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PERSONALIZED FSI-MODELING OF THE AORTIC BULB AND ARCH TO PREDICT ITS MECHANICAL BEHAVIOR AND ASSESS THE LOADS DURING THE CARDIAC CYCLE

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ABSTRACT — The interaction of the blood flow with the aorta is a complex dynamic event described in biomechanics as the Fluid-structure interaction. In this study we've developed a method for creation of a personalized 3D dynamic model of the aortic bulb and arch for the prediction of its mechanical behavior using FSI-analysis. We found that the accuracy of predicting geometric aortic deformities based on FSI modeling is on average 92%.

KEYWORDS — aorta, aortic valve, hemodynamics, FSI-modeling.

RELEVANCE

The interaction of the blood flow with the aorta is a complex dynamic event described in biomechanics as the interaction of a fluid and a deformable body (Fluid-structure interaction or FSI). The existing methods of in vivo visualization and quantitative analysis in silico allow us to model these processes in order to study the pathogenesis of diseases of the cardiovascular system, predict risks and plan surgical interventions [1]. The FSI method is widely used for numerical modeling of the blood-vessel interaction [2, 3, 4]. It combines the methods of computational fluid dynamics and structural (dynamic) analysis. Today, FSI is widely used in predicting the risks of aneurysms and their ruptures. Previously, no attempts have been made to study changes in the biomechanical properties of the aorta in aortic valve stenosis using personalized FSI modeling based on MSCT data.

Aim: to create a personalized FSI model of the patient's aortic segment and then to evaluate its mechanical behavior during the cardiac cycle.

MATERIALS AND METHODS

Functional MSCT-coronarography data were used to model the aortic segment. Based on these data, in the InobitekDicom Viewer software, a multiplanar reconstruction of the zone of interest was generated, including the anatomical structures of the heart and aorta. For the aortic valve, the ascending aorta, and the aortic arch, routine segmentation was performed in three projections. From the resulting set of contours, a three-dimensional model was created, which was then converted into a polygonal STL model (Fig. 1).

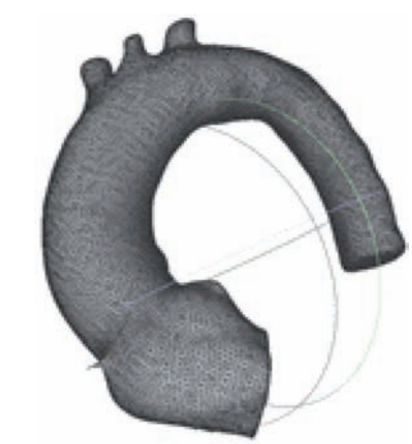

Fig. 1. *STL model of the zone of interest*

Editing and reverse engineering of the STL model was performed in the SolidWorks software. The aortic wall and its root were generated using the SW ScanTo3D utility. The valves and commissures of the aortic valve were modeled using standard SW tools.

The CAD model of the zone includes the structures of the aorta, the fibrous ring, the valves, commissures and sinuses of the Valsalva (Fig. 2).

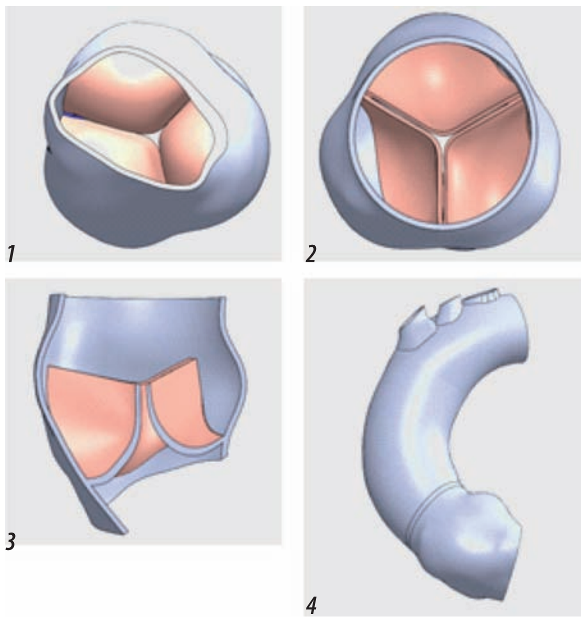

***Fig. 2.** Aortic valve model: 1 — bottom view, 2 — top view, 3 — split view, 4 — full CAD model*

Preprocessing of the CAD model for FSI analysis was performed in HyperMesh software. The calculated KE-grid was generated taking into account the anatomical and morphological features of the aortic wall.

The resulting CE model was imported as an orphan grid in Abaqus CAE to set the mechanical properties of the materials and set the boundary conditions for the biomechanical analysis of the model. To optimize the computational load, we introduced the following boundary conditions: the model is fixed (Fig. 3) at the entrance (the plane of the sinotubular junction of the aorta) and at the exit of the blood flow (in the area of the brachiocephalic trunk, the left common carotid artery and the left subclavian artery) in 4 nodes located in the centers of the above areas.

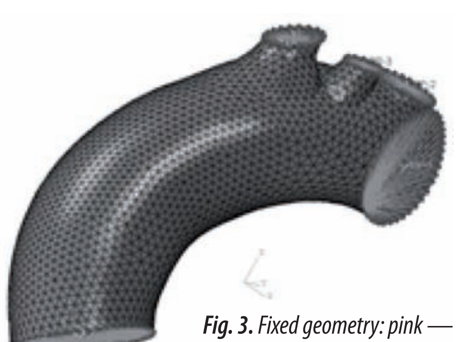

***Fig. 3.** Fixed geometry: pink — connected elements of the aortic wall without restrictions of degrees of freedom, the intersection of yellow lines — a node with a fixed geometry*

Each node is connected by the condition of the continuum distribution with the elements of the aortic wall in the planes of sections at the entrance and exit, without limiting the degrees of freedom of the connected elements. In the area of the border of the arch and the descending part of the aorta, the model is fixed in the area of the arterial ligament with the condition of the distribution of the continuum with the elements of the aortic wall in the cross-sectional plane without limiting the degrees of freedom of the connected elements.

The blood flow is specified as laminar, the flow rate at the peak of the systole is v = 1.2 m/s (Fig. 4) [5], the flow input is the entire area in the plane of the sinotubular junction of the aorta, the output is the areas of the brachiocephalic trunk, the left common carotid artery, the left subclavian artery, the border of the arch and the descending aorta (outlet pressure P = 0).

The connection condition (FSI) between the aorta and the fluid was set by the Fluid-Structure Co-simulation boundary parameter. This parameter describes the interaction between the Computational Fluid Dynamics (CFD) module and the Abaqus CAE Implicit Dynamic Analysis (Dynamic/Implicit) module. The choice of the Dynamic/Implicit module is based on the hypothesis of small deformations in the simulated segment, which eliminates the need to use adaptive meshes.

For the subsequent formulation of the FSI problem, the flow region was modeled. The final grid of finite elements for aortic structures consists of 32109 tetrahedral elements, for the flow region (blood) — 34999 tetrahedral elements. To model the anisotropic properties of aortic structures, we used the Holzapfel-Gasser-Ogden (HGO) anisotropic material model. To evaluate the proposed model, an FSI analysis of the aortic segment, including the ascending section and the aortic arch, was performed during systole (normal). The results of the analysis were compared with the MSCT data and analyzed by the expert control method. In this paper, the model adequacy criteria were taken as the deformed states of the FSI model, which were compared with the displacements on the MSCT at the corresponding moments of the systole. Aortic valve stenosis was modeled by changing the area and peak flow rate during systole at the model inlet.

RESULTS

For the validation model, Mises displacement, pressure, and stress plots were obtained for the aortic

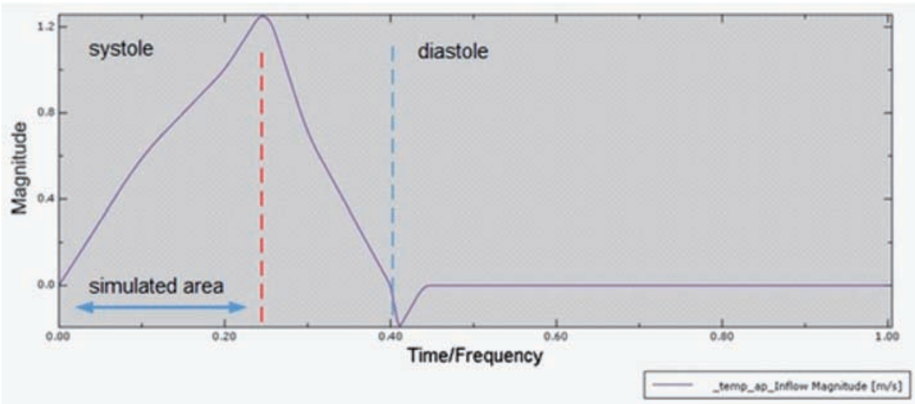

Fig. 4. *Graph of changes in the flow rate during the cardiac cycle. The simulated area is 0.23 seconds from the beginning to the peak of the systole*

wall. Changes in the blood flow characteristics in the model are described. All initial conditions were modeled for systole at time t = 0 in accordance with the MSCT data at the same time. The FSI analysis made it possible to predict the behavior of the aortic wall during a systole lasting 0.23 seconds. The prediction result (displacement) was compared with the MSCT at time t = 0.1 s, and t = 0.23 c corresponding to the peak of systole (Fig. 5).

the 3D reconstruction of the MSCT for the corresponding time points. The overlay of each STL-grid was carried out by means of rigid registration of images based on the intensity (Fig. 6).

The IoU coefficient for the volume model was calculated as the arithmetic mean IoU of all 2D images. The maximum value of the coefficient for the two forecasts of the FSI model is 0.96, and the minimum value is 0.73. The average IoU value for the two models

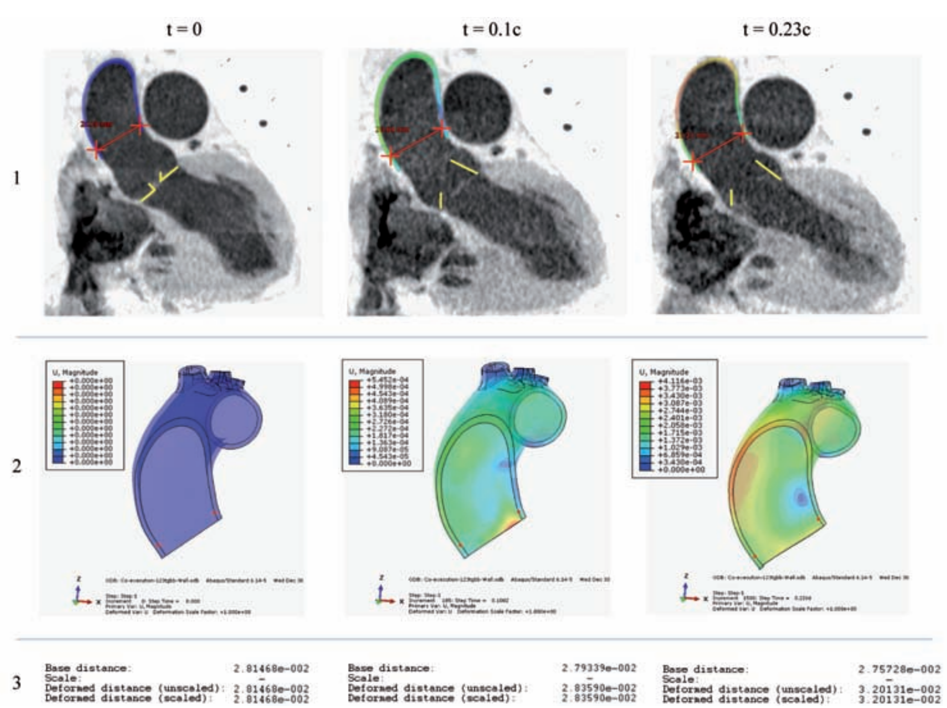

Fig. 5. *Plots of movements in meters (line 2) at the corresponding moment*

We investigated the geometric deviations of the FSI simulation from the MSCT data by superimposing and analyzing the STL meshes extracted from the solver output file at time t = 0, t = 0.1 c, t = 0.23 c, on

was 0.92. Figure 7 shows the Mises stress plots (1), the pressure distribution along the aortic wall (2), and the flow characteristics at the peak of systole t = 0.23 s (3) in normal, predicted by FSI modeling.

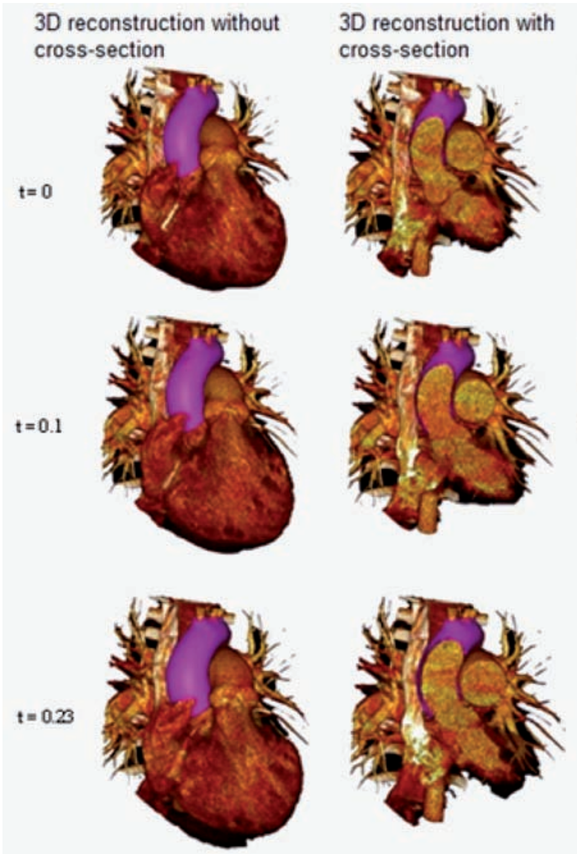

Fig. 6. *MSCT-FSI combined 3D reconstructions. The deformed STL meshes are highlighted in pink. The anatomical structures of MSCT reconstruction are encoded by a soft tissue imaging filter*

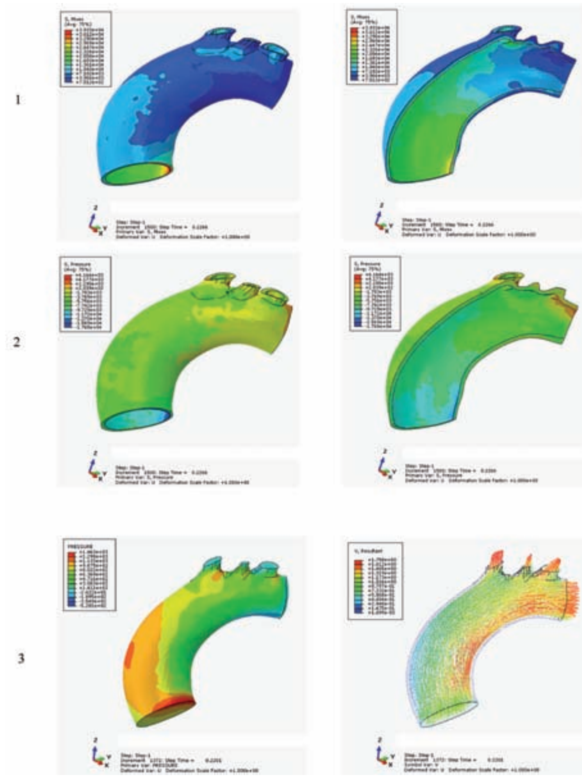

Fig. 7. *Prediction of hemodynamics and mechanical behavior of the aorta in normal conditions*

CONCLUSION

We established that the accuracy of predicting geometric aortic deformities based on FSI modeling is on average 92%. The results of modeling using the proposed methods do not contradict the previously obtained data in silico. The predicted deformed states correspond well to the in vivo data.

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