Technische Universität München

IAS TUM Institute for Advanced Study

Advanced Cardiac Mechanics Emulator
Simulating the beating human heart

Project partners

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Heart model construction, material behavior and parallel implementation of fluid-structure interaction (FSI)

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Electro-physiological behavior

Motivation

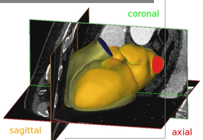
- We develop a four chamber computational multiphysics model of the heart to simulate the electro-physiology-fluid-structure interaction of the human cardiac cycle for both healthy and diseased individuals.
- The heart is mainly composed of muscles, a physiological meaningful fiber organization and material law for contraction is required.
- The preceding excitation is modeled correctly in order to obtain a correct contraction sequence.
- Finally the entire multiphysics model is put together to drive the fluid-structure interaction cardiac emulator.
- The emulator will be useful in studying healthy physiology as well pathological phenomena.

The following aspects of the model are already achieved or will be accomplished in the near future:
- High accuracy mesh of a patient-specific cardiac anatomy including ~850.000 elements
- Implementation of a patient-specific fiber organization
- Derivation of a material law for passive and active behavior of the cardiac tissue
- Modeling the interaction of excitation and contraction of muscle fibers
- Calculus of the fluid behavior utilizing Optimal-transport-meshfree method (OTM) and development of a mixed finite element / OTM fluid-structure interaction procedure

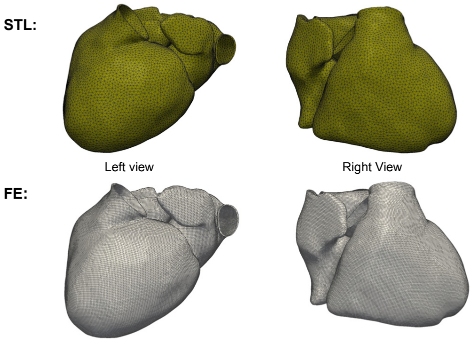
Final goal: Whole heart simulation of the cardiac cycle including the correct valve-movement

Geometry

- Manual segmentation of blood and myocardial tissue from high-resolution CT-images* via low level image processing techniques
- Calculus of Stereolitographies (STL) from the segmented masks and subsequent creation of the FE-grid via commercial programs



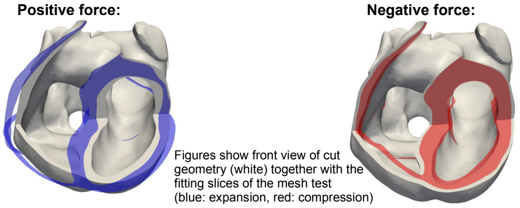
*CT- Imaging courtesy of Centre for Radiology, Klinikum rechts der Isar



Testing mesh robustness with respect to large deformation

Positive force:

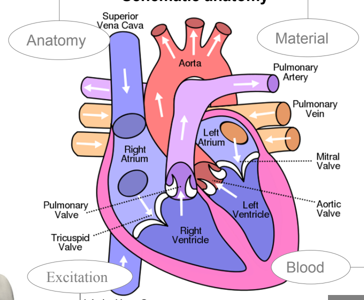
Negative force:



Figures show front view of cut geometry (white) together with the fitting slices of the mesh test (blue: expansion, red: compression)

The heart

Schematic anatomy



Picture from http://commons.wikimedia.org/wiki/File:Diagram_of_the_human_heart_(cropped).svg

Fiber model

- Segmentation of a fiber template from freely available diffusion-tensor MRI data [1]
- Registration of the template onto our geometry
- Reorientation of the corresponding fiber values according to a local variant of the PPD-algorithm of [2]

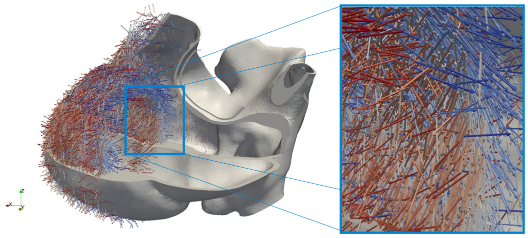


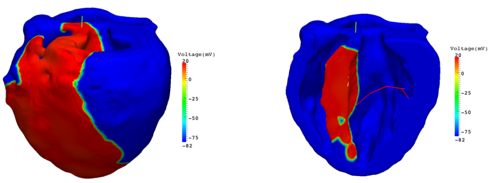
Figure shows a cut geometry including the ventricular fiber orientation. Vectors are colored according to their x-values. Left: Detail showing fiber organization of the ventricular septum

[1] http://gforge.icm.jhu.edu/gf/project/dtmri_data_sets

[2] Alexander, D.C. , Pierpaoli, C. , Basser, P.J. and Gee, J.C. (2001), Spatial transformation of diffusion tensor magnetic resonance images, IEEE Transaction on Medical Imaging, 20: 1131-1139

Electrophysiology

For the correct description of the cardiac contraction the following aspects have to be considered:
- Modeling the conduction system
- Calculus of excitation wave propagation
- Incorporation of anisotropic conductivity values for fiber and cross-fiber direction
- Correspondence between electrical stimulus and mechanical response



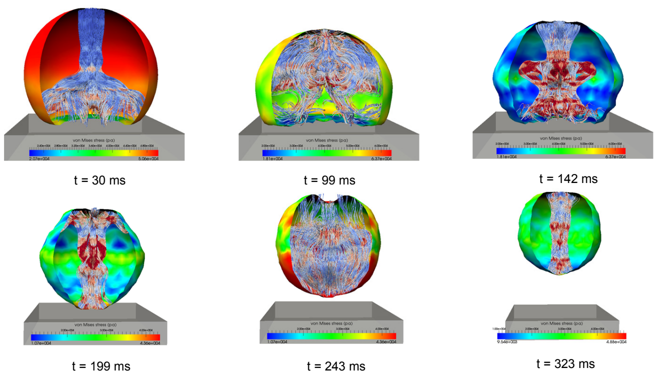
Snapshots of the excitation wave in a mammalian ventricular geometry where color indicates voltage amplitude.

Right: Red beams represent the Purkinje fiber network which is responsible for electrical conduction.

OTM

The optimal transportation meshfree method was first presented in [3] and combines:
- Generalization of the optimal transportation problem proposed by Benamou & Brenier [4] to arbitrary geometries
- Meshfree sampling with max-ent interpolation

The theory is derived for both elastic solids and Euler fluids and can be extended to viscous and inelastic material behavior. A fluid-structure interaction test case is visualized below, where a gas-filled ballon bounces from a rigid wall:



[3] Li, B., Habbal, F. and Ortiz, M. (2010), Optimal transportation meshfree approximation schemes for fluid and plastic flows. International Journal for Numerical Methods in Engineering, 83: 1541–1579. doi: 10.1002/nme.2869

[4] Benamou JD, Brenier Y. A numerical method for the optimal time-continuous mass transport and related problems. Monge-Ampere Equation: Applications to Geometry and Optimization. Contemporary Mathematics, vol. 226. American Mathematical Society: Providence, Rhode Island, U.S.A., 1999; 1–11.