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Feasibility of *In Vivo* Human Aortic Valve Modeling Using Real-Time 3D Echocardiography

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Abstract

Background—Surgical techniques for aortic valve (AV) repair are directed towards restoring normal structural relationships in the aortic root and rely on detailed assessment of root and valve anatomy. Noninvasive three-dimensional (3D) imaging and modeling may assist in patient selection and operative planning.

Methods—Transesophageal real-time 3D echocardiographic images of 5 patients with normal AV were acquired. The aortic root and the annulus were manually segmented at end diastole using a 36-point rotational template. AV leaflets and the coaptation zone were manually segmented in parallel 1mm cross sections. Quantitative 3D models of the AV and root were generated and used to measure standard anatomic parameters and compared to conventional 2D echocardiographic measurements. All measurements are given as mean $\pm$ standard deviation.

Results—Annular, sinus and sinotubular junction (STJ) areas were $4.1 \pm 0.6 \text{ cm}^2$, $7.5 \pm 1.2 \text{ cm}^2$ and $3.9 \pm 1.0 \text{ cm}^2$, respectively. Root diameters (measured in three locations) by 3D model inspection and 2D echo measurement correlated ($R^2 = .75$). Non-coapted areas of the left, right and non-coronary leaflets were $1.9 \pm 0.2 \text{ cm}^2$, $1.6 \pm 0.3 \text{ cm}^2$ and $1.6 \pm 0.3 \text{ cm}^2$, respectively. Mean coaptation areas for the left-right, left-noncoronary, and right-noncoronary coaptation zones were $87.7 \pm 36.9 \text{ mm}^2$, $69.9 \pm 20.7 \text{ mm}^2$, and $114.2 \pm 23.0 \text{ mm}^2$, respectively. The mean ratio of non-coapted leaflet area to annular area was 1.3 ± 0.2 .

Conclusion—High resolution 3D models of the *in vivo* normal human aortic root and valve were generated using 3D echocardiography. Quantitative 3D models and analysis may assist in characterization of pathology and decision-making for AV repair.

Keywords

echocardiography; aortic valve repair; modeling

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Introduction

Although cross-sectional imaging modalities – including both computed tomography and magnetic resonance imaging – are available to study the aortic root in great detail,¹ anatomic evaluation of the aortic valve (AV) leaflets has been generally accomplished with standard two-dimensional (2D) echocardiographic techniques. This was acceptable as AV replacement (AVR) has been the standard treatment for any AV pathology; however, with new studies demonstrating efficacy of AV repair²⁻⁴ for aortic valve insufficiency (AI), enhanced definition and visualization of AV leaflet anatomy is essential.⁵ Surgical techniques for AV repair are directed towards restoring normal structural relationships in the aortic root and leaflets and rely on detailed assessment of AV anatomy. Although quantitative modeling of the mitral valve has been described⁶⁻¹⁰, similar analysis of the AV is lacking.

While native 3D images can be rendered and visualized in “real time” in “native” unmanipulated formats (Figure 1), little or no quantitative information can be gleaned from these visualization techniques. In this study, we describe a technique of quantitative 3D reconstruction of the aortic root and leaflets from real-time 3D echocardiographic (rt-3DE) images that may be helpful both for planning AV repair and for studying disease processes, in a real-time, repeatable, dynamic fashion.

Patients and Methods

Subjects

Rt-3D-TEE images of 5 patients undergoing transesophageal echocardiography for reasons unrelated to AV (i.e. patients with a structurally and functionally normal AV) were analyzed. All studies were performed under light sedation by an experienced cardiologist in the echocardiography lab at the Hospital of the University of Pennsylvania. Electrocardiographically gated, full-volume data sets were acquired using an iE-33 platform (Philips Medical Systems, Andover, MA) equipped with a 2-7MHz X7-2t TEE matrix-array transducer. Care was taken to include the aortic valve and the sinus segment in its entirety throughout the acquisition. The protocol was approved by the University of Pennsylvania School of Medicine Institutional Review Board.

Image Segmentation

Each full-volume data set was exported to an Echo-View 5.4 (TomTec Imaging Systems, Munich, Germany) software workstation for image analysis. This customized software allows for the interactive manipulation including rotation, translation, surface rendering, and measurement of fully 3D data sets. All analysis was performed at end diastole.

The plane of the aortic valve orifice was rotated into a short-axis view. The geometric center of the aortic valve was then translated to the intersection of two orthogonal long-axis planes of the aortic root. A rotational template consisting of 18 long-axis cross-sectional planes separated by 10° increments was superimposed on the 3D image. Annular points were identified on each of the 18 long-axis rotational planes. Free-hand curves were constructed from the annular points along the height of the root at each rotational plane for root reconstruction. The sinotubular junction was manually identified in each plane.

The leaflets were segmented in pairs (right coronary-left coronary, left coronary–noncoronary, and right coronary-noncoronary) in parallel long axis cross-sections spaced 1mm apart, resulting in a 500 to 1000 point data set for each valve. Each individual segmentation point was assigned to the left, right or the non-coronary leaflet. The coaptation zones between the leaflets were independently identified in each parallel cross-section.

The Cartesian coordinates of the segmented AV annulus, root, and leaflets were exported to Matlab (The Mathworks Inc., Natick, MA). Total segmentation time for each valve was 4-6 hours.

Annular Analysis

The center of gravity of the resultant 36-point annular data set was translated to the origin. The plane defined by the lowest point in each of the three sinus segments was designated the annular plane. The plane parallel to the annular plane and encompassing the maximum area of the root was defined as the sinus plane. The STJ plane was defined as the least squares fit of the manually-delineated STJ points. At each planar location, aortic area and mean diameter was calculated.

Leaflet Analysis

Smoothing splines were constructed for each leaflet data set using the Matlab TPAPS function. The smoothing parameter was assigned automatically for each data set by the function. The resulting surface splines were meshed for 3D rendering of their surfaces. A Delaunay triangulation was used to exclude mesh points that fell outside the borders described by the annular and leaflet data points. Leaflet and coaptation surface areas were calculated from meshed 3D models.

2D Parameters and Statistics

Aortic diameters at the annulus, sinus segment, and STJ were directly measured at end diastole from standard two-dimensional echocardiographic images. 2D and 3D measures of aortic diameter were compared using linear regression analysis. Furthermore, interobserver variability was assessed by comparing two different observers' 3D segmentations relative to aortic diameter, using both linear regression and Bland-Altman analyses. All data are presented as mean $\pm$ standard deviation.

Results

Fully quantitative models of the aortic annulus, root leaflets were generated in all subjects (Figure 2). Mean annular, sinus and sinotubular junction (STJ) areas were $4.1 \pm 0.6 \text{ cm}^2$, $7.5 \pm 1.2 \text{ cm}^2$ and $3.9 \pm 1.0 \text{ cm}^2$, respectively. As demonstrated in Figure 3, root diameters determined from 3D models were similar to diameters obtained from 2D images at the level of the annulus ($R^2 = .75$). Interobserver comparisons of 3D models demonstrated good correlation ($R^2 = .80$) and Bland-Altman analysis yielded no significant bias, as demonstrated in Figure 4.

Mean non-coapted (load bearing) areas of the left, right, and non-coronary leaflets were $1.9 \pm 0.2 \text{ cm}^2$, $1.6 \pm 0.3 \text{ cm}^2$, and $1.6 \pm 0.3 \text{ cm}^2$ respectively. Mean coaptation areas for the left-right, left-noncoronary, and right-noncoronary coaptation zones were $87.7 \pm 36.9 \text{ mm}^2$, $69.9 \pm 20.7 \text{ mm}^2$, and $114.2 \pm 23.0 \text{ mm}^2$ respectively. The mean ratio total non-coapted leaflet area to annular area was 1.3 ± 0.2 .

Comment

3D echocardiography has been extensively applied to MV disease; however, its role in evaluation of the AV has been mostly limited to case reports or small series involving assessment of aortic stenosis.¹¹⁻¹⁶ Recently, Calleja et. al.¹⁷ demonstrated techniques for automated 3D modeling of the aortic valve. Quantitative modeling of in vivo human AV has been more frequently accomplished using cardiac CT.¹⁸⁻²⁰ In the current study, the feasibility of generating patient-specific high resolution 3D models of the aortic root under

physiologic loading conditions from rt-3DE is demonstrated. The technique allows for detailed anatomic analysis of the aortic root, including the valve leaflets. These preliminary results suggest that measurements made from 3D reconstructions are consistent with aortic diameters derived from 2D echocardiography. Other valve characteristics, including and especially leaflet areas and coaptation areas, are inherently three-dimensional measures, and cannot be assessed using 2D echocardiography. However, no attempt to validate the leaflet coaptation measures or leaflet geometries were undertaken: such efforts might be reasonable in future laboratory projects.

Other shortcomings in this work include the absence of a gold-standard comparison to validate the 3D reconstructions of the AV derived from rt-3DE. While not a rigorous calibration of the measurements derived from the 3D models, the presented agreement between 2D echocardiographic and 3D aortic diameters is reassuring. The authors would contend that 3D aortic valve modeling is in its infancy, and that rt-3DE-derived models may constitute the “gold-standard” against which cardiac MRI or cardiac CT methods should be validated. In addition, the current study only demonstrates the feasibility of 3D modeling of the healthy trileaflet *in vivo* human AV; no diseased valves nor bicuspid valves were included in this study. Finally, no comparison of measurements or 3D models to *ex vivo* aortic valves were undertaken in this study; similar efforts would require an animal model and we have heretofore been unsuccessful adequately imaging large mammal aortic valves using 3D TEE.

Future work on 3D modeling of the AV from rt-3DE will include extension and application of these techniques to pathologic valves. In addition, efforts to make image processing, segmentation, and model generation fully automatic, are compelling. The authors believe that these methods will lead to better characterization of pathology and guide decision-making and assessment for aortic valve repair. Furthermore, there is great interest in studying the effect of leaflet geometry in evolution of valve and ascending aortic pathology, in both TAV and BAV morphologies. The 3D models generated using these methods can be subjected to finite element analysis for estimation of leaflet stress and deformation. Finally, these techniques can be used to quantify derangement of anatomic parameters in patients with aortic root pathology, and to assess the success of surgical interventions in restoring normalcy.

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Figure 1.

Real-time 3D echocardiogram of a tricuspid aortic valve, viewed in long axis (A), and from the ascending aorta (B and C). The valve is closed in panels A & B, and open in panel C. The 3D rendering depicted is accomplished in Tomtec's Echo-View software, but does not lend itself to quantitative analysis of valve morphology.

Figure 2.
3D model of aortic valve, with superimposed cross-sectional real-time 3D echocardiographic image.

Figure 3.

Correlation between real-time 3D echocardiographic measurement of aortic diameter (using models as generated per Figure 2) and traditional 2D measure of aortic diameter.

Figure 4. Correlation (A) and Bland-Altman analysis (B) of two observers' measurements of aortic diameter using 3D models derived from echocardiography.