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PhD position on
Modeling and simulation of the heart perfusion
Modélisation et simulation de la perfusion du coeur

Subject

The heart contraction is a complex multiphysics problem that has been studied for many years. It initiates with the electrical depolarization of the tissue which is the source of the heart contraction. This phenomenon is then coupled to the solid mechanics deformation of the heart which allows to pump the blood in the whole circulation. Here we see the 3 classical ingredients studied today which are, electrophysiology (reaction diffusion), solid mechanics (non-linear elasticity) and fluid-structure interaction in the cardiac cavity and circulation system. However up to now, a phenomenon has been much less studied in the community which is the fact that the heart tissue is itself perfused by the blood that the heart is pumping. This phenomenon is a typical poromechanics problem. Poromechanics has been studied for ages in geophysics but the modeling of promechanics phenomenon for the heart requires to deal with large fluid acceleration phenomena and large displacements, two conditions that differ from classical modeling assumptions in geophysics. In this respect, D. Chapelle and P. Moireau have proposed original poromechanics models which are compatible with these assumptions [2]. The resulting model appear to correspond to a fluid-structure interaction problem between a solid and a incompressible fluid driven by Navier-Stokes equation. Both models are set in the same domain and the coupling is operated in the interior and on the domain boundary. To follow this work, the PhD of Bruno Burtschell from 2013 to 2016 was the opportunity to propose and analyze numerical time and space discretizations for this original model [1] and to implement them in the team finite element code. te We have now the opportunity to study how this model can be used in the context of cardiac perfusion. In this respect several modeling and numerical bricks need to be developed. First, this poromechanics model should be coupled to a blood source, namely the fluid ejected by the heart through the coronary tree. This means that we have to develop adequate models of the coronary tree up to a certain level of bifurcation. As a full description will bring prohibitive computational cost, these models should be reduced by asymptotic techniques for instance by considering 1D circulation models. Moreover, the tree of arteries (and corresponding vessels) must also be deformed to follow the heart contraction. And finally, it should be coupled by transmission conditions to model how the blood is distributed to the tissue.

Then this model can be enriched to model how oxygen is transported to the heart tissue, and therefore to take into account the oxygen demand and supply of the heart, a key modeling ingredient in numerous pathologies (vascular stenosis and corresponding infarct) which is still out of reach of the current modeling effort in the world.

Note finally that this overall modeling process is not specific to the heart as we encounter the same issues when modeling the lung with the arterial perfusion but also the airways distribution. Identically in electrophysiology, the Purkinje network is also a network that "perfused" electrically the tissue.

Organization

This PhD will be hosted in MΞDISIM, an Inria project-team, joint with Ecole Polytechnique, part of LMS (Laboratoire de Mécanique des Solides, UMR-7649 Ecole Polytechnique - Mines ParisTech - CNRS/INSIS), and affiliated with the Inria Saclay Ile-de-France Research Center on the Ecole Polytechnique campus. This team aims at proposing novel mathematical and numerical methods and tools in the realm of the biomechanical modeling of tissues and organs, with a non-exclusive focus on the cardiovascular system. The PhD Thesis will be co-supervised by **Philippe Moireau** and **Dominique Chapelle**, Senior researchers in the team. Sébastien Imperiale, junior researcher in the team, specialist on transmission conditions and multiscale modeling will also interact with the PhD student.

Moreover, this PhD Thesis will be carried out as a close collaboration between MΞDISIM and REO from Inria Paris with Celine Grandmont who is a specialist of fluid-structure interaction and coupling phenomena from circulation trees to continuous perfused model as she works on this topic for the modeling of the lungs.

Candidate profile

For this subject, we are looking for a candidate with a strong level in continuum mechanics and an interest for multidisciplinary modeling approaches. Moreover, we expect the candidate to have a solid background in numerical methods and their implementation so that he/she can face the simulations of such a complex multiphysics problem.

References

[1] Bruno Burtschell. *Mechanical modeling and numerical methods for poromechanics : Application to myocardium perfusion.* Theses, Université Paris-Saclay, September 2016.

[2] D. Chapelle and P. Moireau. General coupling of porous flows and hyperelastic formulations-From thermodynamics principles to energy balance and compatible time schemes. *European Journal of Mechanics - B/Fluids*, 46:82–96, 2014.