Numerical assessment of blood damage through prosthetic heart valves

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***Abstract*—The aim of the present work is to present a computational tool for simulating the fluid-structure interaction of blood flow through prosthetic heart valves. The complex flow fields past different valve models are responsible for different level of stresses on blood cells that could be related to thromboembolic complications. Mechanical hemolysis is estimated by means of a coarse-grained strain-based model, employing an accurate representation of the single red blood cell membrane. The different propensity of several prostheses to thromboembolic complications is finally evaluated.**

***Keywords*—Immersed boundary, aortic valves, hemolysis**

THANKS to considerable improvements in prosthetic heart valve design and surgical procedures achieved in the last years, the surgical replacement of a diseased heart valve with an artificial one is a safe and routine clinical practice worldwide. Approximately half of the implanted devices are mechanical valves and half are bio-prosthetic.

The bi-leaflet valve is the most popular mechanical design: the valve is made of two semilunar rigid disks attached to a rigid valve ring by small hinges. Bio-prosthetic (or tissue) valves are composed of three deformable leaflets that open closely resembling the native tri-leaflet aortic valve. A major concern related to such devices is that blood elements might be exposed to non-physiologic conditions that are responsible for high shearing and damage. In fact, existing mechanical valves, despite their lifelong durability, need anticoagulation therapy. Tissue valves are free of anticoagulation therapy, but have limited lifetime. Recently a concept of an innovative mechanical model, with a tri-leaflet design has been presented, with a physiological operating mode that should avoid blood damage (see Figure 1).

In this work, a numerical approach is presented in order to accurately predict the flow patterns through such devices and then evaluate the blood damage. The method combines a finite-difference flow solver strongly coupled with a finite-element structural solver for fluid-structure interaction [1]. A suitable version of the immersed boundary technique is employed for handling rigid and deformable geometries, while direct numerical simulation is utilized to solve the complex fluid-structure-interaction problem and obtain detailed information of the flow patterns. Realistic geometries for the valves and ascending aorta are considered. Very different flow fields are obtained for the different valve models, also characterized by distinct levels of stresses acting on the blood cells (see Figure 1).

In order to predict possible membrane damage of the red blood cells (mechanical hemolysis) induced by abnormal stress levels, a large number of Lagrangian tracer particles are released at the inlet of the computational domain (upstream of the valve), and blood damage is evaluated along each trajectory using a high-fidelity hemolysis model [2]. The model employs an accurate representation of the single red blood cell, which is based on a coarse-grained molecular model of the erythrocyte membrane spectrin cytoskeleton [3]. In this way, under the hydrodynamic loadings, the instantaneous shape distortion of the cells and consequent damage are evaluated, accounting for the finite response time of cell deformation and relaxation. Hemolysis index for three valve models are evaluated, assessing the different propensity of the prostheses to thromboembolic complications.

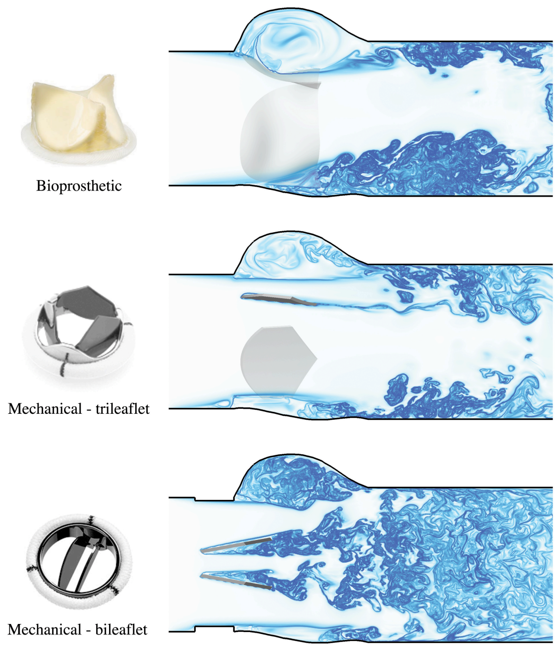

FIGURE 1: PULSATILE FLOW THROUGH PROSTHETIC AORTIC VALVES: DECELERATION PHASE. BACKWARD FINITE TIME LYAPUNOV EXPONENT FIELDS IN A SYMMETRY PLANE FOR THREE DIFFERENT VALVE MODELS.

REFERENCES

[1] M. D. de Tullio and G. Pascazio, "A moving–least–squares immersed boundary method for simulating the fluid–structure interaction of elastic bodies with arbitrary thickness", *Journal of Computational Physics,* vol. 325, pp. 201-225, 2016.

[2] H.M. Exxeldin, M.D. de Tullio, M. Vanella, S.D. Solares, E. Balaras, "A strain–based model for mechanical hemolysis based on a coarse-grained red blood cell model", *Annals of Biomedical Engineering,* vol. 43, pp. 1398-1409, 2015.

[3] D.A. Fedosov, B. Caswell and G.E. Karniadakis, "A multiscale red blood cell model with accurate mechanics, rheology, dynamics", *Biophysical Journal,* vol. 98, pp. 2215-2225, 2010.

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