

3-D COMPUTATIONAL MODELS FOR THE SIMULATION OF MITRAL VALVE ANNULOPLASTY

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INTRODUCTION

Normal left ventricle shape, papillary muscle and chordae tendineae alignment prevent mitral valve leaflet prolapse during ventricular systole. Dysfunction of any one or more components of the “valvular-ventricular complex” can lead to mitral regurgitation and, consequently, to heart failure if untreated. Several surgical techniques have been introduced to accomplish the variability of the mechanisms of regurgitation. In particular, left ventricle ischemia can lead to mitral regurgitation, as it causes the misplacement of the papillary muscles. In this case a possible surgical solution consists in restoring the physiological geometry of the sub-valvular apparatus by means of the implant of an annuloplasty ring [1].

The present study has been developed in order to evaluate the stress distribution on the mitral valve leaflets and on the chordae tendinae, and to quantify the regurgitation area following the implantation of an annuloplasty ring in presence of acute left ventricular ischemia. A computational finite element model approach has been used to assess the effect of an innovative annuloplasty ring, which could be thought of as an evolution of a classical D-shaped ring (ratio between the anterior to posterior leaflet and the intercommissural distance equal to 3:4), and to compare it with the effect of the D-shaped annuloplasty ring itself.

MATERIALS AND METHODS

Three different conditions have been simulated by means of finite element 3-D models: i) a pathological mitral valve affected by a misplacement of the papillary muscles and with no annuloplasty ring; ii) a mitral valve affected by the above mentioned pathology with a D-shaped annuloplasty ring; iii) the same mitral valve corrected with the modified annuloplasty ring. The three different models are depicted in Fig.1. They include all the structural components of the natural valve: the annulus, the anterior and posterior leaflets, the chordae tendineae and both the anterolateral and posteromedial papillary muscles. In model i), developed on the basis of a previous model [2], the annulus has been assumed to be circular with a diameter of 32 mm. The anterior annular length is 42 mm and the posterior annular length

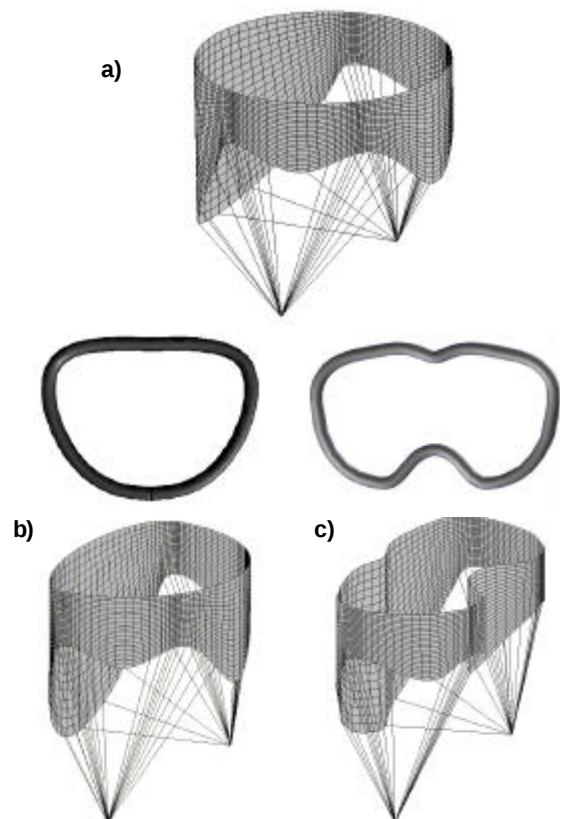


Figure 1. Mitral valve 3-D models. a) no annuloplasty ring; b) D-shaped ring; c) modified annuloplasty ring;

is 58 mm. The annular shape in models ii) and iii) has been then modified in accordance with the features of the annuloplasty rings considered. The mitral valve leaflet profile has been generated

according with the data reported by Kunzelman et al. [3]. The anterior and posterior leaflet heights are equal to 24 mm and 14 mm respectively, while the anterolateral and posteromedial commissural heights are equal to 0.9 mm. The 3-D leaflet profile and the 3-D model of the valve leaflets have been generated by means of GAMBIT (Fluent Inc. Lebanon, Illinois). After discretization, the model consists of 2280 four-node shell elements. The thickness of the leaflet elements has been assumed to be constant and equal to 0.8 mm.

Chordae tendineae have been modeled by means of 40 truss elements with a constant section equal to 0.8 mm^2 . Only the marginal chordae, which are those inserted directly into the free edge of the leaflets, have been considered, as they bear the main part of the pressure loads on the leaflets [4]. The truss elements are placed between the nodes of the leaflet profile and the papillary muscle origins, which are placed symmetrically 30 mm lower the valve annulus as shown in Fig.1a.

The valve leaflet tissue is assumed to be linear and anisotropic; its Young Modulus is assumed to be 6 MPa in the direction parallel to the annulus and 2 MPa in the direction perpendicular to it, and Poisson ratio is assumed to be equal to 0.49. These assumptions are in accordance with data reported by Kunzelman et al. [5].

The chordae tendinae tissue has been modeled as a non-linear elastic material, on the basis of the real stress-strain relationship calculated through in vivo tests. Concerning the boundary conditions, in each model the nodes of the annulus have been constrained with respect to the translations (spherical joints), that is in model i) no annular contraction is simulated, while in models ii) and iii) the annuloplasty rings are assumed to be rigid. When simulating the papillary muscles displacement, a displacement up to 6 mm away from the valve orifice along is imposed to the nodes that represent their tips.

A homogenous pressure up to 120 mmHg has been applied to close the valve. ABAQUS code (ABAQUS/Explicit, Hibbit, Karlsson & Sorensen, Version 6.2.1) has been used to perform the numerical dynamic analyses.

RESULTS

Figure 2 shows the von Mises stress distribution in the mitral valve leaflets when a 6 mm papillary muscles displacement is simulated in the following cases: i) no annuloplasty ring is implanted; ii) a D-shaped annuloplasty ring is implanted; iii) the modified D-shaped annuloplasty ring is implanted. The maximum values are observed in the commissural and fessural regions. When no contentive ring is implanted, the von Mises stress maximum value is + 3092 kPa (+171,6 % with respect to what observed when papillary muscles are in the physiological position). The maximum von Mises stress decreases when a D-shaped or a modified annuloplasty ring is implanted and is equal to + 2300 kPa and + 2250 kPa respectively. Further, stresses acting on the chordae tendinae have been calculated: in all the three models the maximum stress value has been observed in the anterior chordae and it is equal to 4470, 3623 and 3689 kPa in model i), ii) and iii), respectively. Moreover, orifice area (OA) and regurgitation area (RA) values are reported in Table 1.

DISCUSSION

The results of the calculations performed with the three models confirm that annuloplasty ring implantation is mandatory in presence of left ventricular ischemia, in order to reduce the mechanical stresses on the valve leaflets and to restore leaflet coaptation. Moreover, the modified ring herein analyzed appears to be an effective device: if compared to a standard D-shaped ring, it offers a larger orifice area in diastole, and is more effective in restoring leaflet coaptation and

reducing mitral regurgitation in systole. Further developments will include the simulation of the annular motion .

	Model i)	Model ii)	Model iii)
Regurgitation Area (RA) [cm^2]	1.6	0.49	0.39
Orifice Area (OA) [cm^2]	8.04	5.1	5.8
(RA/OA)*100	19.9	9.6	6.7

Table 1. regurgitation area (RA) and orifice area (OA) values for the three models.

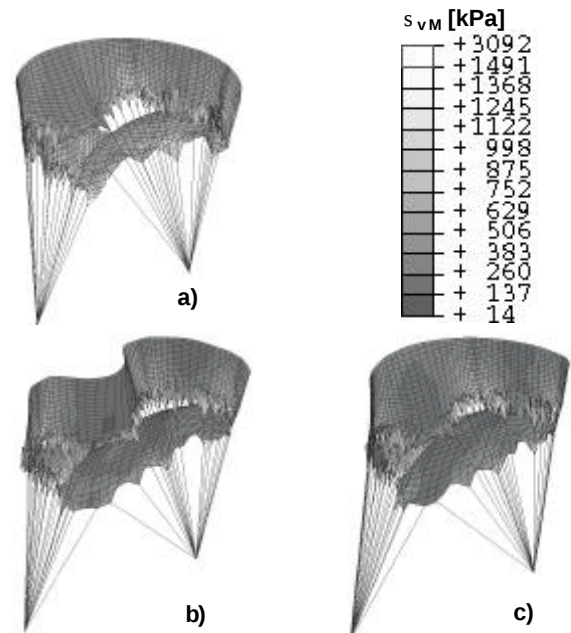


Figure 2. von Mises stress distribution on the leaflets. a) no annuloplasty ring; b) D-shaped annuloplasty ring; c) Seguin modified annuloplasty ring;

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