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Accounting for turbulence in cardiovascular biomechanics

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Computational Fluid Dynamics (CFD) is now a well-established technique to get an insight into haemodynamics in the cardiovascular system. Huge progresses have been made during the last decade in terms of blood dynamics understanding under in vitro and in vivo conditions and the number of published papers in the domain has drastically increased. These fast progresses have been made possible thanks to the experience gained since the 80's in other research fields like aerodynamics where CFD is being used as a key ingredient of any design and/or research efforts. However, cardiovascular blood flows in the heart or the largest arteries share some very specific characteristics that are not always present in other research fields. Notably: they are dominated by unsteadiness because of the pulsatile nature of the heart flux; they are often neither laminar nor turbulent but rather transitional because of the moderate Reynolds number; they take place in 3D complex geometries which are most often time varying.

In the present study, we present a numerical framework appropriate for accounting for the transitional nature of blood flows in large vessels, organs or biomedical devices. The YALES2BIO solver (http://www.math.univ-montp2.fr/~yales2bio/) used in this study is a fully explicit, massively parallel, 3D CFD in-house code dedicated to the resolution of microscopic and macroscopic cardiovascular flows [1]. It relies heavily on the YALES2 solver, widely validated for complex engineering applications [2]. It is based on low-dissipative, fourth-order finite-volume approximations and an explicit fourth-order Runge-Kutta scheme for time integration. Because of the moderate Reynolds number and the expected transitional nature of the flow, Reynolds Averaged Navier-Stokes (RANS) approaches for modelling turbulence (e.g. k-ε model) are not appropriate since they rely on the assumption that turbulence is fully developed and ergodic. Even if adaptations have been proposed in order to handle transition, they essentially require the user to prescribe the transition location in advance. Taking advantage of the low-dissipative nature of YALES2BIO, the Large Eddy Simulation approach is followed in the present study. In this view, only the smallest scales are modelled (scales smaller than the mesh size) while the evolution of the large scales is computed by solving a filtered version of the flow equations. A subgrid-scale model must then be used in order to account for the effect of the unresolved scales on the dynamics of the resolved ones. This is usually done by an eddy-viscosity-based model. Since blood flows are usually strongly confined and piloted by the wall motions, an advanced subgrid scale model able to represent the proper turbulence damping near solid walls is used [3].

Results for an actual human left heart will be presented. The geometry of the heart cavities and associated wall motion are extracted from 4D medical images while the valves of the heart are accounted for thanks to low order geometrical models. A mixed Arbitrary Lagrangian-Eulerian / Immersed Boundary framework is used to handle the geometry evolutions over the cardiac cycle, as observed from the 4D medical images [4-6]. On top of retrieving the main fluid flow phenomena commonly observed in the left heart, the methodology allows studying the heart flow dynamics, including the turbulence characteristics and cycle-to-cycle variations. The latter turn out to be quite important, notably in late diastole, as exemplified in Fig. 1. Implications in terms residence time and thrombotic risk assessment will be discussed.

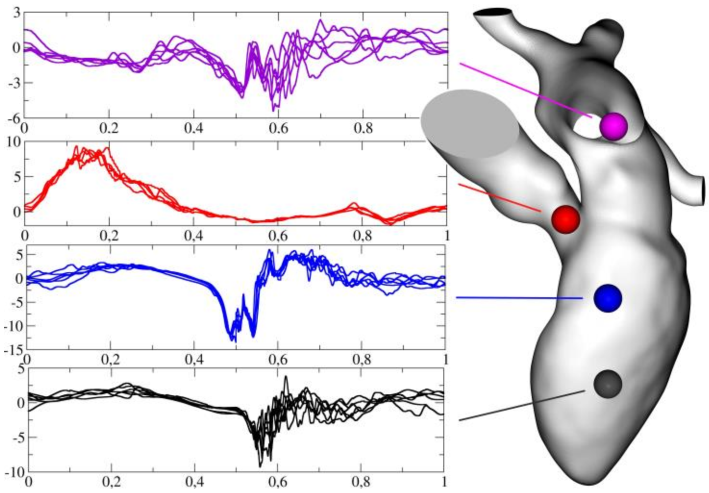

Figure 1:

Temporal evolutions of the scaled vertical velocity at four different locations within the left heart. Six cycles are reported to illustrate the cycle-to-cycle variations.

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