Fluid-Structure Interaction Model of a Percutaneous Aortic Valve: Comparison with an In Vitro Test and Feasibility Study in a Patient-Specific Case

POLITECNICO DI MILANO

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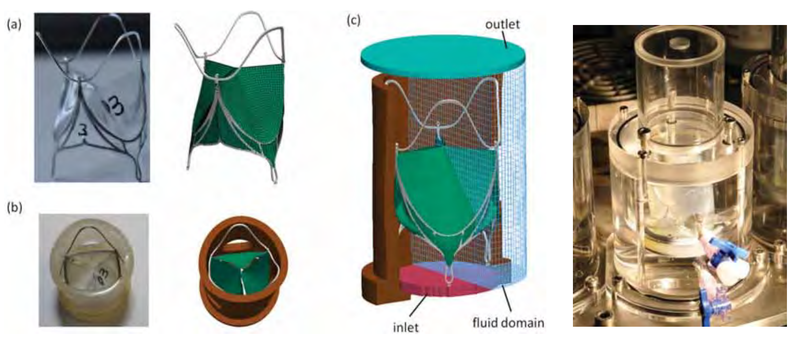
Introduction

Transcatheter aortic valve replacement (TAVR) represents an established recent technology in a high risk patient base. Many influence factors determining TAVR performance are still not well understood. In this study, **a fluid-structure interaction (FSI) model** of a purposely designed self-expandable transcatheter aortic valve is proposed. An **in vitro durability experiment** was carried out to test the stented aortic valve and to record the motion behavior of the heart valve prosthesis. The FSI model was built to reproduce the experimental test, and compared to **a simulation on a patient-specific case**. This study aims to develop an FSI model for the study and evaluation of percutaneous aortic valves.

Materials and Methods

In vitro test and FSI model

The in-vitro fatigue test of NiTi stent valve with 600 bpm passed 10^7 cycles. The models were created according to the measurement of the dimension and material properties.

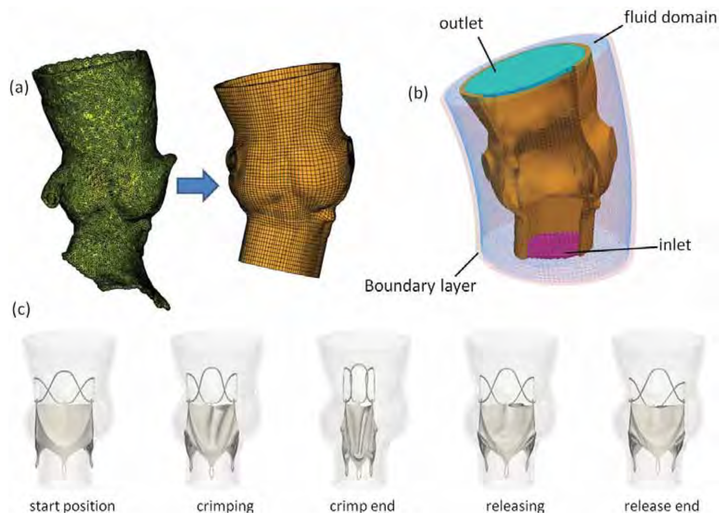


a) Stented valve and corresponding model; b) The stented valve inserted in a testing compartment and the corresponding model; c) FSI model including the valve, the compartment and the inlet, outlet and fluid domain

CVE FT-2 accelerated durability test system

FSI model for patient-specific case

The aortic root model was created based on 3D anatomy of stereo lithography (STL) format, which was reconstructed from CT images.

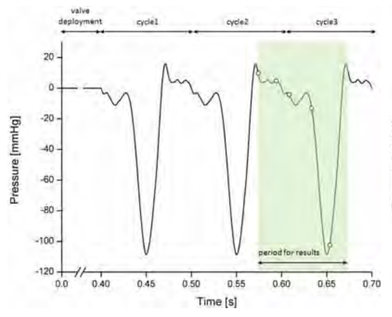


a) Anatomy of the aortic root of the patient-specific case and meshed model; b) FSI model with inlet, outlet, fluid domain and the boundary layer; c) the deployment procedure of the valve into the aortic root

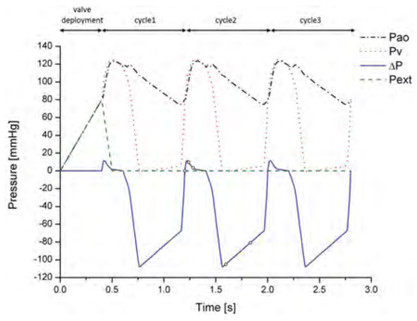
Boundary conditions and FSI coupling

The pressure upstream during in-vitro test and pressure tracings were applied for the FSI model of in-vitro and patient specific case, respectively. After the valve deployment, three cycles were run for both cases to ensure the stable simulation.

Fluid-structure coupling was set up between the fluid and the leaflets plus compartment (in-vitro case); and the fluid and the leaflets plus aortic root (patient specific case).



Pressure of upstream during the in vitro test imposed as boundary condition at the inlet section

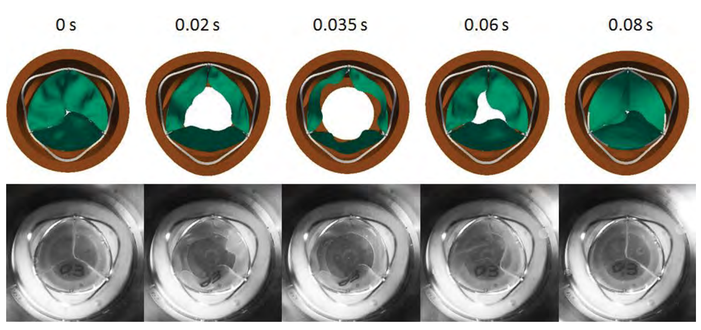


Aortic (ao), ventricular (v) and extramural (ext) pressure tracings used in the patient-specific FSI simulation

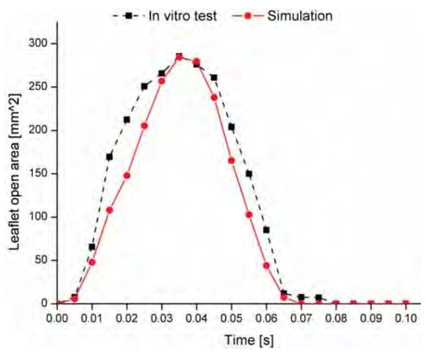
Results

Computational and experimental results for the in vitro case

The FSI simulation reflected leaflet kinematics similar to the experiment, and the difference of opening area between simulation and experiment was 0.42% at the time of maximum opening.

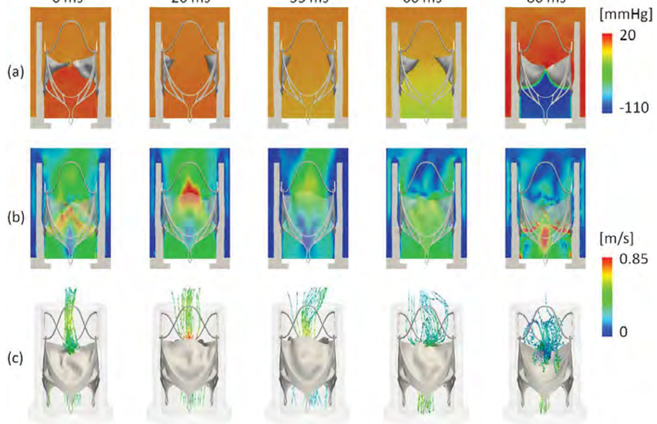


Top views of the valve kinematics at five time instants for the FSI simulation (top) and the in vitro test (bottom).

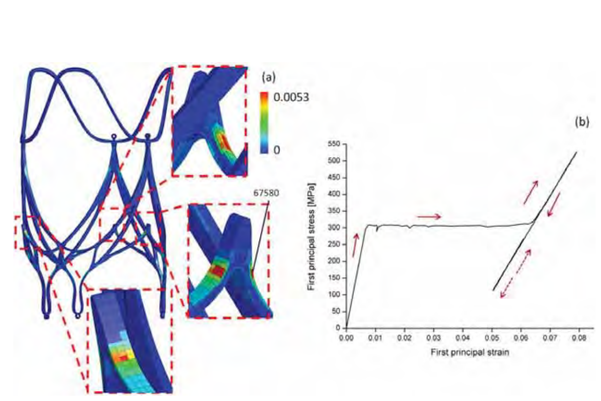


Leaflet open areas of the in vitro test and the FSI simulation in the period of 0.1 second.

From the FSI simulation, fluid pressure distribution, velocity magnitude, and pathline with respect to velocity can also be evaluated. These results provide a clear indication how the fluid part was interacting with the structural part. Furthermore, the strain-stress changes of the stent frame can be followed and the distribution of the strain amplitude in stent can be calculated.



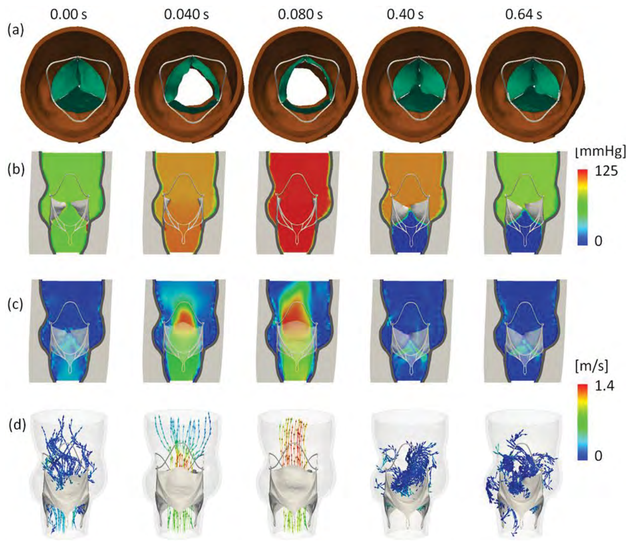
Pressure (a) and velocity (b) contour maps of the in vitro FSI simulation. Pathlines colored with respect to velocities are also reported (c).



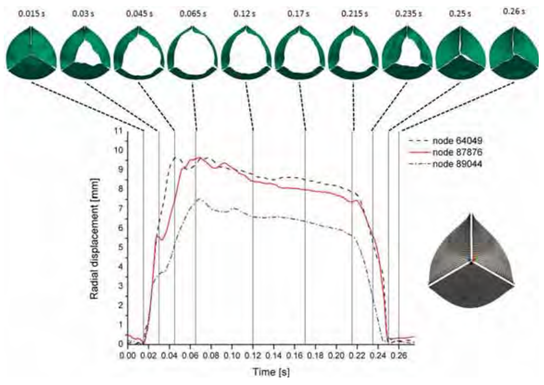
(a)Alternate strain distribution in the stent frame; (b) element 67580 was chosen to show its strain-stress changes during the whole simulation. The dashed arrows indicate the fatigue cycles.

Computational results for the patient-specific case

FSI simulation predicted the leaflet kinetics, blood pressure, velocity magnitude after the valve was implanted into the aorta root. In particular, the simulation evaluated the rapid leaflet open/close time, which is close to the data from in vivo test.



FSI patient-specific case: a) valve kinematics; b) pressure and (c) velocity contour maps; (d) pathlines colored with respect to velocities



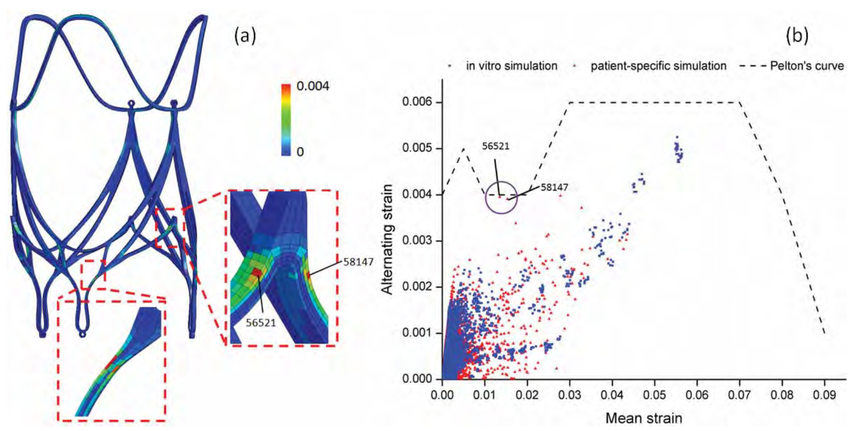
RVOT, RVCT and ET calculated by FSI simulation and measured in vivo

	Node 89044	Node 87876	Node 64049	Average of three nodes	In vivo data
RVOT [ms]	44	53	32	43	43.6±11.6
RVCT [ms]	32	31	31	31.3	31.5±8.8
ET [ms]	232	235	236	234	254±54

ET: ejection time; RVOT: rapid valve opening time; RVCT: rapid valve closing time.

Detailed leaflet kinematics during systolic indicated radial displacement and deformation of the leaflets. The table sums the rapid open/close time and compares them to literature data

Finally the strain amplitudes were calculated and compared to those of in vitro test. The differences between the two cases suggest that in vitro tests following standard might not represent the real behavior of the percutaneous valve.



Alternate strain distribution in the stent frame (a) and constant life diagram of the valve for both cases (b). The circle indicates two elements in the patient specific case are near the fatigue limit

Conclusions

The methods developed represent useful tools in determining design errors or optimization potentials before the fabrication of prototypes and the performance of tests. They thereby help advance the technology of TAVR and make it safer, which will be crucial to lower risk patients.