NOVEL PATIENT-SPECIFIC BEATING HEART MODEL INCORPORATING ACTIVE CONTRACTILITY AND A PSEUDO-FLUID DOMAIN

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Introduction: In this study a framework to construct an efficient patient-specific finite element model of the left ventricle (LV) from tri-planar CINE echography scans is developed. A novel approach of implementing a pseudo-fluid domain inside the ventricle is proposed. Simulations are shown to be several orders of magnitude faster than conventional fluid-structure interaction models of the left ventricle and reveal that the framework is capable of correctly predicting complex pressure-volume (PV) loops for a range of physiological conditions.

Methods: As illustrated in Figure 1A, patient-specific geometries were created by generating splines based on tri-planar CINE echography scans of healthy human hearts using MATLAB. Meshes were generated using 3D continuum elements across two separate domains: a solid domain representing the myocardium, and a pseudo-fluid domain representing the blood in the LV. We develop novel user material subroutines (UMATs) to simulate the actively contractile myocardium in addition to the haemodynamic behaviour of the blood in the ventricle. During systole the pseudo-fluid domain behaviour is based on Windkessel formulation, where the total volume of all elements in the domain is tracked and used to determine the volumetric flow of blood from the LV to the aorta. The behaviour of this domain is governed by a biphasic aortic compliance and the peripheral resistance. Based on MRI and finite element analysis by Concannon and McGarry [1] aortic compliance is shown to be significantly lower at high pressures during systole than during low pressures during diastole [2]. Volume change of the LV is driven by active contractility of the myocardium. This material formulation for the myocardium incorporates sarcomere contractility and remodelling in addition anisotropic collagen structures.

Results: Figure 1B shows the computed distribution of myocardium active stress and fluid pressure during isovolumetric contraction and end-systole. Computed PV loops for the left ventricle are shown in Figure 1C for a case of Inferior Vena Cava Occlusion (IVCO). The model correctly predicts that stroke volume and ventricle pressure reduce over a series of cardiac cycles, as observed clinically. Additionally, in the first cycle a change in slope of the PV curve is computed during systole. However, in subsequent cycles the PV slope is constant during systole as reduced pressure results in a high aortic compliance throughout the cycle, as observed clinically. Computed changes in ventricle pressure as a function of time are also shown in Figure 1(b). Both systolic and diastolic pressure reduce with subsequent cycles. A plot of ventricle volume as a function of time clearly illustrates the change of slope due to biphasic aortic compliance. Finally, computed active contractility as a function of cycle time is shown,

demonstrating rapid rise in contractility during isovolumetric contraction, reduced rate of contractility increase during systole, and rapid reduction during ventricular relaxation phase. The authors are not aware of a previous finite element framework that has successfully simulated the complex patterns of ventricle pressure, volume and active contractility during IVCO. Importantly, our novel approach for simulation of active myocardium interaction with blood in the ventricle allows the simulation of a cardiac cycle in under five minutes, in contrast to several hours of simulation time for established fluid-structure-interaction models.
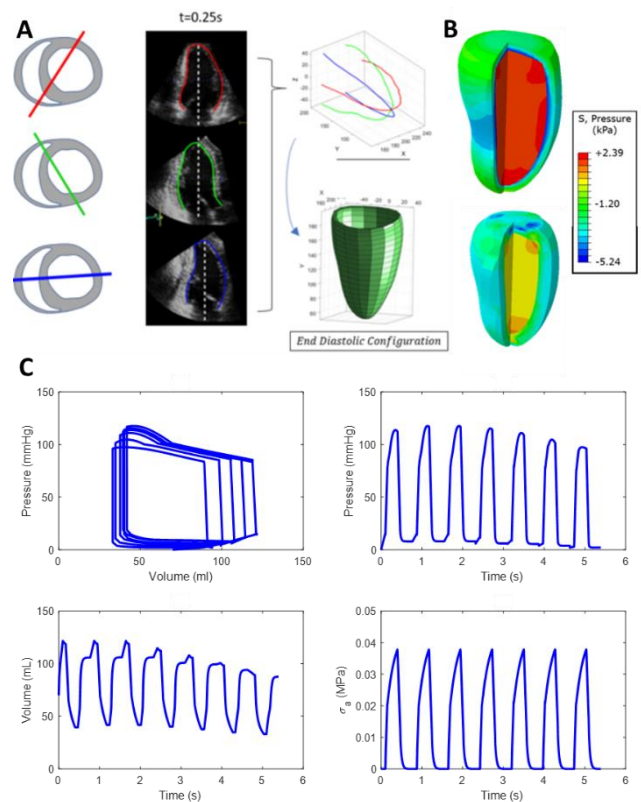

Figure 1: (A) Construction of FE model from tri-planar CINE echography scans; (B) distribution of myocardium active stress and fluid pressure during isovolumetric contraction and end-systole; (C) Computed pressure-volume, pressure-time, volume-time, active contractility-time relationships.

References:
1. Concannon & McGarry (2021); Acta Biomaterialia, 125:154–171
2. Concannon et al., (2020); J Biomech Eng 142(11): 114502.

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