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Editorial

Image-Based Computational and Experimental Biomedical Flows

Huidan (Whitney) Yu

Purdue University in Indianapolis, Indianapolis, IN 46202, USA; yu597@purdue.edu

Fluids is pleased to present a Special Issue named "Image-Based Computational and Experimental Biomedical Flows", a curated collection of thirteen featured research papers that explore the integration between medical imaging data and 4-D (space + time) fluid dynamics for patient-specific cardiovascular flows. This Issue highlights recent developments in both computational and experimental methodologies, delivering valuable insights into the intricate hemodynamic complexities within human vascular systems. By bridging the gap between medical imaging and advanced fluid dynamics, these studies open new avenues for more accurate diagnosis, personalized treatment strategies, and the potential to revolutionize cardiovascular disease management. The featured articles dive deep into a diverse range of topics, including patient-specific modeling of blood flow in major arteries, the hemodynamics of intracranial aneurysms, and the intricate behavior of coronary artery stents. Each paper not only showcases state-of-the-art techniques but also emphasizes the real-world applications of these technologies in understanding and predicting vascular behavior under both healthy and diseased conditions. A recurring theme throughout this Issue is the synergy between computational fluid dynamics (CFD), image-based hemodynamic simulations, and innovative experimental setups, designed to replicate human arterial systems. By leveraging advanced computational tools like the lattice Boltzmann method and OpenFoam and experimental setting such as mock circulation loops, along with physical devices like flow diverter stents, these studies provide highly accurate simulations of blood flow, pressure distributions, and vascular responses.

The contributions in this Special Issue cover a wide range of topics.

Aneurysm Studies: A significant portion of this Issue is devoted to the study of aneurysms, reflecting the critical importance of this pathology in cardiovascular research [1,2]. Souza et al. [3] present a comprehensive analysis of cerebral aneurysms that goes beyond traditional flow studies. By coupling CFD with structural simulations, they investigate not only the flow behavior but also the biomechanical response of the aneurysm wall. Their results, spanning various Reynolds numbers and rheological models, reveal valuable insights into how flow patterns influence wall stresses and deformations, potentially aiding in rupture risk assessment. The cutting-edge topic of flow diverter stents for treating intracranial aneurysms is addressed by both Sanches et al. [4] and Boniforti et al. [5]. Sanches et al. [4] use CFD simulations to quantify the dramatic changes in intra-aneurysmal hemodynamics induced by these devices. They report significant reductions in wall shear stress and flow velocity, coupled with increased turnover time, suggesting a higher likelihood of thrombotic occlusion and reduced rupture risk. Boniforti et al. [5] expand on this work by conducting a detailed numerical investigation of flow diverter treatment, offering insights into optimal device selection based on porosity and other parameters. In a pioneering study, Boniforti et al. [6] apply CFD techniques to investigate an abdominal aortic aneurysm caught in the act of rupturing. By analyzing CT images of the rupturing aneurysm and creating a virtual pre-rupture model, they identify hemodynamic parameters associated with rupture risk. Their findings highlight the potential of CFD as a predictive tool for aneurysm management. Duronio and Di Mascio [7] utilize the open-source CFD software OpenFOAM to simulate blood flow in both healthy and aneurysmal thoracic aortas. Their work not only provides insights into the hemodynamic changes associated with aortic

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aneurysms but also demonstrates the capabilities of open-source tools for patient-specific cardiovascular modeling. Jeken-Rico et al. [1] address a critical methodological challenge by evaluating the impact of domain boundaries on hemodynamic simulations of intracranial aneurysms. Their work provides valuable guidance for researchers and clinicians on how to set up computational domains for accurate and reliable aneurysm simulations, particularly in the complex anatomical context of the Circle of Willis.

Cardiac Function and Disease: Several papers in this Issue focus on cardiac function and specific cardiac pathologies [8–10]. Korte et al. [11] advance the research by analyzing left ventricular hemodynamics in patients with mitral valve insufficiency under both rest and exercise conditions. Their echocardiography-based simulations reveal intriguing differences in kinetic energy patterns between rest and exercise states, as well as between different stages of valve insufficiency. This work demonstrates the potential of computational modeling to provide new diagnostic and prognostic indicators for cardiac function. Baraikan et al. [12] present an ambitious multi-scale modeling framework to quantify myocardial ischemia. By integrating various levels of cardiovascular modeling, from zero-dimensional models to CFD simulations, their approach offers a comprehensive tool for personalizing and predicting ischemic burden, with potential implications for clinical decision-making in coronary artery disease. Ihsan Ali et al. [13] leverage 4-D flow MRI to assess pressure changes in the repaired tetralogy of Fallot patients. This non-invasive imaging technique offers a unique window into the hemodynamics of congenital heart disease, providing valuable data for both clinical assessment and computational model validation.

Arterial Flow and Stenosis: This Issue also addresses the critical topic of vascular flows, particularly in the context of stenosis. Yu et al. [14] make significant strides in improving the accuracy of image-based computational hemodynamics. They develop physiological inlet and outlet boundary conditions based on patient-specific medical data and integrate them into a volumetric lattice Boltzmann method. Their approach, validated on six human aortorenal arterial systems, shows excellent agreement with medical measurements.

Hong et al. [15] develop an innovative mock circulation loop for in vitro hemodynamic measurements in stenosed arteries. This experimental setup bridges the gap between computational and experimental approaches, allowing for the validation of numerical models and the investigation of flow phenomena that may be challenging to capture in silico. Yukhnev et al. [16] present a study that exemplifies the power of combining advanced experimental techniques with computational modeling. They compare ultrasound vector flow measurements to CFD simulations for pulsatile flow in femoral-popliteal bypass grafts, validating computational approaches and showcasing the capabilities of advanced ultrasound imaging in capturing complex flow patterns.

Coronary Artery Interventions: LaDisa et al. [17] provide a comprehensive review of recent advancements in modeling wall shear stress changes induced by coronary artery stents. This paper synthesizes state-of-the-art computational approaches, image-based reconstruction methods, and novel boundary condition implementations, offering a roadmap for future patient-specific modeling efforts in interventional cardiology.

Methodological Advancements: Several papers in this Issue focus on methodological advancements that have broad implications for the field of cardiovascular flow modeling. Yu et al. [14] demonstrate the potential of the lattice Boltzmann method [18–22] for hemodynamics simulations, offering an alternative to traditional Navier–Stokes-based approaches. Jeken-Rico et al. [1] provide crucial insights into the impact of domain boundaries on CFD simulations, addressing a key challenge in the computational modeling of vascular flows. Duronio and Di Mascio [7] showcase the capabilities of open-source CFD software (OpenFOAM) for cardiovascular simulations, potentially democratizing access to advanced modeling tools.

Experimental Techniques: While computational methods dominate this Issue, several papers highlight the crucial role of experimental approaches in validating and complementing numerical simulations. Hong et al. [15] develop a mock circulation loop that allows for detailed in vitro studies of stenosed arteries. Yukhnev et al. [16] demonstrate the

power of advanced ultrasound vector flow measurements in capturing complex arterial flow patterns. Ihsan Ali et al. [13] showcase the potential of 4D flow MRI for non-invasive assessment of cardiovascular hemodynamics.

Multi-scale and Integrated Approaches: A trend towards more comprehensive, multi-scale modeling approaches is evident in several papers. Souza et al. [3] combine fluid dynamics and structural analysis to provide a more complete picture of aneurysm biomechanics. Baraikan et al. [12] present a multi-scale framework that integrates various levels of cardiovascular modeling to study coronary ischemia.

This Special Issue represents the cutting edge of image-based cardiovascular flow modeling and analysis, showcasing the incredible strides being made in this rapidly evolving field. From refining fundamental simulation techniques to tackling highly complex clinical challenges, these studies reveal the immense potential of computational and experimental approaches to transform our understanding of cardiovascular physiology and pathology. By seamlessly integrating computational models, experimental methods, and clinical data, these papers illustrate the remarkable synergy between these domains, driving forward the science of cardiovascular flows. As medical imaging technologies continue to advance and computational power reaches unprecedented heights, the fusion of in silico, in vitro, and in vivo approaches is set to revolutionize the future of cardiovascular medicine [23,24]. The promise of personalized cardiovascular care is no longer a distant goal, but an emerging reality. Patient-specific simulations will soon guide clinical decision-making, enabling tailored treatment strategies that optimize outcomes for each individual. With this confluence of technology and medicine, we stand on the brink of a new era—one where cardiovascular disease can be understood, treated, and potentially prevented with unparalleled precision and insight.

Conflicts of Interest: The authors declare no conflict of interest.

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