Mitral Valve Modelling in Ischemic Patients: Finite Element Analysis from Cardiac Magnetic Resonance Imaging

Carlo A Conti[1], Marco Stevanella[1], Francesco Maffessanti[1], Salvatore Trunfio[2], Emiliano Votta[1], Alberto Roghi[2], Oberdan Parodi[2,3], Enrico G Caiani[1], Alberto Redaelli[1]

[1]Politecnico di Milano, Milano, Italy
[2]Niguarda Ca' Granda Hospital, Milano, Italy
[3]CNR Institute of Clinical Physiology, Pisa, Italy

Abstract

The goal of the present work was to develop a framework for the analysis of time-varying mitral valve (MV) geometry from cardiac magnetic resonance (CMR) imaging, and to integrate these data in a patient-specific simulation of MV closure. CMR imaging of 18 long-axis planes was performed on a healthy subject and on two ischemic patients with MV regurgitation. MV annulus geometry, leaflets surface and papillary muscles position were obtained using custom software. Hyperelastic anisotropic mechanical properties were assigned to the MV tissues, and a pressure load curve was applied to the leaflets. Results concerning healthy MV biomechanics were consistent with previous computational data. Ischemic MV models appear suitable to mimic the pathological malfunctioning of the valve. The proposed models could constitute the basis for the planning of surgical procedures.

1. Introduction

Ischemic mitral regurgitation (IMR) is a common and important complication of ischemic heart disease, associated with excess mortality independently of baseline characteristics and degree of ventricular dysfunction [1]. Because altered annular geometry often contributes to leaflet malcoaptation in ischemic mitral regurgitation, surgical correction is required to restore proper MV function.

Current standard treatment for IMR is the implantation of an annuloplasty ring that downsizes the mitral annulus to increase leaflet coaptation. However, residual or recurrent mitral regurgitation frequently appears after ring annuloplasty, as a consequence of a poor prognosis [2].

Thus, models for predicting surgical outcomes of these repair procedures on the basis of patient preoperative characteristics can provide valuable tools for clinical research and practice.

Finite element models (FEMs) has been proven useful and accurate in the assessment of mitral valve biomechanics [3,4]. However, most of the previously proposed MV FEMs are based on animal or *ex vivo* measurements and lay over simplifying assumptions on MV symmetrical shape, idealized leaflets free margin profile and disregarded papillary muscles (PMs) contraction. Recently, Votta et al. [5] proposed a modelling approach based on transthoracic real-time three-dimensional echocardiography (RT3DE) data acquired from a human healthy subject. This strategy allowed to define the initial MV geometry from the end-diastolic position of mitral annulus and PMs and to use the real annular dynamics as boundary conditions during valve closure.

Cardiac magnetic resonance (CMR) is currently recognized as the gold standard in the clinical evaluation of left ventricular volume, function and myocardial mass. The introduction of the steady-state free precession (SSFP) technique made CMR not only an useful tool for the dynamic evaluation of cardiac chambers but also for the assessment of mitral valve function, as previously reported in literature [6,7]. As a consequence of high spatial and temporal resolutions, CMR could constitute the ideal imaging technique for the detailed quantification of several nuances of the valvular apparatus, such as annular and papillary muscle function or leaflet geometry.

The short-term goal of the study is two-fold: 1) to develop a framework for the quantitative analysis of time-varying MV geometry from CMR imaging, and 2) to integrate these data in a patient-specific structural simulation of MV closure from end-diastole to the systolic peak. The long-term goal of our work is to use these regurgitant valve models as a baseline condition to be compared with different post-operatory scenarios. In particular, we aim at simulating the effects of different types of annuloplasty ring (i.e. flexible and rigid) on the biomechanics of ischemic mitral valves.

2. Materials and methods

Three models were built using our in home software: model A for a healthy MV, models B and C for two regurgitant MVs associated to ischemic diseases. Moreover, the patient whose dataset was used to build model B showed also dilated cardiomyopathy.

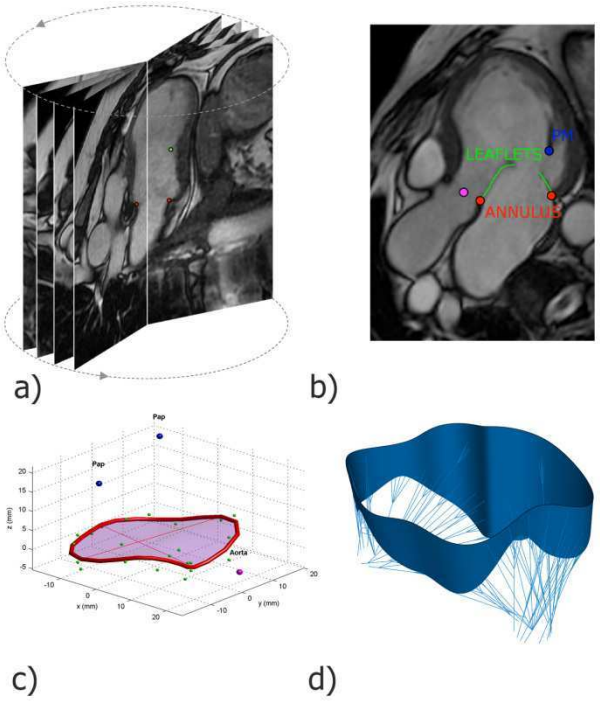

Figure 1. a) Acquired long-axis CMR cut-planes; b) Tracing of annulus (red), leaflet (green), papillary muscle (blue) and position of the aorta (pink) on a cut-plane; c) Annulus profile as reconstructed through our in home software; d) Finite element model obtained from the MV reconstruction algorithm.

2.1. CMR acquisition and processing

CMR imaging of 18 evenly rotated long-axis cut-planes (one every 10 degrees) was performed. Time resolution was equal to 55 frames/cardiac cycle, spatial resolution to 0.78 mm, and slice thickness was 8 mm (Figure 1.a).

For every frame, on each cut-plane the valvular substructures were manually obtained using custom software implemented in MATLAB (The MathWorks Inc., Natick, MA, United States): first, two annular points were identified; second, multiple points defining leaflets profile were selected and connected through cubic splines; finally, a point was marked for each visible PMs tips (Figure 1.b). The three-dimensional coordinates of the points selected on each cut-plane were reconstructed from the position of the latter with respect to the rotation axis. The annular profile was reconstructed by approximating the selected annular points with a 13th order Fourier function (Figure 1.c) and leaflets surface was obtained via Delaunay tessellation of leaflets profile points.

2.2. MV geometrical model

The end-diastolic configuration of the MV was assumed as its unloaded one; the corresponding geometry was thus reconstructed.

Three-dimensional annular profile was defined by Fourier interpolation of the points selected on the mitral annulus in the end-diastolic frame. Leaflets extent and inclination were set consistently with the MRI-derived leaflets free-edge profile. Thirty-nine branched chordae tendineae of three orders were modeled; their number, the corresponding branched structure and insertion sites on the leaflets were defined in accordance to *ex vivo* findings [8].

2.3. Tissues mechanical properties

All tissues were assumed non-linear and elastic. Their mechanical response was described by means of proper strain energy potentials. Leaflets behaviour was described through the hyperelastic and transversely isotropic constitutive model proposed by May-Newman and Yin [9], in which the mechanical response in the direction of the collagen fibers (i.e. parallel to the annulus) is much stiffer than the one in transversal direction (i.e. perpendicular to the annulus). A regionally varying thickness distribution was assigned to the leaflets, consistently with the one proposed in [3], with an average value of 1.32 mm on the anterior leaflet and 1.26 mm on the posterior one.

Chordae tendineae response was assumed isotropic and described through a polynomial strain energy function, whose parameters were defined via interpolation of uniaxial test data from literature [10]. Constant cross-sectional area values of 0.40, 1.15 and 0.79 mm^2 were assigned to marginal, strut and second order chordae, respectively.

2.4. Boundary conditions

The dynamic contraction of mitral annulus and PMs was modeled via kinematic boundary conditions, i.e. imposing time-dependent nodal displacements derived from annular nodes position at each time-frame.

A physiological transvalvular pressure drop, up to 120 mmHg, was applied on the ventricular side of the leaflets. The numerical simulations were performed within the finite element commercial code ABAQUS/Explicit 6.9-1 (SIMULIA, Dassault Systèmes).

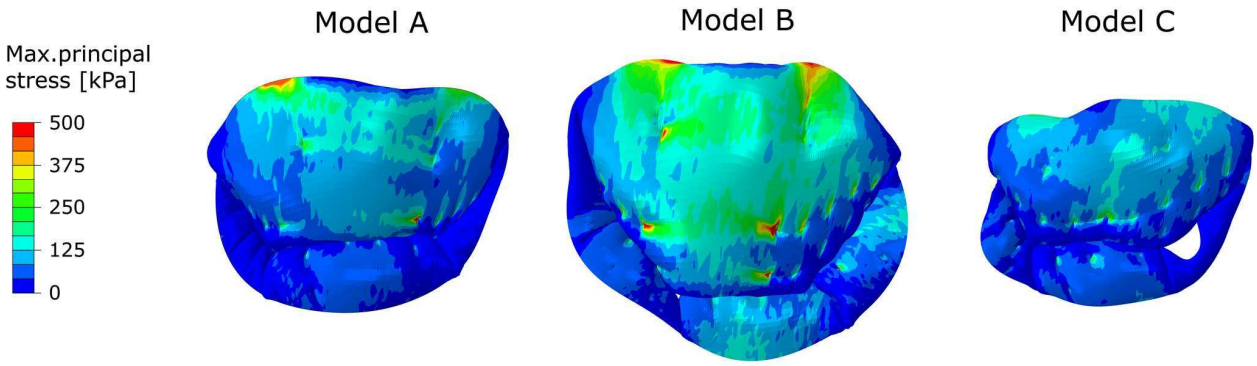

Figure 2. Maximum principal stress distribution on the leaflets at the systolic peak (atrial view) for the simulated healthy valve (model A) and regurgitant valves (models B and C).

3. Results and discussion

In the healthy valve (model A) complete leaflet coaptation occurred at a very low value of transvalvular pressure drop; when a 15 mmHg value was reached, the valve orifice was already occludedconsistently with *in vivo* findings reported in [11], and accordingly with clinical observations the coaptation region corresponded to the leaflets rough zone. After reaching 60 mmHg of transvalvular pressure drop, the valve underwent only minor further deformations, that were mostly associated with the motion of the annulus and PMs.

In the ischemic patients' valves (models B and C), coaptation was incomplete: regurgitant areas were identified near the paracommissures. Location and extent of the regurgitation areas were consistent with CMR images and leaflets' profile as reconstructed through our in home software at peak systole.

The MV tensile state was analysed focusing on systolic peak, as this timeframe is characterized by the maximum pressure load. Leaflets maximum principal stresses were computed (Figure 2). In model A, the region close to the fibrous trigones was the most stressed with peak values equal to 430 kPa. The anterior annular region also showed high tensile values (about 300 kPa), while stress decreased towards the free margin. The posterior leaflet showed considerably lower stresses, with a maximum value of about 120 kPa.

In model B, maximum principal stresses on the leaflet (Figure 2) showed peak values of almost 500 kPa next to the fibrous trigones and near the insertion zones of the strut chordae, and both anterior and posterior leaflet were overall more stressed than the healthy case (300 kPa and 150 kPa, respectively). In model C, maximum principal stresses on the leaflet (Figure 2) showed peak values of almost 290 kPa next to the fibrous trigones, and the stresses values computed on both anterior and posterior leaflet were lower than the values in the previous two cases (i.e. healthy subject and patient with ischemic dilated cardiomyopathy).

As regards tensions in the subvalvular apparatus, PMs reaction force evolved during closure following the transvalvular pressure (Figure 3). In the healthy subject, peak force values were 6.1 N on the anterolateral PM and

Table 1. Chordae tendineae forces (mean value ± standard deviation) obtained for different chordae types in the three simulated configurations. Values are expressed in N.

Chordae tendineae	**Model A**	**Model B**	**Model C**
marginal	0.162 ± 0.107	0.256 ± 0.156	0.109 ± 0.062
basal	0.157 ± 0.121	0.302 ± 0.248	0.143 ± 0.102
commissural	0.153	0.279	0.197
paracommissural	0.239	0.372	0.155
strut	0.898	1.197	0.355

6.9 N on the posteromedial PM, respectively. These forces were unevenly transmitted to the chordae tendineae throughout the simulated time course (Table 1), the average load on a single chorda being highest in the strut chordae (up to 0.9 N at peak systole).

Forces acting on the PMs in the patient with ischemic dilated cardiomyopathy (model B) were much higher than in the healthy one (Figure 3), with systolic peak values of 12.1 N on the posteromedial PM and of 8.3 N on the anterolateral PM (+75% and +36% with respect to the corresponding healthy values).

Lower forces were detected on the PMs in the second ischemic patient (model C) with systolic peak values of 4.2 N on the posteromedial PM and of 5.4 N on the anterolateral PM.

Computed results suggested that dilated cardiomyopathy following ischemic disease may alter the functioning of the valve not only in terms of loss of leaflets coaptation, but also increasing the stresses on the leaflets and the forces acting on the papillary muscles.

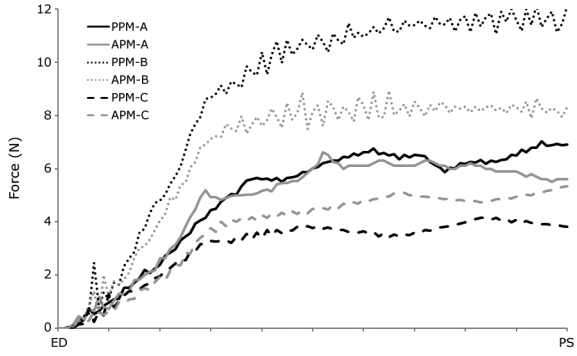

Figure 3. Time course of the force acting on the anterolateral PM (APM, grey) and on the posteromedial PM (PPM, black) in model A (continuous line), model B (dotted line) and model C (dashed line).

5. Conclusions

In this study, we demonstrated the feasibility of a MV model based on patient-specific data obtained from CMR. This approach could overcome the limitations of previously proposed models and give new insight into the complex MV function. These models could constitute the basis for accurate evaluation of MV pathologic conditions and for the planning of surgical procedures.

Acknowledgements

The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under Grant Agreement No. 224635.

References

[1] Grigioni F, Enriquez-Sarano M, Zehr KJ, Bailey KR, Tajik AJ. Ischemic mitral regurgitation: long-term outcome and prognostic implications with quantitative Doppler assessment. Circulation 2001; 103:1759-64.

[2] Jensen H, Jensen MO, Smerup MH, Vind-Kezunovic S, Ringgaard S, Andersen NT, Vestergaard R, Wierup P, Hasenkam JM, Nielsen SL. Impact of papillary muscle relocation as adjunct procedure to mitral ring annuloplasty in functional ischemic mitral regurgitation. Circulation 2009; 120:S92-8.

[3] Kunzelman KS, Einstein DR, Cochran RP. Fluid-structure interaction models of the mitral valve: function in normal and pathological states. Philos Trans R Soc Lond B Biol Sci 2007; 362:1393-406.

[4] Votta E, Maisano F, Bolling SF, Alfieri O, Montevecchi FM, Redaelli A. The Geoform disease-specific annuloplasty system: a finite element study. Ann Thorac Surg 2007; 84:92-101.

[5] Votta E, Caiani E, Veronesi F, Soncini M, Montevecchi FM, Redaelli A. Mitral valve finite-element modelling from ultrasound data: a pilot study for a new approach to understand mitral function and clinical scenarios. Philos Transact A Math Phys Eng Sci 2008; 366:3411-34.

[6] Kaji S, Nasu M, Yamamuro A, Tanabe K, Nagai K, Tani T, Tamita K, Shiratori K, Kinoshita M, Senda M, Okada Y, Morioka S. Annular geometry in patients with chronic ischemic mitral regurgitation: three-dimensional magnetic resonance imaging study. Circulation 2005; 112:I409-14.

[7] Yu HY, Su MY, Liao TY, Peng HH, Lin FY, Tseng WY. Functional mitral regurgitation in chronic ischemic coronary artery disease: analysis of geometric alterations of mitral apparatus with magnetic resonance imaging. J Thorac Cardiovasc Surg 2004; 128:543-51.

[8] Lam JH, Ranganathan N, Wigle ED, Silver MD. Morphology of the human mitral valve. I. Chordae tendineae: a new classification. Circulation 1970; 41:449-58.

[9] May-Newman K, Yin FC. A constitutive law for mitral valve tissue. J Biomech Eng 1998; 120:38-47.

[10] Kunzelman KS, Cochran RP. Mechanical properties of basal and marginal mitral valve chordae tendineae. ASAIO Trans 1990; 36:M405-8.

[11] Timek T, Glasson JR, Dagum P, Green GR, Nistal JF, Komeda M, Daughters GT, Bolger AF, Foppiano LE, Ingels NB, Jr., Miller DC. Ring annuloplasty prevents delayed leaflet coaptation and mitral regurgitation during acute left ventricular ischemia. J Thorac Cardiovasc Surg 2000; 119:774-83.

Address for correspondence.

Dr Carlo A Conti
Dipartimento di Bioingegneria
Politecnico di Milano
Piazza Leonardo da Vinci 32, Milano, Italy
E-mail: carlo.conti@mail.polimi.it