3D patient-specific computational simulation of aortic root based on finite element method

In case of heart malformations, complex changes in left ventricular geometry are in most cases caused by continuous exposure to cardiovascular risk factors and/or hemodynamic conditions, which usually start as a physiological response. Altered cardiac work and associated aortic stenosis, aortic root dilatation, valvular malformations such as Bicuspid Aortic Valve (BAV), are commonly related with significant morbidity, mortality and healthcare costs. The presented study gives the insight into the model-based simulation of cardiac cycle and aortic root with bicuspid valve, employing the in-house finite element PAK software and aims to propose an advanced approach for the assessment of biomechanical characteristics (stresses, pressures, displacements) based on computational modelling. The structural and computational fluid dynamics (CFD) analysis is performed on the three-dimensional (3D) patient-specific model of aortic root with BAV, by applying equivalent material characteristics and boundary conditions. The Computed Tomography (CT) scan images are segmented in order to obtain the 3D finite element mesh. The initial results for this single case, displacements and Von Mises stress distribution (for structural analysis), as well as shear stress and pressure distribution (for CFD analysis) were quantified concerning anatomical patient's structures. The regions of abnormal stresses on the aortic leaflets and annulus, with asymmetrically open bicuspid valve, were related to the increased pressures and shear stresses and analyzed for this patient-specific case. Due to the difficulties in obtaining such characteristics *in vitro* or *in vivo*, the performed computational analysis gave better insight into the biomechanics of the aortic root with BAV that is needed to achieve improvements in surgical repair techniques and presurgical planning.

Keywords: Patient-specific model, aortic root, bicuspid valve, computational modelling, finite element method

1. Motivation

In case of heart malformations, complex changes in left ventricular geometry and connected aortic structures are in most cases caused by continuous exposure to cardiovascular risk factors and/or hemodynamic conditions, which usually start as a physiological response. Altered cardiac work, associated with aortic stenosis and Bicuspid Aortic Valve (BAV) is commonly related with significant morbidity, mortality and healthcare costs. Early detection of these malformations is very important because heart maintains its flow at the cost of increased pressure initiating pathophysiological processes that lead to unfavorable clinical outcomes [1]. Moreover, aortic stenosis affecting a bicuspid aortic valve (BAV) is the most common indication for surgical aortic valve replacement in patients <70 years of age.

There are various diagnostic techniques of aortic stenosis, BAV and associated heart malformations, such as Echocardiography, Computed Tomography and Magnetic Resonance Imaging. After obtaining the images using some of the above-mentioned techniques, additional analysis can be performed in terms of image processing, feature extraction and 3D model creation. The segmentation of individual patient-specific anatomy can be used for more detailed and faster analysis of the patient, as well as for building up the patient-specific models for computational CFD, and/or structural simulations. The main aim of this work is to perform computational simulation of three-dimensional (3D) BAV by employing patient-specific Finite Element (FE) analysis to and analyze and visualize the related biomechanical characteristics (stresses, pressures, and displacements).

2. Research questions

In the era of personalized medicine, early and accurate prediction of individuals at high risk of cardiomyopathies would allow preventive, therapeutic, or surgical measures to be applied to the patient before any of life-threatening events take place. It is therefore important to develop computational techniques that can contribute in the 3D patient-specific and personalized analysis of individuals and high risk.

In the previous studies of BAV considering FE analysis, the complex motion of the aortic leaflets during a cardiac cycle had been computed, identifying the regions of stress concentrations in the valvular structure. From the hemodynamics point of view, the altered aortic valve anatomy is a key factor in pathological flow characteristics which causes the aortic wall degradation [2]. In addition, there is strong evidence that BAV influences flow conditions in the ascending aorta [3], which consequently have impact on pathological shear stress and wall pressure profiles. The shear stress and pressure alterations form normal patterns may be considered as important trigger factors for a degenerative process in the aortic wall structures. Due to the difficulties in obtaining such characteristics *in vitro* or *in vivo*, this computational analysis may have impact on personalized medicine, patient risk assessment and better preparedness for surgical treatments.

3. Methodology

The presented study gives the insight into the model-based simulation of aortic root with BAV, employing the in-house finite element PAK software and aims to propose an advanced approach for the assessment of biomechanical characteristics (stresses, pressures, displacements) based on computational modelling. The 3D patient-specific geometry of aortic root with BAV was reconstructed based on Computed Tomography (CT) scan images, in order to obtain the 3D finite element mesh. The complex anatomy of aortic root requires detailed segmentation in order to capture all substructures of patient-specific geometry, as altered geometry affects the biomechanical parameters.

Two types of analyses: i) structural analysis and ii) computational fluid dynamics (CFD) were performed in PAK software, with applied equivalent material characteristics of BAV and boundary conditions. PAK is a high-performance finite element (FE) software for solving complex coupled multi-physics/multi-scale problems, with main application in cardiovascular domain [4]. It also can interact with different computational solutions and solvers. It should me mentioned that both computational simulations include simplifications and assumptions on the geometrical and material properties due to complicated biological structure of aortic root.

4. Solution/Discussion

In the last years, different computational studies have demonstrated that *in silico* approach and computational tools are very useful for investigating the biomechanical characteristics of the both aortic root and aortic valve which are difficult to obtain *in vitro* or *in vivo*.

After employing the in-house PAK FE software for structural and CFD analysis, the obtained results included the wall displacements and Von Mises stress distribution, as well as pressure and shear stress distribution, in accordance to the previous studies [5, 6]. The performed computational simulation allowed assessment of the BAV biomechanical implications for this specific patient.

The initial results for this single case, displacements and Von Mises stress distribution (for structural analysis), as well as shear stress and pressure distribution (for CFD analysis) are quantified concerning anatomical patient's structures. The regions of abnormal stresses on the aortic leaflets and annulus, with asymmetrically open bicuspid valve, were related to the increased pressures and shear stresses and analyzed for this patient-specific case. Due to the difficulties in obtaining such characteristics *in vitro* or *in vivo*, the performed computational analysis gave better insight into the biomechanics of the aortic root with BAV that is needed to achieve improvements in surgical repair techniques and presurgical planning.

The computational modelling based on FE analysis could offer solutions to some of the problems in current healthcare practice, while its ability to run simulations and be predictive could help to identify the likely outcomes for patients. The performed study is the first step in further investigation and development of more advanced and complex 3D models.

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6. References

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