-dimensional transesophageal echocardiography measurements to be significantly smaller than MDCT measurements. Using a novel, off-label use of a widely available echocardiography analysis software package, we have found 3-dimensional transesophageal echocardiography aortic annulus measurements to be similar to MDCT measurements. In addition, we have shown measurements by both modalities to be equally predictive of paravalvular regurgitation, an important complication of transcatheter aortic valve replacement that may lead to morbidity and mortality. Given that transesophageal echocardiography is a relatively safe procedure that is often used intraoperatively during transcatheter aortic valve replacement, it is desirable to use it as an alternative or a complement to MDCT for aortic annulus sizing. Our method can potentially be used by echocardiographers intra- or preprocedurally for aortic annulus sizing in cases where MDCT cannot be performed or where confirmation of sizing is desired.