A novel FSI-RBF mesh morphing environment to design a new polymeric aortic valve

E. Gasparotti[1,2], E. Vignali[1,2], U.Cella[3], L. Geronzi[2], E. Costa[4] and S. Celi[1]

[1] BioCardioLab, Fondazione CNR-Regione Toscana "G. Monasterio", Massa, Italy;

[2] Department of Information Engineering, University of Pisa, Pisa, Italy;

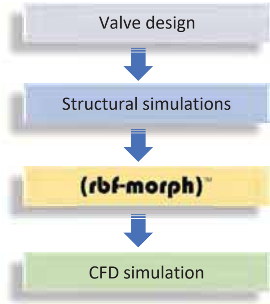
[3] Department of Enterprise Engineering Mario Lucertini, University of Rome Tor Vergata, Rome, Italy;

[4] RINA Consulting S.p.A., Rome, Italy;

Introduction

Aortic Valve (AV) stenosis is one of the most serious heart disease; it refers to a shrinkage of the AV that obstruct the blood flow from the left ventricle to the aorta. Polymeric AV could potentially offer an optimum solution for a heart valve substitute by significantly reducing blood coagulation problems, maintaining excellent properties in term of longevity and strength [1]. In the context of predictive medicine and prosthesis optimization analysis, computational fluid dynamical and structural methods play a crucial role on to study the behavior of the implanted valves[2].
The mesh morphing techniques and in particular the theoretical basis of RBF was established [3] to manage problems of multidimensional interpolation. These approaches has been demonstrated to be useful for the study of hemodynamic CFD problems [4].

Aim of the study: evaluate the mesh morphing technique effectiveness to develop an innovative polymeric AV. A novel combined approach based on structural simulations and CFD simulations coupled with rbf-morph tool is presented to simulate the fluid dynamic of valve during the opening phase.

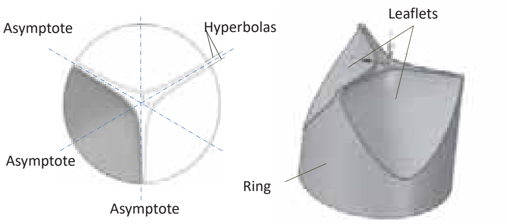


Materials and Methods

Valve cad design: the leaflet shape was defined in SpaceClaim software implementing elliptic hyperbolic surface equations[5]:

$$\begin{cases} x(t_1,t_2) = a * \sinh(t_1) * \cos(t_2) \\ y(t_1,t_2) = b * \sinh(t_1) * \sin(t_2) \\ z(t_1,t_2) = c * \cosh(t_1) \end{cases}$$

The fraction c/a is the slope of hyperbola curve asymptotes, was assumed equal to $\sqrt{3}/3$ to realize symmetric leaflets.



Structural simulations: the finite element analyses of the AV during the heart cardiac cycle were conducted using Ansys by simulating the systolic (valve opening) and the diastolic phases (valve closing) separately.

Valve Material properties:

- Ring: isotropic linear elastic (E=4.6 MPa, v=0.4) [6]
- Leaflet: isotropic linear elastic (E=6.5 MPa, v=0.4)

Element type: tetraedrons ('solid187')

Element number: 700000 cells

Boundary conditions: bottom ring surface fixed

Load conditions: aortic and ventricular transient pressures

Loaded surfaces: internal and external leaflet

rbf-morph tool: imposes a fluid domains adaptation to CFD analysis on the basis of deformed shapes of the valve, extracted from the previous structural simulation. Two different deformed configurations were exported from the structural simulation and used as target by the mesh morphing technique to fit the displacement field applied on the fluid domain mesh (source) during the CFD simulation.

Source nodes Target nodes

FSI morphing simulation: a pressure based transient fluid dynamic analysis was run, in which the Realizable k-ε turbulence model was adopted. The boundary layer was solved by using standard wall functions. The fluid was considered as incompressible and non-Newtonian, the viscosity was modeled through the Carreau formulation.

Element type: structured hexaedrical

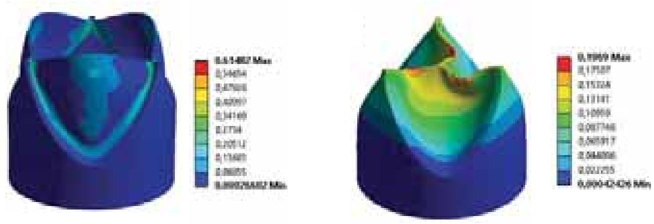
Element number: 7000000 cells

Inlet conditions: aortic flow

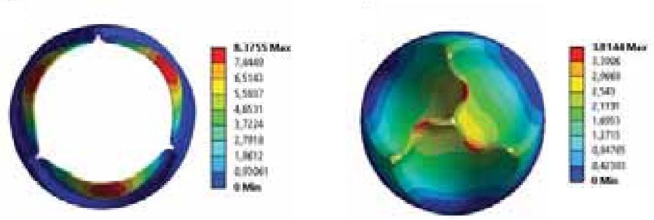
Outlet conditions: systolic aortic pressure

Results and Discussion

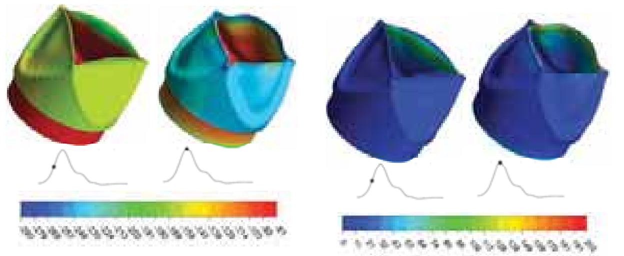
Structural simulations: The equivalent strain assumes the maximum value (0.6 mm/mm) in leaflet region during the systolic phase and at the maximum valve opening.
The reported maximum strain was lower than the corresponding ultimate strain value of the material (4.73 mm/mm) reported by material Carbosil (DSM) material.
No static damage occurs in the aortic valve during the entire cardiac cycle.



During the opening phase the maximum radial displacement of the leaflet was equal to 8.4 mm. The resulting GOA is equal to 310 mm² which is within the range of commercial valves.
In the closing phase, the maximum radial contraction of the leaflet was equal to 3.8 mm.



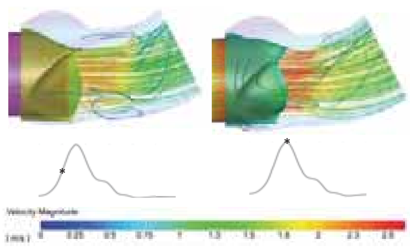
FSI morphing simulation: From the CFD simulations the pressure and wall shear stress (WSS) fields during the valve opening and closing can be observed in Fig. and Fig. , respectively. In the acceleration phase, it as possible to observe a uniform pressure distribution on both the external and internal leaflet surfaces. On the contrary, a pressure gradient was visible on the internal surface of the leaflet during the peak systolic phase. The WSS assumes a maximum value equal to 202 Pa in the internal surfaces of the leaflets.



Pressure field (mmHg)

Wall shear stress field (Pa)

The maximum fluid velocities are reached in the aortic peak and are equal to 2.6 m/s.



Conclusion

- The AV opening kinematics were successfully transferred to the CFD analysis through the mesh morphing technique.
- The effectiveness of the FSI morphing simulation to reproduce the fluid dynamic field of the AV was demonstrated.
- The designed AV was able to reproduce the kinematic and fluid dynamic performances of the native AV

[1] Bezuidenhout D. et al, Biomaterials, 2015.
[2] Ghosh R. et al, J. Biomech. Eng., 2018.
[3] Biancolini M.E., 2018.
[4] K. Capellini et al. J Biomech Eng, 2017.
[5] Jiang H. et al, Medical Engineering Physics, 2004.
[6] Gasparotti E. et al Int. J. Poly. Mat.Polymeric Biomat., 2019.

Contacts: gasparotti@ftgm.it
bcl.ftgm.it

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