Published in final edited form as:

Int J Numer Method Biomed Eng. 2017 June ; 33(6): . doi:10.1002/cnm.2831.

Computational Virtual Evaluation of the Effect of Annuloplasty Ring Shape

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Abstract

Mitral regurgitation (MR) is a result of mitral valve (MV) pathology. Its etiology can be categorized as degenerative or functional MR. Ring annuloplasty aims to reconfigure a dilated mitral annulus to its normal size and shape. We investigated the effect of annuloplasty ring shape on MR outcome using our established 3D echocardiography-based computational MV evaluation protocols. Virtual patient MV models were created from 3D transesophageal echocardiographic data in patients with MR due to mitral annular dilation. Two distinct annuloplasty rings (Physio II and GeoForm) were designed and virtually implanted to the patient MVs. Dynamic FE simulations of MV function were performed for each MV following virtual ring annuloplasty of either ring, and physiologic and biomechanical characteristics of MV function were compared. Excessive stress values appeared primarily in the mid-anterior and mid-posterior regions, and lack of leaflet coaptation was found in pre-annuloplasty patient MVs. Both rings demonstrated marked reduction of stresses and efficient leaflet coaptation. The Physio II ring demonstrated more evenly distributed stress reduction across the leaflets and annulus compared to the GeoForm ring. Conversely, the highly non-planar curvature of the GeoForm ring more effectively increased leaflet coaptation compared to the Physio II ring. This indicates that the shape of annuloplasty ring affects post-annuloplasty physiologic and biomechanical conditions, which can lead to tissue alteration over a longer period of time following ring annuloplasty. This virtual ring annuloplasty simulation strategy provides detailed physiologic and biomechanical information and may help better plan the optimal ring selection and improved patient-specific MV repairs.

Keywords

Mitral valve; Mitral regurgitation; Ring annuloplasty; Mitral valve repair; Virtual surgery; Computational simulation

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1. Introduction

Mitral regurgitation (MR), also known as mitral insufficiency, is the primary result of mitral valve (MV) pathology. MR occurs when the MV is not properly closed during systole while the left ventricle pumps the blood toward the aorta, leading to backflow into the left atrium and decreased blood volume into the systemic circulation [1]. The etiology of MR can essentially be categorized into two groups: degenerative or functional MR [2]. Degenerative MV diseases are the most common pathologies involving severe MR. Elongation or rupture of the chordae tendineae, excessive expansion of leaflet tissue, severe annular dilation, or any combinations of these abnormalities result in mitral leaflet prolapse [3]. Functional MR develops in association with regional or global enlargement of the left ventricle which is often accompanied by annular dilation and malformed displacement of the papillary muscles [4].

MV repair is a standard surgical intervention for treatment of malfunctioning MVs having severe MR [5]. The goal of MV repair is to preserve the native MV tissue and restore normal valvular function by restructuring partial portions of the MV apparatus. To achieve a successful repair of a pathologic MV, clinicians evaluate the etiology, pathomorphology, and functional type of the regurgitation, and then select the most appropriate surgical techniques. There are a number of standard surgical techniques such as resection, neochordoplasty, plication, patching, and chordal transplantation to repair different types of pathologic MVs. Ring annuloplasty aims to reconfigure a dilated mitral annulus to its normal size and shape [6–8]. Ring annuloplasty is performed in combination with various MV repair techniques [7, 9].

A number of annuloplasty rings are currently available in different shapes, sizes and materials. Cardiothoracic surgeons determine the most appropriate ring for each patient generally based on his/her experience and preference in addition to the standard clinical guidelines for ring annuloplasty procedure. It is challenging to predict (prior to ring annuloplasty) the extent of restoration of normal MV function following implantation of a certain type of ring and surgical procedure to each patient.

Computational evaluation of MV function using finite element (FE) methods is a valuable tool to assess the biomechanical aspects of the MV apparatus following surgical intervention [10–13]. Several recent studies reported ring annuloplasty simulations using FE techniques under various physiologic conditions [14, 15]. Although these studies provide valuable information as to the effect of annuloplasty rings from a biomechanical perspective, it is still difficult to directly translate this information to the clinical setting to predict patient-specific ring annuloplasty outcomes. Employment of virtual ring annuloplasty techniques to patient-specific MV models can provide more realistic and more specific information pertaining to the effect of differing ring types on a particular pathologic MV.

In the present study, we investigated the effect of annuloplasty ring shape on patient-specific MVs using our established 3D echocardiography-based computational MV evaluation protocols [10–13]. Two distinct prototype annuloplasty rings (physiologic shape vs. non-physiologic shape) were virtually implanted in patient MV models having considerable MR.

The first annuloplasty ring was the Physio II (Edwards Lifesciences Inc, Irvine, CA, USA) which restores a flattened mitral annulus to a saddle (i.e., physiologic) shape [5]. The second annuloplasty ring was the GeoForm (Edwards Lifesciences Inc, Irvine, CA, USA) with a non-physiologic shape developed particularly to enhance leaflet coaptation for functional MR [5]. We performed dynamic FE simulations of MV function for each pathologic MV following virtual ring annuloplasty of the Physio II or GeoForm rings, and compared physiologic and biomechanical characteristics of post-annuloplasty MV function.

2. Materials and methods

2.1. Virtual patient MV modeling

This study was approved by the Committee for the Protection of Human Subjects at The University of Texas Health Science Center at Houston. Details of our computational protocols for individualized patient MV modeling and dynamic FE simulation of MV function are described in our previous work [13]. Briefly, virtual patient MV models were created from 3D transesophageal echocardiographic data in two patients having considerable MR due to mitral annular dilation. Virtual patient MV modeling was conducted using MATLAB (The Mathworks Inc., Natick, MA), and computational simulations for virtual ring annuloplasty and MV dynamics evaluation performed using ABAQUS (SIMULIA, Providence, RI).

The virtual patient MV modeling protocol includes acquisition of 3D echocardiographic image data, segmentation of the MV leaflets and annulus, 3D reconstruction of the MV leaflets and annulus, surface meshing of the leaflets, modeling of the chordae tendineae, and incorporation of dynamic motion of the annulus and papillary muscles. First, the primary geometric information including the annulus, both leaflets and the location of the papillary muscle tips at end diastole was identified from patient 3D TEE data. The leaflets and annulus were segmented, modeled using the 3D non-uniform rational B-spline (NURBS) surface modeling technique, and meshed (Patient 1 – 5,190 shell elements, Patient 2 – 5,226 shell elements). A total of 24 marginal chordae tendineae were created using 3D line elements to connect the marginal edge of both anterior and posterior leaflets and the papillary muscles [16, 17]. In addition, the two strut chordae tendineae were created by connecting the upper portion of the rough zone of the anterior leaflet and the papillary muscles. Distributed insertion of the chordae was performed around the papillary muscles.

A Fung-type elastic constitutive model was utilized to implement the anisotropic hyperelastic material characteristics of the MV leaflets [13, 18, 19]. Briefly, the Cauchy stress (σ) and the Green-Lagrange strain ($\mathbf{E}$) are represented as

$$\sigma = \frac{1}{J} \mathbf{F} \frac{\partial W}{\partial \mathbf{E}} \mathbf{F}^T \quad (1)$$

where J refers to the determinant of the deformation gradient ($\mathbf{F}$). Four parameters (c , A_1 , A_2 and A_3) are utilized to define the strain energy function W :

$$W = \frac{c}{2} [e^Q - 1], \quad Q = A_1 E_{11}^2 + A_2 E_{22}^2 + 2A_3 E_{11} E_{22} \quad (2)$$

The leaflet tissue is assumed to be nearly incompressible and hyperelastic ($J = \det \mathbf{F} = 1$), and the stress-strain relationship is described as

$$\sigma_c = (2E_{11} + 1) \exp(Q) (A_1 E_{11} + A_3 E_{22}) \quad (3)$$

$$\sigma_r = (2E_{22} + 1) \exp(Q) (A_3 E_{11} + A_2 E_{22}) \quad (4)$$

The principal material coordinates of the fiber directions were defined on the circumferential (σ_c) and radial (σ_r) directions across the leaflet surface. Material parameters of the anterior and posterior leaflet tissue determined by biaxial mechanical testing data in a previous study [18] were implemented into the Fung-type elastic constitutive model under the ABAQUS (SIMULIA, Providence, RI) platform. The leaflet thickness was set to be 0.69 mm and 0.51 mm for the anterior and posterior leaflets, respectively [20].

The Ogden models were implemented to define the nonlinear hyperelastic material behavior of the posterior marginal chordae, anterior marginal chordae, and strut chordae [21]. Cross-sectional areas of the posterior marginal chordae, anterior marginal chordae, and strut chordae were set to be 0.27 mm², 0.29 mm², and 0.61 mm², respectively [21]. Physiologic soft tissue density (1,100 kg/m³) and Poisson's ratio (0.48) were applied to the MV models [13, 14, 22].

2.2. Virtual ring annuloplasty

Two distinct prototype annuloplasty rings (Physio II and GeoForm) were virtually implanted into the patient MVs, and outcome compared (Figure 1). The Physio II ring has a physiologically-shaped structure with elevated anterior and posterior regions in a saddle shape to maximize spreading stress distribution across the MV leaflets and annulus [15]. The GeoForm ring has a non-physiologic shape with a markedly reduced anteroposterior distance and elevated posterior region to treat functional MR [5, 14].

Figure 2 demonstrates our computational protocol to perform virtual ring annuloplasty with post-repair MV function simulation. The standard clinical guidelines for ring annuloplasty describes that the selection of an annuloplasty ring type (i.e., shape) with a proper size is determined based on the morphologic dimension of each pathologic MV [23, 24]. In order to determine proper ring sizes (both Physio II and GeoForm) for the patients in this study, anatomic characteristics of the pathologic MVs were evaluated by measuring the intercommissural distance and anterior leaflet height of each patient MV. Similar to standard clinical guidelines, a proper ring size having the closest length to the intercommissural distance of the patient MV at end diastole was selected. Once a proper ring size was determined, the configuration of the virtual 3D annuloplasty ring was created from our

annuloplasty ring design database. We have recently developed a novel virtual 3D annuloplasty ring modeling platform providing a variety of types and sizes of annuloplasty rings that are currently available [10].

It is important to appropriately position the selected ring configuration over the pre-repair mitral annulus to generate the most realistic virtual ring annuloplasty simulation and subsequent MV function simulation. First, discrete 3D profiles of the virtual ring configuration and the pre-repair mitral annulus were positioned with the intercommissural lines of the ring and mitral annulus superimposed (Figure 3). The ring configuration was then tilted with respect to the intercommissural line (y-axis in Figure 3) such that the least square linear lines of the 3D profiles of the ring and the patient's mitral annulus were aligned to be parallel. Lastly, appropriate nodal displacements were applied along the pre-repair mitral annulus towards the ring configuration to complete the virtual ring annuloplasty simulation.

2.3. Dynamic FE simulation of MV function

For pre-annuloplasty (i.e., pathologic) MV simulations, dynamic mitral annular motion of each patient MV was modeled using two geometric configurations of the annulus at peak systolic pressure and at end diastole from the 3D echocardiographic data. Dynamic annular motion was defined using time-varying nonlinear nodal displacements along the annulus between these two configurations based on experimentally determined average mitral annular motion data across the cardiac cycle [13, 25]. As the stiffness of the annuloplasty rings (Young's modulus >90 GPa) are extremely larger than MV tissue [26], fixed boundary conditions were applied to the post-annuloplasty mitral annulus (i.e., ring configuration) to fully restrict annular motion during dynamic FE simulation of post-annuloplasty MV function.

Physiologic transvalvular pressure gradient across the cardiac cycle (duration = 1.8 seconds, peak systolic pressure = 126 mmHg) [27] was implemented into the dynamic FE simulations of both pre- and post-annuloplasty MV function. We utilized the general contact algorithm with the penalty method (friction coefficient = 0.05) to define coaptation between the two MV leaflets and self-contact in each leaflet during the closing phase. Similarly, the general contact algorithm was employed to simulate the leaflet-chordae interaction. Further details of dynamic FE simulation of MV function are described in previous studies [12, 13, 28, 29].

We performed MV function simulations prior to and following virtual ring annuloplasty (using both annuloplasty rings) in two patients having MR. Severe MR was found along the A1-P1 plane in patient 1. Patient 2 had mild MR near the A2-P2 coaptation region. Stress distributions across the mitral leaflets and annulus, and extent of leaflet coaptation were qualitatively and quantitatively determined for pre- and post-annuloplasty MVs to assess the effect of annuloplasty ring shape.

3. Results

3.1. Doppler ultrasound data and virtual MV models

Figure 4 demonstrates the Doppler ultrasound data of the two patient MVs and the corresponding virtual MV models. Severe MR was found at peak systolic pressure in the Doppler ultrasound data in patient 1. This clinical observation corresponded to computational evaluation of the virtual MV model identifying considerable lack of leaflet coaptation in the anterolateral commissural region. In patient 2, Doppler ultrasound revealed moderate MR during systole. Similarly, the dynamic FE simulation of the corresponding pathologic MV showed malcoaptation between the MV leaflets in the region with MR. These data indicate that our individualized virtual MV evaluation data correspond well to clinical observations in identifying physiologic characteristics and severity of MR.

3.2. Structural evaluation of the leaflets and annulus

Figure 5 demonstrates stress distributions across the MV leaflets and around the annulus at peak systolic pressure before and after virtual ring annuloplasty. A threshold stress value was set to 0.32 MPa to efficiently demonstrate marked alterations of excessive stress occurrence following virtual ring annuloplasty. In patient 1, the pre-annuloplasty MV displayed large stress values near the mid-anterior and mid-posterior annulus. With the Physio II ring implanted, most large stress values including the excessive stress concentration near the mitral-aortic junction disappeared, and the maximum stress value markedly dropped from 3.3 MPa to 0.3 MPa. Ring annuloplasty with the GeoForm ring also demonstrated considerably reduced stress distribution across the MV leaflets and annulus (maximum stress = 0.4 MPa). A small degree of stress concentration remained in the mid-posterior leaflet, presumably due to considerable pulling of the P2 scallop following virtual implantation of the GeoForm ring.

Although the pre-annuloplasty MV in patient 2 had more irregular annular shape compared to patient 1, alteration of stress distribution patterns was similar. Excessive stresses were found primarily in the mid-posterior region of the pre-annuloplasty MV. These large stresses in the posterior leaflet were alleviated and maximum stress was reduced by 6% and 43% after ring annuloplasty was performed using the Physio II and GeoForm ring, respectively. Additional large stress concentrations appeared near the mitral-aortic junction along the radial direction after restoration of the normal annular shape following Physio II implantation. Similar to patient 1, the GeoForm ring demonstrated a small increase of stress concentration near the mid-posterior leaflet.

Average regional stress distributions in six subregions of the leaflets at peak systolic pressure before and after virtual ring annuloplasty are shown in Table 1. The A1 subregion of patient 1 revealed the largest reduction (−72%) of average stress when the GeoForm ring was virtually implanted. In contrast, the average regional stress increased by 9.1% in the A1 region of patient 2 following virtual ring annuloplasty.

3.3. Quantitative evaluation of leaflet coaptation

Leaflet coaptation at peak systolic pressure was evaluated to determine the degree of restoration of normal MV function following virtual ring annuloplasty (Figure 6). The pre-annuloplasty MV in patient 1 showed a large deficiency of leaflet contact in the anterolateral commissural region. The region where the computational simulation demonstrated leaflet malcoaptation corresponded to the region where a regurgitant jet was found in the Doppler ultrasound data. Following implantation of either the Physio II or the GeoForm ring, the overall degree of leaflet coaptation increased and the non-contact region disappeared. Patient 2 revealed insufficient leaflet coaptation in the mid-anterior and posterior region, i.e., the A2-P2 scallop. Virtual ring annuloplasty with the Physio II ring increased leaflet coaptation and restored full leaflet coaptation. The GeoForm ring further improved the extent of full restoration of leaflet coaptation.

Both qualitative and quantitative evaluation of leaflet coaptation along the septolateral direction was performed to provide more clinically relevant information. Figure 7 demonstrates cross-sectional MV morphologies over regions where MR occurred before and after virtual ring annuloplasty. We found that both pre-annuloplasty MVs were involved with large lack of coaptation between the two leaflets and these physiologic abnormalities were successfully repaired after virtual ring annuloplasty. Coaptation lengths along the A1-P1 and A2-P2 cross-sectional planes were calculated in the pre- and post-annuloplasty MVs (Figure 8). Coaptation length was defined as the distance from the top of the contacting tract to the free marginal edge of the leaflet. In patient 1, the actual anteroposterior (A2-P2) coaptation length from the 3D TEE data was 6.5 mm at peak systolic pressure, and the corresponding pre-annuloplasty coaptation length from the MV simulation was 6.6 mm (difference = 1.5%). Leaflet coaptation in the A2-P2 plane was considerably enhanced after virtual ring annuloplasty, particularly when the GeoForm ring was utilized. The pre-annuloplasty MV showed no coaptation in the A1-P1 plane, but the coaptation length in the same region increased to 2.5 mm and 3.0 mm after ring annuloplasty using the Physio II and GeoForm rings, respectively. In patient 2, the primary region of malcoaptation (A2-P2) revealed no coaptation, and virtual ring annuloplasty restored the coaptation length to 4.8 mm (Physio II) and 10.3 mm (GeoForm).

4. Discussion

Ring annuloplasty has been developed to reduce an enlarged anterior-posterior mitral annular distance, restore normal or efficaciously functional annular shape, and successfully ameliorate the MR. Saddle-shaped rings allow larger leaflet curvature compared to flat rings following annuloplasty, potentially providing decreased stress concentration and improved long-term clinical outcomes [30]. From a perspective of leaflet coaptation, saddle-shaped ring annuloplasty allows a more preferred morphologic and functional leaflet coaptation including coaptation angle, coaptation area and coaptation tenting height during systole compared to flat ring annuloplasty involving immobilization of the posterior leaflet [31]. The Physio II ring, one of the most popular annuloplasty rings to date, has a D shape with the anterior region of the ring structure being nearly straight and the posterior portion has a curvature to restore the original shape of the mitral annulus [32–34]. In contrast, the

GeoForm ring was designed to elevate mid-posterior annulus toward the anterior direction to effectively reduce the anterior-posterior distance and minimize reduction of the annular surface area [14, 35]. The GeoForm ring is generally utilized for the treatment of functional MR induced by both ischemic and non-ischemic dilated cardiomyopathy. Annuloplasty using the GeoForm ring decreases tenting volume and valve circumference, improves left ventricular function and dimension, diminishes functional MR, and increases ejection fraction and cardiac output [36, 37]. Although each of commercially available annuloplasty rings has unique as well as common advantages from design, determination and prediction of post-annuloplasty functional and physiologic characteristics as well as indications for rings in patients are still controversial. In addition to conventional evaluation of MV pathologies using echocardiography, the determination of biomechanical characteristics pre- and post-annuloplasty including regional stress distribution, leaflet curvature, leaflet coaptation, leaflet contact pressure distribution, chordal stress, and annular reaction can provide the further insights to assess the status and severity of MV pathologies and optimize repair methodologies.

In this study, we implemented digitized annuloplasty ring profiles into patient MV models created from 3D echocardiographic image data and performed virtual ring annuloplasty simulations to predict physiologic and biomechanical characteristics of the post-annuloplasty MVs. Prior to further discussion, it is important to address several important engineering and computational factors implemented in the present study. Standard clinical guidelines for ring implantation is described such that appropriate placement of sutures is performed along the annulus fibrosus of the MV followed by equally and evenly placing sutures into a prosthetic ring to avoid any malposition of the ring or distortion of the annulus [24]. In practice, four primary landmarks are identified when placing sutures to tighten the ring; two mid-lines of the anterior and posterior leaflets and two commissures. The intercommissural distance is generally identical on the annulus and the ring, and the four landmark positions of the ring are placed at the exact corresponding positions of the annulus. This ring alignment protocol allows remodeling of a proper annular shape and optimized leaflet coaptation. In our virtual ring annuloplasty protocol, the exactly identical approach was designed in terms of ring alignment. Four landmark positions of each ring and the patient MV models were identified and corresponding anteroposterior (A-P) and intercommissural (AI-Pm) planes correctly aligned during virtual ring placement (Figure 3). Virtual suturing was then performed by applying nodal displacement along the mitral annulus towards the ring configuration which contained the same number of nodal points. Although this computational protocol may not represent a completely identical procedure of ring annuloplasty compared to the clinical intervention, we believe that this virtual evaluation strategy can provide excellent comparative information pertaining to post-annuloplasty biomechanical characteristics following different types of ring implantation.

Both annuloplasty rings clearly demonstrated marked reduction of large stress areas (Figure 5). The Physio II ring demonstrated more evenly distributed stress reduction across the leaflets and annulus compared to the GeoForm ring in patient 1. In patient 2, large stress values spreading towards the radial direction was found near the mitral-aortic junction in the post-annuloplasty MV with the Physio II ring. It is inferred that the overall elevation of the mitral-aortic junction region following implantation of the saddle-shaped Physio II ring

induced a hoisting effect on the strut chordae leading to increase in stress distribution. The GeoForm ring induced relatively large stress values in the mid-posterior leaflet along the radial direction in both patients, presumably due to the particular ring shape with elevated mid-posterior annulus toward the anterior direction. However, this highly non-planar curvature of the GeoForm ring helped to more effectively increase leaflet coaptation in the A2-P2 scallop compared to the Physio II ring (Figure 6). Although both annuloplasty rings efficiently restored leaflet coaptation, the GeoForm ring revealed a further increased degree of leaflet coaptation (Figure 7 and 8). This indicates that the shape of annuloplasty ring affects post-annuloplasty physiologic and biomechanical conditions, which can lead to tissue alteration over a longer period of time. This is why individualized virtual biomechanical evaluation of pre- and post-annuloplasty MV function is important and may have a great impact on preparation and pre-surgical planning of MV repair for severe MR treatment.

Votta et al. presented an excellent study to perform parametric studies to compare the effect of ring shape (Physio vs. GeoForm), ring size, and papillary muscle displacement [14]. Although they utilized a parametrically generated MV geometry and linear material properties for the MV tissue, they found important post-repair characteristics of these two annuloplasty rings such that GeoForm ring had further increased coaptation, further decreased maximum leaflet stresses, and induced much larger local stresses near the annular region compared to the Physio ring. In the present study, we performed more complicated dynamic FE simulations to investigate the effect of annuloplasty ring shape on patient-oriented pathologic MV models suffering from MR due to annular dilation. By performing a solid computational protocol using patient 3D echocardiographic data to simulate standard clinical guidelines-based virtual ring annuloplasty with the use of the Physio II and GeoForm rings, we clearly demonstrated the effect of annuloplasty ring shape on reduction/rearrangement of stress distribution and restoration of leaflet coaptation. We selected the two patient MVs having different degrees and locations of MR as well as different pre-repair pathologic annular shapes. While patient 1 had an enlarged left ventricle involving mitral annular dilation, patient 2 had a normal size of the left ventricle. As we utilized actual patient 3D TEE data to create virtual MV models, we believe that it is not appropriate to manipulate additional papillary muscle displacement. Therefore, we focused on evaluate the effect of annuloplasty ring shape on post-repair MV function of the pathologic MVs, especially from the biomechanical and physiologic perspectives.

There are several limitations and engineering simplifications involved in the present study. 1) While we extracted the leaflet/annulus geometry and annular motion from the patient 3D echocardiographic data, information pertaining to the actual chordal distribution was not available from 3D TEE data due to the limited spatial and temporal resolution issues of the currently available clinical imaging modality. Therefore, information of the average number and location of the chordae tendineae from previously reported clinical data [16, 17] were implemented to create the marginal and strut chordae. 2) Another important factor is that experimentally measured tissue thickness, tissue density, and material properties of the leaflets and chordae from previous studies were utilized as these variables are not available from current imaging technologies in vivo. We have recently reported studies in which our virtual MV simulation strategy was quantitatively and qualitatively compared with clinical evaluation for various MV pathology cases [11–13, 28, 38, 39]. The present study is focused

on evaluation of the effect of ring shape on post-annuloplasty functional and biomechanical characteristics of MV dynamics. Given that the identical computational assumptions are employed, the virtual ring annuloplasty simulation strategy provides valuable comparative information in terms of prediction of the effect of ring shape. 3) We decided not to implement the prestress that occurred during virtual ring annuloplasty procedure into the subsequent simulations of post-annuloplasty MV dynamics as even after an annuloplasty ring is implanted, the chordae usually do not get taut until the left ventricle is filled with saline to test whether there is any leakage following ring placement. Another reason for this decision is that in most cases virtual ring annuloplasty did not form considerable prestresses in the leaflets, primarily due to the direction of the nodal displacement from a large dilated annular geometry to a smaller post-annuloplasty annular dimension. However, prestresses generated during virtual ring annuloplasty procedure may affect the subsequent leaflet stress distribution in particular pathologic MV repair cases. 4) Although in vivo stiffness can be up to three orders of magnitude larger than ex vivo stiffness in thin biologic membranes such as MV leaflet tissue [40, 41], material properties experimentally determined from ex vivo biaxial tests were utilized without accounting for the prestrain effect. While the effect of prestrain and residual stress in thin biologic membranes is a relatively new concept and still not fully understood, prestrain and residual stress information may play an important role in computational evaluation of in vivo MV dynamics. 5) Hemodynamic effects of blood flow needs to be further incorporated into our current computational MV evaluation system. Dynamic FE simulations of MV function were performed using physiologic damping conditions, which closely mimic blood fluid effects on deformation and stress distribution on the leaflets in an FE structural simulation platform. A comprehensive 3D fluid-structure interaction model will be required to fully determine the physiologic characteristics of MV dynamics including regional blood flow information and normal and shear pressure distributions over the leaflets and chordae. 6) The highly non-planar curvature of the GeoForm with elevated mid-posterior annulus would considerably increase stress and strain values in the vicinity of the posterior left ventricular wall where the papillary muscles are located at and the chordae are connected to. As the left ventricle was not included in the MV apparatus modeling in this study, detailed information pertaining to the effect of ring annuloplasty on the post-repair structural characteristics of the left ventricle is not available. 7) Lastly, computational evaluation and prediction of post-annuloplasty MV dynamics may provide valuable structural information as to immediate post-annuloplasty tissue conditions, but long-term post-annuloplasty effects should be carefully determined as regional tissue remodeling may occur leading to structural alterations of the MV apparatus.

5. Summary

We have evaluated the effect of annuloplasty ring shape (Physio II and GeoForm rings) on reduction of stress distribution and restoration of leaflet coaptation using computational evaluation techniques and patient 3D echocardiographic data. This virtual ring annuloplasty simulation strategy provides detailed physiologic and biomechanical information pre- and post-annuloplasty. This may help better plan the optimal ring selection and improve patient-specific MV repair procedures.

Acknowledgments

This work was in part supported by the National Institutes of Health (R01HL109597).

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Figure 1. Geometric configurations of the physiologic and non-physiologic rings for virtual ring annuloplasty: Physio II and GeoForm. A – anterior, P – posterior, Al – anterolateral commissure, Pm – posteromedial commissure.

Figure 2. Computational protocol for virtual ring annuloplasty and MV function simulation using the Physio II and GeoForm rings.

Figure 3. Positioning of the virtual ring configuration over the pre-repair mitral annulus (Physio II vs. GeoForm). LA – left atrium, LV – left ventricle, A – anterior, P – posterior, Al – anterolateral commissure, Pm – posteromedial commissure.

Figure 4.

Doppler ultrasound data in two patient MVs having MR (top), and corresponding virtual MV models demonstrating leaflet malcoaptation at peak systolic pressure (bottom). LA – left atrium, LV – left ventricle, A – anterior, P – posterior, AI – anterolateral commissure, Pm – posteromedial commissure, A1 – lateral anterior, A2 – central anterior, A3 – medial anterior, P1 – lateral posterior, P2 – central posterior, P3 – medial posterior.

Figure 5. Stress distributions across the MV leaflets and around the annulus at peak systolic pressure before and after virtual ring annuloplasty. A – anterior, P – posterior, AI – anterolateral commissure, Pm – posteromedial commissure.

Figure 6. Leaflet coaptation at peak systolic pressure prior to and following virtual annuloplasty using the Physio II and GeoForm rings (from anterior ventricular viewpoint). A – anterior, AI – anterolateral commissure, Pm – posteromedial commissure.

Figure 7.

Cross-sectional MV morphologies over regions where MR occurred in each patient before and after virtual ring annuloplasty. A1 – lateral anterior, A2 – central anterior, P1 – lateral posterior, P2 – central posterior.

Figure 8. Coaptation lengths in the A1-P1 and A2-P2 planes before and after virtual ring annuloplasty. A – anterior, P – posterior, Al – anterolateral commissure, Pm – posteromedial commissure, A1 – lateral anterior, A2 – central anterior, P1 – lateral posterior, P2 – central posterior.

Average regional stress distributions in six subregions of the leaflets at peak systolic pressure before and after virtual ring annuloplasty (mean $\pm$ standard deviation, unit = MPa).

Table 1

		Pre-annuloplasty	Post-annuloplasty (Physio II)	Post-annuloplasty (GeoForm)
Patient 1	A1	0.50 $\pm$ 0.01	0.20 $\pm$ 0.01	0.14 $\pm$ 0.01
	A2	0.35 $\pm$ 0.01	0.15 $\pm$ 0.01	0.13 $\pm$ 0.01
	A3	0.24 $\pm$ 0.01	0.14 $\pm$ 0.01	0.13 $\pm$ 0.01
	P1	0.11 $\pm$ 0.01	0.08 $\pm$ 0.01	0.05 $\pm$ 0.01
	P2	0.23 $\pm$ 0.01	0.14 $\pm$ 0.01	0.15 $\pm$ 0.01
	P3	0.13 $\pm$ 0.01	0.07 $\pm$ 0.01	0.09 $\pm$ 0.01
	A1	0.11 $\pm$ 0.02	0.12 $\pm$ 0.02	0.12 $\pm$ 0.02
Patient 2	A2	0.21 $\pm$ 0.01	0.22 $\pm$ 0.01	0.13 $\pm$ 0.01
	A3	0.25 $\pm$ 0.01	0.24 $\pm$ 0.01	0.12 $\pm$ 0.01
	P1	0.11 $\pm$ 0.01	0.10 $\pm$ 0.01	0.09 $\pm$ 0.01
	P2	0.27 $\pm$ 0.01	0.18 $\pm$ 0.01	0.15 $\pm$ 0.01
	P3	0.21 $\pm$ 0.01	0.11 $\pm$ 0.01	0.10 $\pm$ 0.01