FINITE ELEMENT ANALYSIS APPLIED TO THE TRANSCATHETER MITRAL VALVE THERAPY: STUDYING THE PRESENT, IMAGINING THE FUTURE

▶ Video clip is available online.

To the Editor:

Ejiofor and colleagues¹ concluded that redo mitral valve replacement surgery can be performed with acceptable results despite the high operative risk. Mitral valve repair conferred better long-term survival than did replacement, making the repair cohort a benchmark for transcatheter intervention.

This report highlights “teething” issues of the procedure before a wider application.

Catheter-based interventions are the result of technological evolution of mechanical intervention in the field of transcatheter valve therapy.²⁻⁴ The clinical trials have focused primarily on patients with primary severe mitral regurgitation, reasonable life expectancy, and prohibitive surgical risk because of comorbidities. Results of ongoing randomized trials of transcatheter mitral therapy (TMiT) edge-to-edge in patients with heart failure and secondary mitral regurgitation (COAPT/NCT01626079, RESHAPE-HF/NCT01772108, MITRA-FR/NCT01920698) are imminent and may shed light on patient suitability. The last mentioned study (MITRA-FR/NCT01920698) is of particular interest from a biomechanics perspective, because mitral regurgitation recurrence occurred within 6 months after TMiT edge-to-edge. The wider application of transcatheter mitral valve therapy (TMVT) is limited by long-term durability concerns of new devices, thereby excluding younger patients with intermediate to low risk. Expansion to include these patients⁵ involves exposing them to the uncertainty of

VIDEO 1. Simulation of Von Mises average stress distribution after biomechanical simulation of transcatheter valve therapy. Video available at: [https://www.jtcvs.org/article/S0022-5223\(18\)32507-8/fulltext](https://www.jtcvs.org/article/S0022-5223(18)32507-8/fulltext).

long-term effectiveness. TMVT results should not be inferior to surgical intervention for patients undergoing transmitral valve replacement, transmitral mitral valve-in-valve, and transmitral mitral valve-in-ring or TMiT edge-to-edge.

Finite element analysis (FEA) biomodeling allows development of predictive models for short and long-term follow-up by means of computed biomodeling applied to TMVT. FEA involves calculating the stress and strain coefficients of the complex structures within a small geometric area, whereby its behavior can be mathematically anticipated (Videos 1 and 2). Its widespread use in cardiology and cardiac surgery is limited because of clinician hesitancy stemming from the lack of related clinical studies, thereby curtailing its potential effectiveness.⁶ Application of FEA biomodeling can be clinically validated through a comparative analysis

VIDEO 2. Biomechanical simulation of transcatheter valve therapy that show the main step of finite element analysis model: Stent crimping, catheter removing and stent self-expansion. Video available at: [https://www.jtcvs.org/article/S0022-5223\(18\)32507-8/fulltext](https://www.jtcvs.org/article/S0022-5223(18)32507-8/fulltext).

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with computed dynamic computed tomographic scan, magnetic resonance imaging, or 3-dimensional transesophageal echocardiographic reconstruction of the mitral valve.^{7,8}

Transmitral valve replacement, transmitral mitral valve-in-valve, and TMViR therapies are subject to higher levels of stress and strain of valve leaflets and attachment of the stent in the trigonal area during the systole as the mitral valve bulges into the left atrium.⁹ FEA is able to foresee these biomechanical perturbations in quasistatic boundary conditions and during fatigued dynamic stress¹⁰; both potentially are responsible for early risk of structural valve deterioration. This is likely accentuated during crimping movements in 14F dispensing systems, especially with the latest transcatheter valve therapy generations with thinner leaflets.

In TMiT edge-to-edge, the mechanical behavior of the mitral valve differs between leaflets and connective scaffolding. The current trend of biomodelling mitral valve leaflets involves using anisotropic hyperelastic materials with a preferred anisotropic direction defined by a single collagen family within an isotropic matrix.¹⁰ Understanding the functioning mechanisms are essential for lasting results. For TMiT edge-to-edge, a scallop of the anterior leaflet is attached to its counterpart (Figure 1). In vitro studies of mechanical testing have raised concerns about the active components present in the mitral leaflets and the presence of prestrains

FIGURE 1. Three-dimensional transesophageal echocardiographic view en face from left atrium illustrates transmitral valve therapy edge-to-edge for mitral prolapse of P2-P3 scallop junction.

contributing to physiologic deformations during peak systole of the mitral valve, highlighting insufficiency of biomodeling in numerical studies of the mitral apparatus. In vitro studies^{11,12} performed on porcine anterior mitral leaflets in a simulator yielded measures of circumferential and radial strains ranging between 15% and 40% at peak systole. These strains were measured in vivo by Krishnamurthy and colleagues¹³ with a linear inverse FEA technique to estimate material stiffness of bovine anterior leaflets, suggesting the possible underestimation of leaflet stiffness. The tips of the papillary muscles should be fixed, varying by only a few millimeters in distance between the implantation base of the papillary muscles during end-diastole and end-systole. The relative distance between the plane of the annulus and the tips of the papillary muscles is almost constant in degenerative diseases but not in secondary mitral regurgitation resulting from tethering traction. Edge-to-edge without ring annuloplasty, which improves the malcoaptation of the leaflets by reducing the anteroposterior diameter, may be insufficient to reduce the stress load of the anterior leaflet. These findings were noted by De Bonis and coworkers.¹⁴ A later study by the same group¹⁵ showed the MitraClip (Abbott Vascular, Santa Clara, Calif) device to be an independent predictor of mitral regurgitation recurrence in a similar patient cohort. It is hoped that further studies of subgroup analysis between conventional Mitral valve surgery versus TMiT edge-to-edge through FEA application may clarify TMVT limits.

Three-dimensional transesophageal echocardiographic biomodeling through FEA can measure the stress and strain of the mitral apparatus and predict clinical evolution. Simultaneous predictive biomodeling through FEA and computed 3-dimensional imaging may be useful for predicting the success of the long-term implantation of TMVTs.

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