Application of fluid-structure interaction to investigate a malformed biological heart valve: a three dimensional study of the bicuspid aortic valve

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Abstract: - A Bicuspid Aortic Valve (BAV) is a congenital cardiovascular abnormality and is associated with aortic complications such as aortic stenosis (i.e. restricted opening of the valve). A three-dimensional fluid-structure interaction model has been developed to study the mechanical stress and fluid dynamics of a BAV. An idealised aorta model was generated and meshed. Material properties and boundary conditions were set accordingly to simulate blood and the natural aortic valve leaflets. Two main findings were that the BAV model was unable to open properly and that von Mises stress concentrated at the attachment to the aorta of the aortic valve cusps. Such changes are likely associated to the flow patterns predicted which included recirculation downstream from the valve itself and peak velocity between the valve cusps. These findings are important because they demonstrate that some of the clinical complications associated with a congenitally malformed aortic valve could caused by changes in the mechanical function of the biological heart valve.

Key-Words: Bicuspid Aortic Valve, Finite Element, Fluid Dynamics, Fluid-Structure Interaction, Heart Valve Mechanics, Multi-Physics

1 Introduction

A Bicuspid Aortic Valve (BAV) is a common congenital cardiovascular anomaly, which occurs in approximately 2% of the population [1]. A healthy aortic heart valve consists of three valve cusps. In the case of a BAV, however, a functional cusp is lost and so the congenital malformation results in only two cusps. BAVs are associated with complications which can require surgical replacement; otherwise an increased risk of cardiac diseases, such as myocardial infarction, which can result in mortality will occur if these associations are neglected [1]. Complexities such as failure to open completely (aortic stenosis) and valve damage can increase the risk of degeneration of the heart valve in patients with BAV [2,3].

Several studies have investigated how the healthy tricuspid aortic valve functions. However, few studies have focused on the BAV [2,4-6]. Of the few available BAV studies some have used computational fluid dynamics alone to investigate the valve [2,5]. However, the aortic valve relies on deformation for it to function adequately. Therefore, flow predictions are likely limited. Another study used fluid-structure interaction to predict flow across the aortic root (the region of blood vessel immediately adjacent to the aortic valve) [6]. A more recent two-dimensional fluid-structure interaction study though has demonstrated that ignoring larger regions of the aorta (the blood vessel containing the aortic valve), is likely to limit predictions [4]. This is because in a BAV recirculation may not be confined to regions of the aorta adjacent to the valve. This is unlike a healthy aorta, and may be a consequence of the valve being congenitally malformed.

To further understand the consequences of the aortic valve being functionally bicuspid, a three-dimensional fluid-structure interaction model is necessary which includes a greater section of the aorta. This is not currently available. Therefore, the aim of this study was to develop a three dimensional fluid-structure interaction model of a congenitally bicuspid aortic valve which included the aortic root, ascending and descending aorta.

2 Methods

2.1 Geometry

An idealised BAV model was generated using Solidworks (Solidworks, Concord, MA, USA). The model included the bicuspid valve itself (see fig. 1) within the aorta (see fig. 2). The model included not just the aorta in the immediate vicinity of the valve (i.e. aortic root) but also that downstream from the valve. The dimensions for the aorta, aortic root and the valve cusps were obtained from literature [7,8]. The aorta radius was 12.5 mm (i.e. equivalent to the flow inlet; see section 2.2). The valve cusps were 28.5 mm long and 0.3 mm thick, and spanned the radius of the aorta. For simplification purposes, the radius of the ascending aorta, aorta arch and descending aorta were taken to be equal to that of the aortic root.

2.2 Material properties

The valve cusps were modelled as linearly elastic with a Young's modulus of 1.5 MPa, Poisson's ratio of 0.49, and density of 1×10^3 kg.m^{-3} [4]. Blood was taken to be an incompressible Newtonian fluid with the same density as valve cusps and a viscosity of 4.3×10^{-3} Pa.s [4].

2.3 Boundary conditions

Blood flow was simulated during left ventricular systole. This is the stage at which blood is pumped out from the heart's left ventricle through the aorta, and its aortic valve, and towards the body.

An inlet velocity of 0.175 m.s^{-1} was applied at the base of the aortic root (i.e. at the 'entry' of the aortic valve). This inflow rate approximates the heart blood flow rate at 5 litres per minute in a resting man [7]. A pressure outlet was defined downstream from the aortic valve, at the descending thoracic aorta. This section of the aorta is downstream from the valve. The aorta was simulated as a rigid boundary and a no-slip boundary condition was applied.

The cusps that form the aortic valve were simulated as deformable (see section 2.2). Two boundary conditions were applied to cusps. Firstly, the ends of the cusps were defined as fixed at the lower aortic root (i.e. they were restricted from moving at their attachment to the wall of the aorta). Secondly, the loading of the valve cusps (which induced deformation) was induced by the flow of fluid around it. It should be noted that valve cusp deformation provided a constraint for fluid velocity at the shared fluid-solid boundary.

2.4 Mesh & solver

The meshes of the models were generated using Ansys (Ansys v13.0, Ansys Inc., Canonsburg PA, USA). Meshes were translated into a suitable input file for use with LS-DYNA (LSTC, Livermore CA, USA). Eight-node hexahedral brick solid elements were created in the fluid model whilst the valve cusps were meshed with three-node triangular shell elements. The model consisted of 11028 elements.

An Arbitrary Lagrange-Euler mesh was used for the fluid-structure interaction analysis. On shared boundaries each element of either the structural or the fluid was allowed to have a combination of different material properties, which were the blood and valve materials in this analysis. An Arbitrary Lagrange-Euler coupling penalty formulation was introduced to track the relative displacement between the corresponding coupling points of the fluid and solid nodes. Fluid-structure interaction analysis was performed using LS-DYNA under steady state analysis.

3 Results

The aortic valve cusps experienced a peak Von Mises stress of 134 kPa. This peak stress was located towards the attachment at the aortic wall (fig. 1). Lower stresses were predicted towards the unrestricted edge of the cusps (around 50 kPa).

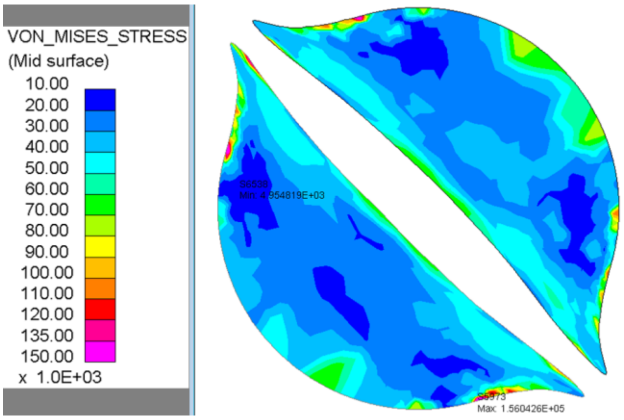

Fig. 1 Stresses across the bicuspid aortic valve.

The cusps, however, did not open fully (as would be expected for a healthy aortic valve). It was at the centre of these restricted cusps that the maximum fluid velocity was predicted (0.24 m.s^{-1}; fig. 2).

Recirculation did occur at the aortic root. However, this continued downstream from the valve.

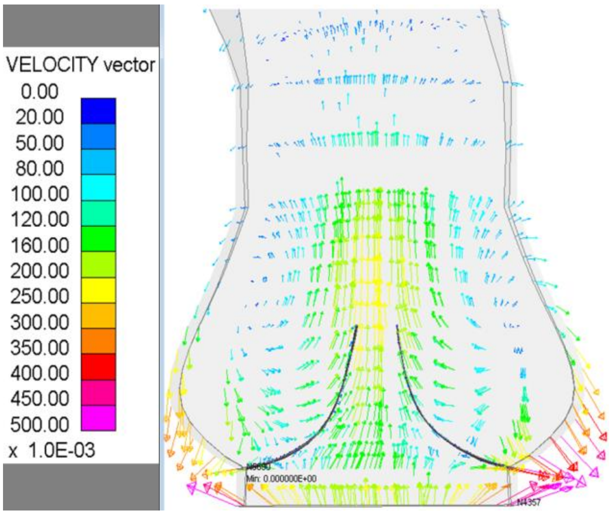

Fig. 2 Flow patterns within the aorta.

4 Conclusion

A three-dimensional fluid-structure interaction model of an idealised but congenitally bicuspid aortic valve has been simulated. This model has been used to predict velocity and recirculation around the valve and stress induced within the valve. In the BAV model the valve cusps did not open fully. This may due to the straight and less redundant tissue of the cusps that resulted in a narrow opening [1]. The low mobility of the fused cusps suggests that the valve's inability to open completely may lead to turbulent flow.

The valve stresses predicted in this study were similar to that predicted using a two-dimensional fluid-structure interaction full aorta model at 0.2 s [4]. However, the peak velocity was lower in this study. This demonstrates differences between a two- and three-dimensional study. The results here show that flow parameters are likely affected by the three-dimensional valve geometry. For example, a BAV with lower orientation symmetric may experience a stronger jet and higher stress [5].

However, a fluid-structure interaction model is necessary for BAV simulations as the valve undergoes deformations that alter the area of flow for the fluid. Therefore, a computational fluid dynamics analysis on its own is likely to over-estimate velocity predictions as it fails to incorporate valve opening. Increased velocity predictions are likely to lead to errors in turbulence predictions during valve opening. A model that only includes the aortic root cannot make such predictions when such changes occur downstream from the aortic valve.

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References:

[1] Yener, N., Oktar, G.L., Erer, D. *et al.*, Bicuspid aortic valve, *Annals of Thoracic and Cardiovascular Surgery*, 8, 5, 2002, pp. 264-267.

[2] Robicsek, F., Thubrikar, M.J., Cook, J.W. *et al.*, The congenitally bicuspid aortic valve: how does it function? Why does it fail?, *Annals of Thoracic Surgery*, 77, 1, 2004, pp. 177-185.

[3] Siu, S.C., Silversides, C.K., Bicuspid aortic valve disease, *Journal of the American College of Cardiology*, 55, 25, 2010, pp. 2789-2800.

[4] Kuan, M.Y.S., Espino, D.M., Systolic fluid-structure interaction model of the congenitally bicuspid aortic valve: assessment of modelling requirements, *Computer Methods in Biomechanics and Biomedical Engineering*, Submitted.

[5] Viscardi, F., Vergara, G., Antiga, L. *et al.*, Comparative finite element model analysis of ascending aortic flow in bicuspid and tricuspid aortic valve, *Artificial Organs*, 34, 12, 2010, pp. 1114-1120.

[6] Weinberg, E.J., Mofrad, M.R.K., A multiscale computational comparison of the bicuspid and tricuspid aortic valves in relation to calcific aortic stenosis, *Journal of Biomechanics*, 41, 16, 2008, pp. 3482-3487.

[7] Levick, J.R., *An Introduction to Cardiovascular Physiology*, Butterworth-Heinemann, 1995.

[8] De Hart, J., Peters, G.W.M., Schreurs, P.J.G. *et al.*, A three-dimensional computational analysis of fluid-structure interaction in the aortic valve, *Journal of Biomechanics*, 36, 1, 2003, pp. 103-112.