Automated Quantitative 3-Dimensional Modeling of the Aortic Valve and Root by 3-Dimensional Transesophageal Echocardiography in Normals, Aortic Regurgitation, and Aortic Stenosis

Comparison to Computed Tomography in Normals and Clinical Implications

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Background—We tested the ability of a novel automated 3-dimensional (3D) algorithm to model and quantify the aortic root from 3D transesophageal echocardiography (TEE) and computed tomographic (CT) data.

Methods and Results—We compared the quantitative parameters obtained by automated modeling from 3D TEE (n=20) and CT data (n=20) to those made by 2D TEE and targeted 2D from 3D TEE and CT in patients without valve disease (normals). We also compared the automated 3D TEE measurements in severe aortic stenosis (n=14), dilated root without aortic regurgitation (n=15), and dilated root with aortic regurgitation (n=20). The automated 3D TEE sagittal annular diameter was significantly greater than the 2D TEE measurements (P=0.004). This was also true for the 3D TEE and CT coronal annular diameters (P<0.01). The average 3D TEE and CT annular diameter was greater than both their respective 2D and 3D sagittal diameters (P<0.001). There was no significant difference in 2D and 3D measurements of the sinotubular junction and sinus of vasa saliva diameters (P>0.05) in normals, but these were significantly different (P<0.05) in normals. The 3 automated intercommissural distance and leaflet length and height did not show significant differences in the normals (P>0.05), but all 3 were significantly different compared with the abnormal group (P<0.05). The automated 3D annulus commissure coronary ostia distances in normals showed significant difference between 3D TEE and CT (P<0.05); also, these parameters by automated 3D TEE were significantly different in abnormal (P<0.05). Finally, the automated 3D measurements showed excellent reproducibility for all parameters.

Conclusions—Automated quantitative 3D modeling of the aortic root from 3D TEE or CT data is technically feasible and provides unique data that may aid surgical and transcatheter interventions. (Circ Cardiovasc Imaging. 2013;6:99-108.)

Key Words: 3D echocardiography ■ 3D modeling ■ aortic root ■ aortic valve

The progress in surgery of the aortic root1 and the evolution of transcatheter aortic valve (AV) replacement as an alternative to surgical treatment in selected patients2,3 have refocused the need for quantitative imaging of the aortic root during transcatheter AV replacement and valve-sparing aortic root surgery.1-6 In this study, we (1) assessed the ability of automated quantitative modeling of the AV and root from 3D transesophageal echocardiography (TEE) and computed tomographic (CT) data in patients with normal AV and root (normal), (2) compared the measures of the AV and the root obtained by 2D TEE and CT to that obtained by the automated modeling algorithm applied to the respective 3D TEE and CT data in normals, and (3) tested the ability of the automated 3D modeling algorithm to distinguish the abnormal anatomy in patients with severe aortic stenosis (AS) and those with dilated aortic root with without aortic regurgitation (AR).

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Methods

Patient Population

The normal population consisted of 40 patients who prospectively underwent either clinically indicated TEE (n=20) or CT (n=20) for reasons other than AV or root disease and were found to have

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morphologically and functionally normal AV and root on TEE or CT. The abnormal population included 14 patients with severe AS, 15 patients with dilated root and trace/no AR, and 20 patients with dilated root and moderate/severe AR. These latter patients underwent clinically indicated TEE examination. The study was approved by the Institutional Review Board of the Ohio State University.

Echocardiography
A standard, 2D TEE was performed using an iE33 system (Philips Medical System, Andover, MA) equipped with an X72t-TEE probe with the capability of multiplane 2D and 3D real-time and gated imaging. Gated 3D TEE images of the AV and the root in the short axis and long axis orientations were acquired (Figure 1, top). AV gradients, calculation of AV area using the continuity equation, and semi-quantitative assessment of the AR severity using color and spectral Doppler parameters were done from a standard TTE examination.

Cardiac CT Imaging
CT was done using a 64-slice multidetector CT (Siemens Medical Solutions USA Inc., Malvern, PA) with 0.6 mm collimation, 100 to 120 kVp, 500 to 900 mAs, and retrospective ECG gating with dose modulation. All patients received beta blockers or calcium channel blockers to achieve a target heart rate of ≤65 beats/min before the CT study. The field of view extended from just below the diaphragm to the level of mid ascending thoracic aorta. Contrast (Omnipaque, 65–75 mL) was injected through a peripheral intravenous catheter (18–20 gauge) followed by a saline bolus (40–60 mL) at 4 mL/s during an acquisition with inspiratory breath hold. Scans were reconstructed for multiple cardiac phases with a slice thickness of 0.6 mm yielding an isotropic spatial resolution (Figure 2).

Quantitative Measurements

Manual 2D Measurements
In the standard 2D TEE, the sagittal annulus diameter (between the insertion of the noncoronary cusp and the right coronary cusp), the intersinus distance (sinus of valsalva [SOV] diameter), and the sinotubular diameter (sinotubular junction [STJ]) were measured (Figure IA and IC in online-only Data Supplement). Targeted sagittal and coronal 2D annulus diameters were measured from the 3D TEE (Figure IB in online-only Data Supplement) and CT using multiplanar reformatting to obtain the sagittal and coronal views with the left ventricle, left ventricular outflow tract, and proximal aorta in the same 2D cut plane (Figure IIA in online-only Data Supplement). In addition, SOV and STJ diameters were measured (Figure IIB in online-only Data Supplement).

Automated 3D Measurements
The 3D TEE and the CT data were analyzed using dedicated software (Auto Valve Analysis, Siemens, CA) that automatically models the AV and the root. The principles of the automated modeling of the AV and the root using this algorithm have been described before. Briefly, the orthogonal long axis and the short axis views (Figure 1A) automatically extracted from volume TEE or CT data (Figure 2B) were aligned and shown in the 3 quadrants of the screen for visual inspection along with the 3D source 3D data (Figures 1A and 2B). After the identification of end diastole and peak systole frames by the user, the following anatomic landmarks were automatically identified: the lowest point of the insertion of the 3 leaflet hinge, the 3 commissures, the midpoint of the 3 leaflet tips, and the 2 coronary ostia (Figures 1B and 2C). After verification of the accuracy of the automated identification, these landmarks were tracked throughout the cardiac cycle (Figures 1C through 1D and 2D) and the surface model was displayed. The cyclic changes in the parameters were measured and displayed as a graph and on the dynamic models from 3D TEE and CT data (Movies I and II, respectively, in online-only Data Supplement). A detailed description of the parameters can be found in the Methods section of the online-only Data Supplement.

Figure 1. Three-dimensional transesophageal echocardiography data acquisition and steps in automated modeling of the aortic root. (Top) Gated short axis (SAX) and long axis (LAX) three-dimensional source data. A, Automated reformatting and alignment of the volume data followed by identification of landmarks in (B) (green commissures, yellow leaflet tips, pink leaflet insertion hinge, and red coronary ostia. C, Surface tracking of the root components in end diastole and D, shows the same at peak systole in the SAX and LAX orientations, respectively.
Data Analysis
Manual 2D and automated 3D measurements were both made from 3D TEE and CT data in the normal population. The following comparisons were made: (1) 2D TEE, targeted 2D from 3D TEE, and automated 3D annular measurements, (2) manual 2D sagittal and coronal annular diameters from CT to respective 3D CT diameters, (3) SOV and STJ diameters between standard 2D TEE and 2D CT to the respective automated 3D measurements, and (4) automated 3D TEE and CT values for each of the parameters in the normals.

In the abnormal population, the manual measurements of annulus, SOV, and STJ diameters from the standard 2D TEE were compared with the automated 3D TEE modeling. Also, automated 3D measurements of intercommisural length (ICD), leaflet height (LL), leaflet height (LH), coaptation height, annulus to commissure distance, annulus to coronary ostia distance, and leaflet tips to coronary ostia distance were compared between the normal and abnormal groups. All 2D echo (S.L., A.C.) and CT (P.T., A.C.) measurements were done independently by 2 readers blinded to all other measurements. Automated modeling of the AV and the root from the 3D data was done by 2 other readers (A.C., H.H.). These repeated measures were used for interobserver variability comparison, whereas intraobserver variability measurements were done 3 months apart. Annulus measurements were done in mid systole and all other measurements were done in end diastole.

Statistical Analysis
Continuous data are expressed as mean±SD and categorical data as frequency or percentage. All data were first analyzed for normal distribution using the Kolmogorov–Smirnov test and visual assessment using normal plots. For comparison of measurements between more than 2 echocardiography methods, repeated measures ANOVA with Student Newman Keuls post hoc analysis was used. For comparison of measurements by 2 echocardiographic or CT methods, paired t test was used. Unpaired t test was used to compare measurements between echocardiography and CT. Differences between methods are reported as bias, levels of agreement (LOA) (2SD) as determined by Bland and Altman. Reproducibility was assessed using (1) intraclass correlation coefficient and (2) Bland–Altman analysis. To determine whether the reproducibility of one technique was better than the other, the absolute difference was taken between the two observers and compared using repeated measures ANOVA with Student Newman Keuls post hoc analysis for the TEE data, and paired t test for the CT data. Comparison between normals and abnormalities were performed using ANOVA and Student Newman Keuls post hoc or unpaired t test. Statistical analyses were performed using SPSS 17.0 (SPSS, Inc, Chicago, IL) and MedCalc (11.0.1.0, Mariakerke, Belgium). A probability value of <0.05 was considered statistically significant.

Results
Demographics, Procedural, and Analysis Data
The normal population consisted of 40 patients who underwent clinically indicated TEE (n=20; men=13) and CT (n=20; men=11). Both these groups had morphologically normal AV and root, and had no AR. The mean age of the TEE group was 65±13 years (range, 32–90 years) and that of the CT group was 54±16 years (range, 31–84 years). The most common indication (80%) for TEE was pre-electrophysiology procedure (atrial fibrillation/ventricular tachycardia ablation or cardioversion), whereas cerebrovascular accident (10%) and suspected endocarditis (10%) were the other indications. The most common indication for CT was preatrial fibrillation ablation (90%). The severe AS group consisted of 14 patients (men=6; mean age, 68±14 years; range, 54–82 years). The mean AV gradient and calculated AV area by TTE was 48±8 mm Hg and 0.7±0.2 cm², respectively. The dilated aortic root group included 35 patients (men=24; mean age, 59±11 years; range, 55–70 years), 15 of which had no AR and 20 with at least moderate AR. All the patients were in normal sinus rhythm.

Gated 3D TEE imaging of the AV and the root took 5 to 10 seconds for 1 dataset at a temporal resolution of 30 to 40 ms (18–24 volumes/s). We acquired 3 to 5 datasets depending on the quality of the data determined by immediate visual inspection for artifacts. CT of the AV and root took 30 to 40 seconds (image acquisition time only) at a temporal resolution of 160 ms. Data from all the studied patients were included in analysis. The mean time to complete automated 3D modeling of the AV and the root was 2.3±0.6 minutes using either 3D TEE (1.1–3.4 minutes) or CT (1.4–2.4 minutes). In the TEE population, 23 of 69 patients had some adjustment done in the automatically detected landmarks and surface display. This 23
comprised 6 of 14 (43%) patients with severe calcific AS, 13 of 35 (37%) with dilated aortic root with and without AR, and 4 of 20 (20%) in the normals. In the CT population, 8 of 20 (40%) patients needed manual adjustment mainly related to leaflet tracking.

Annulus Diameter

Table 1 summarizes the results for the normal population and examination using normal plots. All _P_≤0.2.

Table 1. Two-Dimensional and 3-Dimensional Annulus Diameters by Transesophageal Echocardiography (n=20) and Computed Tomography in Normals (n=20)

<table>
<thead>
<tr>
<th></th>
<th>Standard 2D TEE</th>
<th>Targeted 2D TEE From 3D TEE</th>
<th>2D CT From Volume CT</th>
<th>Automated 3D Modeling (TEE)</th>
<th>Automated 3D Modeling (CT)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sagittal</td>
<td>Sagittal</td>
<td>Coronal</td>
<td>Sagittal</td>
<td>Coronal</td>
</tr>
<tr>
<td>Mean±SD, mm</td>
<td>21.7±1.6*</td>
<td>22.3±1.6*</td>
<td>21.9±1.5</td>
<td>22.3±2.5</td>
<td>24.8±2.3</td>
</tr>
<tr>
<td>Median (IQR), mm</td>
<td>21.8 (2.3)</td>
<td>22.3 (2.0)</td>
<td>21.9 (1.8)</td>
<td>22.1 (2.8)</td>
<td>25.9 (4.4)</td>
</tr>
<tr>
<td>Intraobserver variability</td>
<td>0.81</td>
<td>0.92</td>
<td>0.97</td>
<td>0.96</td>
<td>0.98</td>
</tr>
<tr>
<td>Bias±LOA, mm</td>
<td>0.1±3.3</td>
<td>0.2±2.2</td>
<td>0.2±2.4</td>
<td>0.2±1.5</td>
<td>0.2±1.1</td>
</tr>
<tr>
<td>Variability, %</td>
<td>5.9±4.2</td>
<td>3.6±3.0</td>
<td>3.6±2.9</td>
<td>2.4±2.1</td>
<td>2.3±1.5</td>
</tr>
<tr>
<td></td>
<td>(0.5–13.1)</td>
<td>(0.5–9.9)</td>
<td>(0–13.9)</td>
<td>(0–10.2)</td>
<td>(0–1–6.1)</td>
</tr>
<tr>
<td>Interobserver variability</td>
<td>0.72</td>
<td>0.87</td>
<td>0.43†</td>
<td>0.96</td>
<td>0.95</td>
</tr>
<tr>
<td>Bias±LOA, mm</td>
<td>0.7±4.4</td>
<td>1.2±2.5</td>
<td>2.0±5.2</td>
<td>1.2±1.6</td>
<td>1.0±2.3</td>
</tr>
<tr>
<td>Variability, %</td>
<td>7.9±6.9</td>
<td>6.9±4.3</td>
<td>12.0±9.3</td>
<td>5.7±3.9</td>
<td>5.2±3.1</td>
</tr>
<tr>
<td></td>
<td>(0.4–30.5)</td>
<td>(0.6–19.1)</td>
<td>(0.5–35.1)</td>
<td>(0–12.8)</td>
<td>(0.2–10)</td>
</tr>
</tbody>
</table>

2D indicates 2-dimensional; 3D, 3-dimensional; CT, computed tomography; ICC, intraclass correlation coefficient; IQR, interquartile range; LOA, level of agreement (2SD); and TEE, transesophageal echocardiography.

*ANOVA _P_<0.03 (see text for post hoc analysis). All annular diameters were normally distributed as determined by Kolmogorov–Smirnov test (_P_–0.42–0.98) and visual examination using normal plots. Except _P_=0.01, except †_P_=0.2.
probability values, <0.001 for all). Also in patients with severe AS, although the mean 3D sagittal and coronal diameters were not significantly different, the 2 diameters differed by >3 mm in 4 of the 14 patients (mean difference, 3.7±0.8 mm).

### Sinotubular Junction and Sinus of Valsalva

Table 2 shows the results from 2D CT and TEE and automated 3D CT and TEE. The STJ and SOV diameter in normals by standard 2D TEE and 3D TEE automated modeling was not significantly different (bias±LOA, 0.2±2.7 mm; $P=0.46$).

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**Figure 3.** Representative Bland–Altman plots for annular diameter measurements. A, Sagittal diameter and B, coronal diameter. 2D indicates 2-dimensional; 3D, 3-dimensional; CT, computed tomography; and TEE, transesophageal echocardiography.

**Figure 4.** Representative 2-dimensional and automated 3-dimensional (3D) transesophageal echocardiography (TEE) annulus measurements in normals and abnormals. The 3D sagittal diameters are all larger than 2-dimensional TEE in all groups. The 3D coronal and average diameters are also larger than the corresponding 3D sagittal diameter. AR indicates aortic regurgitation.
and bias±LOA, 0.5±2.9 mm; \( P = 0.13 \), respectively). With CT, there was no significant difference between manual 2D and automated 3D STJ diameters (bias±LOA, 0.1±2.4 mm; \( P = 0.75 \)), but there was a significant difference in SOV diameter

Table 3. Automated 3-Dimensional Transesophageal Echocardiography (n=20) and Computed Tomographic (n=20) Measurements of Leaflet Anatomy and Annulus–Commissure–Ostia Distances in Normals

<table>
<thead>
<tr>
<th>Left</th>
<th>Noncoronary</th>
<th>Right</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automated 3D TEE</td>
<td>Automated 3D CT</td>
<td>Automated 3D TEE vs Automated 3D CT</td>
</tr>
</tbody>
</table>

Leaflet anatomy

ICD, mm

- Mean±SD: 21.3±1.7
- Median (IQR): 21.3 (2.8)

Leaflet free edge length, mm

- Mean±SD: 30.6±2.4
- Median (IQR): 30.5 (2.8)

Leaflet height, mm

- Mean±SD: 14.9±1.2
- Median (IQR): 15.2 (1.8)

Annulus–leaflet–ostia relationship

Annulus–commissure distance, mm

- Mean±SD: 17.2±1.5
- Median (IQR): 16.9 (2.0)

Annulus–ostia distance, mm

- Mean±SD: 11.3±2.1
- Median (IQR): 13.0 (2.8)

Leaflet–ostia distance, mm

- Mean±SD: 11.3±2.1
- Median (IQR): 11.2 (2.8)

All leaflet anatomy and annulus–leaflet–ostia relationship measurements were normally distributed by Kolmogorov–Smirnov test (\( P = 0.29–0.99 \)) and visual inspection of normal plots, comparison between automated 3D TEE and CT was done using unpaired t test. 3D TEE measurements are shown in Figures 5 and 6. 2D indicates 2-dimensional; 3D, 3-dimensional; CT, computed tomography; ICD, intercommissural distance; IOQ, interquartile range; and TEE, transesophageal echocardiography.
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(bias±LOA, 2.1±5.0 mm; \(P=0.002\)). Also for the normals, there was no significant difference in the mean automated 3D TEE and CT STJ and SOV diameters (bias±LOA, 1.4±7.9 mm; \(P=0.07\) and bias±LOA, 0.8±7.9 mm; \(P=0.38\), respectively). The inter- and intraobserver reproducibility of both 2D and 3D measurements of the STJ and SOV and the automated 3D sinus width was good with small individual measurement variability between repeated measures (variability range, 0.1%–8.3%) with no significant difference between measurements for all these parameters \((P=0.10–0.98)\). Finally, using 3D TEE modeling measurements there were no significant differences in the STJ and SOV parameters between normals and severe AS group, but they were all significantly larger in patients with dilated root (with and without AR, post hoc \(P\leq0.001\) for all).

Leaflet Anatomy

The summary results of leaflet ICD, LL, and LH measurements by automated modeling from 3D TEE and CT data are shown in Table 3. In the normal group, there were no significant differences between 3D TEE and 3D CT for all 3 measurements, except for right coronary cusp ICD length. There was, however, a significant difference in the ICD measurements between the 3 leaflets \((P=0.04;\ \text{ANOVA})\) with the noncoronary cusp ICD being larger than the LCC ICD (bias±LOA, 1.5±2.8 mm; \(P=0.05\) by TEE). Similarly, there was a significant difference in the LH between the 3 leaflets \((P=0.01;\ \text{ANOVA TEE and CT})\) with the noncoronary cusp being taller than the right coronary cusp (bias±LOA, 1.4±3.6 mm; \(P=0.01\) by TEE and bias±LOA, 1.9±3.1 mm; \(P=0.01\) by CT). There was no significant difference in LL between the 3 leaflets \((P>0.05;\ \text{ANOVA for both TEE and CT})\). The ICD, LL, and LH measurements had good intra- and interobserver variability with small individual patient variability (range, 0%–12.9%), and nonsignificant differences between repeated measurements \((P\text{ range, 0.07–0.89})\).

Figure IV in online-only Data Supplement shows ICD, LL, and LH values in normals, AS, and dilated roots. Figure 5 shows a representative example of leaflet parameters, in normals and abnormals. In patients with severe AS, only the LL of all 3 leaflets was uniformly decreased compared with normals (LCC: mean difference, 2.4±7.7 mm; noncoronary cusp: mean difference, 3.2±8.8 mm; right coronary cusp: mean difference, 2.6±9.1 mm; \(P=0.02\) for all). In patients with dilated roots, the ICD, LL, and LH showed significant increase in all leaflets compared with normals \((P\leq0.001;\ \text{ANOVA for all})\). Post hoc analysis showed there was marked increase in all 3 measurements in the AR and no AR group compared with normals (post hoc \(P<0.001\) for all) with the increase being greater in the AR compared with the no AR group \((P<0.05\) for all) except for all 3 leaflet heights \((P>0.8\) for all).

Annulus–Leaflet–Ostia Relationship

In normals, the left commissure was closer to the annulus than the right commissure (bias±LOA, 1.5±2.7 mm; \(P=0.0001\) by TEE and bias±LOA, 2.1±2.4 mm; \(P=0.001\) by CT), and the left coronary ostium was also closer to the annulus (bias±LOA, 1.5±3.0 mm; \(P=0.001\) by TEE and bias±LOA, 2.1±2.4 mm; \(P=0.001\) by CT).
However, the distances between the leaflet tip and the coronary ostia were comparable (bias±LOA, 0.4±4.1 mm; P=0.42 by TEE and bias±LOA, 0.2±4.6 mm; P=0.78 by CT). Also, all of these automated 3D measurements showed a small but statistically significant difference between TEE and CT. Mean values for all 3 measures are summarized in Table 3. The inter- and intraobserver variability of these measurements for both 3D TEE and CT was good with individual patient variability ranging from 0% to 14.6% with no statistically significant difference between the repeated measurements (P range, 0.05–0.89).

Automated measurements from 3D TEE in severe AS, and in those with dilated aortic root compared with normals are shown in Figure V in online-only Data Supplement. There was significant reduction in the left and right annulus to commissure distances in patients with severe AS (left: mean difference, 1.4±3.5 mm; P=0.004 and right: mean difference, 1.8±3.9 mm; P=0.002) and in the annulus to coronary ostia distance (left: bias±LOA, 1.6±4.6 mm; P=0.02 and right: bias±LOA, 2.1±5.2 mm; P=0.005) when compared with normals. The distance between leaflet to coronary ostia in diastole was not different when compared with the normals (left: bias±LOA, 0.6±5.0 mm; P=0.4 and right: bias±LOA, 0.1 mm±8.7; P=0.9). In patients with dilated aortic roots without AR, the annulus to commissure distance was not different compared with normals (P≥0.09 for both), but the distance between the annulus to coronary ostia increased (left: bias±LOA, 3.1±5.5 mm; P=0.002 and right: bias±LOA, 3.1±6.8 mm; P<0.01). Thus, the leaflet tip to coronary ostia distance significantly increased compared with normals (left: bias±LOA, 3.8±6.5 mm; P<0.001 and right: bias±LOA, 3.1±7.7 mm; P<0.001). Similarly, in dilated roots with AR all 3 parameters showed significant increase compared with normals (P≤0.04 for all). Figure 6 shows a representative example of annulus–coronary ostia–leaflet relationship in normals and abnormals.

Discussion

We have demonstrated, for the first time, the ability of an automated algorithm to model the AV and root from 3D TEE and CT data. Furthermore, the findings from the study show that this automated modeling algorithm was able to quantify and characterize the distinctive anatomic changes of the AV and the root in AR and severe AS. Finally, the ability to model the quantitative anatomy from any source volume data, such as CT or 3D TEE, enhances the clinical applicability and the versatility of this approach.

Unlike previous work,9–12 our study used an algorithm based on learned-pattern recognition, which automatically models the AV and the root from volume 3D TEE and CT data. Our data in the normal population show that the conventional 2D TEE single-dimensional sagittal diameter measurement underestimates the maximal sagittal diameter measured by 3D TEE and CT modeling. Also, the sagittal diameter is usually smaller than the coronal diameter measured by any 2D or 3D technique and is less reproducible between observers than the automated 3D sagittal diameters. On the contrary, 2D CT sagittal and coronal diameters were as good as the respective automated 3D CT diameters but were less reproducible than the automated 3D CT measurement. Furthermore, automated 3D TEE or CT yielded annular measurements that were comparable and more reproducible than any other 2D method. Finally, the automated average 3D TEE/CT annulus diameter that accounts for the shape of the annulus was ≈12% larger than their respective sagittal diameter. This emphasizes the limitations of 2D single or biplane measurements.13 Whether this average 3D annulus diameter proves to be the best predictor of the valve prosthesis or graft size remains to be tested.
but there is an evidence that the 3D annulus diameter is superior to the 2D diameter in predicting the ultimate prosthesis size in transcatheter AVR.4

Graft sizing during AV-sparing surgery is usually done in the operating room13 in the underpressurized aorta using nonstandardized techniques by application of flexible rulers on the relatively flimsy aortic leaflets. This can be challenging and lead to errors.15 The data from our study is the first to automatically quantify these measurements preoperatively from 3D TEE and CT data. Also, as the ICD increases, the leaflets remodel16 by becoming taller (=20% compared with normals) and longer (20%–30% compared with normals), which may serve to prevent AR, perhaps reaching a threshold when they are no longer compensatory resulting in AR (Figure IV in online-only Data Supplement). Also, the LL may provide preoperative predictive data for leaflet reduction to match a given graft size.

Similar to previous reports9–17 the data from our study also demonstrate longitudinal remodeling in severe AS. In our study, the annulus to commissure distance was reduced by ≈10%, consequently the annulus to coronary ostia was reduced by 10% to 15%. This has implications both for placement and deployment of transcatheter valves, especially in those with small aortic root.5 The measurement of annulus to coronary ostia distance on 2D planes derived from volume data, such as CT, has shown discrepancy with ex vivo measurements.18 This may be because of the differing 2D techniques (Figure VI in online-only Data supplement), which emphasizes the advantage of direct 3D measurement in our study. The minimal distance between the leaflet tips and coronary ostia can also be measured that may help predict potential complications of calcium embolization during transcatheter AV replacement.

Limitations
We have not demonstrated accuracy of these automated measurements compared with independent standards, such as measurements made during surgery. The values reported here, however, are consistent with previously reported measurements made during surgery in the depressurized aorta. We have shown equivalency of data between automated 3D TEE and CT in different normal populations, whereas this is best done in the same patients. Although we have reported measurements from a single point in the cardiac cycle, there were no significant (=7%) cyclic variations of these parameters similar to previous reports with the exception of the AV area. Severe calcification and bicuspid AV may pose significant challenges to automated detection of annulus and this needs to be tested in future studies. Also, small sample size and the retrospective nature of our study means prospective studies are necessary to show feasibility and the impact on procedural and clinical outcomes.

Conclusions
This is the first study to describe the ability of an automated algorithm to model and quantify the aortic root anatomy in normals from 3D TEE and CT data, and from 3D TEE in normals. This unique dynamic 3D modeling approach offers a comprehensive preinterventional quantitative characterization of the trileaflet valve structure and the root in patients with abnormal aortic root.

The rapidity of obtaining the data from any volume data set and the superior reproducibility of the data from the automated 3D method compared with all other manual methods enhance its clinical use and application in routine practice.

References

Disclosures
Dr Vannan is a member of Per Diem Advisory Board, speakers honorarium, and received research support from Siemens. Drs Ionasec and Houle are Siemens Employees. The other authors have no conflicts to report.
Recent developments in aortic root interventions have focused on the need for 3-dimensional imaging of the aortic functional anatomy. In this study, we describe a unique, automated approach to quantify the functional anatomy of the aortic root from any imaging volume data set, such as transesophageal echocardiography or computed tomography. Given the workflow advantages of automation, this approach may enhance the clinical adoption of routine 3-dimensional imaging. Also, the ability to obtain these measurements preintervention may be useful for the optimal selection of patients and type of interventions and perhaps improve outcomes during valve-sparing aortic root surgery or transcatheter aortic valve replacement. This needs to be tested in prospective studies.
Automated Quantitative 3-Dimensional Modeling of the Aortic Valve and Root by 3-Dimensional Transesophageal Echocardiography in Normals, Aortic Regurgitation, and Aortic Stenosis: Comparison to Computed Tomography in Normals and Clinical Implications

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Supplement Material
Methods

Quantitative Measurements: Automated 3-D Measurements

The automated cyclical changes in the following parameters were measured and displayed as a graph and on the dynamic models from 3-D TEE and CT data (Movies 1 and 2, respectively): 1) Annular diameters: the sagittal diameter (distance between the middle of the insertion of the RCC and the opposite N-L commissure), the coronal diameter (distance between the midpoint of the insertion of the LCC and the R-N commissure), and the average diameter was the 3-D circumference of the most basal attachment of the leaflets divided by π, 2) the diameter of the SOV (diameter of circumference of the widest 3-D area detected along the root divided by π), 3) the STJ diameter (diameter of the circumference enclosing the smallest 3-D area identified immediately above the level of the sinuses divided by π), 4) leaflet height (LH) (distance from the hinge to leaflet free edge), 5) leaflet free edge length (LL) (leaflet length between two commissural attachments), 6) inter-commissural distance (ICD) (length between the two commissural insertions of a cusp) 7) sinus width (L, NC, R) (linear distance from the widest point of each sinus to its adjacent point (the commissure between 2 other cusps), 8) distance of the leaflet edge to the coronary ostia, 9) distance from the annulus to the coronary ostia and 10) distance from the annulus to the commissure.

The automated modeling method relies on recent advances in discriminative learning to automatically estimate patient-specific parameters from unseen volumetric data. A hierarchical scheme is applied to robustly detect valvular anatomical models, which capture complex morphologic, dynamic, and pathologic variations. Training and validation of the used machine-learning algorithms was performed on a large database (500+ studies) of manually annotated examples, while the robustness and accuracy of the underlying technology has been proven in numerous medical imaging applications.
and other fields. It is important to note that the method is not limited to data from a specific vendor and may be extended to other imaging sources such as CMR.

**Figures**

**Figure I:** shows the manual 2-D annulus measurements made from standard 2-D TEE (A), targeted 2-D from 3-D Echo (B) and sinus of valsalva and sino-tubular junction (SOV,STJ) diameters in standard 2-D TEE (C). R, L, N = right, left and non-cori- onary cusps, LV = left ventricle, Ao = aorta.

![Figure I](image1.png)

**Figure II:** Manual 2-D CT sagittal and coronal annulus diameters (A) and the SOV and STJ diameters measurements. R, L, N = right, left and non-cori- onary cusps, LV = left ventricle, Ao = aorta.

![Figure II](image2.png)
**Figure III:** Sagittal, Coronal and Average 3-D TEE annulus diameters showing means and range of the values in the various groups. There is no significant difference between normals and AS. The dilated root group with and without AR have significantly larger annulus (*) compared to normals, those with AR having the largest annular dimensions.

<table>
<thead>
<tr>
<th></th>
<th>Sagittal</th>
<th>Coronal</th>
<th>Average</th>
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<tr>
<td>Normal</td>
<td>24.8</td>
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<td>24.0</td>
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<tr>
<td>AS</td>
<td>27.7</td>
<td>27.5</td>
<td>27.8</td>
</tr>
<tr>
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<td>34.0</td>
<td>24.0</td>
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<tr>
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<td>21.0</td>
<td>20.8</td>
<td>20.7</td>
</tr>
<tr>
<td>AS</td>
<td>21.0</td>
<td>20.8</td>
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<tr>
<td>Dilated Root No AR</td>
<td>24.0</td>
<td>24.0</td>
<td>27.3</td>
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<tr>
<td>Dilated Root With AR</td>
<td>24.0</td>
<td>24.0</td>
<td>24.4</td>
</tr>
</tbody>
</table>

*(n=20) (n=14) (n=15) (n=20) (n=20) (n=20)*
Figure IV: Automated quantitative 3-D TEE remodeling of leaflets in normals, severe aortic stenosis and dilated root without and with AR. In the normals, there is a non-significant asymmetry in the ICD distances, LL and LH. As the ICD distances increase in dilated aortic root, the LL and LH increase as well. With continued increase in AR, the development of AR is associated with attenuation of further increase in LH whereas the LL continues to increase. In severe AS, the LH of all 3 leaflets are decreased compared to normals. (ICD = inter-commissural distance, LL = leaflet length, LH = leaflet height, AR = aortic regurgitation, AS = aortic stenosis. * denotes statistically significant, details in text.)
**Figure V:** shows the means and range of values for 3-D TEE quantification of annulus-commissure-coronary ostia distances in the various groups. In the AS group, there is significant (*) decrease in annulus-commissure distance resulting in a significant decrease in annulus-coronary ostia distance, although there is overlap with the normals. The leaflet tip to coronary ostia distance is not significantly different compared to normals in diastole. All these parameters are significantly increased in the dilated root group as expected.
Figure VI: Panel A and B illustrate the aortic leaflets (arrows) both in diastole (A) and systole (B). The signal to noise and contrast to noise ratio in B is poor compared to A due to systolic phase dose modulation used to minimize patient radiation exposure. This makes it difficult to measure leaflet height in systole as compared to in diastole (B). Panels C and D illustrate two different techniques to measure the ostium to hinge height both for the right and left coronary arteries.
Figure Legend for Movie Files

**Movie 1** automated measurements from 3-D TEE modeling in normal.

**Movie 2** automated measurements from 3-D CT modeling in normal.