Impact of leaflets solid elements discretization on patient-specific aortic root FE models biomechanics

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***Abstract*— Finite element models (FEMs) have been widely used to quantify aortic root (AR) biomechanics and its role in several pathologies. Among these, the progression of aortic valve calcification represents a particularly relevant condition.**
In this context, the discretization of the valve leaflets has a key role; in the literature, shell elements are typically used, but a more reliable computation of leaflet stresses might be obtained through the use of solid elements.
To compare these two discretization approaches, we implemented a semi-automated tool for the generation of image-based aortic root FEMs; the tool allows for discretizing the valve leaflets using shell or solid hexahedral elements, and for setting space-dependent patterns of leaflets thickness for solid leaflets. The ARs of three healthy subjects were modeled, and their biomechanics throughout the cardiac cycle were computed.
Results highlighted that the use of solid elements leads to a more reliable quantification of leaflets stresses and that the local leaflet thickness strongly influences stresses patterns.

***Keywords*— Finite element biomechanical model, aortic root, cMRI, aortic valve leaflets**

I. Introduction

THE aortic root (AR) is the functional and anatomical unit connecting the outlet of left ventricle to the ascending aorta. It includes the aortic valve (AV), the Valsalva sinuses, the aortic annulus, the sino-tubular junction (STJ), the interleaflets triangles and the proximal ascending aorta. To better understand AR structural mechanics and its role into AR pathophysiology, different finite element models (FEMs) have been proposed in the scientific literature. Most of these use shell elements to discretize the geometry of AV leaflets, although this approach likely limits the detailed insight into leaflet stress distribution and into its role in the progression of clinically relevant pathological conditions, such as calcific AV disease. The discretization of AV into solid elements was proposed only by few numerical studies, and its impact on computed leaflet stresses was never investigated. In this scenario, we generated the FEM of a small set of healthy ARs based on medical imaging, and computed AR biomechanics throughout the cardiac cycle. For each FEM, two variants were generated, which were characterized by the use of shell and solid elements, respectively, to discretize AV geometry.

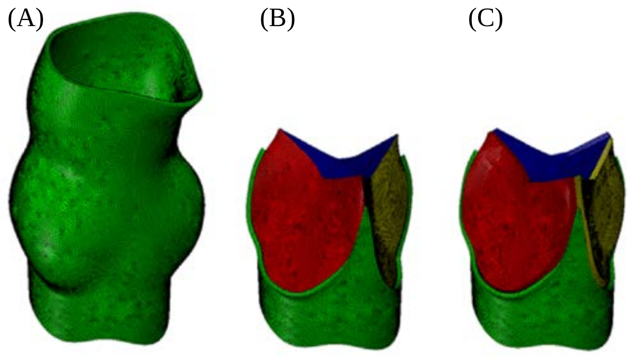
II. Material and methods

A. Acquisition of cMRI data and segmentation

Cardiac MRI was performed on 3 healthy volunteers. T1-weighted cine-cMRI sequences were acquired on 18 planes evenly rotated around the axis passing through the center of the annulus and the center of the sino-tubular junction. Acquisitions were performed on a 1.5 T Achieva scanner (Philips Healthcare Medical System, Irvine, Calif). In-plane spatial resolution and slice thickness were 1.1 mm and 7 mm, respectively. Thirty frames/cardiac cycle were acquired with R-wave triggering. In the first systolic frame, when the transvalvular pressure acting on AV leaflets was considered negligible [2], AR substructures were manually traced through in house Matlab© scripts.

B. Reconstruction and discretization of AR geometry

Through in house Matlab© scripts, AR 3D geometry was obtained a point-cloud, which was filtered to eliminate noise effects. A 3D surface for each AR structure was created and discretized with quadrangular shell elements.



In Figure 1, A) full volume mesh of the aortic wall, B) AV shell model, C) AV solid model. Data are shown for subject 1.

The full volume mesh for the aortic wall was created by extruding the shell element along the local outward normal to generate three layers of hexahedral solid elements with a cumulative thickness of 1.0 mm (Figure 1A).
The AV leaflets shell model was generated by assigning a virtual homogeneous thickness of 0.8 mm to the leaflet shell elements. The AV solid model was obtained through a complex extrusion process to obtain three layers of hexahedral solid elements through the leaflet thickness (Figure 1C). The latter was region-dependent (1.2 mm for the attachment edge and the free margin, 0.3 mm for the belly region), as in [3].

C. Tissues mechanical properties

The mechanical response of the aortic wall was assumed linear, elastic and isotropic, with a 2 MPa Young's modulus and a 0.45 Poisson's ratio. AV leaflets tissue was described as a transversely anisotropic and hyperelastic material using the model originally proposed by Guccione [4]; the model parameters were identified by least square fitting of experimental data from biaxial tensile tests by Billiar and Sacks [5] [6]. The constitutive model was implemented into a VUMAT subroutine for ABAQUS/Explicit©.

D. Computation of aortic wall pre-stresses

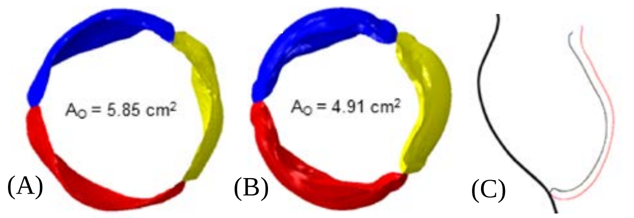
The initial configuration of the AR was defined at early systole, when AV leaflets are approximately unloaded, but the aortic wall is pressurized to 80 mmHg. Consistently, aortic wall pre-stresses were computed through the iterative process described in detail in a recent work by Votta [7].

E. Computation of AR biomechanics

The structural response of the pre-stressed AR over two consecutive cardiac cycles was computed; to this aim, physiological time-dependent ventricular and aortic pressures were applied to the aortic wall upstream from and downstream of the AV, respectively, and a consistent trans-valvular pressure drop was applied to the AV leaflets.

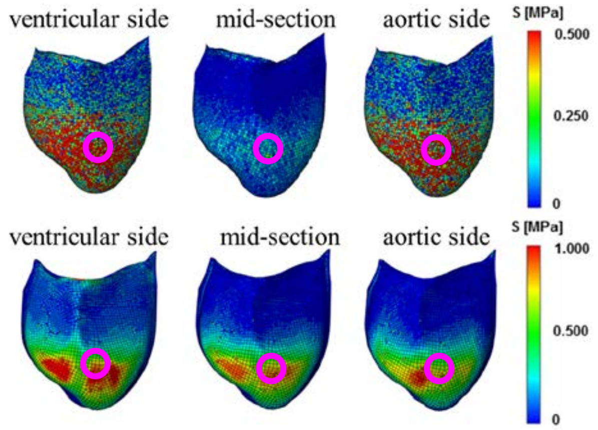
III. RESULTS AND DISCUSSION

AV kinematics as computed by the solid and the shell models were compared. When shell elements were used, leaflets were allowed for wide local rotations at their insertion onto the aortic wall, which behaved as a sort of spherical joint. When solid elements were used, the connection behaved as a deformable encastre, preventing from free rotations. In systole, this effect reflected into a reduced outward motion of the solid leaflet, and hence into a smaller orifice area at peak systole (Figure 2A, 2B). At peak diastole, this effect reflected into a different leaflets profile: when shell elements were used, AV leaflets tended to prolapse (Figure 2C).



In Figure 2, A) shell and B) solid orifice area at peak systole; C) left coronary leaflet profile at peak diastole (red = shell, black = solid). Data are shown for subject 1.

AV mechanical response during the cardiac cycle was evaluated through the analysis of the circumferential stresses on the ventricular and atrial side of the leaflets, as well at their mid-section. Shell models (Figure 3, first line) showed a patchy distribution, in particular on the two AV sides, without a clear separation between the belly region and the cooptation area, and marked differences, up to 981 kPa, were detected between the ventricular and aortic sides (Table I). Conversely, in the solid elements models (Figure 3, second line) the distribution was much smoother and a gradual trend over the three considered layers was visible. Computed stresses values also proved the strong impact of the thickness modulation; in particular, max principal, radial and circumferential stresses were notably increased in the solid thinned belly region as compared to the corresponding value for constant thickness shell models.



In Figure 3, circumferential stress patterns on the ventricular side, mid-section and aortic side for the shell model (first line) and solid model (second line). Data are shown for subject 1. The pink circles highlight the region where values in Table 1 were obtained.

CIRCUMFERENTIAL STRESSES IN THE BELLY REGION

location	*Subject 1*		*Subject 2*		*Subject 3*	
	shell	*solid*	*shell*	*solid*	*shell*	*solid*
V side	0.526	0.770	0.480	0.851	1.054	1.108
Mid-section	0.096	0.640	0.078	0.758	0.073	0.995
A side	0.169	0.548	0.351	0.682	0.497	0.909

In Table I, circumferential stresses (MPa) in the belly region. Values were obtained through averaging over the region highlighted in Figure 3.

IV. CONCLUSION

Computed results highlighted that the use of solid elements has a major impact on AV kinematics, and leads to a more reliable quantification of leaflet stresses and of the associated variations through the leaflet thickness. Moreover, it was evident that leaflet stresses strongly depend on the local leaflet thickness, thus suggesting that in the context of patient-specific modeling a reliable quantification of the patient-specific tissue thickness distribution should be mandatory.

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