Three-Dimensional Ultrasound-Derived Physical Mitral Valve Modeling

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Purpose. Advances in mitral valve repair and adoption have been partly attributed to improvements in echocardiographic imaging technology. To educate and guide repair surgery further, we have developed a methodology for fast production of physical models of the valve using novel three-dimensional (3D) echocardiographic imaging software in combination with stereolithographic printing.

Description. Quantitative virtual mitral valve shape models were developed from 3D transesophageal echocardiographic images using software based on semiautomated image segmentation and continuous medial representation algorithms. These quantitative virtual shape models were then used as input to a commercially available stereolithographic printer to generate a physical model of each valve at end systole and end diastole.

Evaluation. Physical models of normal and diseased valves (ischemic mitral regurgitation and myxomatous degeneration) were constructed. There was good correspondence between the virtual shape models and physical models.

Conclusions. It was feasible to create a physical model of mitral valve geometry under normal, ischemic, and myxomatous valve conditions using 3D printing of 3D echocardiographic data. Printed valves have the potential to guide surgical therapy for mitral valve disease.


Despite the established superiority of mitral valve repair [1], these procedures remain extensively underused relative to valve replacement [2]. This high degree of underutilization has been attributed to the steep learning curve associated with mitral valve repair surgery [2].

The development and adoption of repair techniques has always been closely linked to advances in valve imaging—specifically echocardiography. Carpentier pioneered the advent of mitral repair procedures using only direct intraoperative observation. More generalized application of his techniques required the widespread availability of two-dimensional (2D) echocardiography (2DE) in the late 1970s and early 1980s and progressed further with the availability of intraoperative transesophageal 2DE, beginning in the 1990s [3–5]. Despite ostensibly overcoming many of the limitations of 2DE, the introduction of 3D echocardiography (3DE) has not had a similar transformative effect.

Commercially available 3DE analysis packages allow only for a limited number of quantitative measures to be made offline. Custom software algorithms that permit interactive visualization and automated quantification have been developed, but these techniques are time consuming and labor intensive [6–8].

It has become increasingly apparent that further advancement in mitral repair may be dependent on improvements in enabling imaging technology. We report such a technique. We have developed automated image analysis algorithms that quickly and quantitatively describe mitral valve geometry at any point in the cardiac cycle. These algorithms can be used to generate digital data input to commercially available 3D printers to produce physical models of mitral valves. Such tangible models may be useful in facilitating both the teaching and development of repair techniques.

Technology and Technique

Patient Recruitment

The study was approved by the Institutional Review Board of the University of Pennsylvania. Intraoperative
2D and 3D transesophageal echocardiography was performed in four patients after induction of anesthesia and before sternotomy. Two patients had severe ischemic mitral regurgitation, one patient had severe myxomatous mitral regurgitation, and one patient had a normal mitral valve.

Image Acquisition
Two-dimensional, m-mode, spectral and color Doppler and 3D echocardiographic data were collected with an ultrasound platform (iE33 Model; Philips Medical Systems, Andover, MA) equipped with a 2–7-MHz transesophageal matrix-array transducer. 3D data were collected during four consecutive heart beats, and the images were reconstructed with the following imaging parameters: frame rate = 17–30 Hz; depth =12–16 cm; image dimensions = 224 × 208 × 208 voxels; isotropic resolution = 0.6–0.8 mm³. Image analysis was performed on midsystolic and diastolic image frames.

Image Segmentation and Geometric Modeling
Virtual models of the mitral valve were constructed from 3D ultrasound data using a 3D model-based segmentation method detailed previously [9, 10]. The algorithm involves several steps of user initialization, including (1) identification of leaflet location along the long-axis dimension of the image volume and (2) outlining of the mitral annulus and anterior leaflet in 2D projection images generated from the 3D image. Points automatically identified on the leaflet surfaces are then detected and dilated to create a tight region of interest containing the mitral leaflets. 3D active contour evolution generates binary segmentations of the mitral leaflets in the region of interest. To create a geometric model of the mitral leaflets in these segmented images, a medial template (continuous medial representation) of the mitral leaflets is deformed through a Bayesian optimization process to capture leaflet geometry in the segmented image data.

3D Printing
The virtual model data were used as input to a Dimension Elite 3D Printer to create physical models from acrylonitrile butadiene styrene plastic material. The stereolithographic file was imported into CatalystEX, and final model dimensions were set. The point thickness of each layer was set for 0.254 mm (0.010 inches). The highest resolution settings of the printer were 0.178 mm (0.007 inches).

Clinical Experience
We created physical mitral valve models from one patient with normal valve function, who underwent cardiovascular surgery unrelated to the mitral valve. This patient had normal diastolic leaflet motion and systolic coaptation without mitral regurgitation by transesophageal echocardiography. A model in end-diastole was created from echocardiographic data in Figure 1A. Diastolic views of the virtual model and the physical model are shown in Figures 1B–1E. Similar views of the virtual model and physical model in their midsystolic configuration are shown in Figures 1F–1I. The saddle shape of the mitral valve annulus can be appreciated from views of the valve in profile in diastole (Figs 1D, 1E) and systole (Figs 1H, 1I). The systolic augmentation of annular saddle shape can be seen by comparing Figure 1E to Figure 1I.

Physical models from two patients with severe ischemic mitral regurgitation are shown in Figure 2. Comparison of the two patients demonstrates how variable the geometric valve distortions can be in ischemic mitral regurgitation. In both patients, the annulus was dilated. In patient 1...
(Figs 2A–2F), the annulus was markedly flatter than normal, and there was both anterior and posterior leaflet tethering. In patient 2 (Figs 2G–2L), the saddle shape was relatively preserved and the majority of leaflet tethering was on the P2 region of the posterior leaflet and was much more pronounced than in patient 1. Patient 2 also had thicker leaflets than patient 1 did.

Virtual and physical models for a patient with moderate myxomatous valve degeneration are shown in Figure 3. The valve was moderately thickened, and there was severe mitral regurgitation directed toward the septum, which corresponded with a partially flail P2 segment. This patient underwent mitral valve repair with resection of the flail segment and annuloplasty, which resolved the mitral regurgitation. The flat shape of the posterior annulus (Figs 3D, 3E) should be compared to the saddle shape of the normal valve (Fig 1).

Comment

Successful mitral valve repair offers significant clinical benefits over valve replacement. Current ACC/AHA guidelines recommend repair over replacement when valve morphology and surgical expertise indicate that the likelihood of successful repair is high [1]. Mitral valve repair has also been shown to be more cost-effective than valve replacement in the long term [2]. Despite the established benefits of valve repair, the procedure remains extensively underutilized relative to valve replacement.

Advances in the application of 2DE during the last two decades of the 20th century improved and expanded the performance of mitral valve repair surgery. The integration of this preoperative echocardiographic data with the results of intraoperative anatomic valve analysis represents the current state of the art for mitral valve repair. This approach can be challenging for less experienced surgeons. It requires the assimilation of dynamic

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Fig 2. Virtual and physical models of two patients with severe ischemic mitral regurgitation depicted in systole. (A) Virtual model and (B) physical model viewed from the atrium. (C) Virtual model and (D) physical model as viewed from anterior to posterior commissure, in which the flat annulus can be appreciated. (E) Virtual model and (F) physical model as viewed obliquely from the atrium. (G) Virtual model and (H) physical model of a second patient with ischemic mitral regurgitation viewed from the atrium. (I) Virtual model and (J) physical model viewed commissure to commissure. (K) Virtual model and (L) physical model as viewed obliquely from the atrium. (AL = anterior mitral valve leaflet; PL = posterior mitral valve leaflet.)

Fig 3. Three-dimensional echocardiography, virtual, and physical models of a patient with severe mitral regurgitation and a flail P2 leaflet segment. (A) Long-axis view of the left ventricle (LV) and atrium during systole. The relative positions of the anterior (AL, red) and posterior mitral valve leaflets (PL, green) are indicated. (B) Virtual model and (C) physical model viewed from the atrium. (D) Virtual model and (E) physical model as viewed in profile from anterior to posterior commissure.
echocardiographic images with direct intraoperative valve analysis in the surgically exposed, arrested heart—all needing to be done in an efficient manner under the time constraints of the aortic cross clamp.

Three-dimensional echocardiography (3DE) was introduced nearly a decade ago, and was heralded as a possible solution to the inherent complexities of teaching and performing mitral valve repair procedures. Unfortunately, it has yet to have a demonstrable impact. Over the past decade, our group has developed novel image analysis software that facilitates quantitative assessment of mitral valve leaflet and annular geometry [9]. The most recent of these advances have produced automated valve imaging algorithms that allow quantitative images of the valve to be made at any point in the cardiac cycle with.

The combination of our automated imaging techniques with routinely available 3D printing devices potentially provides a powerful tool for helping surgeons to hone their mitral valve repair techniques. Having a physical model of the valve (at any or multiple points in the cardiac cycle) for the surgeon to observe and manipulate while interpreting preoperative 2D and 3D echocardiographic imaging should be helpful to both the experienced surgeon and surgeons dedicated to learning valve repair techniques.

These automated imaging methods are still in their early stages and require refinement for better description of leaflet coaptation, chordae, papillary muscle, and left ventricular geometry. Considering the progress made to date, we believe that the routine and rapid imaging of these structures will be achievable in the near future, at which point 3D printing devices will be able to make complete physical models of the mitral valve, at any point in the cardiac cycle, that will greatly facilitate operative planning, procedural improvements, and the teaching of mitral valve repair procedures.

Disclosures and Freedom of Investigation

This work was performed by the Gorman Cardiovascular Research Group and the University of Pennsylvania. The tested technology was not purchased, borrowed or donated to the study. The Authors had full control of the study design, methods used, outcome parameters, analysis of data and production of the written report.

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References


Disclaimer

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