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3D fluid-structure interaction simulations of a commercial bioprosthetic valve.

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Introduction

Aortic valve disease is one of the most common valvular problems in the geriatric population, leading to significant morbidity and increased mortality. Different treatment options are available, ranging from reparation to valve replacement. In the second case, the surgeon can choose in function of the patient between a mechanical or a Bioprosthesic Heart Valve (BHV), generally made of a rigid frame which supports biological tissue. The major disadvantage of these valves is their failure due to structural deterioration. For this reason, the knowledge of flow and stresses acting on the BHV is of paramount importance to examine and enhance the design of more efficient prosthetic devices. The increasing accuracy and cost effectiveness of computer simulations in cardiovascular mechanics allows us to investigate the problem, for example making use of Fluid-Structure Interaction (FSI) simulations. This technique allows a fully coupled interaction between the fluid motion and the mechanics of the surrounding tissues providing a complete and realistic set-up. The goal of this project is to perform FSI simulation on a commercial bioprosthetic valve during the cardiac cycle. This will allow to analyse the hemodynamic performance of the valve, the leaflet kinematics, and estimate the stresses experienced by the leaflets, variables of primary importance to evaluate the failure risk of a BHV.

Methods

A Carpentier-Edwards PERIMOUNT Aortic Heart Valve (Edwards Lifesciences LLC, Irvine, California, size 25 mm, fig. 1A) was scanned with a µCT scan. The images were segmented with the commercial software Mimics (Materialise, Leuven, Belgium) to obtain the desired geometry. The reconstructed valve was placed into a straight rigid tube with three hemispherical enlargements to mimic the sinuses of Valsalva. Two separate meshes were obtained with the open-source software PyFormex. A solid mesh, including three flexible leaflets, consisting of about 5 10^3 tetrahedral elements (fig. 1B), and a fluid mesh, consisting of about 10^5 tetrahedral elements were generated.

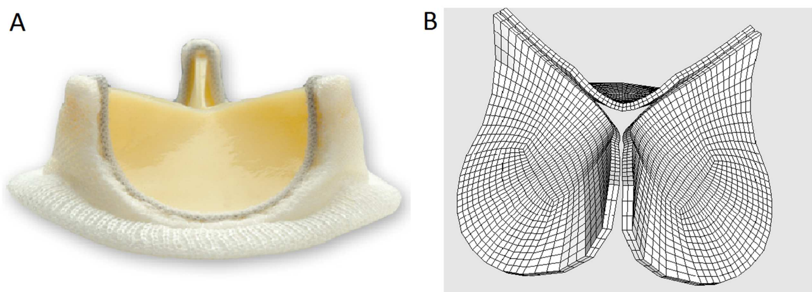

Figure 1: Carpentier-Edwards PERIMOUNT Aortic Heart Valve

An in-house developed code (Tango) allowed the coupling of the structural (Abaqus, Dassault system) and fluid (Fluent, Ansys) solver was used. As a boundary condition, we impose a physiological pressure distribution and no-slip condition on all the wall surfaces. The fluid is described as Newtonian with a laminar flow, the material of the leaflets is linear and elastic. The Navier-Stokes equations in the fluid domain are solved with the arbitrary Lagrangian-Eulerian formulation (ALE). Special attention is given to the coaptation of the leaflets during diastole, a problem that is insufficiently described in the literature for the ALE formulation. Our approach for solving this problem is to hamper the motion of the leaflets as soon as the interleaflet distance is below a predefined threshold. We also preserve a one-layer-cells gap of the fluid domain to avoid the division of the fluid domain. The preservation of the small gap in the fluid domain introduces a non-physical backflow during diastole, which influences the results of the analysis. To reduce this backflow, we introduced an arbitrary porous material in the gap to increase the hydraulic resistance and decrease the residual backflow.

Results

The obtained results show the feasibility and reliability of our ALE-approach of FSI simulations on heart valves with flexible leaflets. As an example, figure 2, displays the valve during the early systolic phase. Figure 2a displays the velocity vectors in the fluid domain and the pressure acting on the leaflets, while in figure 2b the structural stress is plotted for the same time frame.

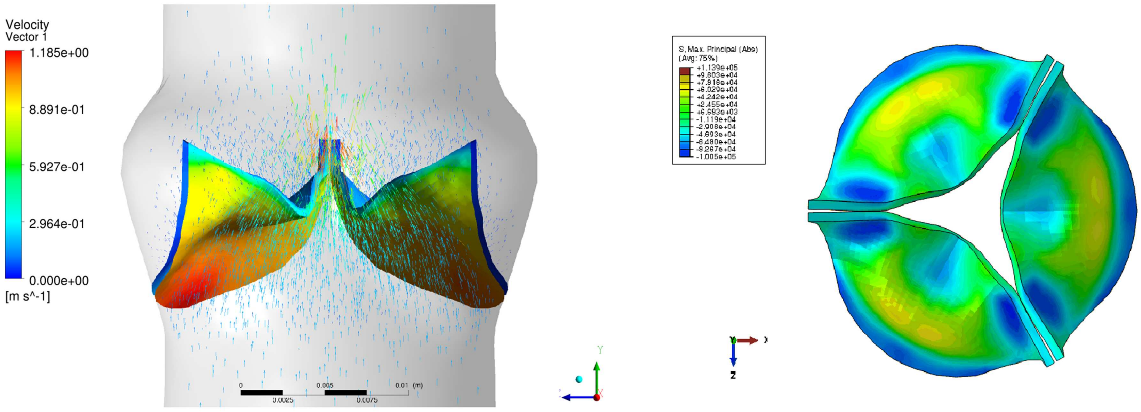

Figure 2: aortic valve during the opening phase. 2A: pressure and velocity vectors, 2B: S. Max Principal

The kinematics of the valve is comparable with previous published *in vitro* tests and with the results of similar computational analysis.

Discussion

In this project, we show the feasibility of implementing an ALE based FSI simulation of a bioprosthetic valve. The 3D simulations allow the investigation of the hemodynamics and the structural behaviour of a BHV. The model is based on a scanned geometry of the analysed device, and might provide an additional tool to cardiac surgeons to investigate the physical causes that can cause the failure of the device. Further investigations are needed to describe more advanced models to better describe the mechanical properties of the valve tissue. In the near future, this methodology will be adapted to perform simulations on different BHV's, to be able to compare their different hemodynamic performances. In a long term perspective, this type of simulations can be used to improve the structural design of the device.