BLOOD FLOW MODELING IN A BEATING HUMAN HEART WITH APPLICATIONS IN MEDICAL DEVICE DESIGN AND PATIENT CARE

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SUMMARY

Cardiovascular disease remains the leading cause of death in developed countries. After the introduction of stents in the 1980s mortality rates declined, yet those gains have since plateaued, signalling the need for a new generation of treatments that are safer and more effective. To achieve this goal, it is important to understand both the physical device-body interaction as well as the physiological changes induced by the device. Computational tools are uniquely capable of accounting for cardiac/vascular tissue mechanics, blood flow, and the interaction between them, yet are currently under-utilized due to their complexity. The SIMULIA Living Heart Model (LHM), an anatomically and physiologically realistic 3D model of a human heart, provides a platform to better understand the human heart in healthy and diseased states as well as to improve the efficacy of cardiovascular medical devices and to guide the clinical treatment of heart disease. In this paper, we focus on the modelling of blood flow which encompasses a wide variety of conceptual and technical approaches. These range from 0D/1D lumped parameter models (LPMs) of the cardiovascular system to highly detailed 3D fluid-structure interaction (FSI) co-simulations. Using applications from medical device design and patient care, we discuss best practices in the context of the problem being modelled and the level of accuracy desired.

1: Lumped Parameter Models (LPM) of the circulatory system

Lumped Parameter Models (LPMs) are 0D/1D system models that use an electrical circuit analogy to model the dynamics of the cardiovascular system. LPMs typically represent important components of the circulatory system and can to be calibrated with patient data by changing the parameters of these components [1]. LPMs can provide real-time insight on cardiac behaviour and are ideally suited for applications where spatial resolution is less critical, such as exploring the parameter space to identify disease conditions.

1.2: Coupling LPMs with 3D models

LPMs can be coupled to 3D models to provide physiologically accurate boundary conditions for 3D CFD blood flow simulations (Figure 1). This principle is applied in SIMULIA Living Heart Model (LHM), wherein blood flow is modelled using a combination of 3D flow inside the heart and a LPM for the external circulation. Parameters of both flow models can be modified to introduce disease- or patient-specific characteristics. Moreover, components representing medical devices can also be integrated into the overall LPM. Figure 1 also shows a LPM with integrated Left Ventricular Assist Device (LVAD), which is coupled to the 3D LHM [2].

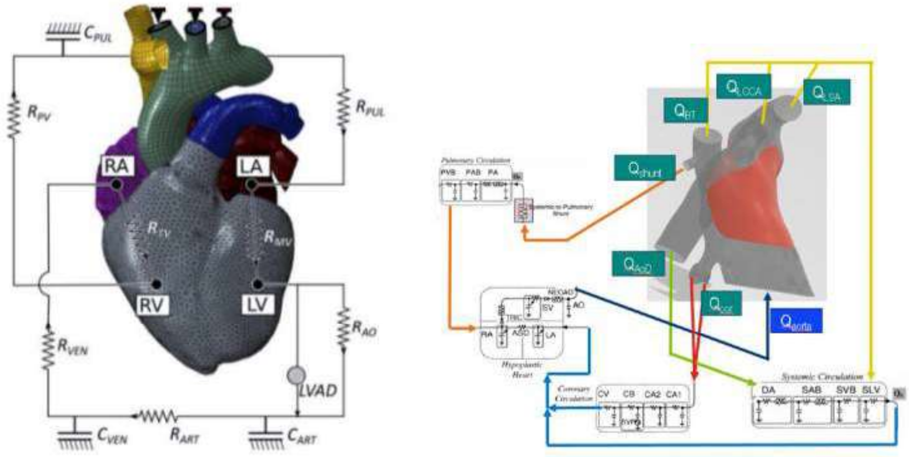

Figure 1: Modified LPM coupled to LHM (left); LPM coupled to CFD model (right)

2: 3D Blood Flow Modelling

3D Computational Fluid Dynamics (CFD) models provide high resolution quantitative and visual information. Multiple approaches are available, including continuum-based (Navier-Stokes) and particle-based (e.g., Lattice-Boltzmann or Smoothed Particle Hydrodynamics) CFD tools. Continuum tools can provide highly accurate fluid flow solutions but may pose practical barriers in situations involving complex geometries and constricted flow. Particle-based tools can overcome these limitations but may be problematic when complex boundary conditions and FSI are required. We present cases using both approaches and discuss best practices in the context of the problem being modelled and the level of accuracy desired.

2.1 Applications in Medical Device Development

The first application involves an implanted mechanical aortic valve. A Fluid-Structure-Interaction analysis was performed, coupling Abaqus/Explicit for the structural analysis and Smoothed Particle Hydrodynamics (SPH) model for blood flow. We observe the resulting loads on the device and compare blood flow patterns before and after implantation (Figure 2a). The same application is then repeated with the Navier-Stokes based CFD code FlowVision that is capable of handling large mesh deformations and constricted flow and can be coupled with Abaqus/Explicit (Figure 2b) [3]. We discuss both techniques.

Figure 2c shows a simulation of flow through a mitral valve that was repaired with an annuloplasty Ring to treat mitral valve regurgitation. The Lattice-Boltzmann solver XFlow was used to assess the amount of regurgitation flow through the repaired valve. The detailed valve geometry with tiny gaps, in combination with the large pressure gradient between left atrium and ventricle make this a challenging simulation for continuum methods, but appropriate for the “meshless” approach of the Lattice-Boltzmann Method.

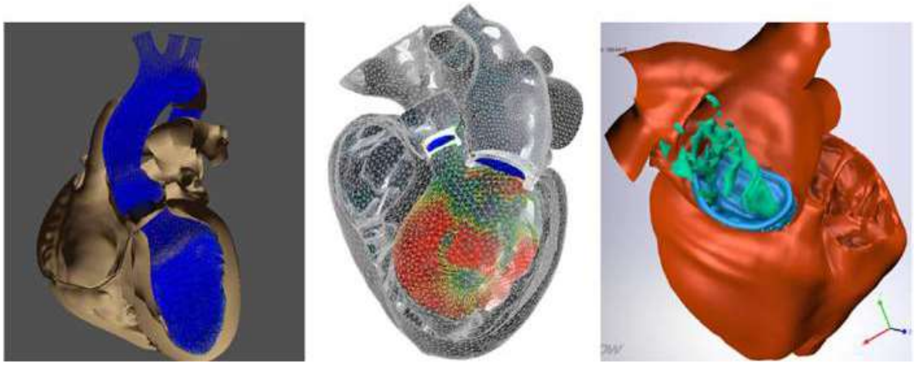

Figure 2: a) Aortic Valve (SPH) b) Aortic Valve (FlowVision) c) Valve repair (XFlow)

2.2 Applications in Patient Care

Blood flow modelling can also be useful to guide surgical interventions; we present two examples. The first case involves a carotid aneurysm wherein spatiotemporal visualization of wall shear stress can indicate the likelihood of rupture of the aneurysm (Figure 3, left). Such applications can be solved efficiently with continuum approaches such as 3DEXPERIENCE CFD. Figure 3 (right) shows velocities on a cut plane through an aneurysm that was treated with an inserted coil, reducing flow and stress inside the aneurysm. The complex coil geometry is difficult to mesh and therefore particle-based Lattice-

Boltzmann approaches are well suited for such problems. In this case, EXA PowerFLOW was used.

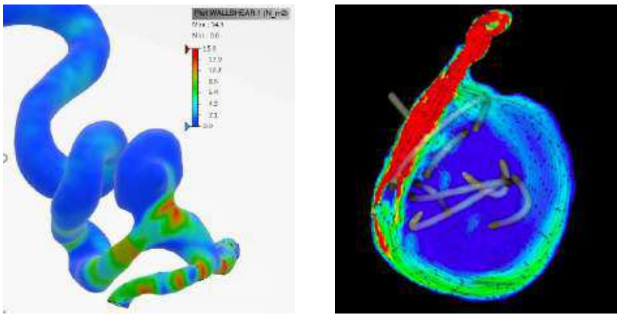

Figure 3: Wall Shear Stress in aneurysm, 3DEXPERIENCE CFD (left); Velocity inside treated aneurysm, EXA PowerFLOW (right)

In the second application, we discuss the importance of blood flow modelling in the surgical treatment of Hypoplastic Left Heart Syndrome (HLHS), a common congenital heart defect in newborns. During the procedure, the aorta has to be remodelled, resulting in significant changes of the blood flow patterns. A 3D CFD model of the aorta is coupled with a LPM of the patient-specific blood circulation and used to predict the post-surgical blood flow patterns in the aorta (Figure 4). Using flow modelling, the surgeon can decide on the optimal anatomic reconstruction for a given patient.

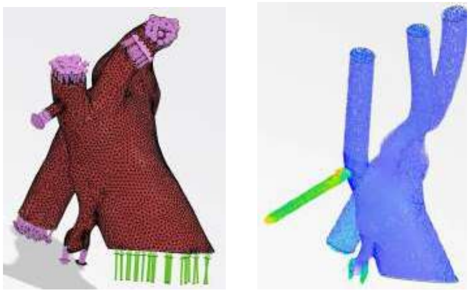

Figure 4: CFD model and results of HLHS anatomy (3DEXPERIENCE CFD)

3: Conclusion

The examples presented demonstrate the value and feasibility of simulation in the context of medical device development and real-world clinical workflows. Regulatory authorities are increasingly supportive of virtual diagnostics and clinical trials and we believe blood flow simulations are poised to make a major impact in this effort.

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