Fully coupled fluid-electro-mechanical cardiovascular simulations

Considered as a physical system, the heart is the most sophisticated pump, the outcome of a million years of evolution, which is tightly coupled. Verification of fluid-electro-mechanical models of the heart require a good amount of reliable, high resolution, thorough in-vivo measurements. However, it is important to exactly quantify the amount of error between the various approaches that can be used to simulate a heartbeat by comparing them to ground truth data. The more detailed the model is, the more computing power it requires, therefore in a unique way and efficiently exploiting supercomputers and parallel programming, the three problems are simulated in a coupled fashion in BSC's in-house multi-physics and multi-scale code, **Alya**. At the organ-level, the cardiac computational model requires the solution of the three tightly coupled fields: fluid mechanics (blood), excitable media (electrophysiology or activation potential propagation) and mechanical action (tissue, mainly cardiac muscle, tendons, wall arteries, valves, etc.). Hearts beats are the result of a sequence of electrochemical excitation waves that are initiated from the Sino atrial node. The electrical impulses induce intracellular calcium cycling, which in turn causes heart muscle to contract. This process, known as excitation-contraction coupling (ECC), is essential to understanding of the heart. On the other hand, mechanical changes that response to neural and hormonal influences also impact on the electrical properties. In addition to these to simulate the arterial blood flow the concepts of fluid mechanics are required. Viscosity can have some marked effects on electromechanical interactions, especially when the system involves the flow of a fluid near a solid boundary. In the analysis of the arterial blood flow, blood has been considered as an incompressible fluid. The model for viscous fluids is restricted to Newtonian fluids whose stress-strain rate relations are linear. The cardiac geometries are produced from several sources of medical data and images, to include as many features as possible, including anatomical data such as muscular fibre structures. In order to set up the simulation scenario, meshes are generated using an ad-hoc meshing tool, BSC's in-house IRIS Mesh. The mechanical deformation part is solved at the same resolution of the electrophysiology mesh, thus avoiding any type of errors induced by interpolation between different meshes used for different physical solvers. In each step, the electrical problem is solved first and then the results from the electrical solution are submitted into the mechanical problem and into the fluid flow problem to simulate the blood flow, whose solution is then used to solve the electrical problem in the next step. Electrophysiology is a modelled by a time-dependent diffusion equation with a non-linear term involving the solution of up to 70 ODEs at each time step. Through a complex electromechanical model, it is coupled with mechanical deformation, which is modelled as a transient non-linear finite strain problem. In turn, solid mechanics is coupled to an incompressible flow motion, solved on a deforming domain either through ALE or IBM approaches. The model is simulated with boundary conditions representing blood pressure and volume constraints, a left ventricular pressure waveform was provided for this study. The pressure was applied normal to the endocardial walls throughout the cardiac cycle. The basal nodes were fixed (base of the ventricles, near the atria, boundary constraints are set simply by attaching base vertices to fixed springs) to prevent them from moving in the longitudinal direction, but were allowed to move freely in the crossectional direction. The model has been numerically solved using an implicit, finite element-based approach. Numerical simulations have been conducted using parallel simulation in tissues of different geometries. The cardiac mechanics is described by the updated Lagrangian approach, which views the problem from the current configuration and takes derivatives and integrals with respect to the spatial coordinates. In perspective of mesh description, the updated Lagrangian description is characterized by making the material points remain coincident with mesh points. The developed model and computer codes have been validated at each step using simple test examples to ensure accuracy in numerical computations. Multiple simulations have been conducted using various meshes and parameters to ensure numerical robustness of the developed model.