ABSTRACT

A Smoothed Particle Hydrodynamics Framework for Multiphysics Simulation of Cardiovascular Hemodynamics and Thrombosis,

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Indian Institute of Technology Kharagpur

By Sumanta Laha

This research presents a numerical framework based on the Smoothed Particle Hydrodynamics (SPH) method to investigate fluid–structure interaction (FSI) and thrombus formation in cardiovascular flows, focusing on the hemodynamics of bi-leaflet mechanical heart valves (BMHVs). Traditional mesh-based methods, such as the Finite Volume Method (FVM), often face difficulties with large deformations and moving valve leaflets due to mesh distortion and remeshing requirements. By contrast, the mesh-free and fully Lagrangian nature of SPH naturally handles large deformations, moving boundaries, and fluid–structure interaction without the need for predefined connectivity or remeshing techniques, making it well suited for studying prosthetic heart valve dynamics.

The primary objective is to establish an integrated SPH framework that simultaneously captures valve hemodynamics, wall shear stress (WSS) metrics, and thrombus formation. This is achieved by validating the SPH-based FSI model against benchmark cases and experimental data, incorporating WSS-derived biomarkers—time-averaged WSS (TAWSS), oscillatory shear index (OSI), and endothelial cell activation potential (ECAP)—and coupling them with a multiscale thrombus growth model. Rather than treating thrombus formation in isolation, the framework links fluid dynamics, leaflet motion, and biochemical processes into a unified simulation environment to evaluate thrombogenic risk across mechanical heart valve.

The results demonstrate that SPH can accurately reproduce key flow features and leaflet dynamics in both simplified and realistic geometries. The validated WSS model enabled the extraction of TAWSS, OSI, and ECAP, showing clear differences between native and mechanical valves. In prosthetic valves, regions of very low shear stress (<0.2 Pa) and excessively high shear stress (>2.5 Pa) were observed, corresponding to zones prone to thrombus deposition and endothelial damage, respectively. The integrated thrombus model further captured clot initiation and growth in valve-specific regions, with validation against benchmark thrombus cases. When applied to different valve orientations, the coupled FSI–thrombus framework identified clinically favourable and unfavourable configurations, demonstrating its potential to guide surgical planning.

In conclusion, this work establishes a validated SPH-based platform that integrates FSI, WSS biomarker analysis, and thrombus formation into a single modelling tool for prosthetic valve assessment. Future developments will incorporate compliant arterial walls, refined turbulence and near-wall treatments, and expanded coagulation pathways, with the ultimate aim of developing a clinically relevant, patient-specific *in-silico* surgical planning tool for cardiac implants.