Numerical assessment of blood damage through prosthetic heart valves

Marco D. de Tullio*

* Department of Mechanics, Mathematics and Management (DMMM)
Politecnico di Bari
Via Re David 200, 70125, Bari, Italy
e-mail: marcodonato.detullio@poliba.it

ABSTRACT

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 valves. 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.

In this work, anumerical 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. In order to evaluate hemolisys, 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.

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