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A novel finite element-based patient-specific mitral valve repair: virtual ring annuloplasty

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Abstract

Alterations of normal mitral valve (MV) function lead to mitral insufficiency, i.e., mitral regurgitation (MR). Mitral repair is the most popular and most efficient surgical intervention for MR treatment. An annuloplasty ring is implanted following complex reconstructive MV repairs to prevent potential reoccurrence of MR. We have developed a novel finite element (FE)-based simulation protocol to perform patient-specific virtual ring annuloplasty following the standard clinical guideline procedure. A virtual MV was created using 3D echocardiographic data in a patient with mitral annular dilation. Proper type and size of the ring were determined in consideration of the MV apparatus geometry. The ring was positioned over the patient MV model and annuloplasty was simulated. Dynamic simulation of MV function across the complete cardiac cycle was performed. Virtual patient-specific annuloplasty simulation well demonstrated morphologic information of the MV apparatus before and after ring implantation. Dynamic simulation of MV function following ring annuloplasty demonstrated markedly reduced stress distribution across the MV leaflets and annulus as well as restored leaflet coaptation compared to pre-annuloplasty. This novel FE-based patient-specific MV repair simulation technique provides quantitative information of functional improvement following ring annuloplasty. Virtual MV repair strategy may effectively evaluate and predict interventional treatment for MV pathology.

Keywords

Mitral valve; annuloplasty; mitral repair; patient-specific; finite element

1. Introduction

The mitral valve (MV) is one of the four valves in the human heart and located between the left ventricle and the left atrium. The MV apparatus consists of four principal substructures: saddle-shaped annulus, anterior and posterior leaflets, chordae tendineae, and papillary muscles [1]. When the left ventricular pressure increases during the systolic phase, the mitral annulus contracts and the two leaflets contact completing closure of the MV. Normal MV

function demonstrates sufficient leaflet coaptation and little regurgitant blood flow from the left ventricle to the left atrium [2].

Alterations of normal MV function lead to mitral insufficiency, i.e., mitral regurgitation (MR). There are three primary functional mechanisms of MR; lack of leaflet coaptation due to annular dilation, leaflet prolapse caused by elongation or rupture of the chordae, and limited movement of the mitral leaflets following left ventricular remodeling [3]. Mitral repair has been utilized as the most popular and most efficient surgical intervention for MR treatment rather than total valve replacement [4]. Undersized ring annuloplasty is commonly performed during MV repair to reduce dilated annular dimension [5]. An annuloplasty ring is implanted following complex reconstructive MV repairs to prevent potential reoccurrence of MR [6].

Detailed quantitative assessment of patient-specific MV function before and after repair can aid in pre-surgical planning and improve interventional outcomes. Computational techniques have been implemented to analyze MV function in various pathologic conditions [7, 8]. Finite element (FE) method provides a valuable tool to predict structural analysis of the MV apparatus following MV repair such as ring annuloplasty [9]. Computational simulation of MV repair may help surgeons to better identify proper repair procedures [10].

Votta et al. [11] reported a comparative simulation study between the Physio and the Geoform annuloplasty rings. More recently, Wong et al. [12] demonstrated the effect of the Physio II and the IMR ETlogix rings. However, these studies employed partial patient-specific MV geometry or animal MV model. In order to accurately assess and predict the effect of ring implantation, it is essential to create a patient-specific MV model using clinical imaging modality.

The objective of this study is to develop a novel FE-based simulation protocol to perform patient-specific virtual ring annuloplasty to repair MR. Standard clinical guidelines for ring annuloplasty surgery were implemented into computational modeling procedures, and dynamic FE simulations of MV function across the cardiac cycle before and after ring implantation were performed.

2. Materials and Methods

2.1. Patient-specific virtual MV modeling

This translational study has been approved by the Committee for the Protection of Human Subjects at The University of Texas Health Science Center at Houston. A patient-specific virtual MV model was created from 3D transesophageal echocardiography (TEE) data of a patient with MR due to annular dilation using our virtual MV modeling protocol developed in previous studies [13]. Briefly, this virtual MV modeling protocol consists of sub-algorithms developed using MATLAB (The Mathworks Inc., Natick, MA) and ABAQUS (SIMULIA, Providence, RI). The modeling protocol includes acquisition of 3D TEE image data, segmentation of the MV leaflets and annulus, 3D reconstruction of the leaflets and annulus, surface mesh, creation of the chordae tendineae, incorporation of dynamic motion of the annulus and papillary muscles, and dynamic FE simulation of MV function. The MV

leaflets and annulus at end diastole were segmented, the 3D leaflets/annulus geometry created using the NURBS surface modeling technique, and meshed. The chordae tendineae were modeled by connecting the papillary muscle tips and the leaflet edges. A Fung-type elastic constitutive model was utilized to model the anisotropic hyperelastic material characteristics of the MV leaflets [14, 15]. The first order Ogden model was implemented to define the nonlinear hyperelastic material behavior of the posterior marginal chordae, and the second order Ogden model for the anterior marginal and strut chordae [7].

2.2. Surgical procedure of ring annuloplasty

The standard clinical guideline of ring annuloplasty procedure [16] is described in Fig. 1. It is important to identify the shape and size of the dilated annulus for proper ring selection (Fig. 1A). Regardless of the type of ring, the selection is based primarily on the MV dimension (base length and anterior leaflet height) of the anterior leaflet.

Two landmark sutures are placed at the commissures and the distance between the sutures (i.e., intercommissural distance) is measured using specifically designed ring sizers (Fig. 1B). Next, the height of the anterior leaflet is measured by stretching the anterior leaflet beneath the sizer. The selected sizer should cover the entire surface area of the anterior leaflet. Most of cases, a good correlation is found between the intercommissural distance and the anterior leaflet height. If the anterior leaflet height extends beyond the inferior edge of the selected sizer, a one size larger ring is implanted to prevent the risk of systolic anterior motion of the anterior leaflet (Fig. 1B). After the proper ring size is determined, a series of 12 to 15 sutures are placed through the ring and the mitral annulus (Fig. 1C). Once the ring is placed on the annulus, saline test is performed prior to tying the sutures in order to identify any potential leakage (Fig. 1D). The quality of ring annuloplasty is also assessed by the leaflet coaptation height and the morphology of the closure line of the leaflets.

2.3. Virtual ring implantation and MV function simulation

A virtual ring annuloplasty simulation protocol has been developed strictly following the standard clinical guidelines of ring annuloplasty procedure (Fig. 2). The protocol is composed of two modeling modules: ring modeling and patient MV modeling. First, a disease-specific ring type is determined to comply with anatomic and pathologic characteristics of the MV. A proper ring size is determined in consideration of two geometric information of the MV apparatus. A ring size with the closest length to the intercommissural distance of the MV at end diastole is selected. The anterior leaflet height is compared with the septolateral diameter of the selected ring. Similar to the standard clinical guideline, a one size larger or smaller ring is selected if the two lengths are significantly different. For example, in this study, the intercommissural length of the patient MV with annular dilation was 40.4 mm and the Physio II ring (Edwards Lifesciences, Irvine, California) with size 40 was selected in consideration of both the intercommissural distance and anterior leaflet height.

Once the type and size of the ring are determined, detailed ring geometry is created. The profiles of the annuloplasty ring geometry are collected from the technical drawings provided by the manufacturer followed by 3D reconstruction of the ring using 3D cubic

spline algorithms. The patient MV model and the virtual ring are aligned such that the intercommissural and septolateral lines of the mitral annulus and the ring are superimposed (Fig. 3A). Positioning of the annuloplasty ring is completed after tilting the least square linear line of the ring to that of the patient mitral annulus (Fig. 3B). Creation and alignment of the virtual annuloplasty ring was performed using MATLAB.

Following the incorporation of the ring placement with the virtual MV model, the annulus of the 3D MV model is deformed to the ring configuration by imposing appropriate nodal displacements. Lastly, physiological transvalvular pressure gradient is applied to the leaflets and dynamic FE simulation of MV function across the complete cardiac cycle is performed. Fixed boundary condition is applied to the annulus assuring no annular deformation of the ring during MV function.

3. Results

3.1. Virtual ring annuloplasty and MV function simulation

Patient-specific virtual ring annuloplasty for the treatment of annular dilation was successfully simulated followed by MV function simulation (Fig. 4). The posterior annular displacement toward the ring configuration was larger than the anterior or commissural annular displacements in this particular patient case (Fig. 4A). Morphology of the MV apparatus was well demonstrated at the fully open position, during the closing phase, and at the fully closed position (Fig. 4B).

3.2. Stress distribution and leaflet coaptation

Stress distributions across the MV leaflets and annulus at peak systole pre- and post-ring annuloplasty are demonstrated in Fig. 5A (from the atrial view). As the range of stress values was considerable, 0.32 MPa was set as the threshold of red color with notation of the maximum stress value to better provide quantitative comparison of stress distribution between the two simulations. The patient MV with annular dilation demonstrated widely spread large stress distribution along the circumferential direction near the anterior saddle-shaped horn as well as in the posterior leaflet. Dynamic simulation of MV function following ring annuloplasty demonstrated markedly reduced stress distribution across the MV leaflets and annulus compared to pre-annuloplasty. In particular, the excessive leaflet stress concentration near the anterior horn disappeared with the repaired mitral annular dimension after ring implantation. The maximum von Mises stress values pre- and post-ring annuloplasty were 3.33 MPa and 0.33 MPa, respectively.

In order to evaluate the effect of ring implantation on restoration of leaflet coaptation, leaflet contact at peak systole was determined before and after ring annuloplasty (Fig. 5B). Full contact and no contact between the two leaflets are displayed in red and blue, respectively (from the anterior view). The patient MV with annular dilation demonstrated a considerable lack of leaflet contact in the mid-anterior and anterolateral commissural region, which corresponded to the location of MR found in the Doppler ultrasound data. Following virtual ring annuloplasty, leaflet coaptation was fully restored.

4. Discussion

Quantitative evaluation of the effect of ring annuloplasty on MV dynamics following MV repair for MR treatment has been a challenge. Previous studies have focused on the effect of types and size of the ring in animal models [5, 11], or utilized simplified FE MV models [11, 12]. Although these studies help us to understand the effect of ring implantation on restoration of MR, dynamic FE simulation using patient-specific MV models directly imported from clinical imaging data can provide improved biomechanical and physiological information of MV function, and help to better predict the degree of recovery to normal MV function following ring annuloplasty.

In the present study, a computational protocol has been demonstrated to create patient MV model using patient 3D TEE data, incorporate of annuloplasty ring with the patient MV model, simulate virtual ring annuloplasty, and perform dynamic FE evaluation of MV function before and after ring annuloplasty. This strategy of virtual ring annuloplasty simulation enabled us to assess quantitative information pertaining to the biomechanical and physiological characteristics of MV function prior to and following the mitral repair. Annular displacement in the posterior region was greater than the anterior region during the ring annuloplasty. Excessive leaflet stress distribution disappeared and leaflet coaptation markedly increased after ring implantation. This indicates that reduced (26%) annular area with the undersized ring contributes to the increase of available leaflet area for coaptation and reduction of the effect of the ventricular pressure on leaflet stress distribution. Chordal stress and reaction forces on the papillary muscles were also reduced.

There are several limitations in this study. In real surgical procedures of ring annuloplasty, the stretched anterior leaflet height is measured to choose a proper ring size. The anterior leaflet height of our patient MV model at end diastole was measured and utilized to determine correct ring size. Ring implantation simulation was performed by superimposing the ring and the MV annulus at end diastole followed by applying nodal displacement along the annulus to the ring configuration. This assumption on the alignment of ring implantation may not exactly mimic the physiologic conditions of the surgical ring implantation procedure. Although the patient-specific MV geometry was acquired from 3D TEE data, the chordae tendineae were modeled based on previous publications [15] due to the limited imaging resolution.

This novel FE-based patient-specific MV repair simulation technique provides quantitative information of functional improvement following ring annuloplasty. This virtual MV repair strategy may effectively evaluate and predict interventional treatment for MV pathology.

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Fig. 1.

Schematics of the standard clinical guideline of ring annuloplasty surgery procedure

Fig. 2.
Flowchart of virtual ring annuloplasty followed by dynamic FE simulation of MV function

Fig. 3.
Alignment of the annuloplasty ring and the patient mitral annulus

Fig. 4.
Virtual ring annuloplasty and MV function simulation

Fig. 5.
Von Mises stress distribution and contact area across the MV leaflets