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The effect of mitral annuloplasty shape in ischemic mitral regurgitation: a finite element simulation

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Abstract

Background—Undersized mitral annuloplasty (MA) is the preferred surgical treatment for chronic ischemic mitral regurgitation (CIMR). However, the preferred shape of undersized MA is unclear.

Methods—A previously described finite element (FE) model of the LV with mitral valve based on magnetic resonance images of a sheep with CIMR after postero-lateral MI was used. Saddle shape (Edwards Physio II) and asymmetric (IMR ETlogix) MA rings were digitized and meshed. Virtual annuloplasty was performed using virtual sutures to attach the MA ring. LV diastole and systole were performed before and after virtual MA of each type.

Results—Both types of MA reduced the septo-lateral dimension of the mitral annulus and abolished mitral regurgitation. The asymmetric MA was associated with lower virtual suture force in the P2 region but higher force in P1 and P3 regions. Although both types of MA reduced fiber stress at the LV base, fiber stress reduction after asymmetric MA was slightly greater. Neither type of MA affected fiber stress at the LV equator or apex. Although both types of MA increased leaflet curvature and reduced leaflet stress, stress reduction with saddle shape MA was slightly greater. Both MA types reduced stress on the mitral chordae.

Conclusions—The effects of saddle shaped and asymmetric MA rings are similar. FE simulations are a powerful tool that may reduce the need for animal and clinical trials.

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Keywords

Myocardial Infarction; Mitral Valve; Mitral Regurgitation; Mitral Repair; Annuloplasty; Finite Element; Stress

Introduction

Chronic ischemic mitral regurgitation (CIMR) affects 1.2 to 2.1 million patients in the United States, with more than 400,000 patients having moderate-to-severe CIMR. [1] The cause is thought to be left ventricular (LV) remodeling after postero-lateral myocardial infarction (MI) in which the posterior papillary muscle moves laterally. [2, 3] This causes both anterior and posterior mitral leaflets to be tethered and Type 3B Carpentier leaflet motion (restricted motion during systole) [4] to occur.

When repair is performed, the type of mitral repair most often employed is undersized mitral annuloplasty. On the other hand, the shape and stiffness of the undersized annuloplasty is controversial. [5, 6]

The mitral annulus is a 3 dimensional structure that is shaped like a saddle during systole. [7, 8] The annulus becomes flat after postero-lateral MI [9, 10] and asymmetric with the P3 region moving outward and towards the LV apex. [11] It has been suggested that ring annuloplasty should force the mitral annulus in IMR back to the saddle shape. [10] Saddle shaped annuloplasty rings include the Physio II (Edwards Lifesciences, Irvine, CA) and the Profile 3D (Medtronic Inc, Minneapolis, MN). Alternatively, annuloplasty rings such as the Carpentier-McCarthy-Adams IMR ETlogix (Edwards Lifesciences) are designed to mimic the asymmetric CIMR annular shape. [12] The IMR ETlogix ring is thought to reduce chordal tension and increase leaflet coaptation. [13]

Finite element (FE) modeling of the mitral valve is becoming more common. Kunzelman [14] developed a sophisticated static and quasi-static finite element models of the mitral valve and a version of that model was used to simulate the effects of flexible and rigid annuloplasty rings. [15] Subsequent publications by Maisano and colleagues and Votta et al describe the simulation of dog bone and dog bone variant ring annuloplasty. [16, 17] However, those simulations made simplifying assumptions, such as the exclusion of the LV as part of the structure. [14, 15] We believe that our previous study was the first to simulate both the LV and mitral valve. [18]

In the current study, we extend our finite element model of the LV with mitral valve to incorporate the ability to perform virtual annuloplasty ring application. We will test the hypotheses that a ring that approximates remodeled CIMR annular shape will have reduced proximal LV stress when compared with a ring that approximates the saddle shape. Physio II and IMR ETlogix rings will be used as examples of saddle shape and asymmetric CIMR shape annuloplasty rings respectively.

Material and Methods

Animals used in this study were treated in compliance with the “Guide for the Care and Use of Laboratory Animals” prepared by the Institute of Laboratory Animal Resources, National Research Council, and published by the National Academy Press, revised 1996.

Finite element model of LV with mitral valve

The finite element model of the LV with mitral valve has been previously described. [18] The finite element model was based on magnetic resonance images (MRI) of a single sheep with CIMR. Briefly, 8 weeks after postero-lateral MI [19] a single sheep underwent trans-diaphragmatic echocardiography and cardiac magnetic resonance imaging (MRI) with tags [20] as previously described. Echocardiography revealed that the animal had developed moderate CIMR. The endocardial and epicardial LV surfaces and mitral valve annulus and leaflets were contoured and meshed. The chordae tendineae could not be identified on the magnetic resonance images and were approximated from anatomic images of a mitral valve from an excised heart. [18]

Material properties

Diastolic and systolic constitutive relationships have been previously described. [18] The animal specific systolic myocardial material constant, T_{max} , was optimized using myocardial strain measure with MRI as standard. [21]

Virtual annuloplasty

Twenty four mm Physio II and an IMR ETLogix annuloplasty rings (Edwards Lifesciences, Inc.) were photographed and then digitized using the KineMat Matlab toolbox (Human Performance Laboratory, University of Calgary). A 3D B-spline was used to represent the 3D geometry of a ring. FE meshes of each ring were created using beam elements. Rings were assumed to be rigid (*MAT_RIGID, LS-DYNA, Livermore, CA).

Each annuloplasty ring mesh was placed near the center of the mitral valve (Figure 1A). Next, 32 virtual sutures were added between the annuloplasty ring and the mitral annulus (Figures 1A and B). The initial 2 virtual sutures were placed from each commissure to the nearest node in the annuloplasty ring. Additional virtual sutures were spaced evenly along the anterior and posterior annulus. Because nodes on the annulus and annuloplasty ring were not exactly aligned, virtual sutures were often slightly oblique to a line perpendicular to the annulus.

Each virtual suture was modeled as a discrete beam element (*MAT_071). A unique feature of *MAT_071 is that an axial tension can be specified for each beam element and this axial tension could mechanically pull the two ends of each element together. Using this feature, the mitral annulus was pulled toward the annuloplasty ring (Figure 1C). The annulus and LV wall contiguous with the annulus were not modified. After annuloplasty ring attachment, the virtual sutures were changed to rigid elements using the *DEFORMABLE_TO_RIGID function in LS-DYNA. Simulation of LV diastole and systole then proceeded as previously described.[18]

Stress and Force Calculations

The LV was divided equally into basal, middle, and apical regions. The LV was also divided into remote, borderzone and infarct regions. Mitral leaflets were each divided into A1 (left anterior), A2, and A3, and P1 (left posterior), P2, and P3 scallops. [22]

LV fiber stress, mitral leaflet von Mises (effective) stress, uniaxial chordal forces and uniaxial forces in the virtual sutures were calculated. The uniaxial forces on the virtual sutures were recorded using a virtual strain gauge technique, where beam elements of close-to-zero length were added between the end of virtual sutures and the mitral annulus. Because the aortic root was not included in the model, virtual suture force was only measured at the posterior annulus. Strain was computed with end-diastole as the reference configuration.

Statistical analysis

Stress and strain were averaged over all elements of each LV or leaflet region and presented as the average $\pm$ standard deviation in each region.

A single finite element model based on a single animal was employed. The results obtained are not stochastic and statistical tests were therefore not appropriate. P values are therefore not reported.

Results

Optimized systolic material properties

The systolic material parameter, T_{max} , was determined to be 199.56 kPa in the remote myocardium and 62.85 kPa in the infarct borderzone.

Effect on annular geometry

The pre-operative (baseline) commissure-commissure (CC) distance is 31.5 mm and septo-lateral (SL) distance is 22.6 mm.

Although both rings are listed as 24 mm by Edwards, as seen in Figure 2, ring dimensions are slightly different. The CC dimension of the Physio II and IMR ETLogix ring were similar at 24.3 and 23.5 mm respectively. The percent reduction in CC distance was therefore similar with Physio II and IMR ETLogix ring reductions of 22.9 and 25.4% respectively. The bigger difference is in the SL dimension where the Physio II is 14.4% larger than the IMR ETLogix ring. Reduction in the SL diameter was therefore more pronounced in the IMR ETLogix ring with Physio II and IMR ETLogix ring reductions of 18.0 and 26.0% respectively.

Force on virtual sutures

Force on the virtual sutures attached to the posterior side of the rings is shown in Figure 3. The IMR ETLogix ring was associated with lower virtual suture force in the P2 region but higher force in P1 and P3 regions.

LV fiber stress reduction

As shown in Figures 4A and 4B, mitral annuloplasty reduced fiber stress at both ED and ES only at the base of the LV. However, fiber stress reduction occurred in the remote, borderzone and infarct zones. Specifically, Physio II and IMR ETlogix rings reduced fiber stress at ES by 2.9 kPa and 3.3 kPa in the remote zone, 2.2 and 3.1 kPa in the borderzone, and 1.6 kPa and 1.9 kPa in the infarct respectively.

LV fiber strain

Similar to fiber stress, mitral annuloplasty reduced fiber strain only at the base of the LV (Figure 5). In the basal region, the Physio II ring led to a larger fiber strain reduction than the IMR ETlogix ring (Physio II: -0.104; IMR ETlogix: -0.107; Control: -0.12).

Leaflet shape

In our previous model, ischemic MR was identified as a gap between the leaflets at end-systole. Figure 6 shows the coaptation profiles of the leaflets at ES for control Physio II and IMR ETLogix simulations. Note that both annuloplasty simulations demonstrated complete closure of the regurgitant gap.

The SL leaflet dimension/ width was reduced after both types of annuloplasty. For instance, the SL width of the anterior leaflet at baseline and with Physio II and IMR ETlogix rings was 14.3, 13.3 and 12.9 mm respectively. As a consequence, annuloplasty was associated with an increase in leaflet curvature. The simulation also suggests that coaptation between the posterior and anterior leaflets occurs higher on the anterior leaflet after annuloplasty with the IMR ETlogix ring.

Leaflet stress reduction

Both rings significantly reduced average effective (von Mises) stress on the anterior and posterior leaflets, as shown in Figure 7A. The Physio II and IMR ETlogix rings respectively reduced stress in the anterior leaflet by 13.2 kPa and 7.1 kPa respectively, and in the posterior leaflet by 15.1 kPa and 10.7 kPa.

Figure 7B shows stress reduction in the six leaflet regions (namely A1–A3, P1–P3). Stress reduction was observed in all regions. Between the Physio II and IMR ETlogix rings, the difference in stress reduction in P2 and P2 regions was minimal. The Physio II ring lowered stress more than the IMR ETlogix ring by 9.2 kPa in the P3 region.

Chordal Stress Reduction

Both rings reduce the chordal stress at end systole. The average chordal stress was 18.4 kPa before annuloplasty ring. The stress was reduced to 13.4 kPa and 9.1 kPa by the Physio II and IMR ETlogix rings, respectively.

Comment

Briefly, we found that both types of MA reduced the septo-lateral dimension of the mitral annulus and abolished mitral regurgitation. The asymmetric MA was associated with lower virtual suture force in the P2 region but higher force in P1 and P3 regions. Although both types of MA reduced fiber stress at the LV base, fiber stress reduction after asymmetric MA was slightly greater. Neither type of MA affected fiber stress at the LV equator or apex. Although both types of MA increased leaflet curvature and reduced leaflet stress, stress reduction with saddle shape MA was slightly greater. Both MA types reduced stress on the mitral chordae.

Recurrent MR after mitral repair for CIMR

Repair of CIMR with an undersized mitral annuloplasty (MA) ring fails in up to 30% of patients. [23–25] Recurrent CIMR is thought due to continued LV remodeling [26, 27] although ring dehiscence may play a role.

Reduction of LV fiber stress

Since LV remodeling is due to an increase LV wall stress [28], it is important to understand the effect of annuloplasty ring shape on the stress in the LV wall. To the best of our knowledge, this study is the first to calculate the effect of undersized mitral annuloplasty on LV wall stress in a finite element model of the mitral valve that includes the LV wall.

We have recently demonstrated that the magnitude of stress calculated with the Young Laplace law is very different than stress in the fiber and cross fiber directions calculated with the finite element method. [29] This is important since there is increasing evidence that stress in the cross fiber direction causes eccentric or volume overload type hypertrophy. [30, 31] Although evidence is less clear, it is probable that end systolic fiber stress causes non-ischemic infarct extension—a process in which normally perfused segments adjacent to the infarct increase in size over time in response to high systolic stress. [32] Our finite element-

based calculations show that end-diastolic and end-systolic fiber stress is decreased after both types of MA. However, the IMR ETlogix annuloplasty ring caused a slightly greater reduction in fiber stress at the LV base and therefore might lead to decreased post operative remodeling and to lower rates of mitral repair failure.

Although stress has not been previously calculated, Cheng and colleagues measured the effect of suture annuloplasty on LV strain in normal sheep and found that systolic fiber strain was reduced from the baseline value of -0.1 ± 0.05 to -0.04 ± 0.05 in the subendocardium of the antero-basal LV. [33] Cheng et al postulated that this was secondary to a decrease in end diastolic fiber length. In our model, the fiber strain in the same region was also reduced albeit with different magnitude (-0.13 ± 0.01 vs. -0.1 ± 0.01). The different magnitude of strain reduction could be partly attributed to the difference between the two models. Cheng et al used normal sheep with an open chest. [33] Our FE model was based on a single sheep after postero-lateral MI. [18]

Ring dehiscence

Ring dehiscence may be an under reported cause of recurrent MR after mitral repair for CIMR. We suggest that forces acting on annuloplasty sutures is a composite of force in the radial direction caused by the undersizing process per se and force perpendicular to the valve plane (vertical direction) caused by the out of valve plane shape of the ring. For instance, the saddle of Physio II and P3 'dip' of the IMR ETlogix rings would produce force perpendicular to the valve plane. The radial component would in turn be determined by the dimensions of the ring in the CC and SL directions. As can be seen from the data in Figure 3, suture force generation is not intuitive. Clearly, further work is needed to make the cause of suture force more clear.

Reductions in leaflet and chordal stress

Mitral leaflets change their shape and material properties over time after inferior MI [34, 35] leading to altered leaflet stress that may be a stimulus for leaflet remodeling. [35, 36] Annuloplasty rings have the potential to reduce the septo-lateral anterior mitral leaflet dimension at ES [37] and increase the mitral leaflet curvature. [38] These could lead to leaflet stress normalization post surgery. [15] In this study, both ring types reduced leaflet stress with the greatest stress reduction occurring in the posterior leaflet. While the Physio II ring did lower effective stress more than the IMR ETlogix ring, it should be noted that leaflet stress has not been implicated in failure of undersized mitral annuloplasty for CIMR. We also observed that both ring types reduced chordal axial force. As with leaflet stress, chordal rupture has not been implicated in the failure of annuloplasty for CIMR.

Study limitations

The current study was based on a single animal and a subsequent study using multiple animal specific finite element models is clearly indicated.

We chose images of the mitral valve immediately before opening as the zero-stress state of the valve. Such a decision was made because the images at this specific time instant present the best MR image quality of the leaflets. However, this timepoint probably precedes the point of early diastolic filling used in our previous studies.

We assumed both rings to be rigid. However, Silberman and colleagues found that patients with CIMR that undergo repair with a flexible ring are more likely to have recurrent MR and have higher mortality. [39] Simulation of flexible ring designs might shed light on the mechanical effects associated with these results.

The three regions of the LV (remote, borderzone and infarct) were assumed to be homogeneous. While there is certainly regional variability in regional material properties, until more precise experimental measurement and/ or computer based calculations of regional systolic and diastolic material properties are available, our methods are a reasonable first order approximation.

Our model did not incorporate fluid-structure interaction. As a consequence, the effects of annuloplasty on dynamic mitral leaflet motion and regurgitant volume was not taken into consideration. Finally, we did not determine the effect of annuloplasty on chamber stiffness and pump function.

Conclusions and Future Directions

The effects of saddle shaped and asymmetric MA rings are similar. In the future, more extreme versions of the saddle shape and asymmetric MA rings will be analyzed to determine if greater degree of stress reduction can be achieved without negative effect. Ultimately, the goal is to use the model to determine the optimal surgical repair of CIMR. We believe that as this model improves it will be a powerful tool for planning future clinical and animal trials, thus reducing the need for expensive and time-consuming studies.

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Figure 1.

Positioning of the Physio II annular configuration (black) and sutures (cyan). **A.** Virtual sutures are about to 'attach' a Physio II ring. **B.** Expanded view of region in A. AL =Anterior leaflet, PL = Posterior leaflet, MA = Mitral annuloplasty, VS = virtual suture. **C.** At end-systole after virtual Physio II attachment. The white shade indicates the cut-plane for creating the leaflet coaptation profiles shown in Figure 6.

Figure 2. Shape of the two mitral annuloplasty rings. **A.** Top view (left) and front view (right) of Physio II ring; **B.** Top view (left) and front view (right) of IMR ETLogix ring.

Figure 3.
Virtual suture force. As discussed in the text only force on the posterior annulus is reported.

Figure 4.
Fiber stress by longitudinal region for the **A**. End-diastole, **B** End-systole.

Figure 5.
End-systolic fiber strain.

Figure 6. Septal-lateral leaflet coaptation profiles at the A2-P2 (A) and A3-P3 (B) regions for control (blue), Physio II (red), and IMR ETlogix (green) ring groups.

Figure 7. Effective stress at end-systole in the anterior and posterior mitral leaflets. A. Anterior and posterior leaflets, B. Broken down by leaflet scallop. A = anterior, P = posterior, 1 = left scallop, 2 = middle scallop, and 3 = right scallop.