Fluid–Structure–Electrophysiology Interaction in the left heart: exploring turbulent flow dynamics for data-driven applications

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Measuring the speed and pressure of blood flow, as well as the shape evolution of the human heart, is crucial for the diagnosis and prognosis of cardiovascular diseases. However, probing in-vivo data can be invasive and poses several challenges. Digital twins emerge as a solution, and fluid-structure interaction models provide a numerical tool to simulate the whole heart dynamics with a high degree of realism and accuracy.

Our in-house multi-GPU code[1] is an ideal solution for this task, being able to reproduce the full multi-physics dynamics of the human heart. Indeed, among all the features of our code, there is the capability to simulate the complex electrophysiology of the human heart via the implementation of models for the electrical network of contractile muscular fibers. Additionally, the code implements and simulates realistic valve dynamics, increasing the simulations' realism.

On top of that, within our code, we can import patient-specific data for the heart geometry at some specific times during the heartbeat, and we can use that to inform and nudge our simulations. Such a numerical tool provides highly realistic digital twins, relying on the information measured in patients. To improve the nudging techniques and investigate the model's sensitivity to different patient data, we use our Fluid-Structure-Electrophysiology Interaction simulations as a ground truth. A preliminary study on the complexity of the hemodynamics with a particular focus on the turbulent features is also required. Therefore, we perform space- and time-spectral analysis using several probes distributed in different heart regions (e.g., atrium, ventricle, and aorta). This information is crucial to investigate how the data-driven simulation is recovering, in a statistical sense, the original ground truth.

Our research aims to both advance the understanding of cardiovascular dynamics from a quantitative point of view and to investigate the possibility of using real-time patient-specific data as input for the simulations to provide digital twins that are as realistic as possible.

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[1]Viola at al., *Scientific reports*, **13(1)** (2023).