INVESTIGATION OF HUMAN MITRAL VALVE MECHANICS USING AN IN-HOUSE HYBRID PHYSICAL-COMPUTATIONAL PLATFORM

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Introduction

The mitral valve (MV) is one of the most complex valves in human heart and prevents backflow of blood from the left ventricle (LV) to left atrium (LA). Given the increasingly high prevalence and significance of structural MV pathologies [1] and lack of diseased, large animal models to study them, it is imperative to develop a platform for modelling and testing of synthetic MVs with added advantages of anatomical consistency, reproducibility, and extended shelf life. In this work, a hybrid physical-computational platform is presented with anatomically informed MV geometry and controlled leaflet thickness capable of mimicking healthy human MV mechanics. The physical model was used to validate the finite element analysis (FEA) model. The validated FEA model can be used for fast parametric studies to investigate the effects of MV structural and/or material changes on its mechanics.

Methods

Physical Model: An idealized 3D MV geometry was created in SolidWorks using healthy human MV measurements [2] and further used to 3D print mould parts for elastomeric casting of silicone MV leaflets with Ecoflex 00-30 silicone and gauze. Chordae were embedded in the leaflets and glued at the other end to 3D printed papillary muscle posts. The fabricated MV annular section was embedded in Moldstar 15 (Fig 1A). A 3D left heart simulator flow rig was constructed for testing the synthetic MV. This rig was filled with blood mimicking mixture consisting of 60:40 water-glycerol volume ratio. To actuate the flow, a position-time curve was defined for the linear motor to create a reciprocal motion to mimic pulsatile physiological pressure associated with a cardiac output of 4.5 l/min and a forward stroke volume of 64 ml at 70 bpm (T=852 ms). Fluid pressures were measured in the LA and LV chambers and used to calculate the transvalvular MV pressure (Fig 1B).

FEA model: MV geometry was discretized into 18444 reduced integration hexahedral elements (C3D8R) with Abaqus (Dassault Systemes, USA - Fig 1C). An isotropic hyperelastic 5th order reduced polynomial material model was fit to Ecoflox 00-30 and guaze tensile test data and applied to each leaflet. Primary marginal chordae were defined in form of spring elements with a stiffness coefficient of 1.6 N/mm [3]. The mitral annulus and papillary muscle posts were fully fixed. Explicit general contact, including self-contact with an isotropic friction coefficient of 0.05 [3] was applied. A surface pressure ranging from -8 to 120 mmHg was applied to the ventricular side of the leaflets, representing a full cardiac cycle of 852 ms at 70 bpm.

Results

Qualitatively, the FEA and physical models showed good agreement in terms of valve closure and leaflet coaptation. However, a slight opening and regurgitant zone (shown in red) was visible in the physical model, which was further investigated quantitatively in ImageJ (NIH, USA) and was 4.22 mm^2 and was equivalent to 2.25% of the orifice area of an open MV in peak diastole. No bulging of the leaflets into the LA was detected in either of the models. The leaflet coaptation length was measured using the midsection cutview of the FEA model to be 6.55 mm, which is within the healthy range of 4.9 ± 3.8 mm [4].

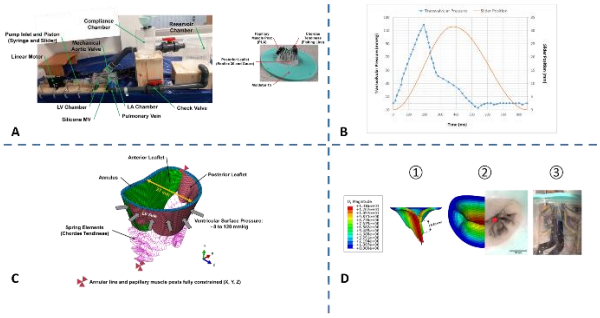

Figure 1 (A) (1) Physical MV model; (2) 3D left heart simulator flow rig. (B) Slider position, physical MV transvalvular pressure vs time curves. (C) FEA MV model setup. (D) (1) FEA displacement at peak systole with midsection cutview showing coaptation length; (2) FEA displacement and physical MV image, atrial view at peak systole; (3) Physical MV side view at peak systole.

Discussion

Preliminary results show good agreement between silicone FEA and physical model. This combined computational-physical platform is a powerful tool that allows for parametric sweep studies of MV non-pathological and pathological changes such as annular dilation, chordae rupture, papilliary muscle position change, and calcification, which could provide insight on their clinical impact and assist with procedure planning and advance medical device development and testing.

References

1. Yadgir S, et al. J. Circ, 1670, 2020. **2.** Oliveira D, et al. J. Anat, 209, 2020. **3.** Prescott B, et al. Vessel Plus, 2019. **4.** Gogoladze, et al. Ann Thorac Surg, 2010.