DASSAULT SYSTEMES

SIMULIA

THE LIVING HEART PROJECT: A ROBUST AND INTEGRATIVE SIMULATOR FOR HUMAN HEART FUNCTION

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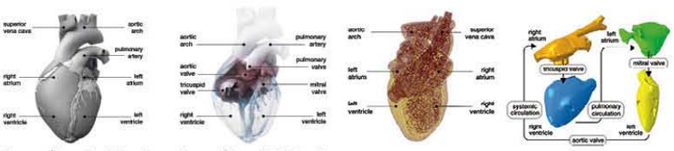
BACKGROUND AND OBJECTIVES

Today, cardiovascular disease (CVD) is the leading cause of death worldwide with CVD-related deaths expected to reach 23 million each year by 2030. In response, there has been a surge of activity by medical researchers, device manufacturers, clinicians, and regulators to address the issue. Yet progress in applying our understanding of human heart function to the design of effective treatments and to accelerate the approval process for new treatments has lagged other industries. A leading factor limiting this progress is the lack of reliable realistic simulation models of the human heart and its environs. To address this limitation, SIMULIA has established a cross-functional community of experts and launched the Living Heart Project to systematically develop increasingly realistic models of the human heart. Here, we present progress on this effort to date.

ELECTROMECHANICAL SIMULATION OF A LIVING HEART

The solid model used for the heart is based on the Zygote 3D Heart Model, and includes well-defined anatomic details of functionally relevant features such as the aortic arch, pulmonary artery, superior vena cava, and the four heart chambers (left and right atria and ventricles). Electrical and mechanical material behaviors are specified for the whole heart and electromechanical coupling is defined. Surface-based fluid cavities are used to represent the chambers, which are then connected through Windkessel-like channels representing internal valves and systemic circulation. Blood flow between chambers is driven by pressure differentials which are in turn based on structural deformation. The heart is thus modelled as an electroactive, deformable entity with internal fluid dynamics. Extensive modelling details of this electro-fluid-structure problem can be found in Baillargeon et al (2014).



Courtesy of Zygote Media Group, Inc. Courtesy of Zygote Media Group, Inc.

Figure 1: External features of anatomical model of human heart (far left) and internal details (center left) Solid model used in this work (center right) and fluid model for blood circulation (far right)

The FE model is discretized with 208,561 linear tetrahedral elements. To account for the anisotropy in cardiac muscle fiber, discrete fiber and sheet orientations are specified on each element in the model.

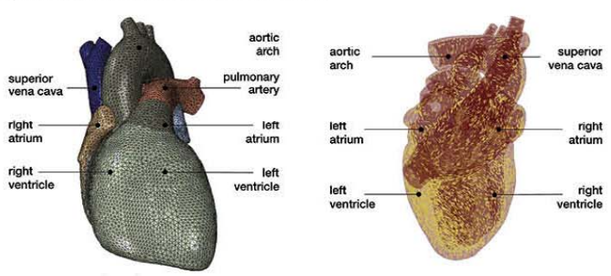


Figure 2: Model discretization (left) and fiber orientation (right)

The analysis uses a sequentially coupled approach, where an electrical analysis is conducted first and the results used to drive the mechanical analysis. In the electrical analysis, the sinoatrial region is excited via a pulse to a depolarization potential of +20 mV and back to the rest potential of -80 mV. This excursion represents a single beat cycle and spans 600 ms. The resulting electric potential distribution across the entire heart is then applied to the mechanical analysis, in which chamber deformation and fluid flow are simulated for the beat cycle. Both the electrical and mechanical analyses are run on 16 cpus and total analysis time is about 94 minutes.

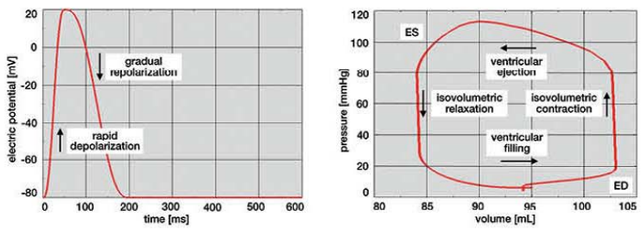


Figure 3: Evolution of electric potential (left) and pressure-volume loop (right)

RESULTS AND DISCUSSION

The electrical excitation spreads rapidly from the sinoatrial node, traversing across the atria, septum, and finally the ventricles. After a short period of complete depolarization, the heart is gradually repolarized in the reverse direction and returns to its unexcited baseline state. The mechanical deformation follows the electrical signal. However, even when the electrical potential is homogeneous across the heart at full excitation, the mechanical deformation is not, thereby highlighting the importance of spatially varying fiber orientation. The fiber contraction and overall cardiac deformation agree well with previous results and clinical observations. We also analyse blood flow dynamics over the cardiac cycle as shown in the pressure-volume loop in Fig. 3. The first phase, ventricular filling, begins with the opening of the mitral valve and continues towards diastole. The second phase, isovolumetric contraction is characterized by a steep increase in pressure. Next, we observe ventricular ejection, during which ventricular volume decreases while pressure remains high. The final phase, isovolumetric relaxation begins with the closing of the aortic valve followed by a steep pressure drop. A new cycle then starts with the reopening of the mitral valve and ventricular filling. The overall pressure-volume loop lies within the clinically expected range.

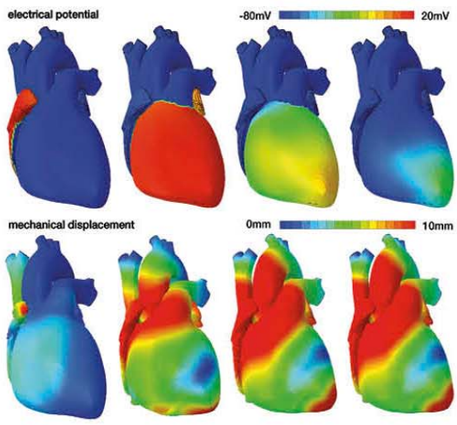


Figure 4: Evolution of electric potential and mechanical displacement

Until recently, whole heart simulations were virtually impossible due to lack of sufficient image resolution and computational power. Recent advances in non-invasive imaging and numerical simulation now allow us to create full 3D models of the entire heart and explore the interplay between electrical and mechanical fields under healthy, diseased, and treatment conditions. In this proof-of-concept study, we have demonstrated the feasibility of modelling the whole heart in a single unified multiphysics environment.

REFERENCES

1. Baillargeon, B., Rebelo, N., Fox, D., Taylor, R., Kuhl, E., "The Living Heart Project: A Robust and Integrative Simulator for Human Heart Function", European Journal of Mechanics A/Solids (2014), (DOI: 10.1002/j.euromechsol.2014.04.001)

2. Zygote Media Group, Inc. 2013 The Zygote Solid 3D Heart Model http://www.3dscience.com/3D_Models/Human_Anatomy/Solid_Models/solid-3d-heart-model