A computational model of the left ventricle – application in cardiomyopathy disease

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Abstract: Cardiomyopathy or structural and functional abnormalities of the ventricular myocardium is a common cardiac disease. It can be commonly classified as hypertrophic (HCM) and dilated (DCM) cardiomyopathy. A computational model was developed to simulate drug effects on heart behavior during the heartbeat cycle. The model includes parametric left ventricle geometry supported with the finite element (FE) code PAK with the implemented methodology for loose coupling fluid-structure interaction (FSI) and coupled electromechanics which enables investigation of the influence of different drugs on the conditions of virtual cardiomyopathy patients. Passive mechanical stresses are calculated using a recently introduced orthotropic material model based on an experimental investigation of passive material properties of the myocardium. Active stresses are calculated using the Hunter excitation model. The basic equations for solid mechanics, fluid dynamics, and excitation are summarized, and the applicability of this model is illustrated on a simple model of the left ventricle which includes inlet mitral and outlet aortic valve cross-sections. The presented computational model can serve as a basis for the in-silico simulation of the drug effects in the common types of cardiomyopathy.

Keywords: cardiac cycle, cardiomyopathy, finite element method, left ventricle model

1. Introduction

Cardiomyopathy is a general name for all anomalies of the ventricular endocardium leading to the stretched, thickened, or stiff heart chamber. Treatment of symptoms of cardiomyopathy using existing types of therapies can only partially affect the

improvement of treatment outcomes, but it is still necessary to introduce new types of treatment that could have a more significant effect on this type of disease.

Testing of drugs for cardiomyopathy can be done by using *in-silico* clinical trials that employ computational modeling and a variety of simulation techniques. In this work, we present the application of finite element (FE) numerical procedure for the simulation of the cardiomyopathy diseased left ventricle model.

2. Materials and Methods

The FE code PAK [1] is used to solve coupled solid mechanics and fluid dynamics fields using the loose coupling procedure. For solid mechanics, two types of stresses are accounted for - passive and active. The determination of passive stresses is based on the recently published experimental investigation of Professor Holzapfel and his research group [2]. For the active stresses in solid material, calcium concentration relation for the heart muscle formulated in [3] is used in our model [4]. Fluid flow is considered as Newtonian and is based on the continuity equation and differential Navier-Stocks equations [6]. The loose coupling procedure is used to solve the solid-fluid interaction: first, we solve the fluid field, then calculate the forces of fluid acting on the surrounding solid domain, and determine the solid deformation. Finally, when solving for a solid domain, we transfer the velocities of the solid to the corresponding fluid nodes. A usual iterative procedure [6] is used for both solid and fluid models.

2. Results

The parametric FE model consists of a fluid domain surrounded by a solid wall (Figure 1a), with prescribed velocities at the inlet (mitral; Figure 1b) and outlet (aortic; Figure 1c) valves.

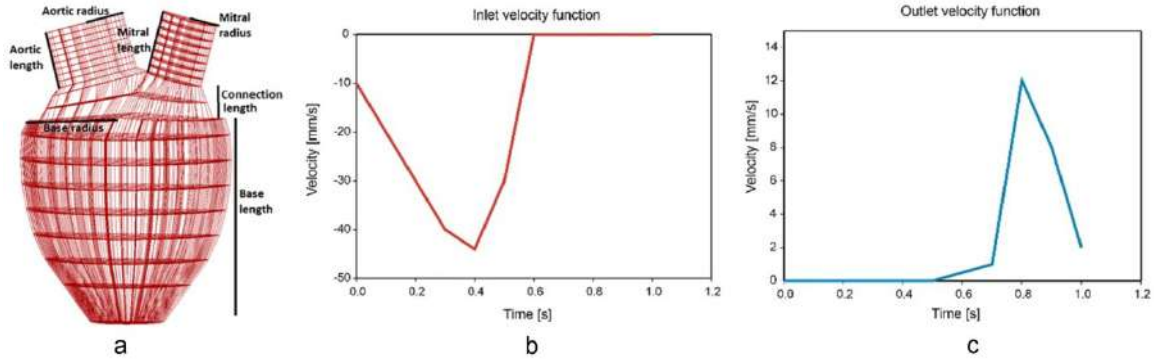

Figure 1. a) Parametric model of the left ventricle with structural mesh. Base, connecting part, and valves (mitral and aortic) parameters noted [7]; Prescribed blood velocities as functions of time: b) Inlet velocity, at mitral valve cross-section, and c) outlet velocity, at aortic valve cross-section.

Velocity and pressure distribution inside the model, during one heartbeat cycle of 1.0s duration, for four different time moments are shown in Figures 2a and 2b. In Figure 2c shows how the displacements are distributed over the ventricle wall.

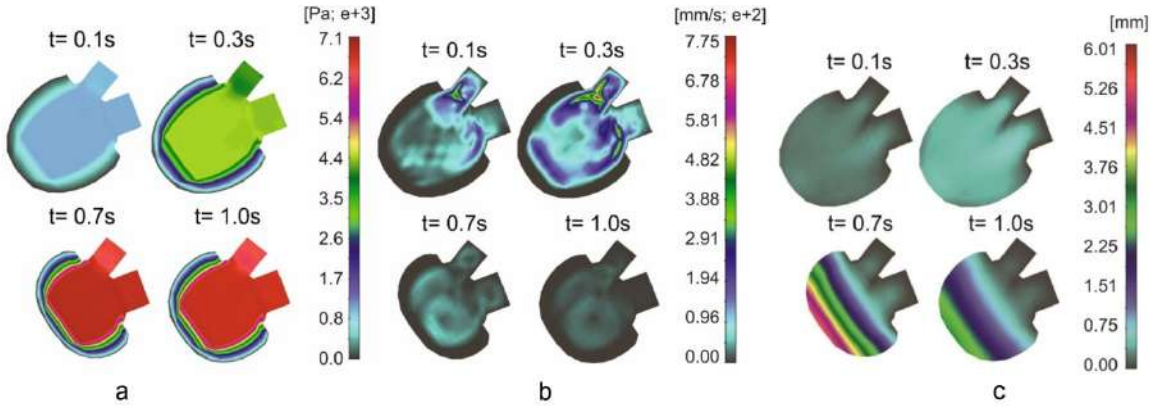

Figure 2. Results for parametric left ventricle model for four different time steps, a) field of velocities within the fluid part, b) pressures inside of the left ventricle, and c) field of displacements for the left ventricle wall.

A computed pressure vs. volume (pV) diagram and a commonly accepted pV diagram for one full cycle is shown in Figures 3a and 3b, while Figure 3c displays a vectorial representation of velocities inside the fluid part of the ventricle.

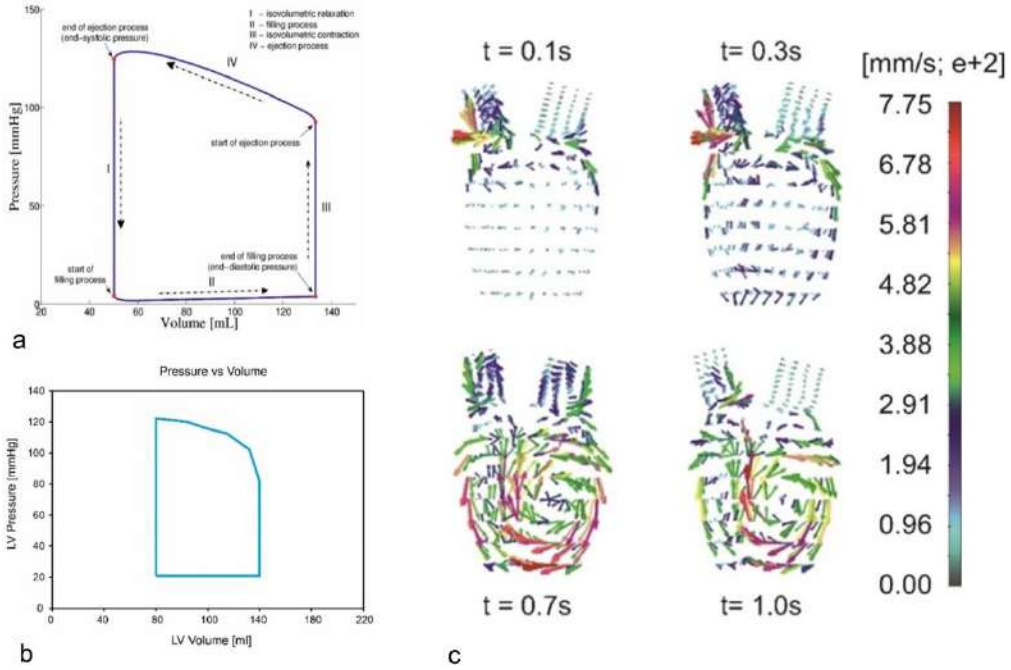

Figure 3. a) Pressure vs Volume diagram for left ventricle with an explanation of notable steps during one full cycle. b) Pressure vs Volume (pV) diagram for left ventricle structural model. Prescribed cycle duration- 1.0 s, 10 time steps. c) Vectorial representation of velocities in a parametrical model of the left ventricle; four different time steps.

3. Conclusions

We have demonstrated that the coupled solid-fluid mechanical model can be used for the simulation of the heartbeat. The calculation was executed using our PAK solver while the model generation was performed by the in-house CAD software. The presented computational model serves as a basic tool for the in-silico simulation of the drug effects in the common types of cardiomyopathy.

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