A Study of Functional Anatomy of Aortic-Mitral Valve Coupling Using 3D Matrix Transesophageal Echocardiography

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Background—Mitral and aortic valves are known to be coupled via fibrous tissue connecting the two annuli. Previous studies evaluating this coupling have been limited to experimental animals using invasive techniques. The new matrix array transesophageal transducer provides high-resolution real-time 3D images of both valves simultaneously. We sought to develop and test a technique for quantitative assessment of mitral and aortic valve dynamics and coupling.

Methods and Results—Matrix array transesophageal (Philips iE33) imaging was performed in 24 patients with normal valves who underwent clinically indicated transesophageal echocardiography. Custom software was used to detect and track the mitral and aortic annuli in 3D space throughout the cardiac cycle, allowing automated measurement of changes in mitral and aortic valve morphology. Mitral annulus surface area and aortic annulus projected area changed reciprocally over time. Mitral annulus surface area was 8.0 ± 2.1 cm² at end-diastole and decreased to 7.7 ± 2.1 cm² in systole, reaching its maximum (10.0 ± 2.2 cm²) at mitral valve opening. Aortic annulus projected area was 4.1 ± 1.2 cm² at end-diastole, then increased during isovolumic contraction reaching its maximum (4.8 ± 1.3 cm²) in the first third of systole and its minimum (3.6 ± 1.0 cm²) during isovolumic relaxation. The angle between the mitral and aortic annuli was maximum (136° ± 13°) at end-diastole and decreased to its minimum value (129° ± 11°) during systole.

Conclusions—This is the first study to report quantitative 3D assessment of the mitral and aortic valve dynamics from matrix array transesophageal images and describe the mitral-aortic coupling in a beating human heart. This ability may have impact on patient evaluation for valvular surgical interventions and prosthesis design. (Circ Cardiovasc Imaging. 2009;2:24-31.)

Key Words: 3D echocardiography ■ imaging ■ mitral valve ■ aortic valve ■ aortic-mitral valve coupling

The mitral and aortic valves are coupled via fibrous tissue connecting the two annuli. An in-depth understanding of the normal mitral-aortic valvular coupling and the ability to accurately assess changes in different disease states may be important, particularly in the context of valvular surgical planning and postsurgical assessment. However, this coupling is difficult to evaluate using 2-dimensional imaging techniques because of the 3-dimensional (3D) anatomy of these structures. Consequently, the aortic and mitral valves have been studied in humans separately as if their function was independent of each other. Assessment of the mitral valve dynamics in humans using 3D echocardiographic techniques, such as gated acquisition of multiple slices for volume reconstruction, and the more recent transthoracic real-time 3D echocardiography (RT3DE) has been previously described. However, data presented in these studies have been limited by either a low temporal resolution, which allows only static measurements at one phase of the cardiac cycle, or by a low spatial resolution, which limits the visualization of valve morphology during dynamic assessment.

Clinical Perspective see p 31

Because the motion of the aortic valve complex is even more difficult to characterize, few studies have addressed in detail the functional anatomy of this valve in 3D. These studies have been mostly limited to invasive techniques based on the implantation of crystals or radiopaque markers in animals. Based on these findings, there is growing evidence that the dynamics of these two annuli throughout the cardiac cycle are interrelated and that mitral-aortic valvular coupling is an integral part of the normal cardiac physiology. To allow the noninvasive evaluation of this coupling, it is essential to have a 3D technique that allows simultaneous imaging of both valves at sufficiently high spatial and temporal resolutions.
The recently developed RT3DE matrix array transesophageal (mTEE) transducer provides 3D images of higher spatial resolution than the earlier transthoracic images. When combined with higher temporal resolution achieved by zoomed full-volume acquisition focused on different valves, the use of this probe results in superb image quality with unparalleled level of spatial and temporal detail. Our hypothesis was that these images could be suitable for (1) detailed study of functional anatomy of the aortic valve and (2) simultaneous analysis of mitral and aortic valves that would allow quantitative assessment of their dynamic behavior and accurate characterization of their coupling. To test this hypothesis, we developed a new software for quantitative analysis of mitral and aortic valve dynamics from mTEE images.

Methods

Protocol

Twenty-four patients (7 males, 17 females; age, 54±20 years; lower quartile, 42.0 years; median, 52.9 years; upper quartile, 72.5 years) were studied during a clinically indicated tranesophageal echocardiography (TEE), which was performed according to standard protocol. Inclusion criteria were (1) normal aortic valve and the absence of aortic root abnormalities and aortic regurgitation; (2) normal mitral valve with no more than trace mitral regurgitation; and (3) normal left ventricular (LV) volumes and function (ejection fraction >55% without wall motion abnormalities). The research portion of the study was approved by the Institutional Review Boards of The University of Chicago. Written informed consent was obtained at the time of consent for the clinical TEE procedure.

Real-Time 3D Echocardiography

Both clinical and research portions of the TEE study were performed using the iE33 ultrasound imaging system (Philips Medical Systems) equipped with the fully sampled mTEE transducer (×7). This transducer uses ~3000 elements, in contrast to the 64 elements currently used in the multiplane TEE probe (Omini 3, Philips). Despite this difference in the number of elements, the sizes of the 2 transducer heads are comparable. The probe was positioned at the midesophageal level at a 120° tilt. The scan volume in the wide-angled acquisition mode included the mitral apparatus, the aortic valve, and proximal ascending aorta, while excluding the mitral and apical ventricular segments to maximize frame rate (Figure 1, bottom). This full-volume mode uses ECG gating to merge 7 narrow pyramidal scans obtained over 7 consecutive heartbeats. To avoid stitch artifacts, special care was taken to stabilize the probe during data acquisition. Because stitch artifacts are easily recognizable in the 3D volume rendering mode in real time, the acquisition was repeated whenever obvious artifacts were noted.

RT3DE Data Analysis

The RT3DE data sets were analyzed using a custom software designed to quantify the dynamic behavior of the mitral annulus (MA) and the aortic annulus (AoA). Briefly, this was achieved by semiautomatically detecting these structures and then automatically tracking them in 3D throughout the cardiac cycle using optical flow and region-based matching techniques,10 which are based on the analysis of speckle noise patterns within the 3D data sets. Then, the tracked points were displayed frame by frame throughout the cardiac cycle to visually verify their position in 3D space, and manual corrections of these points were performed when necessary. Several parameters were automatically measured on the detected annuli throughout the cardiac cycle.

Mitral Valve Annulus Initialization and Measurements

Initially, a cut plane representing the 3-chamber view in the end-diastolic (ED) volume, which was selected as the first frame depicting closed mitral valve, was displayed. In this plane, 2 points were identified on the anterior (MA saddle-horn, MA1) and posterior (MA2) mitral valve annulus (Figure 2A). This initialization was then repeated (MA3 and MA4) on an orthogonal plane crossing the center of the line connecting MA1 and MA2. The middle point of the segment connecting MA1 and MA2 was considered as the MA center. Subsequently, 15 long-axis cut planes evenly rotated around the MA center (12° steps) were automatically displayed to complete the initialization. On each plane, the operator selected 2 points, one on each side of the MA. The same procedure was then applied to the end of isovolumic relaxation (end-IVR) frame. After automatic tracking, MA points were connected using spline interpolation to obtain the annular line (Figure 2D). Finally, a 3D MA surface was generated for each consecutive frame throughout the cardiac cycle by connecting the points with a triangulated mesh. The highest point of MA was used to define the center of mitral valve saddle. The MA was split into 2 parts: (1) the anterior fibrous part computed as 120°-wide MA portion centered on the previously computed saddle point, and (2) the posterior part corresponding to the remaining 240° portion of MA. The sequence of 3D MA surfaces and annular lines was used to obtain the following measurements throughout the cardiac cycle to describe the dynamic behavior of the MA:

1. MA surface area calculated as the sum of areas of all mesh triangles;
2. MA surface area change normalized by the MA surface area at ED;
3. longitudinal displacement of the whole MA and separately its anterior and posterior portions computed as the average motion
of all MA points along the direction orthogonal to the MA surface;
4. mitral valve height, computed as the distance between the highest and the lowest MA points in the direction orthogonal to the mitral valve.

Aortic Valve Annulus Initialization and Measurements

In this study, the term “aortic annulus” refers to the line representing the insertion of the aortic cusps into the sinuses of Valsalva (Figure 2B and 2D). First, 2 points on the AoA were manually initialized at ED phase on a cut plane of the volume data set. Then, the orthogonal plane crossing the center of the line connecting these 2 points was displayed, and 2 additional points were selected on the AoA. From these 4 points, the vector orthogonal to the AoA was automatically computed and used as the vertical axis of the AoA. Fifteen vertical cut planes passing through this axis (12° apart) were displayed one-by-one and 2 AoA points were identified on each plane (Figure 2B). Using these additional points, the vertical axis of the AoA was recalculated. This allowed viewing of a series of cut planes parallel to the AoA, which represent the short axis views of the outflow tract, base of the aortic cusps, cusp coaptation point, interatrial septum, sinus of Valsalva, and sinotubular junction. The positions of the coaptation point and the interatrial septum were manually marked on the ED frame (Figure 2C). The same procedure was then applied to end-systolic (ES) frame.

These AoA points were automatically tracked throughout the cardiac cycle and connected using 3 splines, one for each cusp in every frame (Figure 2D). The interatrial point was used as reference position to identify the noncoronary aortic cusp, and then to identify the left and right cusps. On the ED frame, cusp surfaces were computed and displayed as the mesh connecting every AoA point with the coaptation point.

Finally, the following parameters were calculated at ED phase (Figure 3):

1. area of each aortic cusp as the mesh connecting the AoA points and the coaptation point;
2. cusp free-edge for each cusp as the sum of the distances between the coaptation point and the commissural points pertaining to each cusp;
3. coaptation point height with respect to the lowest AoA point;
4. effective cusp height as the distance between the coaptation point and the lowest point of each cusp AoA portion.

In addition, the following parameters were calculated throughout cardiac cycle:

5. AoA area and length projected on the AoA base plane;
6. AoA nonplanarity defined as the height of commissural points relative to the lowest AoA point;
7. the length of the semilunar segment of AoA corresponding to the insertion site of each cusp;
8. intercommissural distances;
9. distance between AoA and MA centers;
10. angle between the MA and AoA defined as the angle between the line connecting the MA center with the highest MA saddle point and the line connecting this MA saddle point with the AoA center.

Statistical Analysis

Computed parameters were averaged for all patients at ED and when possible at isovolumic contraction (IVC), ES, and end-IVR. Data are presented as mean±SD. Differences between parameters computed...
Table 1. Mitral Annulus Measurements

<table>
<thead>
<tr>
<th>Displacement</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ES MA displacement, mm</td>
<td>7.7±2.8</td>
</tr>
<tr>
<td>ES anterior MA displacement, mm</td>
<td>7.4±2.5*</td>
</tr>
<tr>
<td>ES posterior MA displacement, mm</td>
<td>8.2±3.2*</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Velocity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum systolic velocity, mm/s</td>
<td>40.6±14.3</td>
</tr>
<tr>
<td>Maximum diastolic velocity, mm/s</td>
<td>46.5±25.0</td>
</tr>
</tbody>
</table>

Mitral annulus area

| ED MA area, cm²                  | 8.0±2.1        |
| Minimum MA area (during systole), cm² | 7.7±2.1        |
| Maximum MA area (during early diastole), cm² | 10.0±2.2       |
| End-IVR MA area, cm²             | 9.5±2.2        |
| Minimum systolic MA area change, % of ED area | -4.4±6.1       |
| Maximum diastolic MA area change, % of ED area | 25.4±12.7      |
| Timing of maximum systolic MA area, %RR | 23.0±20.3      |
| Timing of maximum diastolic MA area change, %RR | 63.9±9.0       |
| Height                           | Value          |
| ED MA height, mm                 | 7.4±1.6†       |
| ES MA height, mm                 | 8.1±1.7†       |

*Significant difference at P<0.008 (paired Wilcoxon–Mann–Whitney test).
†Significant difference at P<0.016 (paired Wilcoxon–Mann–Whitney test).

Results

Images obtained with the mTEE transducer were of high quality and allowed MA and AoA tracking throughout the cardiac cycle in all patients. Spatial resolution in the reformatted Cartesian data ranged between 0.3 and 0.9 mm, and the mean temporal resolution was 18.7±8.4 frames per cardiac cycle. Values of the parameters describing MA and AoA behavior are presented in Tables 1 and 2, respectively. Figure 4 depicts the main findings related to mitral and aortic valve coupling for MA area, AoA projected area and mitral-aortic angle in correspondence with blood pressure diagram. Maximum and minimum values were 9.9±2.2 and 7.7±2.1 cm² for MA area, and 4.8±1.3 and 3.6±1.0 cm² for AoA projected area, respectively. When MA area was maximal during early diastole, AoA projected area was at its minimum, and, conversely, when MA area was minimal during systole, AoA projected area reached its maximum value. Thus, the 2 parameters that describe valve area exhibited a synchronized reciprocal behavior. The minimum value for the angle between mitral and aortic valves occurred at ES and was significantly smaller than the angle measured at ED, IVC, and end-IVR (Figure 4).

We found that AoA center remained throughout the cardiac cycle in the same plane, corresponding to the 3-chamber view. This plane also contained the MA center. During the period of IVC, as the LV pressure increased, the AoA moved outward, increasing AoA-MA center distance from 25.0±3.2 to 25.8±3.1 mm (P<0.0001). Subsequently, during systole, as the ventricle ejected, both the AoA and MA moved in synchrony toward the apex. Then, during the IVR, as the pressure in the ventricle declined, the AoA moved inward, reaching minimal distance between the centers of the two annuli (25.0±3.5 mm). Finally, during diastole the AoA moved toward the LV base, thus completing a loop and reaching its original position.

The measured parameters reflected the changes in MA geometry throughout the cardiac cycle. MA surface area (Figure 4) reached its maximum value during early diastole (63.9±9.0% of RR) shortly after mitral valve opening, whereas the MA surface area minimum value occurred during ventricular systole (23.0±20.3% of RR). MA area change from MA area at ED ranged from a minimum value of -4.4±6.1% to a maximum value of 25.4±12.7%. As expected, the MA motion curve resembled the LV volume curve2,12 and reached its maximum distance from MA ED position at ES (7.7±2.8 mm). MA anterior section showed less motion throughout the cardiac cycle than the posterior MA section, with maximum anterior MA displacement (7.4±2.5 mm) being significantly smaller than the posterior value (8.2±3.2 mm). Mitral valve height, which represents MA planarity, was equal to 7.4±1.6 mm at end-diastole, then increased during systole to 8.1±1.7 mm, and subsequently decreased gradually during diastole.

Similarly, parameters describing the changes in AoA geometry throughout the cardiac cycle were quantified. At end-diastole, aortic cusp areas were 1.6±0.7, 1.8±0.8, and 1.7±0.7 cm² for the noncoronary, left and right cusps, respectively. The lengths of the free-cusp edges at end-diastole were 23.6±3.9 mm for the noncoronary, 23.3±4.1 mm for the left, and 22.0±3.7 mm for the right aortic cusps. At ED, the height of the coaptation point above the aortic basal plane was 6.9±1.8 mm, whereas its distance to the 3 lowest AoA cusp points (effective cusp height) was 13.8±2.6, 13.7±2.0, and 13.2±1.9 mm for the noncoronary, left and right cusps, respectively.

The AoA projected area was equal to 4.1±1.2 cm² at end-diastole, then during IVC it rapidly increased reaching its peak (4.8±1.3 cm²) during the first third of systole (19±12% RR), and then gradually decreased to 3.8±1.1 cm² at ES, with its minimum value (3.6±1.0 cm²) measured at 57±17% of RR phase. The same pattern was noted in the total annular length, the projected length of the AoA, and the intercommissural distances. Importantly, the left and right semilunar portions of the AoA, corresponding to the cusp insertion sites into the respective sinus of Valsalva, showed the same behavior of the AoA projected area, whereas the noncoronary semilunar portion showed no significant changes throughout the cardiac cycle despite showing a similar trend. Dimensions of noncoronary intercommissural distance and semilunar AoA segment were significantly bigger than left and right.
In human, transesophageal and real-time 3D transthoracic echocardiography play a fundamental role in the assessment of functional anatomy of these valves,

### Table 2. Aortic Annulus Measurements

<table>
<thead>
<tr>
<th></th>
<th>ED</th>
<th>IVC</th>
<th>ES</th>
<th>End-IVR</th>
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<tbody>
<tr>
<td>NC cusp area, cm²</td>
<td>1.6±0.7</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>L cusp area, cm²</td>
<td>1.8±0.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R cusp area, cm²</td>
<td>1.7±0.7</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>NC cusp effective height, mm</td>
<td>13.8±2.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L cusp effective height, mm</td>
<td>13.7±2.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R cusp effective height, mm</td>
<td>13.2±1.9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NC cusp free-edge length, mm</td>
<td>23.6±3.9</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>L cusp free-edge length, mm</td>
<td>23.3±4.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R cusp free-edge length, mm</td>
<td>22.0±3.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coaptation point height, mm</td>
<td>6.9±1.8</td>
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<td></td>
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<tr>
<td>AoA length,* mm</td>
<td>89.8±13.5</td>
<td>93.6±14.6</td>
<td>84.7±15.5</td>
<td>83.7±15.3</td>
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<tr>
<td>AoA projected area,* cm²</td>
<td>4.1±1.2</td>
<td>4.6±1.3</td>
<td>3.8±1.1</td>
<td>3.7±1.1</td>
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<tr>
<td>AoA length,* mm</td>
<td>73.3±10.9</td>
<td>78.1±11.5</td>
<td>70.3±10.5</td>
<td>69.5±10.6</td>
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<tr>
<td>NC-L cusps commissure height,* mm</td>
<td>7.9±2.1†</td>
<td>7.1±2.2†</td>
<td>6.3±2.2†</td>
<td>6.4±1.8†</td>
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<tr>
<td>L-R cusps commissure height, mm</td>
<td>8.8±2.2</td>
<td>9.4±2.8</td>
<td>8.9±3.3</td>
<td>8.5±3.5</td>
</tr>
<tr>
<td>R-NC cusps commissure height,* mm</td>
<td>9.1±2.1</td>
<td>9.7±2.8</td>
<td>8.9±3.3</td>
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<tr>
<td>Annular length NC cusp, mm</td>
<td>29.3±5.4</td>
<td>31.6±9.1</td>
<td>29.2±5.6</td>
<td>29.4±6.3‡</td>
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<tr>
<td>Annular length L cusp,* mm</td>
<td>30.5±5.5</td>
<td>31.5±6.8</td>
<td>27.8±7.5</td>
<td>27.0±6.9</td>
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<tr>
<td>Annular length R cusp,* mm</td>
<td>29.9±4.9</td>
<td>30.5±5.5</td>
<td>27.7±5.4</td>
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<td>NC intercommissural distance,* mm</td>
<td>19.4±3.1</td>
<td>21.1±4.8</td>
<td>19.9±3.1</td>
<td>19.2±3.3‡</td>
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<td>L intercommissural distance,* mm</td>
<td>20.1±3.2</td>
<td>20.6±3.7</td>
<td>18.4±4.0</td>
<td>18.2±3.5</td>
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<tr>
<td>R intercommissural distance,* mm</td>
<td>19.1±3.2</td>
<td>20.1±3.5</td>
<td>18.4±3.3</td>
<td>17.5±3.0</td>
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<tr>
<td>AoA-MA baricenter distance,* mm</td>
<td>25.0±3.2</td>
<td>25.8±3.1</td>
<td>25.2±2.8</td>
<td>25.0±3.5</td>
</tr>
<tr>
<td>Angle between mitral and aortic valves,* degree (°)</td>
<td>136.2±12.6</td>
<td>135.7±12.2</td>
<td>129.4±11.0</td>
<td>135.6±12.1</td>
</tr>
</tbody>
</table>

*Changes during cardiac cycle are significant at *P*<0.05 by Friedman test.
†Differences between the 3 groups of cusps, including noncoronary (NC), left (L), and right (R) are significant at *P*<0.05 by a 3-factor Friedman test; and NC-L cusp value is the smallest one.
‡Noncoronary cusp value is significantly greater than left and right values, *P*<0.05 (paired Wilcoxon–Mann–Whitney test).

ones at end-IVR. Commissure height (AoA nonplanarity) values are reported in Table 2. Of note, the height of the commissure point between the noncoronary and the left cusps was significantly smaller than the other 2 commissural heights at all phases of the cardiac cycle.

The reproducibility data for AoA parameters is summarized in terms of inter- and intraobserver variability in Table 3. Importantly, intraobserver variability was below 10% for all parameters, and, as expected, the interobserver variability was slightly higher for most parameters.

### Discussion

To date, several imaging modalities have been used to separately study the functional anatomy of the aortic and mitral valve. However, the coupling between the aortic and mitral valves in 3D was studied only in animals using invasive markers. In humans, transesophageal and real-time 3D transthoracic echocardiography play a fundamental role in the assessment of functional anatomy of these valves and can be effectively used to evaluate their potential reparability. The fast-paced developments in annular prosthetic devices used for mitral and aortic valve repair and replacement have created the need for new quantitative methods for accurate assessment of both mitral and aortic valve dynamics as well as their coupling. This is the first study to develop and test a noninvasive technique for detailed characterization of aortic valve dynamics and quantitative evaluation of mitral and aortic valvular coupling throughout the cardiac cycle in a beating human heart using the newly developed mTEE 3D imaging technology. This technology provides high-quality images of the heart because of the proximity of the transducer to the aortic and mitral valves without the interposition of lungs or bone structures.

As expected, the mTEE 3D images showed that the aortic cusps are inserted into the wall of the root in a semilunar fashion. The line corresponding to these insertions has been characterized by having collagenous condensation, which in this study was considered as the AoA. The AoA was visualized in 3 dimensions as having a crown shape (Figure 3), whereas the base of aortic valve was identified as the planar projection of the AoA passing through the lowest points of the AoA. Because there is no consensus on the definition of aortic “commissures” in 3 dimensions, we considered the highest points of the crown-shaped AoA as the commissures (Figure 3).
anterior mitral leaflets, and was characterized by a saddle shape with its highest point in the midsection of the anterior MA, adjacent to the fibrous aortic curtain.\textsuperscript{2,5,21}

Our analysis technique allowed us to perform for the first time in a beating human heart 3D measurements of aortic cusp area, length of the free edges of the cusps, the height of the coaptation point above the AoA basal plane, as well as the effective cusp height. Several animal studies using invasive markers described differences in the motion patterns of the different aortic sinuses.\textsuperscript{9,22} We did not find the exact same asymmetrical behavior in our human study, probably because of multiple reasons including the confounding effects of the open chest preparation coupled with marker implantation, but also the relatively limited resolution of the 3D echocardiographic images and their low signal to noise ratio, which could have lead to inaccurate annular tracking. However, we found that the noncoronary semilunar segment of AoA, unlike the other 2 cusps, does not exhibit significant changes in length during the cardiac cycle, possibly because of the proximity of the basal part of the aortic curtain corresponding to the intertrigonal fibrous tissue of the MA that could constrain the expansion of this particular sinus.\textsuperscript{9,22} In agreement with previous results,\textsuperscript{19} we found that the noncoronary intercommissural distance and semilunar annular length were the largest. However, in our study this difference was only noted when the valve was under minimal stress at the end-IVR period. Interestingly, we observed a previously undescribed loop-like motion of the AoA, the significance of which in terms of pump efficiency will need to be elucidated in future studies.

In agreement with previous studies, our results confirmed that the MA is a deformable structure that changes in dimension and shape during the cardiac cycle.\textsuperscript{2,23,24} Interestingly, we found that the nonplanarity of the saddle shaped MA was not constant throughout the cardiac cycle, but rather increased during systole. In other words, the aortic curtain that is shared with aortic valve acted as an anchor for the anterior part of the mitral annulus, whereas the posterior part was more mobile.

These observations made for the 2 valves suggest that the fibrous continuity acts as an anchor simultaneously affecting the dynamics of both valves, ie, plays an important role in mitral-aortic coupling, refuting the notion of their independent behavior. Consequently, the projected AoA and MA surface areas throughout the cardiac cycle demonstrated coupled reciprocal behavior, which to our knowledge has not

Table 3. Percentage of Inter- and Intraobserver Variability of Principal Index

<table>
<thead>
<tr>
<th></th>
<th>Intraobserver, %</th>
<th>Interobserver, %</th>
</tr>
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<tbody>
<tr>
<td>ED projected area</td>
<td>9.5(\pm)6.6</td>
<td>11.1(\pm)10.8</td>
</tr>
<tr>
<td>Maximum projected area</td>
<td>4.0(\pm)3.0</td>
<td>8.1(\pm)8.0</td>
</tr>
<tr>
<td>Minimum projected area</td>
<td>4.0(\pm)4.0</td>
<td>8.9(\pm)6.4</td>
</tr>
<tr>
<td>ED MA-AoA angle</td>
<td>2.0(\pm)1.6</td>
<td>2.0(\pm)0.9</td>
</tr>
<tr>
<td>ES MA-AoA angle</td>
<td>2.8(\pm)3.8</td>
<td>3.5(\pm)3.7</td>
</tr>
<tr>
<td>ED MA-AoA distance</td>
<td>3.7(\pm)2.1</td>
<td>4.3(\pm)3.4</td>
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<tr>
<td>NC annulus length</td>
<td>8.9(\pm)6.2</td>
<td>10.3(\pm)15.2</td>
</tr>
<tr>
<td>Left annulus length</td>
<td>8.5(\pm)9.6</td>
<td>7.9(\pm)4.7</td>
</tr>
<tr>
<td>Right annulus length</td>
<td>9.6(\pm)6.7</td>
<td>15.9(\pm)9.1</td>
</tr>
</tbody>
</table>

Data are reported as mean\(\pm\)SD; \(n=10\).
anatomy, mitral valve repair, as opposed to replacement, is
quickly acquired without significantly prolonging the procedure.
3D data sets are easy to recognize and additional data sets can be
thus prone to motion artifacts. Nevertheless, such artifacts in
RT3DE mTEE acquisition requires 7 cardiac cycles and is
justifiable in view of risks of sedation and intubation. Also,
of recruiting normal volunteers for TEE studies was not
clinically indicated TEE. Therefore, these patients are not a
normal valves, patients were recruited from those referred for
Although this protocol was designed to study subjects with
changes in shape and position are reciprocally correlated.
Limitations
Although this protocol was designed to study subjects with
maximum and minimum values of MA and AoA projected
areas was inverted when the MA area reached its maximum
value in early diastole, the AoA projected area was minimal,
and vice versa, during systole, whereas the aortic valve was
open, the MA area was minimal, and the AoA projected area
was maximal. This reciprocity may contribute toward improved
efficiency of the heart as a pump, because AoA
contraction may facilitate MA expansion and vice versa.
Another factor characterizing the mitral-aortic coupling is the
angle between the 2 valves. Our results showed that this angle
decreased during ejection, possibly also facilitating ejection
of blood through the aortic root. This finding further supports
the notion of the role of the fibrous continuity as an anchor
that maintains its position when the two annuli move toward
each other. Interestingly, there is evidence in literature that
aortic valve replacement may, at times, improve the severity
of mitral regurgitation.25,26 Moreover, the manner in which
flexible versus nonflexible mitral annular rings affect mitral-
aortic coupling is unknown. These issues can be further
investigated using the technique described in this study. These
findings underscore the need to consider the aortic and mitral
valves jointly, rather than as separate entities, not only because
they are linked anatomically, but also because their dynamic
changes in shape and position are reciprocally correlated.

Clinical Implications
With the improved understanding of mitral valve functional
anatomy, mitral valve repair, as opposed to replacement, is
increasingly becoming the surgical approach of choice. Con-
tinuous development of new prosthetic mitral annuli with a
variety of shapes, specifically designed to preserve the shape
function of the MA based on the knowledge gained through
3D studies, is likely to result in significant improvements in
the outcomes of mitral valve repair. It is also likely that
quantitative analysis of RT3DE mTEE images, such as
described in this study, will enhance the understanding of
Aoa physiology and thus contribute toward the development
of better techniques for aortic valve repair. In addition, our
results demonstrated the potential of the new RT3DE mTEE
technology to quantitatively assess important parameters
describing aortic and mitral valve coupling. This technology
will allow the assessment of the impact of a variety of mitral
and aortic rings on aortic root and MA dynamics, respectively
(Figure 5). In our previous studies, differences were found in
the dynamic behavior of the mitral annulus between func-
tional and ischemic mitral regurgitation.2 We hypothesize that
these differences could significantly affect mitral-aortic cou-
ping. In functional regurgitation, the lack of annular motion
is likely to have a negative impact on the effectiveness of
ventricular ejection. It is also likely that the use of rigid mitral
rings would have similar effects.

Conclusions
To our knowledge, this is the first study to simultaneously
quantify the functional anatomy of the mitral and aortic
valves in 3 dimensions in a beating human heart and to
investigate their coupled behavior using the new RT3DE
mTEE imaging technology. Our methodology was a key
component that allowed us to measure potentially clinically
useful parameters and characterize the unique 3D geometry
of the normal aortic and mitral annuli. The methodology
described in this article may become an important tool for
presurgical planning and serial follow-up of patients with
valvular disease.

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