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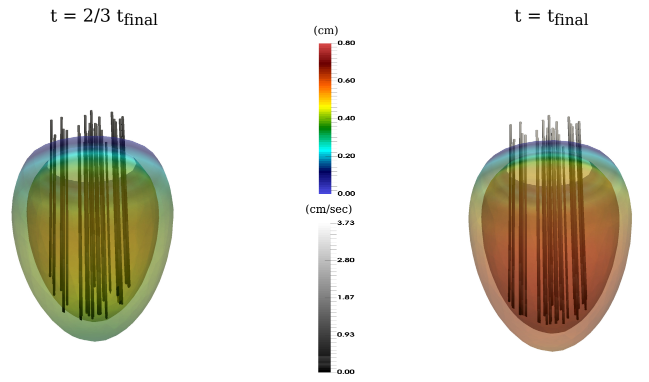
Fluid-Structure Interaction Simulations of the Heart

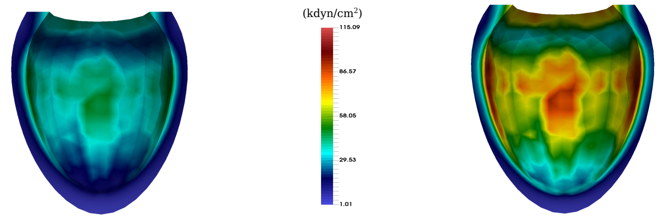
D.Pasadakis[a], M.Nestola[a], F.Maffessanti[a], B.Becsek[b], D.Obrist[b], R.Krause[a]

[a]Università della Svizzera italiana, Institute of Computational Science
[b]University of Bern, ARTORG Center for Biomedical Engineering Research

Diastole of an Idealized Human Left Ventricle



Displacement and fluid streamlines, t$_{\text{final}}$ = 0.5 sec



Von Mises stress, t$_{\text{final}}$ = 0.5 sec

Mesh Generation Techniques

Generation of finite-element surface and volumetric meshes from 3D binary medical images obtained by Computed Tomography (CT), using the mesh generation and processing toolbox iso2mesh.

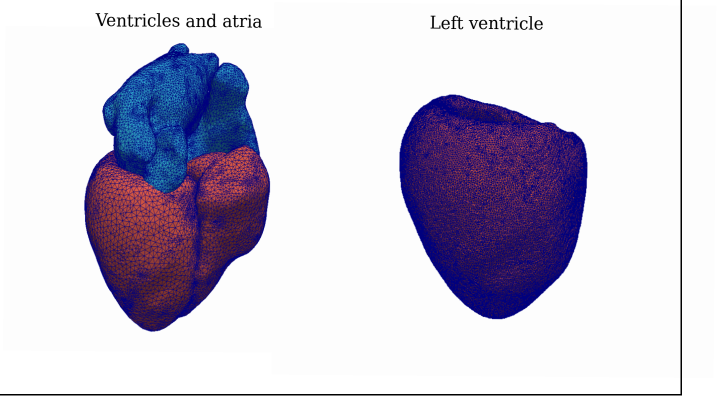
Workflow

i Creation of surface meshes by means of a Constrained Delauney triangulation approach, using the software library CGAL.

ii Surface mesh repairing. Removal of isolated vertices, duplicated triangles and non-manifold edges achieved via the JMeshLib framework.

iii Recreation of the wall thickness for: Left atrium: 2.7 mm, Right atrium: 3.0 mm, Right ventricle: 4.0 mm,

iv Volumetric mesh generation with adaptive resolution. Effective control of the surface and element volume density.


Ventricles and atria

Left ventricle

A Fictitious Domain Method

The Lagrangian formulation is adopted for the mathematical description of the deformable immersed structure and the Eulerian approach is considered for the Incompressible Navier-Stokes equations. The weak form of the Fluid Structure Interaction problem reads:

Find $(\boldsymbol{u}_f, p_f; \boldsymbol{\eta}_s, p_s; \lambda) \subset (\boldsymbol{V}_f \times Q_f \times \boldsymbol{V}_s \times Q_s \times L)$, such that $\forall\, (\boldsymbol{v}_f, q_f; \boldsymbol{v}_s, q_s; \mu) \subset (\boldsymbol{V}_f \times Q_f \times \boldsymbol{V}_s \times Q_s \times L)$:

Equilibria of forces

$$\int_{\Omega_f} \rho_f \frac{\partial \boldsymbol{u}_f}{\partial t} \cdot \boldsymbol{v}_f \, dV + \int_{\Omega_f} \rho_f \left[(\boldsymbol{u}_f \cdot \nabla)\boldsymbol{u}_f\right] \cdot \boldsymbol{v}_f \, dV + \int_{\Omega_f} \sigma(\boldsymbol{u}_f, p_f) \cdot \boldsymbol{v}_f \, dV + \int_{\Gamma} \lambda \cdot \boldsymbol{v}_f \, dS = 0$$

$$\int_{\hat{\Omega}_s} \hat{\rho}_s \frac{\partial^2 \hat{\boldsymbol{\eta}}_s}{\partial t^2} \cdot \hat{\boldsymbol{v}}_s \, dV + \int_{\hat{\Omega}_s} \hat{\boldsymbol{P}}(\hat{\boldsymbol{F}}) \colon \nabla \hat{\boldsymbol{v}}_s \, dV - \int_{\hat{\Omega}_s} \hat{p}_s \hat{J} \hat{\boldsymbol{F}}^{-T} \colon \nabla \hat{\boldsymbol{v}}_s \, dV + \int_{\Gamma} \lambda \cdot \hat{\boldsymbol{v}}_s \, dS = 0$$

Constraints

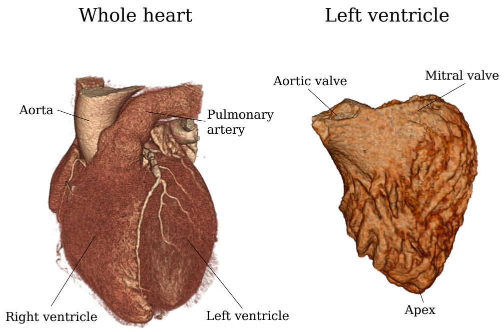
$$\int_{\Omega_f} q_f \nabla \cdot \boldsymbol{u}_f \, dV = 0, \qquad \int_{\Gamma} \mu \cdot \left(\frac{\partial \boldsymbol{\eta}_s}{\partial t} - \boldsymbol{u}_f \right) dS = 0, \qquad \int_{\Omega_s} \left(\hat{J} - 1 \right) q_s \, dV = 0$$

The cardiac tissue was assumed to be incompressible. The transversely isotropic constitutive law by Guccione *et al.* (1995), which is widely used in cardiac modeling is applied. Its strain energy function is given by:

$$W = \frac{C}{2}\left(e^Q - 1\right),$$
$$Q = b_f E_{11}^2 + b_t \left(E_{22}^2 + E_{33}^2 + E_{23}^2 + E_{32}^2\right) + b_{f_s} \left(E_{12}^2 + E_{21}^2 + E_{13}^2 + E_{31}^2\right)$$

Cardiac Segmentation

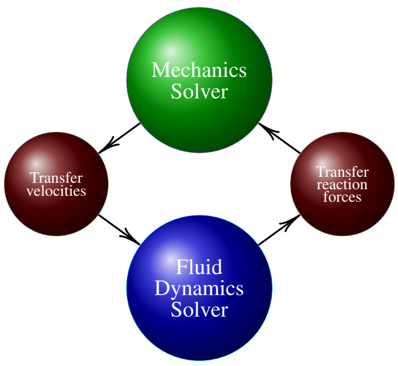
- CT obtained in a 50 year old woman with no history of myocardial infarction or coronary artery disease, referred for chest pain.
- CT scan performed at 83% of the cardiac cycle. In-plane resolution: 0.33 × 0.33 × 0.9 mm. Image size: 512 × 512 × 279 voxels. Field of view: 169 × 169 × 251 mm
- Segmentation performed using ImageJ. Left cavities identified based on the presence of contrast agent. Right cavities obtained by subtraction of the left cavities from the whole heart.


Whole heart

Left ventricle

Solution Approach and Numerical Results on CSCS Piz Daint Cluster

Coupling Strategy


Mechanics Solver

Transfer velocities

Transfer reaction forces

Fluid Dynamics Solver

Specification of variables

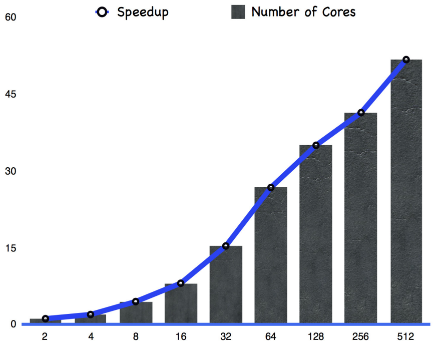
velocities	$\boldsymbol{u}_f, \boldsymbol{\eta}_s$	pressures	p_f, p_s
densities	ρ_f, ρ_s	C	12 kPa
Lagrange multipliers	λ, μ	b_f	2.0
deformation gradient	$\boldsymbol{F}$	b_t	2.0
Green-Lagrange strain tensor	$\boldsymbol{E}$	b_{f_s}	2.0
1st Piola-Kirchhoff	$\boldsymbol{P}$	Surface, Volume	S, V

The relation between the left intraventricular pressure and volume was studied for an inflation period of $\Delta t = 0.5$ sec, yielding results in good agreement with experimental measurements of the diastolic heart phase (Fritz et al. 2013).

t (sec)	Pressure (kdynes/cm^2)	Volume difference (mL)
0.1	9.332	16.109
0.2	9.362	16.587
0.3	12.886	21.190
0.4	15.442	28.374
0.5	15.998	30.812

Scalability

Simulated on CSCS Piz Daint,
a hybrid Cray XC50/XC40 system.



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iii] Q. Fang, D. Boas. *Tetrahedral mesh generation from volumetric binary and gray-scale images*, Proceedings of IEEE International Symposium on Biomedical Imaging, 2009