Blood flow modeling with a finite element living heart model in the FlowVision software complex

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Abstract. The paper presents the living heart finite element model, which can be used for heart beating simulation. The simulation of a human heartbeat is introduced in two settings – with artificial valves and tissue valves. The properties of tissue valves are similar to natural ones. The modelling was held using the FSI technology - fluid structure interaction – two-way coupling of the finite element model of the heart and the blood flow inside it. The finite element model of the heart was created as part of the Living Heart Project (the project of Simulia Dassault company).

1. Introduction.
The active technology development leads to the fact that science is becoming multidisciplinary and its various fields require coupled solutions. Fluid-Structure Interaction is one of such approaches. Fluid-Structure Interaction (FSI) is the interaction of a deformable structure with an external or internal fluid/gas flow. Similar tasks find application in various fields from industry to medicine.

The diseases of the cardiovascular system are the main cause of death from diseases worldwide according to World health Organization [1]. Therefore, there are many projects dedicated to heart modeling. The Living Heart project brings together leading scientists, researchers, developers and doctors to design and validate high-precision personalized digital models of the human heart [2]. The aim of the project is a realistic simulation of blood flow in a beating human heart, taking into account the fluid-structure interaction between blood, heart tissues and artificial mechanical valves.

2. The model of working heart.
The mathematical model of the working heart, which includes electromechanical properties of muscle tissue, the motion of atriums, ventricles and valves (artificial and tissue) in dynamics has been created within the framework of the project. It includes the anatomical components of the heart, such as the mitral and aortic valves, as well as the proximal vasculature: the aortic arch, pulmonary artery and superior vena cava.
The movement of the heart is regulated by realistic physics of electrical and structural processes, as well as the flow of fluid (blood). The model can be used to study both the joint electro-mechanical behavior of the heart, in which the mechanical response is due the electrical excitation, and to study the electrical impulses of the heart separately. The heart model includes the determination of a sequentially coupled electromechanical analysis of the beat cycle with a duration of one second, which corresponds to a heart rate of 60 beats per minute - the standard heart rate of an adult (in a relaxed state). Despite the fact that the model is a healthy heart, it is possible to study abnormal conditions (heart diseases) on it, changing the geometry of the heart components, the properties of tissues and/or loads and boundary conditions. Also, additional components (for example, medical devices) can be connected to the model in order to study their effect on heart function and explore treatment options.

- The finite element model. Figure 1 shows the finite element model of the heart created in the Abaqus FE complex. The model consists of about 130 thousand elements and 450 thousand nodes.
- The FV model. The model in FlowVision has about 120 thousand cells.

![Figure 1. The «Living heart» Abaqus FEA model](image)

3. **The analysis.**

The cardiac cycle can be divided into two stages: systole and diastole. Systole is the process of the left and right ventricles contracting and blood releasing into the aorta from the left ventricle, as well as into the pulmonary trunk from the right ventricle. The aortic and pulmonary valves open during systole. Diastole is the process of relaxing the heart muscle between contractions when mitral and tricuspid valves are open. Three full heart cycles have been simulated to obtain a steady state blood flow.

The motion of the heart is regulated by the physics of electrical and structural processes, as well as by the flow of fluid (blood). Two stages were used to simulate the work of the heart in the finite element code: electrical and mechanical analysis.

Firstly, the electrical analysis has been performed to obtain electrical potentials. They were used as a source of excitation for subsequent mechanical analysis. During the diastole, an electric potential pulse is applied to a specific set of nodes for 200 ms, with an electric potential from -80 mV to 20 mV (Figure 2).
The mechanical analysis contains a multi-step calculation (Table 1). The first step - preloading - a linear pressure increase in the chamber, with which an approximate state of the heart is achieved. The next two steps - a stroke - an impulse of electric potential is applied to the heart, first expansion and then compression of the ventricles takes place, and then - cardio relaxation and the phase of ventricles filling. These two steps last 1 second and complete the heart cycle. They repeat for several times, forming several cycles.

**Table 1.** A multi-step calculation of the mechanical analysis.

| Number | Name of the step | Step duration, sec | Description |
|--------|------------------|--------------------|-------------|
| 1      | Pre-load         | 0.3                | Achieving an approximate pre-stressed state of the heart by 70% diastole using a linear pressure increase in the chambers |
| 2      | Beat             | 0.5                | The phase of the cardiac cycle during which an impulse of electric potential is applied, expansion and compression of the ventricles of the heart occur |
| 3      | Recovery         | 0.5                | Cardio relaxation and ventricular filling phase |

The first heart model was without valves (Figure 3).
Figure 3. The problem statement for a model without valves: general view of the model and boundary conditions

The CFD surface – the flowing part of the heart – is used for blood flow simulation. It covers the inner cavity of the whole heart, including part of the proximal vascular system. Fluid Structure Interaction (FSI) technology is used for the correct motion of the valves during the mechanical analysis phase. FSI calculation is possible due to the bundle FlowVision CFD - SIMULIA Abaqus. In SIMULIA Abaqus, the deformation of the heart muscle and valves is simulated, and the movements of the FE-nodes are transmitted to FlowVision. That leads to the blood flow occurrence and a pressure changing. Hemodynamics is fully simulated in FlowVision and forces are transmitted through the CFD surface to the FE mesh. In 2016, mechanical valves, represented by the plates, that can move under the fluid flow, were added to the model. The model included all heart valves: pulmonary, aortic, tricuspid and mitral (Figure 4).

Figure 4. Location of mechanical valves
The first results were obtained for a model with mechanical valves (Figure 5) in 2017. Later, the model was modified - tissue valves were used instead of mechanical valves, the properties of which were close to natural. Figure 5 shows the blood flow lines in the heart and a heart deformation.

Figure 5. Results for a mechanical valve model: pressure distribution in the chambers

Figure 6. Results for a heart model with tissue valves: blood flow lines during diastole on the left, volumetric velocities in the heart on the right

4. Conclusion.
The results for the complex task of blood flow in a living human heart model are presented. Figures 5 - 6 show a deformation of the heart corresponding to systole and diastole. Blood flow lines show that the movement of blood is characterized by local turbulence, so the layer mixing and blood turbulization in the ventricles can be observed.

In the future, such models will become the basis for surgeons in selecting the optimal treatment for patients with heart diseases - all parameters can be changed and configured for a specific person,
including the addition of blood-circulation assisted devices and artificial valves. Based on the simulation results, articles [3–6] were published. Now work on the project is ongoing.

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