Mechanical mitral valve modeling: Advancing the field through emerging science

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Abstract: Background: Successful mitral valve repair and replacement are dependent upon a full understanding of normal and abnormal mitral valve anatomy and function. The functional components of the mitral valve include: the left atrial wall, the annulus, the leaflets, the chordae tendineae, the papillary muscles, segments of the left ventricular myocardium. Abnormal anatomy or function of any one of these components can result in valvular dysfunction. We sought to assess the outcome of olden challenges of the mechanical behaviors of the mitral valve. Method: Much of our knowledge of abnormal mitral valve function is based on surgical and post-mortem studies while these studies are quantitative in some cases, they are limited by evaluation of valve anatomy in a fixed and nonfunctioning state. A more sophisticated analysis method is necessary to gain a full consideration of mitral valve function. Several groups attempted to model mitral valve anatomy and function by mathematical/physical equations. Result: Preliminary results concerning a different aspect of mitral valve leaflet biomechanics, such as leaflet dynamics, displacements, thickness, stress and strain on leaflets. Conclusion: These data potentially allow the implementation of an image-based approach for patient-specific modeling of mitral valve leaflets. This approach could constitute the basis for accurate evaluation of mitral valve pathologic conditions and for the planning of surgical approaches.

Keywords: Mitral Valve, Mathematical Modeling, Finite Element Method, Stress-Strain of Leaflets, the Geometry of Mitral Valve, Fluid-Structure Interactions

1. Introduction

The left side of the heart accepts oxygenated blood at low pressure from the lungs into the left atrium. The blood then moves to the left ventricle which pumps it forward to the aorta to circulate the body. The heart's valves maintain the unidirectional flow of the blood through the heart, e.g. the mitral valve prevents regurgitation of blood from the left ventricle into the left atrium during ventricular systole and the aortic valve prevents blood flowing back from the aorta into the left ventricle during diastole. The principal fluid phenomena involved in the left ventricular diastolic flow are related to the presence of symmetric structures that develop with the strong jet that enters through the mitral valve (Reul et al., 1981; Saber et al., 2001)¹⁻². It is conjectured that the fibered structure has important effects on the function of the ventricle (Bacanni et al., 2003; Daebritz et al., 2003; Pierrakos and Vlachos, 2010)³⁻⁵.

Figure 1. Schematic presentation of the non-planar, saddle-shaped mitral valve and its characteristic parameters: D_h - distance between high points; D_l - distance between low points of the annulus; H_a - annular height. The mitral annular area is measured as an area of the least squares plane

The human mitral valve is a complex anatomical structure consisting of two valve leaflets, an annulus,

chordate tendineae, and two papillary muscles which are finger-like projections embedded into the underlying left ventricular myocardium. The mitral annulus is a saddle-shaped fibrous ring which seamlessly transitions into the two leaflets (Grashow et al., 2006; van Rijk-Zwikker et al., 1994)⁶⁻⁷ (Figure 1). The leaflets extend into the left ventricle where they are tethered to the papillary muscles via an intricate arrangement of chordae tendineae. The chordae tendineae consist of a complex web of chords that attach all over the leaflets of the valve. They prevent the prolapse of the valve leaflets at systole, and additionally assist in maintaining the geometry and functionality of the ventricle.

The papillary muscles play an important role and are believed to lengthen during isovolumetric contraction and shorten during ejection as well as during isovolumetric relaxation to maintain the chordae at the same deformation level, during opening and closure (Marzilli et al., 1980)⁸.

Figure 2. Schematic presentation of a simulator of the mitral valve

2. Methods and Results

The dynamic behaviour of porcine mitral valves has been studied in vitro by He et al. (2003, 2005) and Sacks et al. (2002)⁹⁻¹¹. The Georgia Tech left heart simulator was used to measure surface strains in the valve leaflets under dynamic loading. The effect of the papillary muscle positions on the dynamic strains was also considered. This research provides important insight into the dynamic behaviour of the native mitral valve. Moreover, it enables a benchmark comparison for the performance of the mitral prosthesis. Both experimental and computational analysis can guide prosthesis design (Figure 2). However, the advantage of a computational model is that material and geometric parameters can be easily changed to determine an optimum design and it enables analysis that may be impractical experimentally (Figure 3). For example, stress and strain distributions can be predicted; the mechanical interaction of the valve leaflets and fluid flow can be simulated in a physiologically realistic environment, e.g. a (prescribed) contracting ventricle. Unfortunately,

computational modelling of the native mitral valve is difficult: the geometry of the chordae and leaflets is complex; the dynamic motion of the left ventricle causes a displacement of the papillary muscle base relative to the mitral annulus; the papillary muscles contract and relax during the cardiac cycle; the geometry of the mitral annulus is dynamic.

Furthermore, large deformation fluid-structure interactions are present during opening and closing phases. For these reasons, to date, only limited numerical research has been performed on mitral valves compared with aortic valves (Bellhouse, 1969; Ming and Zhen, 1986)¹²⁻¹³.

Kunzelmann et al. (1993a, b)¹⁴ developed the first three-dimensional (3-D) finite-element model of the mitral valve using ANSYS. The open and closed mitral apparatus geometry was determined from resin casts of porcine mitral valves. This was used to construct a finite-element model that incorporated all essential anatomical components and regional tissue thickness (Figure 4).

Figure 3. A) Parameters used to define the geometry of Mitral valve. B) The numerical calculation of geometric parameters of a mitral valve in MATLAB software

Figure 4. A) three-dimensional Finite element models of the mitral valve. It presented a model of the leaflets only to assess the effect of annular shape on leaflet curvature and stress. B) Geometry of mechanical model: leaflets, commissures, branched chords and multiple papillary insertions.

The limitation of this model is that they assumed constant leaflet thickness, used non-linear isotropic material models and did not include fluid flow. Anisotropic material properties were related to the collagen fibre orientation determined from previous studies. The closing phase of the mitral valve was simulated using a physiological time-dependent loading and solved using a quasi-static approach. The model was applied to give extensive further insight into the functioning and malfunctioning of the mitral apparatus, e.g. to consider: the effects of chordae rupture, annular dilatation and leaflet perforation (Kunzelmann *et al.*, 1993a)¹⁵; the effect of replacing chordae tendineae with ePFTF suture (Reimink *et al.*, 1996; Kunzelmann and Cochran, 1993)^{16–17}; annular dilatation (Kunzelmann *et al.*, 1997)¹⁸; the effect of papillary muscle position on mitral valve function (Cochran and Kunzelmann, 1998)¹⁹; altered collagen concentration in mitral valve leaflets (Kunzelmann *et al.*, 1998b)²⁰. Note that in many of Kunzelmann's studies, the papillary muscle tips (which the chordae attached to) were spatially fixed in position relative to a fixed mitral annulus. There is physiological justification for this: the subsequent contraction and motion

of the papillary muscles has the effect of fixing the distance between the papillary muscle tips and the mitral annulus plane. Thus the lack of papillary muscle motion in the rigid left ventricular models does reflect the constant papillary muscle tip to annular plane distance (Figure 4).

Salgo *et al.* (2002)²¹ presented a three-dimensional finite element model of the leaflets to assess the effect of annular shape on leaflet curvature and stress. The microstructure of mitral valve tissue is altered in response to stress resulting in changes in tissue thickness, stiffness or both. In this model simulations of such changes increased tissue stiffness resulted in increased leaflet and chordae stresses, as well as reduced coaptation.

Einstein *et al.* (2010)²² recently developed the first computational model, which accounts for the coupled fluid–structure interactions of the local blood flow and the mitral valve leaflets, during the closing phase of the cycle. The mitral leaflets were modelled as nonlinear membranes and the leaflet material was characterised as an orientated Gaussian distributed population of crimped collagen fibres embedded in an isotropic medium consisting of glycoproteins and elastin (Figure 5A).

Figure 6. A) Mitral leaflet tissue material behavior is characterized as an oriented entangled population of crimped collagen fibers B) The chordae attachment points (CAPs) and the whole computational model of the mitral valve

Figure 7. A) Time course of principle stress in the anterior and posterior leaflets in the normal model. Time: (a) 0.023, (b) 0.047, (c) 0.070, (d) 0.093, (e) 0.117 and (f) 0.140 s. Red colour denotes the highest stress and dark blue the lowest B) (a) Circumferential and (b) radial strains at 0.14 s in normal model. Values with negative numbers are compressive strains.

The chordae were modeled as nonlinearly elastic tension cables. The papillary tips were fixed in position relative to the mitral annulus. Symmetry boundary conditions were applied on the septal–lateral midplane to reduce computational cost. The valve was immersed in a domain of Newtonian blood with ventricular and atrial pressure diagrams applied to the ventricular and atrial surfaces of

the blood domain (Figure 5B). Model predictions showed excellent agreement with available transmitral flow, papillary force and first heart sound acoustic data.

Lim *et al.* (2010)²³ recently developed the first asymmetric model of the mitral valve complex using ANSYS 5.7 for the whole cardiac cycle. They observed that the motion is highly complex, and involves irregular

twisting and skewing and that the annulus and papillary tip motions are 3-D in the atrioventricular chamber. Thus asymmetric boundary conditions are necessary for effective modelling of twisting or pulling of mitral valve. Distance tracings between ultrasound crystals placed in the sheep mitral valve were converted into 3-D coordinates to reconstruct an initial asymmetric mitral model and subsequent boundary conditions. The leaflets were modeled with linear isotropic material properties and uniform thickness. Nonlinear, real time left ventricular and aortic pressure loads were applied synchronously. The quasi-static deformations were determined over one time cycle. This study provided new insight into the distribution of leaflet stress in the mitral valve Figure 6:

In addition to the high leaflet stress that occurs during peak pressure loading, a prominent secondary peak (not observed previously) was observed during isovolumic relaxation of the ventricle. Note this model uses a quasi-static approach to model the valve deformation, i.e. it does not model the fluid-structure interactions.

3. Recent Achievement

Ranjbar S. Karvandi M. (2013)²⁴⁻²⁵ recently developed the first novel left ventricular myocardial model

mathematically based on echocardiography, by MATLAB software and LSDYNA software in normal subjects Figures 7 and 8, which dynamic orientation contraction (through the cardiac cycle) of every individual myocardial fiber could be created by adding together the sequential steps of the multiple fragmented sectors of that fiber. The left ventricular myocardial modeling of the heart shows that in normal cases myocardial fibers initiate from the posterior-basal region of the heart, continues through the left ventricular free wall, reaches the septum, loops around the apex, ascends, and ends at the superior-anterior edge of left ventricle. This approach could overcome the limitations of previously proposed models and give new insight into the complex mitral valve function. This approach shows the effect of fiber formation on left ventricular myocardium and mitral valve efficiency.

Figure 8. The route of a fiber in the left ventricle

Figure 9. A) Impact of the direction of blood flow path to the left ventricular torsional deformation. B) Mathematical modeling of the left ventricle related to myocardial fiber paths.

Disclosure

There is no conflict of interest.

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