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Doctoral Dissertation  
Doctoral Program in Bioengineering and Medical-Surgical Sciences (38<sup>th</sup> Cycle)

# Fluid–Structure Interaction Modelling for the Biomechanical Study of Heart Valve Prostheses

**Mariachiara Arminio**

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## **Supervisors**

Prof. C. Chiastra, Supervisor  
Prof. D. Gallo, Co-Supervisor  
Prof. U. Morbiducci, Co-Supervisor

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# Summary

Heart valve disease is a major cardiovascular pathology whose prevalence is expected to increase as a consequence of population aging. Heart valve replacement, which involves the implantation of a prosthetic valve to restore the physiological function of a diseased native valve, represents a widely adopted therapeutic strategy. Although heart valve replacement is currently regarded as a safe and effective standard of care, ongoing research aims to further improve clinical outcomes and long-term prosthesis performance.

Clinical outcomes after heart valve replacement are strongly influenced by the biomechanical performance of the implanted heart valve prosthesis. In particular, prosthetic heart valves induce non-physiological flow patterns that can promote adverse events such as thromboembolism and structural valve degeneration. These phenomena are closely related to the geometric configuration of the prosthesis, the chosen implantation strategy, and the resulting alterations in downstream flow hemodynamics. In this context, *in silico* modeling represents a powerful approach for investigating valve biomechanics with reduced time and cost compared to experimental set-ups. Among computational approaches, fluid-structure interaction (FSI) simulations enable the study of heart valve biomechanics as governed by the interaction between the implanted prosthetic device and blood flow. Consequently, FSI simulations can be conveniently used to i) support *in silico* tests informing device total product life cycle and ii) conduct patient-specific investigations aiding in clinical decision-making. Building on these capabilities, the present doctoral dissertation explores the application of FSI simulations to two distinct types of heart valve prostheses: bileaflet aortic mechanical heart valves and percutaneous pulmonary valves.

In the first part of this thesis, an FSI framework for the simulation of bileaflet aortic mechanical heart valves is presented. The reliability of the framework was assessed through comparison with previously published data. The framework was

then employed to investigate the impact of device design and aortic curvature on valve hemodynamics by simulating three commercially available valves in aortic models characterized by different curvatures. The results showed a marked impact of valve design on flow patterns and large-scale vorticity transport downstream of the device. Moreover, neglecting aortic curvature led to an underestimation of vortex generation when compared with simulations performed in curved aortic geometries. These findings suggest that the biomechanical characterization of mechanical heart valves may benefit from the inclusion of curved aortic anatomies in both *in vitro* and *in silico* testing set-ups.

In the second part of this thesis, an FSI framework for patient-specific simulation of percutaneous pulmonary valves based on routinely acquired clinical data is presented. The framework was applied to six patient-specific scenarios, including two cases characterized by valve narrowing. The simulations reproduced peak transvalvular pressure drops in good agreement with available clinical measurements and captured valve biomechanics arising from the interaction between the valve leaflets and blood flow. This enabled the investigation of how patient-specific anatomy modulates flow patterns within the pulmonary arteries. Additionally, the framework was used to evaluate the effects of valve orientation, implantation height, and ellipticity in a patient-specific context.

Overall, the frameworks developed in this thesis underscore the potential of FSI simulations as a powerful and versatile tool for biomechanical assessment of heart valve prostheses. Specifically, this work enables i) a deeper understanding of the biomechanics of bileaflet aortic mechanical heart valves within semi-idealized set-ups, and ii) detailed exploration of percutaneous pulmonary valve biomechanics in patient-specific settings.