MATHEMATICAL AND NUMERICAL MODELS FOR THE FLUID DYNAMICS OF THE HUMAN HEART

ALBERTO ZINGARO

In silico simulations of the heart and blood circulation represent a valuable tool to analyze the cardiac function and to enhance the understanding of cardiovascular diseases. In this thesis, we introduce a Computational Fluid Dynamics (CFD) model for the numerical simulation of the heart hemodynamics in both physiological and pathological conditions, by accounting for all the physical processes that influence cardiac flows: moving domain and interaction with electromechanics, transitional-turbulent flows, cardiac valves and coupling with the external circulation. We propose a volume-based displacement model for the left atrium in physiological conditions and we simulate the atrial hemodynamics by considering both idealized and patient specific-geometries [1]. A lumped-parameter (0D) closed-loop circulation model serves as input to provide the CFD simulations with flowrates, pressures and atrial displacement. We further extend the computational model to account for atrial fibrillation in patient-specific CFD simulations. We investigate the effects of atrial fibrillation on the left atrium hemodynamics and we quantify an increasing blood stasis, especially in the left atrial appendage, where a dramatic washout reduction is observed [2]. The transitional blood flow regime is simulated by means of the Variational Multiscale - Large Eddy Simulation (VMS-LES) method, acting as both a stabilization and a turbulence model. We investigate the role of the VMS-LES method in transitional hemodynamic flows: if relatively coarse meshes are used, numerical results suggest that the additional stabilization terms introduced by the VMS-LES method allow to better predict transitional effects and cycle-to-cycle blood flow variations than the standard Streamline Upwind Petrov-Galerkin method [1]. We simulate the hemodynamics of the left heart and we integrate the electromechanical activity in the CFD model by employing a 3D ventricular electromechanical model. We propose a novel preprocessing procedure that combines the harmonic extension of the ventricular electromechanical displacement with the motion of the left atrium based on the 0D model. To better match the 3D CFD with the remaining blood circulation, we devise a coupled 3D-0D model made of the 3D CFD model of the left heart and the 0D circulation model: from a numerical point of view, we solve the coupled model by a segregated scheme, and we develop algorithms to solve the integrated system comprising fluid dynamics, displacement, valves and circulation models. Numerical simulations on a healthy left heart show that biomarkers and flow patterns are accurately reproduced when compared with in-vivo data [3]. We then expand our computational model to the hemodynamics of the four heart chambers finally bringing to an integrated multiscale CFD model of the whole human heart. This represents one of the few attempts in the literature to model the whole heart hemodynamics.

References

[1] A. Zingaro, F. Menghini, L. Dede', A. Quarteroni, *Hemodynamics of the heart's left atrium based on a Variational Multiscale-LES numerical method* European Journal of Mechanics-B/Fluids, 89, pp. 380–400, 2021.

[2] M. Corti, A. Zingaro, L. Dede', A. Quarteroni, *Impact of Atrial Fibrillation on Left Atrium Haemodynamics: A Computational Fluid Dynamics Study* arXiv preprint, arXiv:2202.10893, 2022.

[3] A. Zingaro, I. Fumagalli, L. Dede', M. Fedele, P.C. Africa, A. Corno, A. Quarteroni, *A geometric multiscale model for the numerical simulation of blood flow in the human left heart* Discrete and Continuous Dynamical System - S, 2022.

MOX - Laboratory of Modeling and Scientific Computing, Department of Mathematics, Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133, Milano

Email address: `alberto.zingaro@polimi.it`