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Fluid Structure Interaction for Biomedical Applications

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The challenge of an accurate mapping of human circulation has brought up the need for close interdisciplinary collaboration between mathematicians, engineers and clinical doctors. Applied and Computational Mathematics are in the core of the effort to decode normal and pathological blood flow in the human vascular system.

The advances in imaging modalities and computer software enabled surface rendering of Computed-Tomography (CT) or Magnetic Resonance Imaging (MRI) data [1]. the extractions of three-dimensional patient-specific vascular structures have aided vascular surgeons in critical decisions about the diagnosis and treatment of life-threatening pathological conditions.

Computational Fluid Dynamics The combination of the three-dimensional patient-specific models with computational fluid dynamics (CFD) is a new chapter currently being written by various groups around the world. The basic idea is to simulate blood flow within patient-specific vascular geometries to predict the hemodynamic patterns and properties such as velocity, pressure and wall stresses. The enhanced information could further assist in surgical planning and personalize the treatment possibly by extending the directives that are currently applied in the whole cohort of vascular patients especially those suffering from aneurysms. For instance, the current guide for surgical intervention in case of abdominal aortic aneurysm (AAA) is solely based on the diameter and the annual growth rate of the abdominal aorta.

The modelling comprehensiveness affects significantly the accuracy of the results and constitutes the main reason that the technique is currently under research and not yet introduced in the mainstream medical practice. In this direction, Fluid-Structure Interaction (FSI) methodologies give an edge to the technique making it more appealing to the medical community. FSI simulations are a great step since they account for the dynamic interaction between the vessel hemodynamics and wall deformation, well ahead of the simplified assumption of solid arterial wall. Respective simulations have been conducted by several researchers decrypting the biomechanical behavior of arterial vessels [2-4]. Recently performed FSI numerical studies in patient-specific AAAs reconstructed from CT scans reveal complex flow trajectories within the aortic lumen [5]. The disturbed flow patterns indicate a potential mechanism for the formation and growth of thrombus and lipid deposition. These studies show the need for advanced mathematical and numerical models that can describe the complex vessel geometries especially under pathological conditions.

Fluid-Solid Coupling Techniques Fluid and tissue interaction in complex geometries can be addressed by a class of methods. In late 1970's, the Arbitrary Lagrangian-Eulerian (ALE) method was combining the advantages of a purely Eulerian formulation that involves a stationary mesh and of a purely Lagrangian formulation that associates the particles with the nodes of a respectively moving mesh. The methodology however requires a mesh-update procedure introducing a high computational cost.

Several years later, Peskin introduced the Immersed Boundary Method (IBM) to simulate cardiac mechanics along with blood flow [6]. The methodology formulates a free curvilinear mesh, where the Lagrangian variables are defined, that moves upon a fixed Cartesian mesh, where the Eulerian variables are defined, without adaptation constraints. Since the introduction of the IBM, numerous modifications have been proposed such as the Immersed Finite Element method (IFEM) [7] or the Extended Immersed Boundary Method (EIBM) [8] where the continuity of fluid and solid domains is imposed by higher-ordered reproducing kernel particle method (RKPM) delta functions, compared to the Dirac delta that is involved in IBM [9].

The above referred techniques involve non-conforming mesh methods meaning that interface conditions are imposed on the equations and there is no need for re-meshing [10,11]. On the other hand, sharp interface methods require that the mesh conforms to the interface which is now treated as a physical boundary. The latter approach is a more pertinent technique for biomedical applications since the interface needs to be located in detail.

Another FSI approach is the coupled momentum method introduced by Figueroa et al., describing blood flow in three-dimensional deformable models of arteries [12]. The variational equations of the vessel wall deformation serve as boundary conditions for the fluid domain. The strong coupling of the degrees-of-freedom of the fluid and the solid domains in a monolithic way lead to a robust numerical scheme. According to this approach, a single system of both solid and fluid equations is formed and solved simultaneously [13].

The transformation of the solid and fluid differential equations in generalized curvilinear coordinates (GCC) is a vital feature that can make the methodology consistent with complex geometries [14,15]. This consistency request comes on top of the general FSI approach highly increasing the modeling complexity.

Applied Mathematics and FSI from the above, it is clear that applied and computational mathematics are the foundations behind most elegant approaches developed from researchers in the FSI field. A proper approach for the biomedical problem of interest can reduce significantly the computational cost and ensure the convergence to the solution with minimal implementation effort. The optimization of respective techniques would further close the gap between numerical simulations and clinical practice persuading for their reliability, usefulness and eventually establishing their role in difficult medical decision making.

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