Towards a digital twin for myocardial ischemia: from coronary hemodynamics to cardiac perfusion

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Abstract:
Introduction – Effective management of patients suffering from coronary artery disease greatly benefits from the combined knowledge of coronary hemodynamics and cardiac perfusion at the tissue level. The use of a digital twin to quantify the relevance of coronary lesions would overcome the limitations of the late-stage clinical exams, such as invasiveness or high radiation exposure. We present a framework to address the most critical issues: personalized boundary conditions, 3D multiscale modelling of hemodynamics, and personalized coronary-myocardium association.
Methods – A fully 3D finite-element model of the entire coronary circulation is employed, featuring Navier-Stokes description of the hemodynamics in the epicardial coronaries coupled with a multicompartment Darcy formulation for the microvasculature. The model includes a special formulation accounting for microvessels compliance and cardiac contraction. Personalized boundary conditions are built as hyperemic pressure waveforms starting from routine patients measurement at rest. The geometric coupling between each epicardial coronary and the corresponding perfusion region is implemented through a novel tool, based on ex-vivo detailed morphometric human coronary data, which accounts for the presence of transversal vessels along the main branches. Simulations are run using the Finite Elements software lifex, developed at MOX (DMAT), in cooperation with LaBS (DCMC), PoliMi.
Results – The model successfully reproduces all the characteristic features of coronary hemodynamics, including phasic flow patterns with high diastolic arterial inflow, mostly diastolic perfusion and high systolic venous outflow. Applied to human patients (CT-reconstructed geometries), the model shows high predictive power with respect to the Fractional Flow Reserve (FFR) index and good accordance with stress CT perfusion maps, although precise localization of perfusion defects is challenging. When validated against detailed coronary data, our tool for coronary-myocardium association shows significantly better performances with respect to the previous strategy, allowing for a more precise evaluation of the functional relevance of coronary lesions.