Is it possible to assess the best mitral valve repair in the individual patient? Preliminary results of a finite element study from magnetic resonance imaging data

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Objectives: Finite element modeling was adopted to quantitatively compare, for the first time and on a patient-specific basis, the biomechanical effects of a broad spectrum of different neochordal implantation techniques for the repair of isolated posterior mitral leaflet prolapse.

Methods: Cardiac magnetic resonance images were acquired from 4 patients undergoing surgery. A patient-specific 3-dimensional model of the mitral apparatus and the motion of the annulus and papillary muscles were reconstructed. The location and extent of the prolapsing region were confirmed by intraoperative findings, and the mechanical properties of the mitral leaflets, chordae tendineae and expanded polytetrafluoroethylene neochordae were included. Mitral systolic biomechanics was simulated under preoperative conditions and after 5 different neochordal procedures: single neochorda, double neochorda, standard neochordal loop with 3 neochordae of the same length and 2 premeasured loops with 1 common neochordal loop and 3 different branched neochordae arising from it, alternatively one third and two thirds of the entire length.

Results: The best repair in terms of biomechanics was achieved with a specific neochordal technique in the single patient, according to the location of the prolapsing region. However, all techniques achieved a slight reduction in papillary muscle forces and tension relief in intact native chordae proximal to the prolapsing region. Multiple neochordae implantation improved the repositioning of the prolapsing region below the annular plane and better redistributed mechanical stresses on the leaflet.

Conclusions: Although applied on a small cohort of patients, systematic biomechanical differences were noticed between neochordal techniques, potentially affecting their short- to long-term clinical outcomes. This study opens the way to patient-specific optimization of neochordal techniques. (J Thorac Cardiovasc Surg 2014;148:1025-34)

ACD

Degenerative mitral valve (MV) prolapse is the most common mitral disease in western countries.[1] Posterior leaflet prolapse is the most common pathologic feature of a degenerative MV. Several conservative surgical techniques have become popular, the first of which dates back to 1983.[2] However, recent studies have demonstrated comparable clinical outcomes, together with potentially superior results in terms of physiology, with techniques that respect rather than resect the diseased portion of the MV.[3] Most of these techniques rely on the use of neochordal implantation (NCI); its principal drawback is related to the precise assessment of neochordal length during surgical intervention.[4,5] For that reason, several techniques have been used to correctly measure neochordal length, fundamentally based on anatomical in vivo measurement in the beating heart using transesophageal echocardiography[6] or functional in vivo measurement in the standstill heart with intermittent saline injection.[7] Furthermore, single[8] and multiple neochordal stitching have been reported.[9] These techniques have been proved effective in the relief of MV prolapse and associated with excellent mid- to long-term outcomes.[10]

Although in the last few decades finite element (FE) modeling has been increasingly adopted to study the mitral valve and quantify its biomechanics, under both physiologic and pathologic conditions,[11] few literature studies have addressed the impact of NCI on MV biomechanics using the FE technique.[12-14] A pioneer study was performed by Kunzelman and colleagues[13] on a paradigmatic MV model derived from fresh porcine hearts. A more recent study[14] overcame the shortcomings of previous paradigmatic FE models via a computational protocol able to virtually simulate the effects of increasing the number of artificial sutures, although based on a single MV geometry.

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Abbreviations and Acronyms

cMRI = cardiac magnetic resonance imaging
CoA = coaptation area
CoL = coaptation length
DN = double neochordal implantation
ePTFE = expanded polytetrafluoroethylene
F_{ePTFE} = artificial suture tension
F_{nc} = native chordal tension
F_{PM} = papillary muscles forces
FE = finite element
FED = fibroelastic deficiency
IPP = isolated posterior leaflet prolapse
MV = mitral valve
LN = nonstandard premeasured neochordal implantation with common loop of one third of the entire length
LNH = nonstandard premeasured neochordal implantation with common loop of two thirds of the entire length
NCI = neochordal implantation
PM = papillary muscle
Pre-model = preoperative model
Phys-model = physiologic model
S_I = maximum principal stress
S_I^{MAX} = peak value of maximum principal stresses along the leaflet free margin
SL = standard loop implantation
SN = single neochordal implantation

However, no study has ever investigated the biomechanics underlying the above-mentioned spectrum of different surgical NCI techniques and, in particular, using a patient-specific multidisciplinary approach combining bioengineering, radiological, and surgical methods. Therefore, it was the aim of this study to investigate degenerative MVs with isolated P2-scallop prolapse using a computational evaluation protocol based on the FE method and combining patient-specific MV modeling from cardiac magnetic resonance imaging (cMRI) and intraoperative surgical findings to assess the biomechanical effects of different clinical scenarios of P2 prolapse, as well as of different surgical techniques for NCI.

MATERIALS AND METHODS

The outline of the developed framework is reported qualitatively in Figure 1. The analysis process involved different tasks, as detailed in the following sections.

cMRI Acquisition

Four patients scheduled for surgical repair of isolated posterior leaflet prolapse (IPP) caused by fibroelastic deficiency (FED) were enrolled in the study (Table 1) at a single university hospital. As per protocol, all patients were in stable sinus rhythm preoperatively. These patients were chosen from 20 contemporary cases of MV P2 prolapse analyzed by cMRI because of the different mechanisms underlying a common functional isolated P2 prolapse. In detail, patient 1 had rupture of a single primary chorda arising from the posteromedial papillary muscle (PM) and anchoring on the midportion of P2; patient 2 had a triple primary chordal rupture, also arising from the posteromedial PM and anchoring on mid-P2; patient 3 had a single primary chordal rupture arising from the posteromedial PM and anchoring at the cleft area of P2 next to P3 scallop; patient 4 had a single primary chordal rupture arising from the anterolateral PM and anchoring on mid-P2.

At each preoperative acquisition, cine cMRI images were acquired on 18 cut planes evenly rotated around the axis passing through the annular center and aligned with the left ventricle long axis (Figure 1, *1*). Thirty cardiac frames were acquired on each plane, with different temporal resolution according to the R-R interval of each patient; cMRI images were acquired using a 3.0-T TX Achieva system (Philips Medical System, Irvine, Calif) with a pixel spacing of 1.25 mm and a slice thickness of 8 mm.

Three-Dimensional cMRI-Derived MV Model

The cMRI quantification of the MV apparatus was accomplished using a standardized published technique.[15] Briefly, segmentation of the set of images was realized using dedicated software developed in MATLAB (The MathWorks Inc, Natick, Mass). The position of reference points for relevant MV substructures (ie, mitral annulus, leaflet free margin, and PMs) was selected manually within the set of images. The coordinates of the points identified were then automatically transformed in the three-dimensional (3D) space using the information stored in the appropriate DICOM fields in order to reproduce a complete and patient-specific 3D geometric model of the MV apparatus. Moreover, segmentation of the set of cine cMRI images allowed the motion of both the mitral annulus and PMs to be tracked throughout the R-R interval. Relevant parameters were then computed from the 3D model obtained in order to assess MV geometry at the midsystolic frame (Table 1).

The initial stress-free MV geometry was reconstructed with reference to end diastole (ie, the last frame preceding closure of the leaflets) and following the approach proposed by Stevanella and colleagues[15]: a complete 3D model of the mitral apparatus was reconstructed at the selected frame, including the extent of each MV leaflet and the chordal apparatus, defined in accordance with ex vivo findings,[16-18] previous work by the group,[11,15] and in particular the appearance of the heart during surgery. Intraoperative measurements were carried out during surgery in order to assess the length of individual posterior and anterior scallops and the height of the anterior and posterior commissures. Moreover, the exact location and extent of the prolapsing region were defined and further details on the IPP lesion were added: (1) the number and type (first, second, third order) of the chordae involved; (2) individual rupture or elongation; (3) PM origin of ruptured/elongated chordae; (4) P2-scallop insertion of ruptured/elongated chordae.

Simulation Setup

The simulation setup was performed as already detailed in previous works.[15] MV 3D numerical models were completed including the mathematical description of the complex mechanical properties of MV leaflets,[19] native chordae tendineae,[20] and expanded polytetrafluoroethylene (ePTFE) neochordae.[21,22] All simulations were carried out using the commercial solver ABAQUS Explicit 6.10 (SIMULIA; Dassault Systèmes, Providence, RI). MV closure was simulated from end diastole to peak systole, defined as the midsystolic frame within the R-R interval.

Suture Length and NCI

For each cMRI-derived model, the systolic MV biomechanics was first simulated, reproducing the preoperative scenario of MV lesions and dysfunctions (Pre-model). From the Pre-model, a physiologic MV model (Phys-model) was derived, which was characterized by complete and intact