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Multiphysics simulation of the effect of leaflet thickness inhomogeneity and material anisotropy on the stress–strain distribution on the aortic valve

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ABSTRACT

This study developed a realistic 3D FSI computational model of the aortic valve using the fixed-grid method, which was eventually employed to investigate the effect of the leaflet thickness inhomogeneity and leaflet mechanical nonlinearity and anisotropy on the simulation results. The leaflet anisotropy and thickness inhomogeneity were found to significantly affect the valve stress–strain distribution. However, their effect on valve dynamics and fluid flow through the valve were minor. Comparison of the simulation results against *in-vivo* and *in-vitro* data indicated good agreement between the computational models and experimental data. The study highlighted the importance of simulating multi-physics phenomena (such as fluid flow and structural deformation), regional leaflet thickness inhomogeneity and anisotropic nonlinear mechanical properties, to accurately predict the stress–strain distribution on the natural aortic valve.

1. Introduction

Over the last four decades, there has been a considerable interest in developing realistic computational models of heart valves, with a view to understanding their function in normal and pathological conditions, aiding the development of artificial valves, and optimizing surgical procedures (Friedman et al., 2010). In spite of recent advances in computational resources and numerical techniques, the development of physiologically-relevant computational models of heart valves still represents a challenge, due to their complex geometries and large deformations during the cardiac cycle.

A number of constitutive equations have been employed in modeling the biomechanics of the native and bioprosthetic aortic valve leaflets, including linear elastic (Gould et al., 1976; Cataloglu et al., 1977; Gnyaneshwar et al., 2002), bilinear or multilinear elastic (Hamid et al., 1986; Mohammadi et al., 2009), linear orthotropic (Grande et al., 1998; Katayama et al., 2008; Kalyana et al., 2015), nonlinear elastic (Black et al., 1991; Carmody et al., 2006), isotropic matrix with fiber-reinforcement (De Hart et al., 2003; Driessen et al., 2007) and Fung-type nonlinear anisotropic (Sun et al., 2003; Kim et al., 2006; Labrosse et al., 2015). Patterson et al. (1996) reported that using the nonlinear elastic model had a significant effect on leaflet behavior and stress magnitude compared to the linear elastic model. Burriesci et al. (1999) compared the behavior of a bicuspid pericardial prosthetic heart valve using isotropic nonlinear and orthotropic nonlinear material models and found that orthotropy has a great impact on the stress distribution. A similar finding was reported by Li et al. (2001) on a trileaflet aortic valve.

The thickness of the aortic valve leaflet varies regionally (Cataloglu et al., 1977; Thubrikar, 1990; Grande et al., 1998; Wang et al., 2008). A number of numerical studies compared the stress distribution on the aortic valve using uniform and non-uniform leaflet thickness and found significant differences in the stress distribution and magnitude (Cataloglu et al., 1977; Li et al., 2001; Luo et al., 2003). However, these studies were static and only the maximum transvalvular pressure gradient was considered. In

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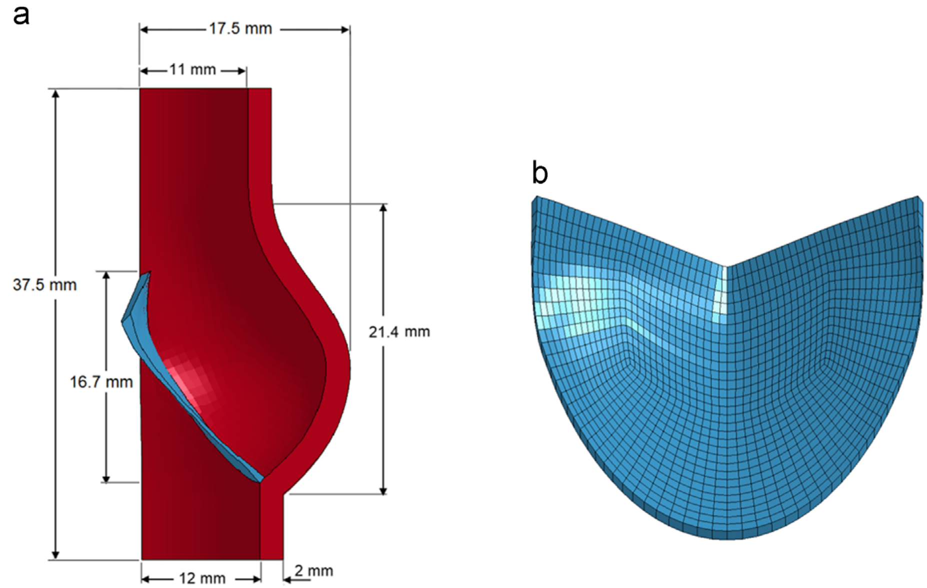

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Leaflet region	Right, left thickness (mm)	Noncoronary thickness (mm)
Attachment edge	1.16	0.155
Belly	0.18–0.58	0.18–0.58
Coaptation area	0.68–1.29	0.68–1.65
Free margin	1.53	1.96
Nodulus of Aranti	2.06	2.75

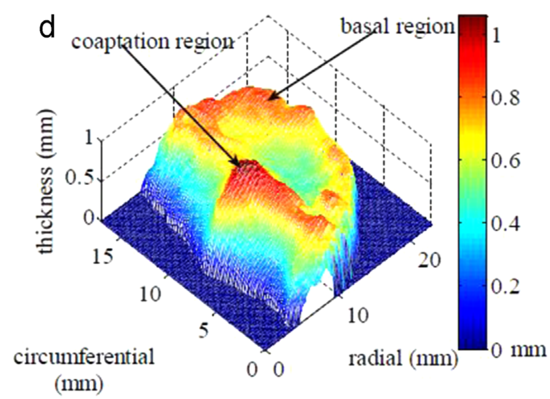

Fig. 1. (a) Schematic of the aortic valve showing the geometry and dimensions, (b) computational mesh of the aortic valve leaflet used for uniform and varied thickness models. (c) and (d) Measurements of the leaflet thickness by Grande et al. (1998) and Wang et al. (2008) were adopted in this study.

addition, these studies did not account for the leaflet coaptation, or most vitally, the interaction of the fluid with the valve structure.

A numerical simulation that closely represents the physiological aortic valve dynamics, incorporating leaflets opening and closing and root dilation, requires coupling the governing equations of the valve structure deformation and blood flow using a fluid–structure-interaction (FSI) methodology. Over years, many FSI methods have been developed and there are mainly categorized into two general approaches; the Arbitrary Lagrangian Eulerian (ALE) and fixed-mesh (Eulerian) methods. In The ALE approach, two conforming meshes are used for the fluid and the structure while in the Eulerian two separate meshes are used. The ALE method has been successfully applied to only bileaflet mechanical heart valves where the leaflets were modeled as rigid bodies (Dumont et al., 2007; Nobili et al., 2008; Guivier-Curien et al., 2009). The main drawback of this method is its inability to cope with large deformation problems. Owing to this, this method failed in the FSI modeling of natural and prosthetic valves, where the leaflets undergo large displacement during the systolic phase and large deformation during the diastolic phase. Fixed-grid methods, in which the fluid mesh remains unchanged, have been shown to be capable of solving FSI problems where the structure undergoes large deformations in complex geometries. Different fixed-mesh methods have been proposed to study FSI of the aortic valve. These include the immersed boundary method (IBM) (Peskin, 1972; Griffith et al., 2009), sharp-interface immersed boundary method (Borazjani, 2013), sharp-interface level set method (Vigmostad et al., 2010), fictitious domain (De Hart et al., 2003; van Loon et al., 2004) and Multi-Material Arbitrary Lagrangian Eulerian (MM-ALE) methods (Nicosia et al., 2003; Carmody et al., 2006; Ranga et al., 2006; Weinberg and Kaazempur Mofrad, 2007). Previous fixed-grid studies have either used uniform leaflet thickness, non-physiological boundary conditions, or simplified leaflet material models. In addition, they have not been validated in detail, apart from the case of the study by Weinberg and Kaazempur Mofrad (Weinberg and Kaazempur Mofrad, 2007).

In the present work, 3D FSI models of the natural aortic valve were developed using the fixed-grid FSI method (MM-ALE) to study the effect of the non-uniform leaflet thickness and leaflet mechanical anisotropy properties on the leaflet stress–strain distribution, valve dynamics and fluid flow through the valve.

2. Material and methods

2.1. FSI method

The explicit finite element software LS-DYNA (971, LSTC, Livermore, CA) that employs the fixed-mesh MM-ALE method was utilized in the simulations. This method used a Split-Operator method to split the computation in each time step into two steps. Initially, the conservation equations were solved in the Lagrangian formulation by setting the mesh velocity to the fluid velocity, and the changes in the internal energy and velocity that occurred due to the external and internal