PATIENT-SPECIFIC MATERIAL CALIBRATION OF TAVI PATIENTS

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Introduction

As a result of the success of transcatheter aortic valve implantation (TAVI), several complex and accurate in-silico models have been implemented to model this treatment and therefore to assess its structural and hemodynamic consequences. However, the actual material properties of anatomical parts remain unknown and uncertain. This study seeks to provide a calibration of patient-specific constitutive parameters for both the aortic wall and calcific aortic valve using an inverse analysis and electrocardiogram-gated computed tomography (ECG-gated CT) images.

Methods

Finite Element (FE) models were developed for a group of n.20 patients underwent TAVI with the SAPIEN 3 Ultra transcatheter heart valve (Edwards Lifesciences, USA) with Abaqus\Explicit solver (v.2021hf7, Dassault Systèmes, FR). For each patient CT scans at diastolic phase were segmented in Mimics software (Mimics Innovation Suite v.22, Materialise, BE) to reconstruct the LVOT geometry, calcific plaques, and aortic wall [1]. Given the undetectability of aortic valve leaflets, they were shaped according to a parametric model based on anatomic measurement and landmarks using Rhino software (v.7.1, McNeel & associates, USA) [2]. The inverse approach adopts a quadratic regression model to link the input variables (i.e., the material properties) to the output variables. The regression model consisted of an optimization algorithm to minimize the difference between predicted and CT-based measurements. Specifically, the output variables of interest for the aortic wall and the calcified valve were the peak systolic strain of the aortic root and orifice valve area, respectively. Assuming linear elastic material behaviors for both the aortic wall and orifice area, the Young's modulus is the only parameters to investigate, as the Poisson's coefficient was fixed to 0.475 to account of an incompressible material [3].

For each patient, n.10 simulations of the cardiac beat were carried out varying each time randomly the material properties in their interval of definition [0.8-10 MPa]. For each simulation, the systolic strains (NE) and the nodal coordinates of valve free edges were automatically exported using python scripts. The orifice valve area was then calculated into the Grasshopper plug-in of Rhinoceros. As the solution can lead to two different optimized material parameter sets, the Young's moduli were selected from the solution falling in the interval definition. If both values were contained in the range, these were averaged.

Results and Discussion

Aortic valve leaflets were found to have a stiff behavior with elastic modulus of 10.8±3.0 MPa, and this is likely caused by the constraining effect of embedded calcifications in severe stenosis condition. The aortic wall behavior was characterized by an elastic modulus of 5.9±3 MPa, also suggesting a stiff behavior of the aorta as compared to literature data when the aortic wall is assumed as linear elastic.

Once the optimal material parameters were achieved, a new analysis was carried out for each patient using the optimized material properties. For the aortic wall, the deformed shape was exported and compared to that from the CT images at systole. The root mean square error (RMSE) was used to quantify the difference between model predictions and CT images. The relative errors for the aortic wall were in the range of 8.6% to 13.6 % with more marked differences in the distal LVOT than in the sinus and ascending aorta. Not any statistical difference was observed between predictions and CT-based measurements ($p=0.145$). The relative errors for the valve between predictions and CT-based measurements were in the range of 0.08% to 11.86%, suggesting a realistic evaluation of the biomechanical response of the stenotic aortic valve.

Given the elderly population of patients undergoing TAVI, the current ex-vivo material descriptors reported in literature are not suitable. In this setting, the major novelty of this study is the development of a non-invasive inverse approach for the assessment of reliable material properties for the aortic root of patients with severe aortic valve stenosis.

Though a linear elastic material behavior was assumed, the present inverse analysis can be extended to the assessment of multiple materials descriptors and thus complex constitutive relationship.

Overall, numerical simulations of the pre-TAVI scenario here presented were found in agreement with CT imaging, thereby leading to a robust non-invasive approach for in-vivo assessment of material properties that could enhance the prediction of TAVI in-silico models.

References

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