Biomechanical drawbacks of different techniques of mitral neochordal implantation: When an apparently optimal repair can fail

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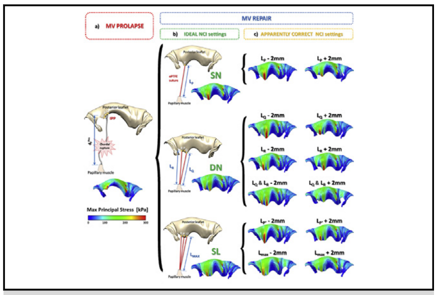
ABSTRACT

Objectives: Intraoperative assessment of the proper neochordal length during mitral plasty may be complex sometimes. Patient-specific finite element models were used to elucidate the biomechanical drawbacks underlying an apparently correct mitral repair for isolated posterior prolapse.

Methods: Preoperative patient-specific models were derived from cardiac magnetic resonance images; integrated with intraoperative surgical details to assess the location and extent of the prolapsing region, including the number and type of diseased chordae; and complemented by the biomechanical properties of mitral leaflets, chordae tendineae, and artificial neochordae. We investigated postoperative mitral valve biomechanics in a wide spectrum of different techniques (single neochorda, double neochordae, and preconfigured neochordal loop), all reestablishing adequate valvular competence, but differing in suboptimal millimetric expanded polytetrafluoroethylene suture lengths in a range of ±2 mm, compared with the corresponding "ideal repair."

Results: Despite the absence of residual regurgitation, alterations in chordal forces and leaflet stresses arose simulating suboptimal repairs; alterations were increasingly relevant as more complex prolapse anatomies were considered and were worst when simulating single neochorda implantation. Multiple chordae implantations were less sensitive to errors in neochordal length tuning, but associated postoperative biomechanics were hampered when asymmetric configurations were reproduced. Computational outcomes were consistent with the presence and entity of recurrent mitral regurgitation at midterm follow-up of simulated patients.

Conclusions: Suboptimal suture length tuning significantly alters chordal forces and leaflet stresses, which may be key parameters in determining the long-term outcome of the repair. The comparison of the different simulated techniques suggests possible criteria for the selection and implementation of neochordae implantation techniques. (J Thorac Cardiovasc Surg 2015;150:1303-12)



Study workflow: simulations of mitral prolapse and ideal and suboptimal mitral repairs.

Central Message

Millimetric suboptimal suture length during mitral plasty induces significant biomechanical consequences on the entire mitral apparatus.

Perspective

Mitral neochordoplasty largely depends on the intraoperative assessment of the appropriate length of artificial sutures. Patient-specific numeric models can explain the biomechanical drawbacks due to a suboptimal millimetric tuning of suture length, elucidate their relationship with patient-specific features and neochordal suture lengths, and lead the way to a more reproducible and effective surgery.

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Mitral valve (MV) plasty has successfully superseded valve replacement as the standard method for the treatment of degenerative MV prolapse.[1,2] Several well-described approaches are currently available from leaflet resection to expanded polytetrafluoroethylene (ePTFE) neochordal implantation (NCI), with both surgical approaches associated

Abbreviations and Acronyms

cMRI	= cardiac magnetic resonance imaging
CoA	= coaptation area
DN	= double neochorda
ePTFE	= expanded polytetrafluoroethylene
FE	= finite element
F_{ePTFE}	= artificial suture tension
F_{nc}	= native chordal tension
IPP	= isolated posterior prolapse
Δl_{NCI}	= millimetric variation in the tuning of neochordal length
MR	= mitral regurgitation
MV	= mitral valve
NCI	= neochordal implantation
Phys-model	= physiologic model
PM	= papillary muscle
Pre-model	= preoperative model
S_I	= maximum principal stress
S_I^{MAX}	= peak value of maximum principal stresses along the leaflet free margin
SL	= standard loop
SN	= single neochorda

with excellent results in early and late outcomes.[3-5] Since the clinical introduction of NCI in the late 1980s, the procedure has become an established technique[6,7] proven to be safe and effective for both the anterior and posterior leaflets,[8] allowing for a more physiologic repair with preserved leaflet mobility compared with resection techniques. However, the results of NCI largely depend on the appropriate number and length of the ePTFE sutures,[9] which are still highly demanding issues, almost entirely based on the surgeon's expertise.[10-13] Furthermore, when tuning the proper repair configuration with NCI, surgeons may have to progressively adjust the initially attempted repair to overcome residual mitral regurgitation (MR), although at the price of a longer and more difficult procedure. Therefore, a better understanding of the biomechanical effects of different NCI techniques on the MV apparatus and their relationship with patient-specific features and neochordal suture lengths may lead the way to a more reproducible and effective surgery, thus avoiding potential biomechanical drawbacks associated with a suboptimal repair. This aim can be pursued by means of finite element (FE) modeling, widely adopted today for the numeric analysis of the MV.[14-16]

MATERIALS AND METHODS

Background of the Present Study

In a recent study,[17] we adopted patient-specific FE models to quantify the biomechanical effects of different ePTFE neochordal techniques in different morphologies of MV isolated posterior prolapse (IPP). Our results strongly suggested that different NCI techniques may equivalently recover MV coaptation while inducing notably different biomechanical consequences on the surrounding tissues, potentially affecting postoperative remodeling. These differences were dependent on both NCI techniques and patient-specific IPP. However, "ideal" NCI techniques may require millimetric adjustments, which are difficult to obtain in the "real daily surgical world" because of the subjective nature of manual surgical gestures.

In the present work, using different NCI techniques, we evaluated the biomechanical effects of apparently correct repairs (ie, without residual MR) due to a suboptimal millimetric ePTFE suture length.

Patient-Specific Mitral Valve Finite Element Modeling

The institutional review board approved the study, and informed consent was obtained from all patients. Four patients in stable sinus rhythm were selected from 20 contemporary cases affected by fibroelastic deficiency and scheduled for surgical repair of IPP due to chordal rupture. Selected patients fit the paradigm of a candidate for NCI, in that they had P2 prolapse characterized by different IPP mechanisms: single primary chordal rupture anchoring on mid-P2 (patients 1 and 4); triple primary chordal rupture anchoring on mid-P2 (patient 2); and single paracommissural, between P2 and P3 scallops, primary chordal rupture (patient 3).[17] Cardiac magnetic resonance imaging (cMRI) acquisitions were preoperatively performed on the selected patients through a 3.0T TX Achieva system (Philips Medical System, Irvine, Calif), with 1.25-mm in-plane resolution and 8-mm slice thickness, following a well-established protocol of acquisition.[18] With the use of dedicated software (MATLAB, The MathWorks Inc, Natick, Mass), reference points were manually traced on all MV substructures in the end-diastolic frame (ie, the last frame preceding transient leaflets closure) and used to obtain the 3-dimensional model of the MV apparatus, which was assumed to be stress-free in this condition.[14,18] The 3-dimensional model was refined on the basis of intraoperative measurements of the annulus to free edge extent of the MV leaflets at different reference points and on details of the IPP lesion (eg, number and type of the chordae involved, papillary muscle [PM], and posterior leaflet insertion). Models were completed by a realistic description of the stress-strain response of MV tissues and ePTFE neochordae.[17,18]

The mitral annulus and PMs were traced on cMRI frames from end diastole to peak systole (ie, the mid-systolic frame within the R-R interval) to derive the respective motion, which was imposed as a boundary condition together with a standard time-dependent transvalvular pressure load to simulate MV closure from end diastole to peak systole. The commercial solver ABAQUS Explicit 6.10 (SIMULIA, Dassault Systèmes, Vélizy-Villacoublay, France) was used.

With this simulation setup, the following 3 general conditions were analyzed for each MV (Figure 1):

- Physiologic model (Phys-model), characterized by an intact chordal apparatus and providing the physiologic level of MV coaptation and distance between the insertion of the ruptured chordae and the corresponding PM head.
- Preoperative model (Pre-model), reproducing the actual MV lesion and dysfunction (Figure 1, *A*).
- Postoperative models (NCI models), reproducing 3 different NCI techniques: single neochorda (SN), double neochorda (DN), and a standard loop (SL) consisting of 3 premeasured neochordae of the same length anchored to the PM tip (Figure 1, *B* and *C*).[17] For each technique, an "ideal" setting and several suboptimal although realistic settings (named "apparently correct") were simulated. In the "ideal" SN and DN, neochordal length was tuned to reproduce the distance between the PM tip and the "leaflet" sites of NCI, as computed in the Phys-model. In the ideal SL, the length of each loop was equal to the maximal distance (L_{max}) of the 3 insertion points from the PM tip, as computed in the Phys-model (Figure 1, *B*). Conversely, "apparently correct" settings of NCI techniques were simulated as follows: SN with ideal suture length altered by ±2 mm (L_P ±2 mm); DN with separate alteration by ±2 mm of each single ideal neochorda (L_Q ± 2 mm, L_R ± 2 mm) or alteration of both ideal sutures (L_Q and L_R ±2 mm); SL with the length of the 3 loops

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