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A coupled mitral valve–left ventricle model with fluid–structure interaction

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ABSTRACT

Understanding the interaction between the valves and walls of the heart is important in assessing and subsequently treating heart dysfunction. This study presents an integrated model of the mitral valve (MV) coupled to the left ventricle (LV), with the geometry derived from in vivo clinical magnetic resonance images. Numerical simulations using this coupled MV–LV model are developed using an immersed boundary/finite element method. The model incorporates detailed valvular features, left ventricular contraction, nonlinear soft tissue mechanics, and fluid-mediated interactions between the MV and LV wall. We use the model to simulate cardiac function from diastole to systole. Numerically predicted LV pump function agrees well with in vivo data of the imaged healthy volunteer, including the peak aortic flow rate, the systolic ejection duration, and the LV ejection fraction. In vivo MV dynamics are qualitatively captured. We further demonstrate that the diastolic filling pressure increases significantly with impaired myocardial active relaxation to maintain a normal cardiac output. This is consistent with clinical observations. The coupled model has the potential to advance our fundamental knowledge of mechanisms underlying MV–LV interaction, and help in risk stratification and optimisation of therapies for heart diseases.

1. Introduction

The mitral valve (MV) has a complex structure that includes two distinct asymmetric leaflets, a mitral annulus, and chordae tendineae that connect the leaflets to papillary muscles that attach to the wall of the left ventricle (LV). MV dysfunction remains a major medical problem because of its close link to cardiac dysfunction leading to morbidity and premature mortality [1].

Computational modelling for understanding MV mechanics promises more effective MV repairs and replacement [2–5]. Biomechanical MV models have been developed for several decades, starting from the simplified two-dimensional approximation to three-dimensional models, and to multi-physics/-scale models [6–12]. Most previous studies were based on structural and quasi-static analysis applicable to a closed valve [13]; however, MV function during the cardiac cycle cannot be fully assessed without modelling the ventricular dynamics and the fluid–structure interaction (FSI) between the MV, ventricles, and the blood flow [13,14].

Because of the complex interactions between the MV, the submitral apparatus, the heart walls, and the associated blood flow, very few modelling studies have been carried out that integrate the MV and ventricles in a single model [15–17]. Kunzelman, Einstein, and co-workers first simulated normal and pathological mitral function [18–20] with FSI using LS-DYNA (Livermore Software Technology Corporation, Livermore, CA, USA) by putting a MV into a straight tube. Using a similar modelling approach, Lau et al. [21] compared MV dynamics with and without FSI, and they found that valvular closure configuration is different when using the FSI MV model. Similar findings were reported by Toma et al. [22]. Over the last few years, there have also been a number of FSI valvular models using immersed boundary (IB) method to study the flow across the MV [23–25]. In a series of studies, Toma et al. [22,26,27] developed an FSI MV model based on in vitro MV experimental system to study the function of the chordal structure, and good agreement was found between the computational model and in vitro experimental measurements. However, none of the aforementioned MV models accounted for the MV interaction with the LV dynamics. Indeed, Lau et al. [21] found that even with a fixed U-shaped ventricle, the flow pattern was substantially different from that estimated using a tubular geometry. Despite the advancements

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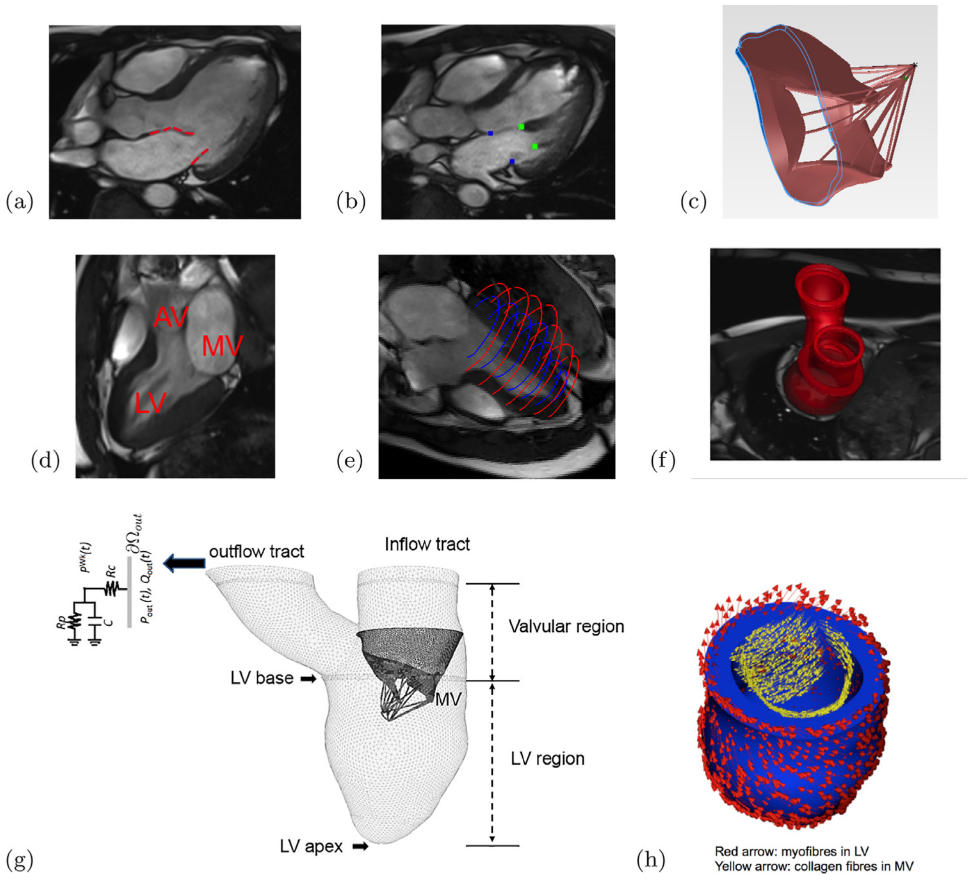

Fig. 1. The CMR-derived MV–LV model. (a) The MV leaflets were segmented from a stack of MR images of a volunteer at early-diastole, (b) positions of the papillary muscle heads and the annulus ring, (c) reconstructed MV geometry with chordae, (d) an MR image showing the LV and location of the outflow tract (AV) and inflow tract (MV), (e) the LV wall delineation from short and long axis MR images, (f) the reconstructed LV model, in which the LV model is divided into four part: the LV region bellow the LV base, the valvular region, and the inflow and outflow tracts, (g) the coupled MV–LV model, and (h) the rule-based fibre orientations in the LV and the MV. (For interpretation of the references to colour in the text, the reader is referred to the web version of this article.)

in computational modelling of individual MV [12,13] and LV models [28–30], it remains challenging to develop an integrated MV–LV model that includes the strong coupling between the valvular deformation and the blood flow. Reasons for this include limited data for model construction, difficult choices of boundary conditions, and large computational resources required by these simulations.

Wenk et al. [15] reported a purely structural MV–LV model using LS-DYNA that included the LV, MV, and chordae tendineae. This model was later extended to study MV stress distributions using a saddle-shaped and asymmetric mitral annuloplasty ring [16]. A more complete whole-heart model was recently developed using a human cardiac function simulator in the Dassault Systèmes *Living Heart* project [17], which included four ventricular chambers, cardiac valves, electrophysiology, and detailed myofibre and collagen architecture. Using the same simulator, effects of different mitral annulus ring were studied by Rausch et al. [31]. However, this simulator does not account for detailed FSI.

The earliest valve–heart coupling model that includes FSI is credited to Peskin and McQueen's pioneering work in the 1970s [32–34] using the classical IB approach [35]. Using this same method, Yin et al. [36] investigated fluid vortices associated with the LV motion as a prescribed moving boundary. Recently, Chandran and Kim [37] reported a prototype FSI MV dynamics in a simplified LV chamber model during diastolic filling using an immersed interface-like approach. One of the key limitations of these coupled models is the simplified representation of the biomechanics of the LV wall. To date, there has been no work reported a coupled MV–LV model which has full FSI and based on realistic geometry and experimentally-based models of soft tissue mechanics.

This study reports an integrated MV–LV FSI model derived from in vivo images of a healthy volunteer. Although some simplifications are made, this is the first three-dimensional FSI MV–LV model that includes MV dynamics, LV contraction, and experimentally constrained descriptions of nonlinear soft tissue mechanics. This work is built on our previous models of the MV [24,25] and LV [29,38]. The model is implemented using a hybrid immersed boundary method with finite element elasticity (IB/FE) [39].

2. Methodology

2.1. MV–LV model construction

A cardiac magnetic resonance (CMR) study was performed on a healthy volunteer (male, age 28). The study was approved by the local NHS Research Ethics Committee, and written informed consent was obtained before the CMR scan. Twelve imaging planes along the LV outflow tract (LVOT) view were imaged to cover the whole MV region shown in Fig. 1(a). LV geometry and function were imaged with conventional short-axis and long-axis cine images. The parameters for the LVOT MV cine images were: slice thickness: 3 mm with 0 gap; in-plane pixel size: $0.7 \times 0.7\,\text{mm}^2$; field of view: $302 \times 400\,\text{mm}^2$; frame rate: 25 per cardiac cycle. Short-axis cine images covered the LV region from the basal plane to the apex, with slice thickness: 7 mm with 3 mm gap; in-plane pixel size: $1.3 \times 1.3\,\text{mm}^2$; frame rate: 25 per cardiac cycle.