Patient-specific finite element analysis of transcatheter aortic valve implantation

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Abstract. *Aortic valve stenosis represents an important public health problem which can be treated through transcatheter aortic valve implantation. Being a quite recent technology, many aspects related to such a minimally-invasive procedure need further investigation (e.g., paravalvular leakage). The well-established finite element method represents a possible technology to study such aspects within a virtual computer-based framework. Herein, we propose a patient-specific study which includes native leaflets and calcifications with the goal of evaluating the postoperative performance of the implanted prosthetic valve.*

Keywords: aortic valve; TAVI; patient-specific modeling; finite element analysis.

1 INTRODUCTION

Calcific aortic stenosis (AS) is a common aortic valve disorder [1], especially in elder patients, inducing a narrowing of the aortic valve opening. The impact of such a cardiovascular disease is constantly increasing due to higher life expectancy and population average age [2].
In the last decade, a minimally-invasive therapeutic option, called transcatheter aortic valve implantation (TAVI), has become a valuable alternative to open-heart surgery for the treatment of AS [3, 4]. It consists in the delivery and positioning of an aortic valve prosthesis, made of a biological valve sewn into a metallic frame, over the stenotic native valve.
As for other minimally-invasive procedures, the clinical outcomes are strictly related to patient selection, operator skills, and dedicated pre-procedural planning based on accurate medical imaging and analysis [5].
Moving from such considerations, the present work proposes a systematic approach to realistically simulate TAVI, tailored to the clinical practice; in particular, we propose a study, based on the analysis of pre-operative medical images of two real patients who underwent TAVI, with the final aim of predicting the post-operative performance of the prosthesis depending on to the specific anatomical features. The present work represents a step forward with respect to the current state of the art, addressing novel issues and considering the following innovative aspects: i) the aortic valve model is complete of both the aortic sinuses and the native valve leaflets, ii) the calcific plaque is also included within the model on the basis of imaging data, iii) the geometry of the prosthetic stent is very accurate, being obtained from micro-CT reconstruction.

2 METHODS

Two patients are recruited for the present study, both with severe symptomatic aortic stenosis. In both cases, the preoperative planning is based on CT examinations performed using a dual-source computed tomography scanner. For both patients the Edwards SAPIEN XT size 26 has been selected by physicians as the optimal device for implantation.

2.1 Modeling of the native aortic valve

The CT data sets are processed using ITK-Snap v2.4 [6] in order to highlight both the aortic lumen and the calcific regions. In particular, the aortic lumen data can be extracted as STL (stereolitographic) file and elaborated to obtain a suitable mesh for finite element analysis. Native leaflets can be then geometrically reconstructed within the obtained aortic root anatomy by integrating CT information of the attachment lines and ultrasound measurements of the leaflet free margins. Finally, the whole aortic valve model can be overlapped with the calcium regions extracted from CT images so that specific section and material properties (associated with calcium) can be assigned to the elements of the native leaflets intersecting real calcifications (see Figure 1).

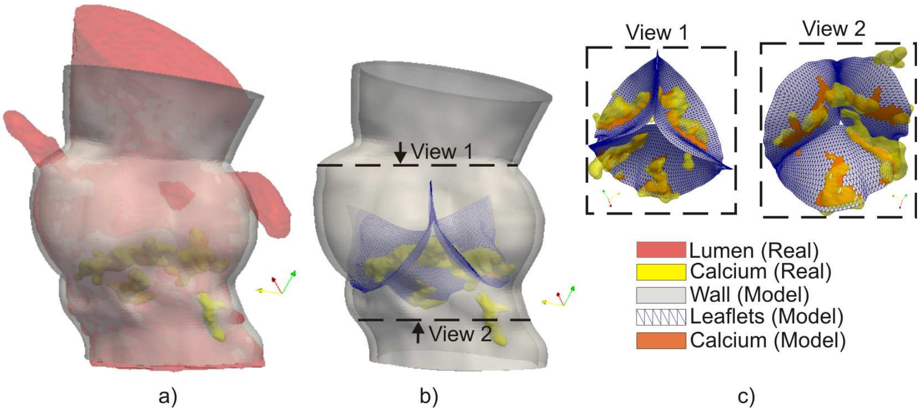

Figure 1: Rendering of the STL file vs aortic model created for simulations: a) the real aortic root lumen (red) and calcifications (yellow) are overlapped to the aortic wall model (grey); b) the closed native leaflets (blue mesh) of our model are perfectly matching with real calcifications obtained by processing CT images; c) top and bottom views are shown.

The aortic wall model of *Patient 1* is meshed using 265976 tetrahedral elements for the healthy region and 2936 for the calcific part while the leaflets are discretized using 3212 shell elements with reduced integration for the healthy tissue and 427 for the calcific region.
The aortic wall model of *Patient 2* is completely calcium-free because all the calcifications are localized in the leaflets. The model is meshed using 135558 tetrahedral elements; the healthy tissue of the leaflets is discretized using 3258 shell elements with reduced integration (S4R) while for the calcific plaque 342 elements are used.
For the sake of simplicity, all material models are assumed to be isotropic and homogenous. In particular, an elastic modulus of 8 MPa and a density of 1100 kg/m^3 are assigned to the leaflet tissue while the aortic root wall is modeled with a modulus and density of 2 MPa and 2000 kg/m^3, respectively [7]; moreover, for all healthy tissues, a Poisson ratio of 0.45 is adopted. Aortic wall and native valve leaflets are assumed to be 2.5 and 0.5 mm thick, respectively [8]. The plaque is assumed to be characterized by an elastic modulus of 10 MPa, a Poisson ratio of 0.35, and a density of 2000 kg/m^3,; the thickness of calcific shell elements is chosen equal to 1.4 mm [9].

2.2 Modeling of the Edwards SAPIEN prosthesis

As previously stated, both patients were treated with an Edwards Lifesciences SAPIEN XT size 26. A faithful geometrical model of this device is based on a high-resolution micro-CT scan of a real device sample, extracted during a failed surgical procedure. The obtained stent model is meshed using 84435 solid elements with reduced integration. A Von Mises plasticity model with an isotropic hardening is adopted for the stent material with the following parameters: density of 8000 kg/m^3, Young modulus of 196000 MPa, yield stress of 375 MPa, and Poisson ration of 0.3 [8].

2.3 Finite element simulations

The TAVI procedures is a complex intervention composed by several steps; to realistically reproduce the whole procedure, we set-up a simulation strategy consisting in the following two main stages:

a. stent crimping and deployment: in this step, the prosthesis stent model is crimped to achieve the catheter diameter which, for a transapical approach, is usually 24 French (8 mm); then, the prosthetic stent is expanded within the patient-specific aortic root to reproduce the implantation due to balloon expansion;

b. valve mapping and closure: the prosthetic leaflets are mapped onto the implanted stent and a physiological pressure of 0.01 MPa is applied to virtually recreate the diastolic behavior of the SAPIEN device, as already discussed in [8].

All the analyses are performed using Abaqus/Explicit v6.10 (Simulia, Dassáult Systems, Providence, RI, USA). In Figure 2 the main procedural steps of TAVI simulation are shown.

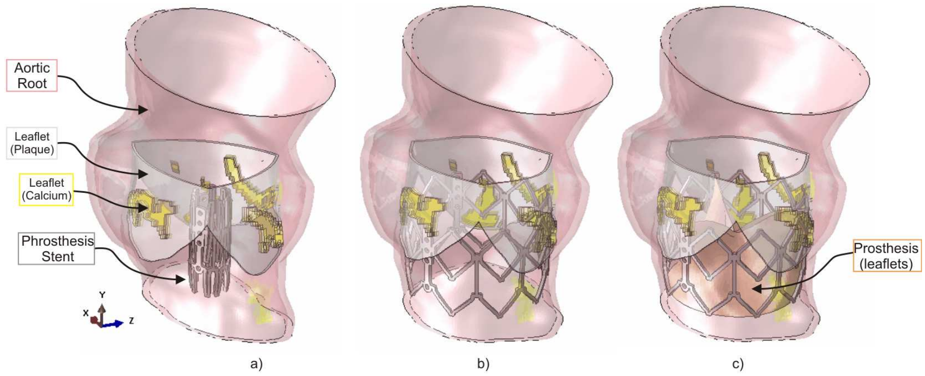

Figure 2: Procedural steps of TAVI reproduced through a simulation strategy: a) the crimped stent is properly placed inside the aortic root model; b) the stent is expanded within the patient-specific aortic root; c) prosthetic leaflet closure is reproduced to evaluate postoperative performance.

3 RESULTS

The simulation of stent crimping and deployment allows the computation of the aortic root configuration change induced by prosthesis apposition and the associated stress distribution; through the second stage of simulation (i.e., valve mapping and closure), we may evaluate the competence of the prosthesis leaflets. In this manner, we have a computer-based tool able to quantitatively provide clinically relevant patient-specific information of the TAVI performance. In particular, we can evaluate: i) diameter variation of the aortic virtual ring; ii) distribution of aortic wall stress during the prosthesis deployment; iii) risk of paravalvular leakage (see Figure 3); iv) coaptation of the prosthetic leaflets.

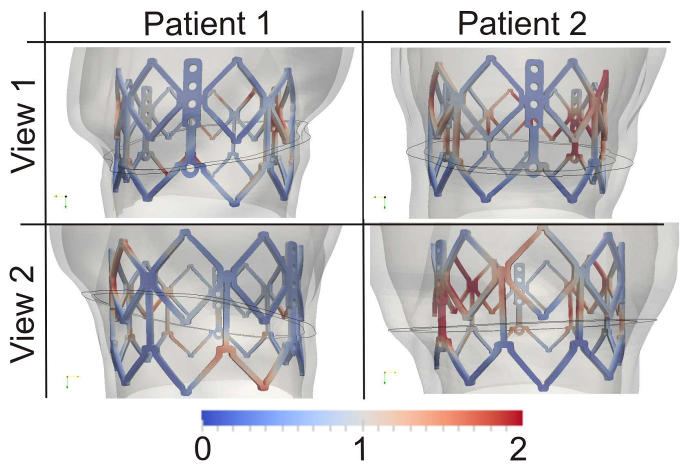

Figure 3: Evaluation of the degree of apposition between the prosthesis stent and the patient-specific root anatomy: a contour plot of the distance [mm] between the aortic wall and the prosthetic stent is represented.

4 CONCLUSIONS

We believe that, with the present study, a step forward in the direction of creating a computational tool able to support TAVI preoperative planning has been addressed. Patient-specific finite element analyses including native leaflets and calcifications and considering realistic prosthetic models may give useful clinical information to guide the surgeon towards an optimal operation choice.

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