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Mitral Valve Repair Using ePTFE Sutures for Ruptured Mitral Chordae Tendineae: A Computational Simulation Study

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Abstract

Mitral valve repair using expanded polytetrafluoroethylene (ePTFE) sutures is an established and preferred interventional method to resolve the complex pathophysiologic problems associated with chordal rupture. We developed a novel computational evaluation protocol to determine the effect of the artificial sutures on restoring mitral valve function following valve repair. A virtual mitral valve was created using three-dimensional echocardiographic data in a patient with ruptured mitral chordae tendineae. Virtual repairs were designed by adding artificial sutures between the papillary muscles and the posterior leaflet where the native chordae were ruptured. Dynamic finite element simulations were performed to evaluate pre- and post-repair mitral valve function. Abnormal posterior leaflet prolapse and mitral regurgitation was clearly demonstrated in the mitral valve with ruptured chordae. Following virtual repair to reconstruct ruptured chordae, the severity of the posterior leaflet prolapse decreased and stress concentration was markedly reduced both in the leaflet tissue and the intact native chordae. Complete leaflet coaptation was restored when four or six sutures were utilized. Computational simulations provided quantitative information of functional improvement following mitral valve repair. This novel simulation strategy may provide a powerful tool for evaluation and prediction of interventional treatment for ruptured mitral chordae tendineae.

Keywords

Mitral valve; Three-dimensional echocardiography; Mitral repair; Chordae tendineae; Simulation; Finite element

INTRODUCTION

Mitral valve (MV) incompetence results from impairment of the components of the MV apparatus and leads to mitral regurgitation (MR). Examples such as MV prolapse have an effect on the biomechanical characteristics of the MV structure yielding large deformation of the MV leaflets and chordae tendineae. As the chordae tendineae play the primary role in anchoring the leaflets and supporting the subvalvular structures, severe MR is usually observed when one or more of the chordae tendineae are ruptured.

Ruptured mitral chordae tendineae (RMCT) can be repaired by reconstructing or replacing the chordae tendineae with or without annuloplasty.¹ A variety of surgical treatments are currently available for RMCT management. Due to the limited availability of healthy tissue surrounding the damaged tissue, it is technically challenging to reconstruct the valvular and subvalvular

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apparatus of the MV with RMCT. In recent years, there has been an increased interest in the use of artificial chordae to replace ruptured ones.²

A number of studies have investigated failure mechanisms of the MV apparatus tissue using ex-vivo and in-vivo approaches.^{3,4} Expanded polytetrafluoroethylene (ePTFE) sutures for chordae repair surgery are one of the most popular methods to form neochordae to repair RMCT.² Experimental animal studies have demonstrated that ePTFE sutures can restore leaflet coaptation and effectively reduce regurgitation.^{5,6} Clinical studies of the long-term effect of the ePTFE sutures used for MV repair have reported that these sutures are safe, effective and reproducible to repair RMCT.^{2,7} However, the ePTFE sutures occasionally fail due to degeneration, calcification and rupture likely due to different material behaviors between the ePTFE sutures and the native chordae.⁸ Patient-specific computational simulation of the MV with RMCT can help us understand the complex functional and biomechanical information of the MV before and after repair using ePTFE sutures.

Detailed morphology of the MV leaflets and annulus can be determined functionally and anatomically using 3D transesophageal echocardiography (TEE).⁹ Computational simulation using numerical analysis methods can also be utilized to assess the functional and biomechanical characteristics of the MV apparatus during valvular function.^{10,11}

The purpose of the present study is to develop a novel evaluation protocol to create a virtual MV model using 3D TEE data in a patient with posterior partial RMCT and to determine the effect of ePTFE sutures on restoring MV function following virtual repair.

MATERIALS AND METHODS

Modeling of the MV with RMCT Using Patient 3D TEE Data

The Committee for the Protection of Human Subjects at The University of Texas Health Science Center at Houston has approved this translational study. A written informed consent was obtained prior to 3D TEE data acquisition. An iE33 ultrasound unit (Philips Medical Systems, Bothell, WA) with a 3D TEE transducer (frame rate = 25–56 fps) was used to collect 3D geometric data of the MV apparatus including the anterior and posterior leaflets, and mitral annulus from a patient with RMCT. The 3D TEE data clearly demonstrated MV prolapse of the pathologic MV with a large flail P2 scallop due to RMCT (Fig. 1).

Fig. 2A presents a schematic protocol of our computational MV evaluation procedure to create a virtual MV with RMCT using patient 3D TEE data followed by virtual repair of the valve and computational simulation of the virtually repaired MV. The ECG-gated patient 3D TEE data containing the full volumetric image data of the anterior/posterior leaflets and mitral annulus at end diastole were transferred from the ultrasound system to a personal computer. The mitral leaflets and annulus were segmented and traced in eighteen evenly positioned cutplane images in the cylindrical coordinate system.^{10,11} These segmented geometric data were transformed into the Cartesian coordinate system. The 3D mitral leaflets and annulus were created using a non-uniform rational B-spline (NURBS) surface modeling technique, imported into finite element software, ABAQUS (SIMULIA, Providence, RI), and meshed with 5,560 triangular shell elements (S3R element type). Based on the patient's echocardiogram report indicating that the middle scallop (P2) of the posterior leaflet had many ruptured chordae tendineae resulting in severe posterior leaflet prolapse (flail P2 scallop), a total of 21 chordae tendineae including two strut chordae were modeled connecting the papillary muscles and the anterior and posterior leaflet nodes except the P2 region of the posterior leaflet. Six line elements (T3D2 element type) were utilized to model each chordae tendineae. The location of the papillary muscles was determined in the patient TEE data, and the chordae insertion was distributed around the papillary muscles.

Virtual repair was designed by adding ePTFE sutures between the posterior papillary muscles and the P2 scallop where the chordae were ruptured to determine how efficiently the chordal replacement would restore MV function, particularly in terms of the degree of leaflet coaptation and the degree of MR.

Modeling of Virtual Repair of the Ruptured Chordae

Morphologic characteristics of the virtual MV with the ruptured posterior scallop chordae clearly demonstrated asymmetric leaflet shape in the P2 region (Fig. 2A) that has a marginal length of 22 mm where no chordae are attached.

As 4-0 to 6-0 ePTFE sutures are the most popular sizes for chordae repair intervention,² 5-0 ePTFE suture was utilized for this virtual repair study. Virtual repairs using two, four and six 5-0 ePTFE sutures were designed to evaluate post-repair MV function (Fig. 2B). Each ePTFE suture was modeled by adding two line elements (T3D2 element type) between the posterior papillary muscles (where the ruptured native chordae would have been located) and the posterior leaflet (i.e., P2 region) with a bite distance of 2 mm from the marginal edge (Fig. 2B). The ePTFE suture length was identified using the bulging height of the posterior leaflet from the annular plane at peak systole measured in the preoperative patient TEE data. The ePTFE suture length was determined by subtracting this bulging height from the distance between the papillary muscle tip and the posterior marginal edge in the leaflet coaptation.¹² The average distance between the sutures was 7.0 mm, 5.1 mm and 2.9 mm in the virtual repair simulations with two, four and six 5-0 ePTFE sutures, respectively.

Computational Evaluation of MV Function

The MV leaflet tissue was modeled as a hyperelastic material using a Fung-type elastic constitutive model considering the anisotropic characteristics with respect to the circumferential and radial directions.^{11,13,14} Leaflet thickness was set to be 0.69 mm and 0.51 mm for the anterior and posterior leaflets, respectively.¹⁵

The chordae tendineae were modeled as nonlinear hyperelastic materials using the 1st order Ogden model for the posterior marginal chordae and the 2nd order Ogden models for the anterior marginal and strut chordae.¹⁶ The cross-sectional areas of the anterior marginal chordae, posterior marginal chordae, and strut chordae were set to be 0.29 mm², 0.27 mm² and 0.61 mm², respectively.¹⁶ The density and Poisson's ratio of the whole MV apparatus were set to be 1,100 kg/m³ and 0.48, respectively.^{17,18}

In order to incorporate the patient-specific annular motion, the annular geometry at peak systole was transformed into the local coordinate of the virtual MV model at end diastole. Dynamic motion of the annulus and papillary muscles were defined as time-dependent nonlinear nodal displacements.^{10,11} Time-varying transvalvular physiologic pressure gradient across the left ventricle and left atrium was applied on the virtual MV leaflets for dynamic finite element simulations over the complete cardiac cycle. The maximum systolic and diastolic pressure values were approximately 12.0 kPa and -0.3 kPa, respectively. In order to account for the coaptation between the two MV leaflets and self-contact in each leaflet during the closing phase, the general contact algorithm with the penalty constraint enforcement method was utilized. The friction coefficient was assumed to be 0.05.¹⁹ Further details of our protocol for MV modeling and dynamic finite element analysis are described in previous studies.^{10,11}

RESULTS

Validation Studies of the Modeling and Simulation Protocols

In the present study, we have strictly followed our previously reported computational protocols for virtual MV modeling and MV function simulation.^{10,11} We have performed additional qualitative and quantitative validation studies with respect to leaflet deformation, MR characteristics, and chordal reaction forces.

Fig. 3 demonstrates the cross-sectional (A3-P1) view of the leaflet morphology at peak systole superimposed by the simulation-predicted leaflet deformation. There was a good agreement in leaflet deformation between the virtual MV simulation data and the patient's echocardiographic data.

There was severe eccentric MR found in the 2D Doppler ultrasound images on the cross-sectional view (A3-P1) at peak systole in the MV with RMCT (Fig. 4). The regurgitant jet was anteriorly directed at peak systole due to abnormal bulging of the posterior mitral leaflet in the P2 region. Dynamic finite element simulation of the pathologic MV demonstrated the posterior leaflet bulged toward the anterolateral commissure with a large prolapse in the P2 region (Fig. 4). This computational evaluation corresponded well to the physiologic MR characteristics observed in the 2D and 3D TEE data.

Another quantitative validation was performed using the reactive forces exerted on the papillary muscles. The total chordal forces exerted on the anterolateral and posteromedial papillary muscles at peak systole computed in the simulation of the MV with RMCT were 4.6 N and 4.2 N, respectively, which well corresponded to previous in-vitro experimental data (4.5 N).²⁰

Morphologic and Functional Characteristics of the MV with RMCT

The annular diameter (commissure-to-commissure) of the MV with RMCT was 4.2 cm at end diastole and 4.3 cm at peak systole. The septolateral diameter of the annulus at end diastole (4.3 cm) was reduced by 16% at peak systole (3.7 cm). Morphologic and functional characteristics of the MV with RMCT at peak systole following virtual repair are shown in Fig. 5A. The edges of the anterior and posterior mitral leaflets on the half-cut (A2-P2) plane are displayed in blue and red, respectively, to better demonstrate the posterior leaflet prolapse and leaflet coaptation at peak systole. In the MV with RMCT, the posterior leaflet was subject to severe prolapse toward the left atrium resulting in no contact between the leaflets at peak systole.

Following virtual repair of the MV with RMCT using two ePTFE sutures, the severity of the posterior leaflet prolapse decreased and coaptation between the MV leaflets increased. However, a small degree of bulging remained in the basal region of the posterior leaflet at peak systole. With four or six ePTFE sutures utilized in virtual repair, little prolapse was found in the posterior leaflet at peak systole. There was little difference between virtual chordae repair models using four and six ePTFE sutures in terms of leaflet deformation.

Stress Distribution across the MV Leaflets Following Virtual Repair

Stress distribution across the mitral leaflets and annulus of the pathologic and virtually repaired MVs at peak systole are shown in Fig. 5B. In the MV with RMCT, relatively large stress values (>0.6 MPa) were found around the mitral annulus-aorta junction in the anterior leaflet. Low stresses occurred in the anterolateral and posteromedial commissural regions (<0.2 MPa). Excessively large stress concentration (>1.0 MPa) occurred along the free marginal edge of the posterior leaflet in the P2 region where the chordae were ruptured. The maximum stress

(3.1 MPa) in the leaflets was localized near the mitral annulus–aorta junction in the anterior leaflet.

Following virtual MV repair using two 5-0 ePTFE sutures, the excessive stress concentration disappeared and the maximum stress (1.4 MPa) was markedly reduced. Relatively large stress concentration (>0.6 MPa) was observed near the chordal attachment points where the two sutures were virtually repaired in the P2 region. Stress values (0.4–0.6 MPa) in the belly region of the anterior leaflet were similar to the MV with RMCT.

When four and six sutures were utilized for virtual chordae repair, better outcomes were obtained compared to the two-suture repair simulation. The greater the number of sutures utilized for virtual chordae repair, the lower the stress concentration near the suture attachment points and the more widely shared the stress distribution. However, there was little difference in the maximum stress values (1.3–1.4 MPa) with respect to the number of sutures for virtual repair. Stress distribution in the anterior leaflet again demonstrated little difference with respect to the number of sutures used for virtual chordae repair.

Leaflet Coaptation and Chordal Stress Distribution

Coaptation of the anterior and posterior mitral leaflets at peak systole markedly increased following virtual chordae repair with ePTFE sutures (Fig. 6A). In the MV with RMCT, severe posterior leaflet prolapse due to the ruptured chordae demonstrated a distinct lack of leaflet contact in the P2 region. With two ePTFE sutures virtually connected between the papillary muscles and the P2 region, increased leaflet contact was clearly observed over P2 resulting in reduced prolapse. However, a moderate degree of MV prolapse and incomplete leaflet coaptation still remained after two-suture repair technique. When four and six sutures were utilized for virtual chordae repair, complete leaflet coaptation with full contact between the two leaflets was restored. There was little difference in the extent of contact region between the virtual chordae repairs using either four or six sutures.

The maximum stress values in the intact native chordae connected to the posterior leaflet ranged from 0.3 MPa to 3.1 MPa at peak systole (Fig. 6B). In the MV with RMCT, the extremely large stresses occurred in the neighboring intact posterior chordae that were adjacent to the ruptured P2 region. The maximum stress value was 3.1 MPa in the intact chordae located at the P2-P3 border, and the posteromedial commissural region demonstrated the smallest chordal stresses. Following virtual chordae repair with two ePTFE sutures, the maximum stress in the neighboring intact posterior chordae was markedly reduced to 1.3 MPa. Further decrease of the maximum chordal stress (0.8 MPa) was attained after virtual repair using either four or six ePTFE sutures. The maximum chordal stress after the virtual repair with four or six sutures ranged between 0.3 MPa and 1.1 MPa.

DISCUSSION

MV repair using ePTFE sutures is an established and preferred interventional method to resolve the complex pathophysiologic problems of MVs with RMCT.^{2,21} Clinical studies have demonstrated that the ePTFE chordae can keep their flexibility following fibrous tissue layering without calcification.^{8,22} However, it is difficult to quantitate the interaction and interdependence between the ePTFE chordae and the native chordae following chordae repair.

In the present study, we developed a novel computational MV evaluation protocol to create a virtual MV model with RMCT using patient-specific 3D TEE data, and investigated the effect of ePTFE sutures on restoring MV function following virtual MV repair. Early studies have reported computational simulation techniques to determine the effect of chordal replacement with ePTFE sutures on MV function.^{23,24} Although these studies demonstrated the feasibility

of computational methods for evaluation of chordae repair, they utilized a simplified virtual MV model with parametrically created MV geometry and linear material characteristics. More recently, several computational studies utilized patient 3D echocardiographic data to evaluate MV function.^{25–29} However, to our knowledge, no study has demonstrated computational MV repair simulations for chordal replacement using patient-specific MV geometry attained directly from 3D TEE data. The use of patient-specific MV geometry and more realistic hyperelastic material modeling can better predict the extent and severity of the abnormality in the MV apparatus with RMCT prior to and following virtual chordae repair.

Computational simulation of virtual MV repair provides assessment of functional improvement following chordae repair in terms of not only post-intervention morphology of the MV structure but also quantitative information concerning the extent of leaflet contact and stress distributions across the MV apparatus. With the transvalvular pressure gradient applied to the MV leaflets, detailed information on tissue deformation, stress distribution, leaflet coaptation and chordal force can be determined at multiple microsecond time intervals over the cardiac cycle. Comprehensive dynamic computational analysis of the MV complex with ruptured chordae can improve our understanding of pre- and post-repair valvular function and determine the roles played by the replacement ePTFE sutures and the intact native chordae in the regions of extreme stress concentration during valvular function.

In the particular RMCT case presented in this study, abnormal prolapsing of the posterior leaflet in the P2 region due to RMCT was clearly demonstrated both in 2D/3D echocardiography and by computational simulation. There was a good agreement in overall leaflet deformation and MR characteristics between the simulation data and the patient echocardiographic data. A recent study demonstrated that the overall leaflet curvature was concave with respect to the left atrium along the entire annular region in normal MVs.³⁰ This particular patient revealed an anomalous bulging of the posterior leaflet in the P2 region due to the ruptured chordae.

Computational simulation predicted large stress concentrations in the posterior leaflet where MR occurred and in the region near the mitral annulus–aorta junction (Fig. 5B), and in the neighboring intact native chordae near the ruptured P2 region (Fig. 6B). This indicates that excessive tensile stresses in the P2 region of the MV leaflet and the neighboring intact native posterior chordae have close interaction and interdependence. The maximum stress values were under or close to the previously reported failure stress values of the MV apparatus (Fig. 5B).^{3,4} Further damage, such as leaflet tearing and additional chordal rupture, can occur when the MV is continuously exposed to excessive stress over time without proper intervention. In particular, stress occurring in the neighboring intact native posterior chordae can continue to increase and exceed the average chordal failure strength (8.0 ± 0.8 MPa),⁴ resulting in additional chordal rupture. This virtual MV repair data demonstrated marked reduction of the excessive stress concentrations in all three simulations irrespective of the suture number. Although the extremely large stress disappeared in the virtual chordae repair using two ePTFE sutures, there remained moderate MV prolapse with MR and considerable stress concentration in the MV leaflet tissue and intact native chordae. Optimal outcomes were predicted when four or six sutures were utilized. This indicates that each patient-specific case has the optimal number of ePTFE sutures to successfully repair the MV with RMCT, but further improvement may not be obtained when additional sutures are utilized for repair (i.e., there would be an optimal number of sutures required).

Although we successfully performed computational simulations of virtual chordae repair surgeries using patient-specific 3D TEE, there are some limitations and simplifications in this study. We utilized previously published MV material properties in our virtual surgery simulations since the actual material properties of the patient's MV tissue were not available.¹¹ The number of intact native chordae in the simulations was determined based on

previous clinical data as acquisition of actual geometric information of the entire patient chordae structure is not feasible utilizing current imaging techniques. Further improvement is necessary to more precisely model the chordae insertion pattern across the leaflet segments in normal and pathologic MVs. Studies with animal models or explanted human valves may provide more reliable mapping information of chordae tendineae insertion. Although, we demonstrated qualitative validation of the geometric information of the patient MV apparatus at peak systole (Fig. 3) and compared the chordal forces exerted on the papillary muscles with previous vitro experimental data, further investigation to verify our computational MV modeling pathologic MVs may help us to verify this virtual MV repair strategy, particularly involving dilated left ventricle and ischemic MVs.

In this study, computational simulations accompanied by patient-specific 3D TEE data of the MV with RMCT allowed us to determine quantitative information on the biomechanical and physiological characteristics of the MV and to predict functional improvement following chordae repair. Virtually repaired MVs demonstrated reduced posterior mitral leaflet prolapse, improved MV leaflet coaptation, and decreased excessive leaflet and chordal stresses. Combined with further clinical studies, our patient-specific virtual MV repair technique may help to determine the optimal number, size and length of ePTFE sutures required for complete MV repair. This novel simulation strategy may provide a powerful tool for evaluation and prediction of interventional RMCT treatments.

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Figure 1.

Echocardiographic data of a patient's MV clearly demonstrating posterior leaflet prolapse with a large flail scallop due to ruptured chordae tendineae in the posterior leaflet. A – anterior; P – posterior; AI – anterolateral; Pm – posteromedial.

Figure 2.

(A) Computational MV evaluation protocol for patient-specific virtual MV repair with chordal replacement using ePTFE sutures. (B) Modeling of virtual MV repair of the patient's MV with chordal replacement using two, four and six ePTFE sutures.

Figure 3. Cross-sectional (A3-P1) view of the leaflet morphology at peak systole superimposed by the simulation-predicted leaflet deformation.

Figure 4. 2D Doppler ultrasound data of the MV with RMCT demonstrating severe eccentric MR at peak systole (top), and computational simulation data of the pathologic MV demonstrating abnormal bulging of the posterior leaflet with a large prolapse in the P2 region (bottom).

Figure 5.

(A) Morphologic and functional characteristics of the MV with RMCT at peak systole following virtual repair using two, four or six ePTFE sutures. The edges of the anterior and posterior mitral leaflets on the half-cut (A2-P2) plane are displayed in blue and red, respectively, to better demonstrate the posterior leaflet prolapse and leaflet coaptation at peak systole. (B) Stress distribution across the mitral leaflets and annulus of the MV with RMCT and virtually repaired MVs at peak systole.

Figure 6. (A) MV leaflet coaptation at peak systole prior to and following virtual repair. (B) Maximum stress distribution in the intact native posterior chordae in the P1 and P3 regions following virtual MV repair.