Biomechanical Analysis of Stentless Quadrileaflet Pericardial Mitral Valve: Implications of Morphologies

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Abstract: To investigate the biomechanical behaviors of a stentless quadrileaflet pericardial mitral, and to obtain the deformation and the stress distribution through the finite element method, we developed the finite element computer model of the stentless quadrileaflet mitral valve, which includes leaflets, annulus, chordae tendineae and papillary muscle. The analysis represents that the open and the close shapes of the valve from the numerical results were quite close to those observed in the experiment of the hydrodynamic performance in vitro, the stress distribution was relatively uniform, and the maximum Von Mises stress occurred in the base and the border of the leaflets. The model and the finite element computational for identifying deformation and stress distribution of the mitral valve is reasonable and advisable to improve the endurance of the pericardial mitral valve. To study the implications of morphologies, one auxiliary model, with a narrower base of leaflets, was compared with the present model. Comparison results showed that the maximum Von Mises stress on the auxiliary model reached up to 4.1 MPa, which was higher than 1.58 MPa of present one.

Keywords: Finite element analysis, Stentless quadrileaflet pericardial mitral, Stress distribution, Simulation.

1. Introduction

The mitral valve is one of the four valves of the heart, separating the left atrium and the left ventricle. It closes and opens cyclically under varying pressures, which ensures a unidirectional flow of blood from atrium to ventricle [1]. Due to congenital malformations or lesions, the valve will lose the normal physiological function. Hence, replacing the mitral valve is an alternative. Prosthetic valve is made of artificial material that can be implanted into heart instead of the tissue of the heart valves. In terms of the materials, the prosthetic valves can be divided into mechanical and bioprosthesis valve. The main advantage of the mechanical valve is long product life, but it has many clinical conditions that cannot be overcome. The prosthesis has a better hemodynamic performance, although its life issue hasn’t got a satisfactory solution. However, there still are great advantages in the clinical application that cannot be replaced by mechanical valves, so the study of the biological mitral valve are still of significant importance.
The biological mitral valve can be divided into two kinds, the stent and stentless. The traditional stent biological valve has considerable differences from human heart valves. The presence of the flap frame causes the stress concentration and easily leads to the damages of the valve leaflets. Subsequently the mitral valve will lose its function [2, 3]. The structure of the stentless mitral valve is much similar to the body's own valve and has a better hemodynamic performance. The stress distribution is more evenly compared to the stent ones, so the stentless valve can work for longer period [4], which makes it more in line with the physiological requirements.

Historically, several groups attempted to study the replacement of the mitral valve [5-9]. Until 1993, Frater and Liao et al. [10] developed the stentless quadrileaflet Mitral Valve (QMV), whose model has a large anterior, two commissural, and one posterior cusp all have chordae tendineae attached to them. Although this model is similar to native mitral valve, the flaw of the asymmetrical design is that the valve leaflets cannot stretch fully [11]. The Second Xiangya Hospital of Central South University developed the new CS Stentless Quadrileaflet Mitral Valve (PSCV) [12] on the basis of QMV, but the asymmetrical design was still not in the mainstream. Liu Feng et al. [13] continued to optimize the design of the valves (MCSV) on the basis of the PSCV, and this oval model will increase the effective orifice area of the mitral valve, while the symmetrical design caused the valve leaflets closing completely. Wang Yan [14], referring to the MCSV model, designed the quadrileaflet pericardial mitral valve which reduced the MTPG (mitral transvalvular pressure gradient) successfully. The rectangular design is easier to design and implement, and the model has been widely used in clinical and the research progress of the model is relatively mature. This study establishes the geometric model of the stentless pericardial mitral valve designed by Wang Yan, which consists of an annulus, two leaflets, chordae and papillary muscles. The finite element method can be deployed to analysis the stress distribution of this model providing assistance for the design optimization of the prosthetic valve.

An important factor to affect the biological life of the valve is the stress distribution [15]. The biological valves tears because of the excessive mechanical stress in clinical. It is directly related to the stress distribution of the valve leaflets. The valve leaflets torn with perforation occurred in the stress concentration region, so research on the mechanical properties of prosthetic valve is of great significance for the optimal design of the valve structure. Meanwhile, it is helpful to understand the principles of dysfunction of bioprosthetic valves. As the most important valve of the heart, the analysis of the mitral valve has some difficulty in clinical operation, because it would result in irreversible damages to the heart. The results of vitro fatigue test are realistic and intuitive, but the experimental method is not grace but complex, time-consuming and labor-intensive, so domestic and foreign scholars simulated the movement of the mitral valve by using the finite element algorithm, providing guidance and theoretical basis of the valve replacement surgery and cardiac surgery.

The finite element method (FEM) is a high performance, widely-used numerical method. The principle is that the continuous solution domain is discretized into a combination of a group of elements, and the approximation functions assume within each element group of solving unknown domain functions. Mathematical methods are combined expressing the relationship of each group containing the parametric equations. Solving equations brings the approximate solution for the unknown parameters of each node by using the differential function. The most important application of the finite element method in engineering is the optimization of the structure such as the shape of the structure optimization and the analysis of structural strength. After half a century of development and application in engineering field, finite element method has proven to be an effective simulation method for engineering problems having already solved a large number of practical engineering problems. It has played a huge role in accelerating industrial technology development.

This paper analyses the rectangular pericardial mitral valve and an auxiliary model by using finite element method. By analyzing the present model and the auxiliary model, we can figure out the implications of the base leaflets. By establishing the geometric model, defining the material and meshing the model, we obtain the finite element model, set the boundary and load conditions to simulate open and closed state of the mitral valve, and obtain the results of the stress distribution.

2. Material and Methods

The geometry model of the valve was generated by UGS NX (Unigraphics NX, Release 8.0), which is a software product that can provide engineering solutions. The finite element (FE) program, ANSYS (Release 12.0) was used to perform all simulations. ANSYS is a multi-purpose finite element program typically used to solve the problem of the structure, fluid and more.

2.1. Geometry Model

We developed the geometry model of the stentless quadrileaflet mitral valve according to the bionical rules. This model is composed of leaflets (anterior and posterior), annulus, chordae tendineae and papillary muscle. In the main part of the stress analysis, the anterior and posterior valves play the most important role in the cardiac cycle, so we focus on the analysis of the anterior and posterior valves [16]. The geometry model is shown as Fig. 1.
2.1. Material and Loads

The mitral leaflet tissue exhibits a highly nonlinear mechanical response, leading to the complexity of the material pericardial tissue fibrous. Because the mitral valve is little influenced by the force value, so the anisotropic performance effect is not obvious and it can be treated as a linear elastic model. The experiment was based on the stress-strain curve of the clinical trial. The material model in the tangent elastic modulus reaches 8.75 MPa under the stress of 0.4 MPa, which is similar to the normal human biological valve tissue elastic modulus [17]. Poisson's ratio is set to 0.45 [18], and the pericardial tissue thickness is set to 0.25 mm [18]. The equation of physical stress and strain is created on the basis of those values.

As the annulus and papillary muscle is relatively at a fixed position throughout the cardiac cycle, it can be assumed that the annulus and papillary muscle keeps the displacement, rotational degrees of freedom unfettered. The base of leaflet displacement is zero and the freedom of rotation degree does not impose any constraint.

Mitral valve contracts and relaxes in the cardiac cycle in the dual role of the pressure in the ventricle and a trial. Its withstand pressure changes cyclically with the cardiac cycle. This experiment focuses on static stress analysis of the mitral valve, so two time frames are selected: Ventricular diastolic and isovolumic relaxation. Under the ventricular diastolic, the mitral valve opens, the direction of the pressure is pointed to the ventricular-atrial surface. With the normal standard of 5 L/min cardiac output for adults, vitro valve differential pressure reads approximately (0.42 kPa) 3.16 mmHg; Under the ventricular isovolumic relaxation, when the mitral valve leaflets achieves the maximum load of about 120 mmHg (16 kPa), the direction of the pressure from the left ventricle is at the left of the atrium surface.

2.2.2. Meshing

Annulus and valve leaflets use the curve of eight-node shell elements (SHELL93). The most notable feature of the element is its precise simulation of the housing having curved boundaries with properties of plastics, stress steel, large deformation, and large strain, which are well adapted to the deformation of the valve leaflets. Using ANSYS meshing tool MeshTool model to mesh the model and obtain the finite element model (Fig. 2).

3. Results

In this study, we analyze the open and closed states of the mitral valve, then obtain the von Mises by contour plotting of the model in the two states.

3.1. Ventricular Diastolic

The deformation of the mitral valve under ventricular diastolic is shown as Fig. 3. Under the diastolic period, the pressure points from the ventricles to the atrial surface. The mitral valve will open under the pressure, and blood will flow from the left atrium into the left ventricle. As the Fig. 3 shows, the open form is consistent. In the meantime, it meets the mechanical performance, indicating that this model is fitting, can successfully simulate the open state of the mitral valve.

In Fig. 3, the Von Mises stress of the anterior and posterior valve leaflets in the open state is calculated. The stress distribution of the anterior and posterior valve leaflets occurs of a high degree of contrast between the anterior and posterior valve leaflets. Therefore, there is a need to define the valve leaflets contact behavior. In order to simulate the contact between the valve leaflets, two rigid planes of the initial contact surface are established, then we define a target unit (TARGET170) and contact elements (contact 174) on its basis, constitute the two contact pairs, and simulate the behavior of the contact between the valve leaflets in accordance with the face-to-face contact theory. When the mitral valve opens, there is no contact unit.

2.2.1. Definition of Contract

The mitral valve has a greater deformation under ventricular isovolumic relaxation. There are occurrences of a high degree of contrast between the anterior and posterior valve leaflets. Therefore, there is a need to define the valve leaflets contact behavior. In order to simulate the contact between the valve leaflets, two rigid planes of the initial contact surface are established, then we define a target unit (TARGET170) and contact elements (contact 174) on its basis, constitute the two contact pairs, and simulate the behavior of the contact between the valve leaflets in accordance with the face-to-face contact theory. When the mitral valve opens, there is no contact unit.
leaflets is uniform and most reading of the stress level is low and concentrated in 0.073 MPa to 0.36 MPa. The maximum stress occurs at the base of the leaflets, up to 0.513 MPa.

**3.2. Ventricular Isovolumic Relaxation**

Under ventricular isovolumic relaxation, the mitral valve is completely closed, the blood flows from the left ventricle into the left atrium, the pressure is up to 16 kPa. Fig. 4 shows the deformation of the mitral valve when it is closed. In the figure, we can see a high degree of contact of the valve leaflets. The valve leaflets closed well, thereby preventing regurgitation of blood, the morphological performance is consistent with the closure form observed by kinetic experiments, indicating that it is capable of simulating the mitral valve closed state.

In Fig. 4, the Von Mises stress of the anterior and posterior leaflets in the open state is calculated. In the figure, it can be noticed that the stress distribution of anterior and posterior leaflets is still relatively uniform as most of the valve leaflets stress is concentrated in the 0.22 MPa ~ 0.68 MPa. The maximum stress occurs at the base and the border of the leaflets reaching 1.58 MPa. This is consistent with the clinical fact that the position of the mitral valve prone to tearing [19].

The stress on rectangular pericardial mitral valve in the left ventricular diastolic isovolumic relaxation is comparatively evenly distributed, the maximum stress occurs at the base of the valve leaflets (i.e. anterior and posterior valve leaflets and papillary muscle junction). The stress reaches 1.58 MPa under ventricular isovolumic relaxation at the location where the maximum occurs is also consistent with the experiment [16] (Fig. 5). The stress distribution of the stentless pericardial mitral is shown in Table 1.
3.3. The Implications of the Width of the Base of the Leaflets

In this study, one auxiliary model, with a narrower base, whose width is reduced from 7.6 mm to 3.74 mm, 1/8 of the annulus. We compared with the present model in terms of the width of the base leaflets. The stress distribution of the auxiliary model is shown as Fig. 6 and Fig. 7.

In the two models, the stress distribution is relatively uniform, the maximum stress is conformable observed on the base and the border of the leaflets. Compared to the Fig. 3 and Fig. 4, we can see that the maximum stresses on the auxiliary model’s leaflets is higher than the present one. At the systolic peak, the maximum stress of the auxiliary model reaches up to 4.1 MPa, greater than 1.58 MPa as in the present model.

As listed in Table 2, the maximum Von Mises stresses on both leaflets of the two models are contrasted. The auxiliary model experiences the higher stress on each leaflets compared to the present one. The maximum Von Mises stress obtained on the leaflet of the auxiliary model is 4.1 MPa, higher than the other one.

Table 2. Comparison of the Von Mises stresses in the two models (systolic peak).

<table>
<thead>
<tr>
<th>Models</th>
<th>Average stress</th>
<th>The maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present model</td>
<td>0.22MPa-0.68MPa</td>
<td>1.58MPa</td>
</tr>
<tr>
<td>Auxiliary model</td>
<td>0.45MPa-1.8MPa</td>
<td>4.1MPa</td>
</tr>
</tbody>
</table>

4. Discussion

This study analyzes the stress distribution of valve leaflets on the basis of symmetry. The experiments show that our model can accurately simulate the stress distribution of the mitral valve. Since stress is evenly distributed when the mitral valve opens and closes, the maximum stress occurs at the base and border of the leaflets and annulus, which corresponds to the clinical fact that the mitral valve is prone to tearing at the position. This proves that the model and the finite element method are reasonable.

Based on the correctness of the model and the finite element method, we develop an auxiliary model to study the implications of the width of the base leaflets, this topic has not been mentioned in other reports yet. We get richer data by analyzing the different widths, which is beneficial for designing the mitral valve. In the experiment, we can see that there will be higher Von Mises stress with a narrower base, this conclusion can be advisable to the optimization of the mitral valve.

Human mitral valve leaflets are flexible membranous tissue. The anterior valve leaflets are larger while the posterior valve leaflets are smaller and the thickness of the valve leaflets is not uniform. This natural structure makes mitral valve loaded evenly, and thus not easy to be torn off. However, the artificial mitral valve still far from being developed to such a high standard. The experiments show that the anterior and the posterior valve leaflets contact unevenly and Dysraphism easily leads to tearing of the valve leaflets when we simulate the closed status of the valve leaflets, as the stress of the anterior and the posterior valve leaflets are not even.

Therefore, the model used in this study is symmetric for the anterior and the posterior valve
leaflets, such a symmetrical structure design guarantee the valve leaflets is uniformly expanded on the open status, and contact closely in the closed status, thereby eliminating the problem of excessive regurgitation. Meanwhile, it ensures that the stress of the anterior and the posterior valve leaflets is even, as far as possible to achieve the biological properties of the human mitral valve. The symmetrical design of the anterior and the posterior valve leaflets improves the durability of the prosthetic valve, but is still different from the physiological mitral valve. For future study, we will further develop a more complicated stentless mitral valve model, which will be able to simulate the stress distribution of the anterior and the posterior valve leaflets simultaneously. The comparative analysis will provide the better theoretical foundation and reference for the design of the mitral valve.

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