

Fluid-Structure interaction of a human left atrium



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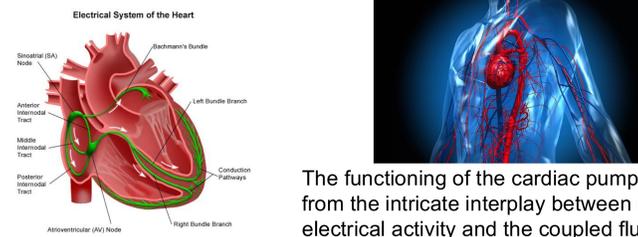
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Abstract

Cardiac models often end at the ECG. We go further—**electrical + mechanical + fluid**—to model the left atrium as an **electro-mechano-fluid pump**. We couple a nonlinear atrial wall to an incompressible flow solver and study how activation drives deformation and flow. Beyond improving physiological insight, this framework is a **stepping stone toward clinical digital twins** that connect directly to patient data for scenario testing, therapy planning, and outcome prediction.

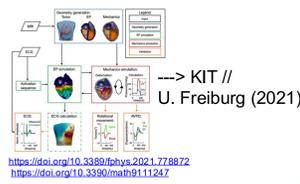
Cardiac blood pumping system



The functioning of the cardiac pump arises from the intricate interplay between its electrical activity and the coupled fluid and solid mechanics.

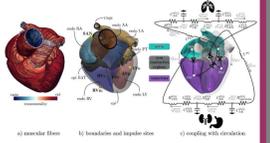
The heart pumps about 5L of blood per minute under resting conditions.

Few full "digital twins"

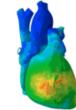


As of today there are only few numerical models that incorporate the three aspects of the cardiac function.

Polytech, Milano // EPFL (2023-2024)
A. Quarteroni



Towards personalized medicine...



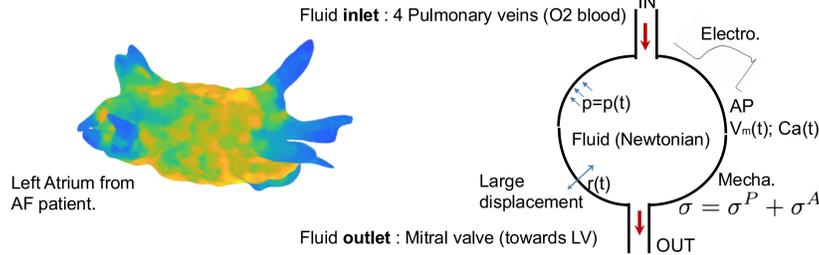
The Living Heart Project

Dassault System Simulia // INRIA FDA

<-BSC, Alya, (Barcelona) 2018-2024
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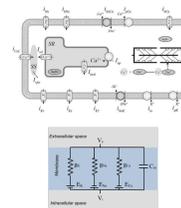
From realistic to simplified geometry



Why? Atrial Fibrillation is the most frequent cardiac disease and is generally located in the left atrium.

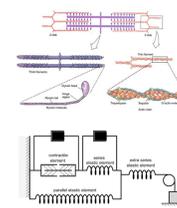
Model ingredients

The electrical part



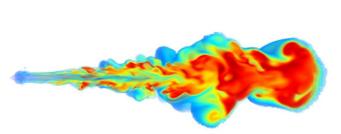
Here Gaussian pulse at $v=0.5$ m/s

The solid part



Here St Venant-Kirchhoff material

The fluid part

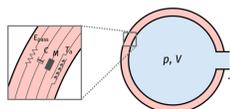


MIGFLOW was initially conceived to deal with the mixture of granular medium + fluid interactions. Here we start using the "pure" fluid mechanical part of the software. <https://www.migflow.be/>
Blood as a Newtonian fluid with $\mu=0.004$ (SI).

Fluid-Structure Interaction

The fluid equations (NS) and the membrane dynamics must agree at the interface.

- Move at the same speed (kinematic condition)
- Share the same forces (dynamic condition)

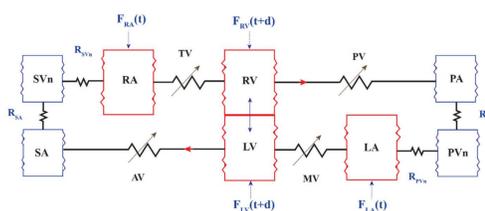


$$\dot{\mathbf{x}}_s^{\mathcal{I}} = \mathbf{v}_f^{\mathcal{I}}$$

$$\mathbf{t}_s^{\mathcal{I}} = \mathbf{t}_f^{\mathcal{I}}$$

We use an **inner FSI fixed-point loop**.
Loop on **fluid** → **forces** → **solid** → **new interface**
→ **update fluid mesh**, until fluid/solid are consistent.

Connection with 0D circulation model



Study of the cardiovascular system subject to significant heart rhythm changes.

- Novelties:
- time-dependent muscle force with constant elasticity
 - new model of the atria
 - inter-ventricular interaction
 - hysteresis in the aortic valve
 - parameters fitted from 14 sheep

$$\mathbf{y}(t) = [V_{la}, V_{sa}, V_{ra}, V_{pa}, V_{pv}, P_{la}, P_{ra}, P_{lv}, P_{rv}]$$

9 variables to integrate (ODEs)

left atrium pressure (5 parameters)

if $dV_{la} < 0$:

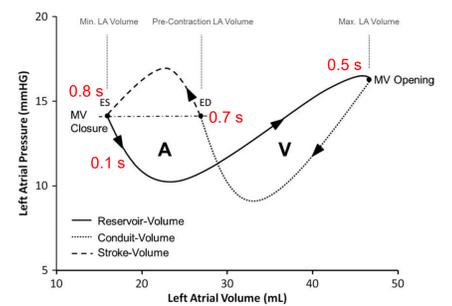
$$dP_{la} = E_{la} dV_{la} + dG_{la} + \alpha_{l1} (V_{la} - V_{unla})$$

else:

$$dP_{la} = \beta_{l1} E_{la} dV_{la} + \gamma_{l1} dG_{la} + \omega_{l1} (V_{la} - V_{unla})$$

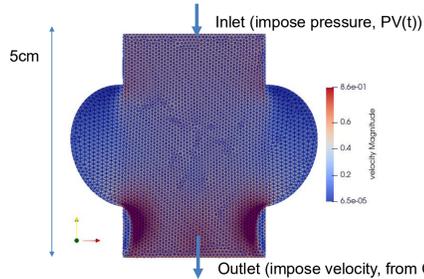
S. Noreen et al., "Mathematical modelling of atrial and ventricular pressure–volume dynamics and their change with heart rate", Math. Bioscience 344 (2022).
doi.org/10.1016/j.mbs.2021.108766

Validation through P-V cycle



- 1. Mitral Valve (MV) Closure (~0.1 sec)**
• Occurs at the beginning of ventricular systole.
- 2. Atrial Relaxation & Reservoir Phase (~0.1–0.5 sec)**
• The left atrium passively fills with blood while the mitral valve is closed.
- 3. Conduit Phase (Early Diastole: ~0.5–0.7 sec)**
• The left atrium acts as a **passive conduit**, transferring blood into the left ventricle (LV).
- 4. Atrial Systole (Booster Pump Function, ~0.7–0.8 sec)**
• The left atrium actively contracts to push the remaining blood into the LV.

Geometry 2D and mesh ALE



The **boundary conditions** at the entrance and exit of the atrium are given by the auxiliary simulation of a general **0D circulation model**.

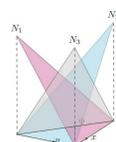
FEM Solvers

Strong form : (Monodomain) $\nabla \cdot [\sigma \nabla V] = \chi (C_m \frac{\partial V}{\partial t} + \sum_i I_{ion}^{(i)} + I_e)$

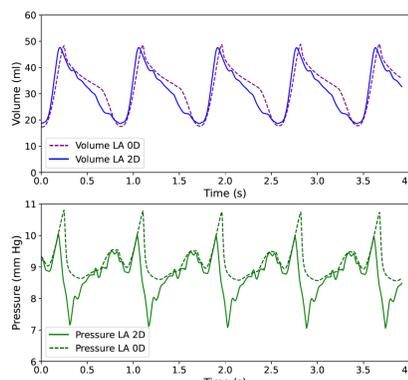
Weak form : $\int_A (\nabla u) \cdot [D \nabla V] dA + \int_A u \dot{V} dA - \int_A u Q dA = 0$

$$u_e(\vec{x}) = V_1 N_1 + V_2 N_2 + V_3 N_3$$

On each element we interpolate the field with the shape functions N_1, N_2, N_3 , and the unknown nodal values. (Linear elements, P1).



Results



The quantitative comparison of the time trace of the pressure and volume are satisfactory, and it is a good starting point in the modelling of the three important aspects of the cardiac activity.

Some additional results can be found here:



Conclusions and Perspectives

- We have built a simple 2D model of the heart cavity (LA) that includes mechanics, fluid and active tension (electricity).
- We use a 0D model to connect the 2D model to general circulation.
- We got a reasonable quantitative agreement btw the 2D and 0D model.
- FSI & BCs were the trickier parts to implement in the 2D model.
- More realistic modeling (all aspects) will be proposed in the future.
- Connections with experiments and medical issues are highly desirable.

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