Construction and initial experience with a four-chambered fluid-structure interaction model of the heart

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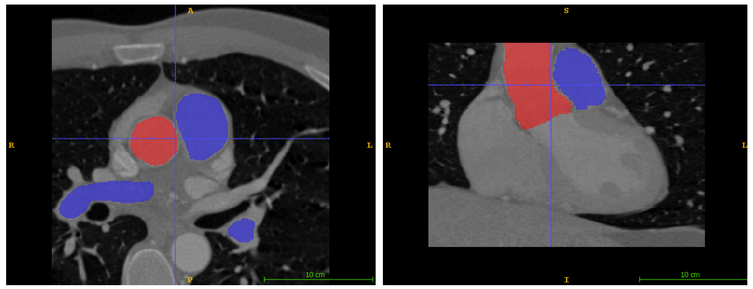
Introduction

Cardiovascular disease is the leading cause of death in the United States, and the estimated cost associated with heart diseases in the U.S. alone is over $200 billion per year [1]. This work aims to develop a comprehensive heart model that couples realistic descriptions of the biomechanics of the heart and its valves to the fluid dynamics of the blood.

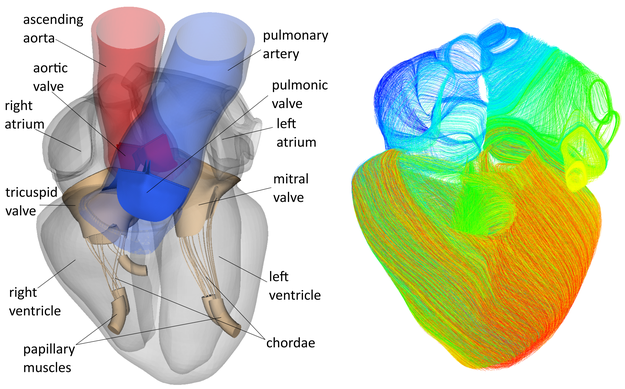
Model Construction

Model geometries of the myocardium and great vessels are constructed by manual segmentation using computed tomography data.



Axial view (left) and coronal view (right)

The valves, papillary muscles, and chordae are idealized geometries. We include a description of the fiber structure of the myocardium and the valve leaflets.



We use an immersed finite element method, defined below, to construct the **fluid-structure interaction** (**FSI**) model of the heart [2,3].

$$\rho\frac{\mathrm{D}\mathbf{u}}{\mathrm{D}t}(\mathbf{x},t) = -\nabla p(\mathbf{x},t) + \mu\nabla^2\mathbf{u}(\mathbf{x},t) + \mathbf{f}(\mathbf{x},t),$$

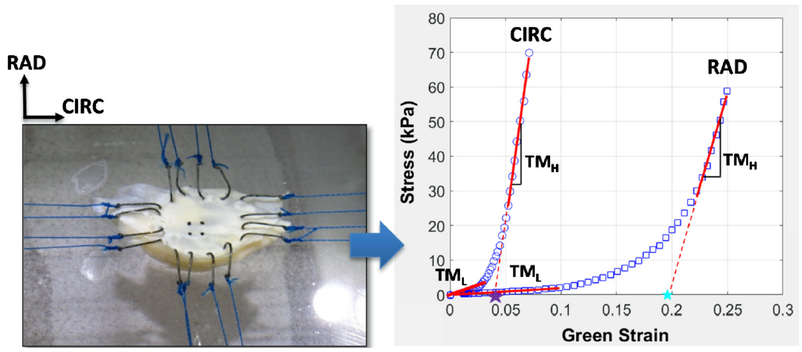
$$\nabla\cdot\mathbf{u}(\mathbf{x},t) = 0,$$

$$\mathbf{f}(\mathbf{x},t) = \int_U \nabla_{\mathbf{X}}\cdot\mathbb{P}(\mathbf{X},t)\,\delta(\mathbf{x}-\boldsymbol{\chi}(\mathbf{X},t))\,\mathrm{d}\mathbf{X} - \int_{\partial U}\mathbb{P}(\mathbf{X},t)\,\mathbf{N}(\mathbf{X})\,\delta(\mathbf{x}-\boldsymbol{\chi}(\mathbf{X},t))\,\mathrm{d}A(\mathbf{X}),$$

$$\frac{\partial\boldsymbol{\chi}}{\partial t}(\mathbf{X},t) = \int_\Omega \mathbf{u}(\mathbf{x},t)\,\delta(\mathbf{x}-\boldsymbol{\chi}(\mathbf{X},t))\,\mathrm{d}\mathbf{x} = \mathbf{u}(\boldsymbol{\chi}(\mathbf{X},t),t).$$

Model Parameterization

The material parameters are generated from human tissue tensile experiments along the fiber axes.



Biaxial tensile analysis experimental setup in the valves (left). Resultant stress-strain curves (right) used for constitutive model fitting [4].

The data are fit to constitutive equations, defined for the valves below, that describe the mechanics in the structure model.

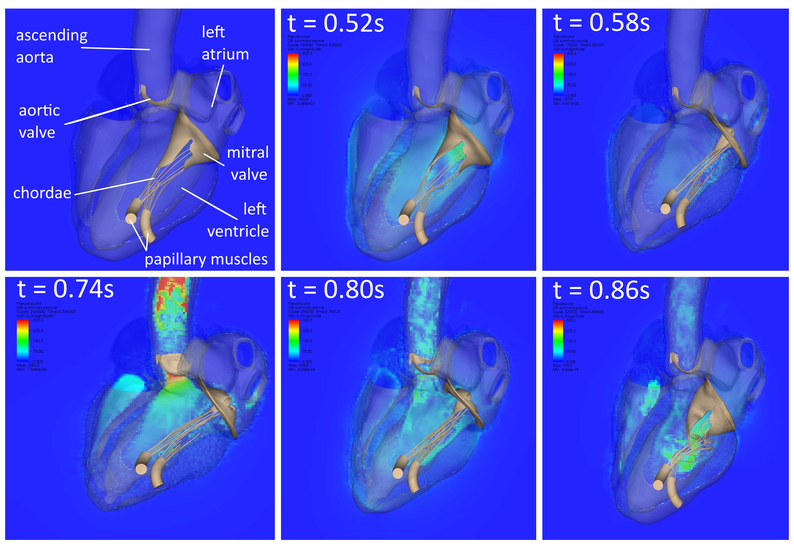
$$W = \frac{1}{2}c(\exp(Q)-1)$$

$$Q = A_1E_{11}^2 + A_2E_{22}^2 + 2A_3E_{11}E_{22} + A_4E_{12}^2 + +2A_5E_{11}E_{12} + 2A_6E_{22}E_{12}$$

$$\mathbb{S} = \frac{\partial W}{\partial \mathbb{E}} = \mathbb{F}^{-1}\mathbb{P}$$

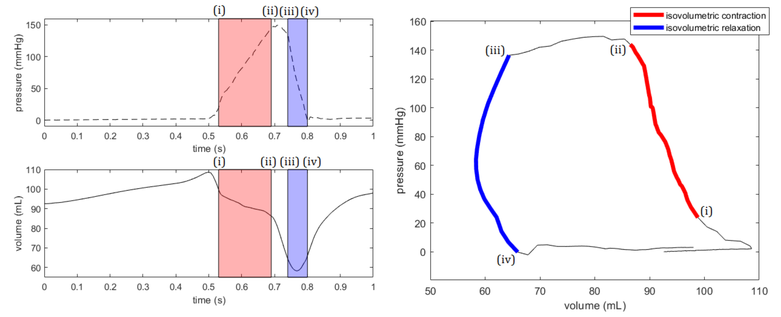
Cardiac Cycle

We can visualize the fluid velocities and structural deformations throughout various points in the cardiac cycle. We focus on the left heart dynamics because of the increased loads and larger fluid velocities.



Pressure-Volume Loop

We collect pressure and volume data from the left ventricle for use in cardiac cycle analysis.



Time dependent plots of the pressure (top left) and volume (bottom left) and the pressure-volume loop (right) of the left ventricle. The labels correspond to the mitral valve closing **(i)**, the aortic valve opening **(ii)**, the aortic valve closing **(iii)**, and the mitral valve opening **(iv)**.

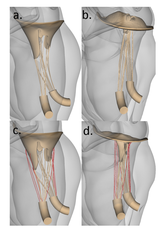
Using the pressure-volume data we calculate some basic statistics to characterize our cardiac cycle.

EDV	ESV	SV	EF	CO
103.9 mL	64.3 mL	39.6 mL	0.38	2.5 L/min

Left ventricular end-diastolic volume (**EDV**) at **(i)**, end-systolic volume (**ESV**) at **(iii)**, stroke volume (**SV**), ejection fraction (**EF**), and cardiac output (**CO**).

Model Improvements

We are working to improve the model through better material descriptions and physiological features. Our recent focus is improving the mitral prolapse highlighted in **b.** We use only *marginal* chordae (**a.**) for the simulations in this poster, but we are testing with additional *strut* chordae (red in **c.**) and with shortening of all the chordae. We see significantly reduction in mitral valve prolapse (**d.**) with these changes.



Conclusions

Employing FSI modeling techniques and material descriptions of cardiac tissues allows us to replicate realistic cardiac cycles. We plan to use the model to study the impact of myopathies on fluid dynamics and conduct computational investigations for potential surgical interventions and implanted devices.

Acknowledgments and Citations

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3. Griffith and Patankar. *Ann Rev Fluid Mech.* 52:421, 2020.
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