

A Multiphysics Approach to the Modeling of Biological Prosthetic Heart Valves

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Abstract

Introduction: Biological heart valves (BHV) basically consist of leaflets made of biological tissues mounted on a supporting frame (stent). Their complex in-vivo behavior can be simulated through FEA which can be especially useful for optimization of implants design before prototypes are built and experimental evaluations conducted.

Use of COMSOL Multiphysics: In order to take full advantage of computational approaches, modeling strategies must consider different aspects, including accurate description of valve geometry, mechanical behavior of leaflets biological tissue and realistic multiphysics simulation of loading condition. Different modules of COMSOL Multiphysics were therefore used to set up structural and fluid-structure interaction (FSI) models. LiveLink and CAD Import Module were used to exchange the complex valve geometry with CAD softwares. Structural analysis was carried out to study the stress distribution and leaflet deformation in response to applied pressure both in opening and closing phase of the cardiac cycle. The Structural Mechanics Module was used to set loads, boundary condition and anisotropic hyper-elastic constitutive laws. In particular an Holzapfel type constitutive law was implemented to reproduce the behavior of chemically treated bovine pericardium controlling preferred fiber orientation (Figure 1) on the valve leaflet by means of PDEs. Fluid-structure interaction analysis was carried out by adding to the model Moving Mesh and physics from the CFD Module. By means of the ALE approach it was then possible to manage modification of fluid domain mesh due to the movement of fluid domain boundaries as a result of structural deformation of the leaflets. FSI analysis allowed the simultaneous analysis of structural and fluid domains, as shown in Figure 2 where 1/6th of a model including part of aortic root is depicted.

Results: Structural analysis was carried out to simulate the cardiac cycle by means of a uniform pressure applied on the surface of the leaflet. This allowed the identification of most stressed regions, which were found to be located near the stent post apex (see Figure 3) and in the belly region near the stent ring. Peak stress value and location were found to be influenced by extensibility, anisotropy and thickness of leaflets. FSI analysis allowed the evaluation of flow velocity field across the valve as well as of important parameters of clinical relevance like pressure gradient and effective orifice area.

Conclusion: Computational approaches can yield detailed insights of functional and structural effects for prosthetic heart valves, especially when structural and fluid dynamics analysis are combined to carry out FSI studies. Taking advantage of COMSOL Multiphysics coupling capabilities between different physics, fluid and solid domain variables could be solved simultaneously with a well integrated and effective approach.

Figures used in the abstract

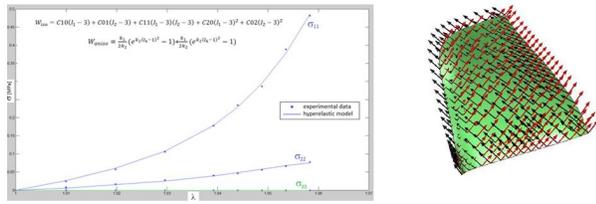


Figure 1: Constitutive law and preferred fiber orientation.

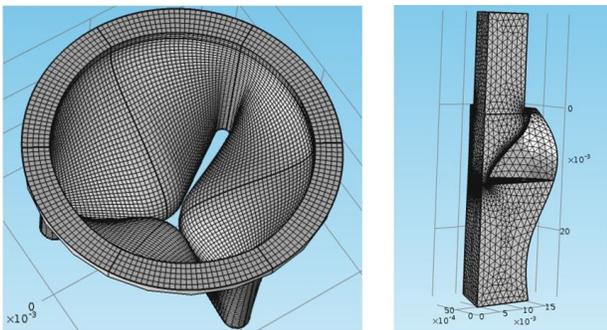


Figure 2: Structural and FSI model.

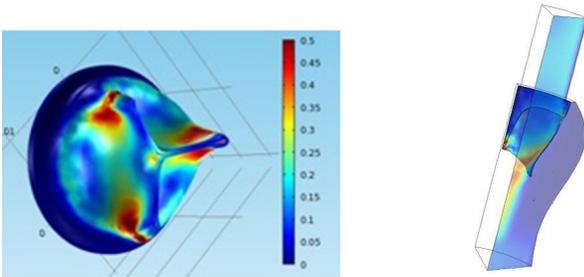


Figure 3: Example of results of structural and FSI analysis.