FLUID-STRUCTURE INTERACTION AND RIGID WALL CFD-MRI COMBINED STUDY OF AORTIC COARCTATION REPAIRS

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INTRODUCTION

Coarctation of the aorta (CoA) is a congenital narrowing of the upper descending aorta, generally adjacent to the site of attachment of the ductus arteriosus, which is sufficiently severe to create a pressure gradient across the area. There is currently an open debate about the causes that lead to re-coarctation, hypertension and/or aneurysm formation after CoA repair in a significant number of cases.

OBJECTIVES

Due to the statistical significance of CoA on all congenital heart diseases it is important to try and find a way of assessing the outcomes of its treatment quantitatively, to ascertain the indications for the different surgical techniques, and to acquire the greatest possible knowledge on the post-surgical physiology.

This study is an analysis of the local haemodynamics and tissue mechanics in sows post-repair using two of the different surgical techniques currently available.

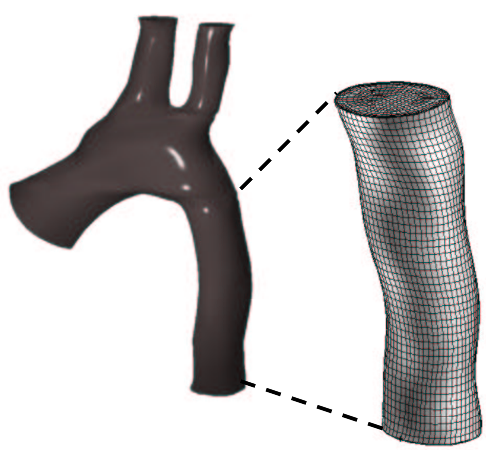

Figure 1. Reconstructed geometry of E/E repair and 3D E/E model

METHODS

The anatomy and haemodynamic conditions of two sows, each weighing 40 kg, were assessed pre- and post-operatively. After the pre-operative MR scans were taken, the sows were operated on using end-to-end repair (E/E) and a Gore-tex graft interposition (GGI) respectively, under non-sterile conditions. A Philips scanner 1.5T was used for the MR acquisition. The geometry was acquired by a high resolution 3D TFE sequence (TR=5.0ms, TE=2.0ms, slice thickness 1.5mm, FoV=188×300, flip angle 25°). The velocity mapping is based on an FFE sequence with the encoding velocity set to 150cm/s for the axial component and to 40cm/s for the secondary components to ensure a high signal-to-noise ratio. In both cases the best coil available was chosen, in order to ensure high signal and uniform magnetisation throughout the scanned region.

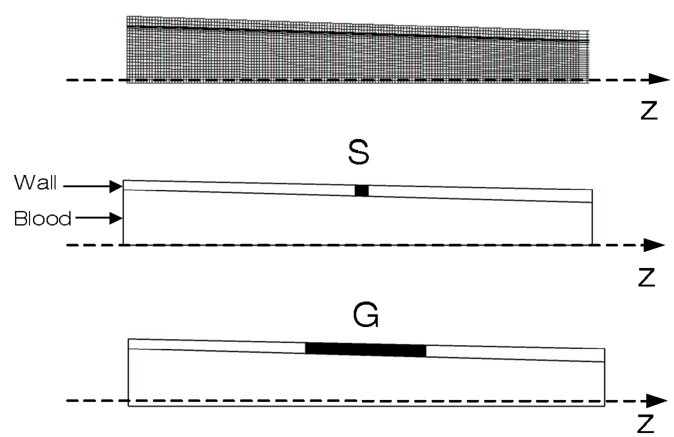

Figure 2. FSI computational mesh for POp model (top), and geometries of the E/E (middle) and GGI (bottom) models; S: suture G: graft

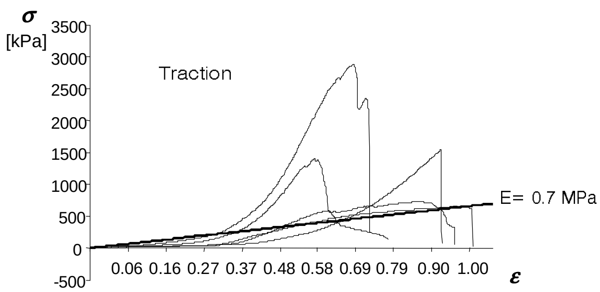

Figure 3. Results of mechanical tests for both axial and circumferential traction (thin). Overlaid: linearised characteristic (bold)

Anatomical scans were taken of the ascending aorta, aortic arch, thoracic descending aorta and a part of the brachiocephalic vessels. The velocity mapping was carried out for the ascending aorta distal to the sinus of Valsalva, for the brachiocephalic vessels (2D only) and for the descending aorta, both slightly distal to the subclavian artery and in the thoracic compartment.

The sows were subsequently put down and the resected aortas, preserved in physiological saline and under ice, were used for mechanical property assessment within 24 hours, by means of a preconditioning phase, relaxation tests and traction-till-rupture tests. Both longitudinal and circumferential viscoelastic characteristics of each specimen were extracted.

Using the acquired data, the geometry was reconstructed [1] (Figure 1) and 4 types of pulsatile computational models of the descending aorta were generated (Figures 1 and 2): a fluid-structure interaction (FSI) axi-symmetrical model for the healthy subject prior to surgery (POp) with a flat inlet profile, compliant wall (E= 0.7 MPa; ν= 0.45), MR-derived mean velocity time course imposed at the inlet; a FSI axi-symmetrical model of the E/E repair with the same inlet conditions as the previous model, compliant wall of the same properties as before and compliant suture line (E=104 MPa; ν= 0.4); a FSI axi-symmetrical model of the GGI repair with the same inlet conditions, compliant wall of the same properties and compliant Gore-tex insert (E=50 MPa; ν= 0.3); a 3D model of the E/E with MR-acquired geometry [2], rigid wall, MR-derived 3D velocity profile inlet condition.

The aortic wall properties used are a linearisation of the mechanical test data (Figure 3) and are in accordance with values cited in the literature [3]. The Gore-tex properties were also found in the literature [3], while the suture properties result from homogenisation of the aortic wall and thread characteristics (Prolene 6.0 or 7.0), and take into account the type and the number of suture stitches normally employed (30 running suture stitches).

All the models were solved using the commercial CFD package FIDAP (Fluent Inc, Lebanon, USA).

RESULTS

The axi-symmetrical models highlight the different wall stress and strain patterns found in the healthy subject as well as in E/E and GGI repairs. While in the POp neither stresses nor strains show any significant change along the vessel wall, in both E/E and GGI the patterns are evident and reflect the material property discontinuities introduced by surgery (Figure 4). All the continuum variables peak at the physical tissue discontinuities, implying that suture lines act as stress concentrators. The absolute intensities of the stresses are on the whole moderate.

The 3D model shows the complexity of the aortic haemodynamics and constitutes a good example of the possible use of coupled MR-CFD methodologies for the study of circulatory physiology. The flow appears to be highly non-symmetrical in all phases of the cardiac cycle and many vortices are present (Figure 5).

CONCLUSIONS AND FURTHER DEVELOPMENTS

FSI simulations can be of enormous help in the study of blood vessel mechanics. Simple models evidence typologies of tissue response thus providing a reference for the analysis of more comprehensive models in the future. 3D models, including both measured velocity profiles and compliant walls, will be attempted in order to obtain better estimates of the stress and strain values and to assess the contribution of compliant walls on the fluid dynamics.

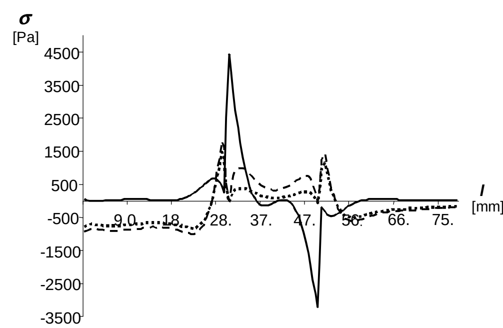

Figure 4. σ_{xx} (— — —), σ_{yy} (· · ·) and τ_{xy} (——) for the GGI model during systolic acceleration

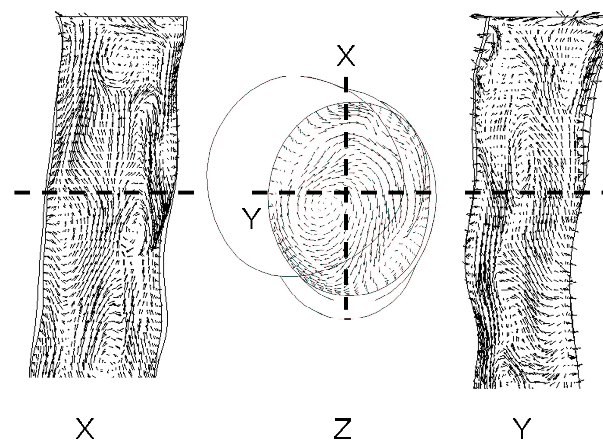

Figure 5. Flow pattern at time 0.4 s (late systole) in the 3D E/E model

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