ABSTRACT

Cardiovascular diseases (CVDs) remain a leading cause of global morbidity and mortality, driven largely by abnormalities in vascular hemodynamics that influence disease initiation, progression, and clinical outcomes. Accurate assessment of blood flow dynamics and associated biomechanical forces is therefore critical for effective diagnosis, risk stratification, and therapeutic planning. While contemporary medical imaging modalities such as Computed Tomography Angiography (CTA) and four-dimensional Flow Magnetic Resonance Imaging (4D Flow MRI) provide anatomical and flow information, they are inherently limited in their ability to directly quantify key hemodynamic and biomechanical indicators, including wall shear stress, oscillatory shear index, pressure, and arterial wall deformation. These limitations motivate the integration of physics-based computational modeling with patient-specific imaging to enable comprehensive, non-invasive evaluation of cardiovascular function.

This thesis presents the development, validation, and clinical translation of a comprehensive patient-specific computational framework for cardiovascular hemodynamic analysis. The proposed framework integrates advanced medical imaging, high-fidelity and reduced-order computational modeling, experimental validation, and uncertainty quantification to provide physiologically realistic and computationally efficient assessments of vascular function and disease progression.

A rigorous data-driven pipeline is established for the acquisition and processing of patient-specific anatomical and physiological information derived from CT angiography, and 4D Flow MRI. Individualized vascular geometries are reconstructed; physiologically consistent boundary conditions are derived using imaging-informed flow waveforms and reduced-order Windkessel models; and arterial wall mechanical properties are incorporated through elasticity estimates informed by pulse wave velocity measurements. This personalization enables the construction of anatomically and physiologically realistic computational fluid dynamics - fluid structure interaction (CFD-FSI) models capable of resolving detailed spatiotemporal variations in blood flow and arterial wall mechanics.

To address the prohibitive computational cost associated with high-fidelity CFD-FSI simulations, the thesis introduces a multi-scale, multi-fidelity modeling strategy. Complementary one-dimensional reduced-order models are employed to efficiently capture

global hemodynamic behavior, while a bifidelity framework based on interpolative decomposition enables accurate reconstruction of clinically relevant local quantities, such as wall shear stress, from low-fidelity simulations. In addition, a computational model linking wall shear stress to endothelial nitric oxide production is incorporated, facilitating investigation of biomechanical-biochemical coupling in vascular physiology.

Recognizing the inherent uncertainties in patient-specific modeling, a systematic uncertainty quantification framework based on non-intrusive polynomial chaos expansion is implemented to assess the impact of uncertain biomechanical parameters, particularly arterial wall thickness and elasticity, on predicted hemodynamic outputs. This approach provides statistically meaningful confidence bounds analogous to experimental error bars, thereby enhancing the interpretability and reliability of simulation results.

Experimental validation is performed using comprehensive Particle Image Velocimetry (PIV) protocol in patient-specific aortic dissection phantoms, enabling high-resolution measurement of complex pathological flow features. The integrated computational framework is also validated against in-vivo 4D Flow MRI measurements. Strong agreement is demonstrated across in-silico, in-vitro, and in-vivo datasets, with accurate reproduction of complex flow patterns, pressure distributions, wall mechanics, and true-false lumen interactions. Clinically relevant hemodynamic indicators, including time-averaged wall shear stress and oscillatory shear index, are resolved with high spatial and temporal fidelity.

Finally, the translational potential of the framework is demonstrated through application to patients with Type B aortic dissection. Image-informed simulations enable individualized hemodynamic assessment and risk stratification, supporting informed clinical decision-making. In addition, a novel non-invasive, simulation-based methodology for estimating local arterial wall elasticity is introduced, demonstrating improved performance over conventional pulse wave velocity-based approach.

Collectively, this thesis establishes a validated, efficient, and clinically translatable computational platform that advances personalized cardiovascular modeling and supports improved assessment of vascular disease progression and management.