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Aortic flow patterns before and after personalised external aortic root support implantation in Marfan patients

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ABSTRACT

Implantation of a personalised external aortic root support (PEARS) in the Marfan aorta is a new procedure that has emerged recently, but its haemodynamic implication has not been investigated. The objective of this study was to compare the flow characteristics and hemodynamic indices in the aorta before and after insertion of PEARS, using combined cardiovascular magnetic resonance imaging (CMR) and computational fluid dynamics (CFD). Pre- and post-PEARS MR images were acquired from 3 patients and used to build patient-specific models and upstream flow conditions, which were incorporated into the CFD simulations. The results revealed that while the qualitative patterns of the haemodynamics were similar before and after PEARS implantation, the post-PEARS aortas had slightly less disturbed flow at the sinuses, as a result of reduced diameters in the post-PEARS aortic roots. Quantitative differences were observed between the pre- and post-PEARS aortas, in that the mean values of helicity flow index (HFI) varied by −10%, 35% and 20% in post-PEARS aortas of Patients 1, 2 and 3, respectively, but all values were within the range reported for normal aortas. Comparisons with MR measured velocities in the descending aorta of Patient 2 demonstrated that the computational models were able to reproduce the important flow features observed in vivo.

1. Introduction

Marfan syndrome (MFS) is a connective tissue disorder which affects the cardiovascular, ocular and skeletal systems (Judge and Dietz, 2005). The development of thoracic aortic aneurysms is the leading cause of death in patients with MFS (Silverman et al., 1995). Treatment consists of regular imaging to determine the progression of aortic dilatation and preventative techniques include total root replacement (TRR), valve sparing root replacements (VSRR) and most recently, the insertion of a personalised external aortic root support (PEARS). In TRR, the aortic root and ascending aorta are replaced using a conduit of woven Dacron incorporating a mechanical valve, with the coronary ostia anastomosed to the tube graft (Bentall and De Bono, 1968). It has been revised both with respect to the surgical technique and the materials used. VSRR also involves radical excision of the diseased aortic root and ascending aorta, however retains the native valve leaflets (David et al., 1995; Yacoub et al., 1998). PEARS refers to a customised device described and introduced by Golesworthy et al. (2004). The insertion of PEARS is a less invasive procedure that conserves the valve and blood/endothelium interface (Pepper et al., 2010; Treasure et al., 2014). Aortic cross-sectional images of the patient are used to create a 3D replica of the aorta via rapid prototyping, on which a medical grade polymer mesh is fitted (Fig. 1). At surgery, the support is placed around the aorta, extending from the aortoventricular junction to just beyond the brachiocephalic artery. Unlike the vascular grafts used in root replacement, the fabric of PEARS becomes incorporated into the vessel wall, creating a composite aortic wall which prevents the ascending aorta from further dilatation (Verbrugghe et al., 2013; Pepper et al., 2014). PEARS is fundamentally different to the Florida sleeve in which an off-the-shelf device made of rigid graft material is placed around the root (Hess et al., 2005).

Due to their sophisticated functions, morphological changes of the aortic root and valve can influence haemodynamics in different parts of the aorta, coronary circulation and systemic circulation. While PEARS theoretically allows the natural expansion and recoil of the root and ascending aorta, its haemodynamic influence has not been investigated. Moreover, current knowledge of

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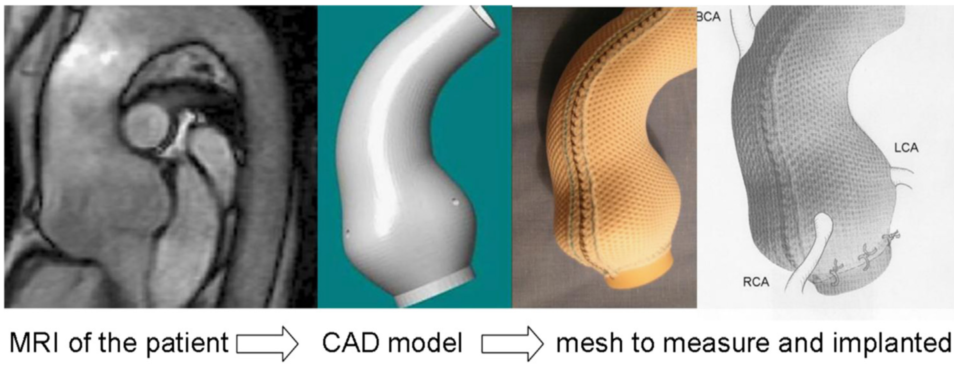

Fig. 1. Magnetic resonance imaging of the aorta and implantation of PEARS.

detailed blood flow patterns in the Marfan aorta is limited. Using flow-sensitive 4D MRI, it has been shown that helical flow is enhanced and systolic wall shear stress (WSS) increased in the Marfan aorta compared to normals (Geiger et al., 2012, 2013). There is evidence that disordered flow causes changes in local WSS (Hope et al., 2010; Lorenz et al., 2014); and WSS in turn alters endothelial cell function and results in arterial remodelling, linked to the development of autophagy such as dilatation or aneurysms (Malek et al., 1999). One of the concerns associated with PEARS is that increased stiffness of the supported aorta will affect the working load of the heart, blood flow patterns and consequently WSS. Furthermore, the aorta distal to the support is unprotected and vulnerable to dilatation, which is of course a limitation more obviously consequences of TRR, VSRR and the Florida sleeve (Treasure et al., 2014).

Numerical simulations combining cardiovascular magnetic resonance (CMR) imaging and computational fluid dynamics (CFD) are commonly used for detailed aortic flow analysis (Tan et al., 2012). Blood flow in the aorta is complex and may involve transition from a well-organised laminar regime to a chaotic turbulent regime, under both normal and pathological conditions (Stein and Sabbah, 1976; Stalder et al., 2011). In an attempt to capture laminar-turbulent transition, CFD studies have employed different simulation methods including direct numerical simulation (DNS), large eddy simulation (LES) and turbulence models based on Reynolds-averaged Navier–Stokes (RANS). DNS is considered the gold standard as it provides numerical solutions of the Navier–Stokes equation by resolving all spatial and temporal scales.

Due to high computational costs associated with DNS, LES and RANS-based turbulence models have been tested as potential alternatives for aortic flow modelling. In LES, large turbulent eddies are resolved and smaller ones are modelled, while in RANS methods, the effect of turbulent fluctuations on mean flow is accounted for via different turbulence models. Mittal et al., (2003) and Paul et al., (2009) employed LES for flow in aortic coarctation while Lantz et al. (2012, 2013) used LES for patient-specific models of the aorta and aortic coarctation. However, no direct comparison of DNS and LES for aortic flow has been found in the literature.

On the other hand, transitional and turbulent flow in arterial stenosis has been studied more extensively. Varghese et al., (2007a, 2007b) performed DNS of steady and pulsatile flows through idealised stenoses, and compared DNS results with LES and RANS-based models (Varghese et al., 2008). Tan et al. (2011) also compared the DNS results of Varghese et al. (2008) with LES and RANS models involving a correlation-based transitional version of the hybrid k-ε/k-ω model, and experimental data (Ahmed and Giddens, 1983a, 1983b). Their study revealed that both dynamic Smagorinsky LES and the RANS transitional model captured the complex transition phenomena under physiological Reynolds numbers and predicted comparable velocity and turbulence intensity profiles (Tan et al., 2011). The RANS transitional model was also found to perform better than the other RANS turbulence models tested for flow in an axisymmetric stenosis (Tan et al., 2008). Positive experience with the RANS transition model was also reported for flow in patient-specific thoracic aortic aneurysms (Tan et al., 2009a, 2009b; Lantz et al., 2011) demonstrating good agreement with in vivo MRI data (Tan et al., 2009b).

Table 1
Summary of patient data.

	Patient 1		Patient 2		Patient 3	
Age at pre-PEARS imaging	38		20		48	
Age at post-PEARS imaging	42		24		49	
Sex	M		F		M	
	Pre	Post	Pre	Post	Pre	Post
BMI	21.97	21.39	26.23	23.46	23.77	24.07
Blood pressure (mmHg)						
Systolic	135	130	110	110	118	110
Diastolic	78	70	60	60	84	70
Pulse	57	60	50	50	34	40
Cardiac output (L/min)	6.0	6.3	6.4	6.9	5.3	6.1
Peak Reynolds number	5304	6324	4502	4443	4944	4459
Mean Reynolds number	1546	1397	1174	1090	1131	1158
Womersley number	13.6	16.0	20.2	22.6	16.7	18.7

In this study, CMR and CFD are applied to Marfan aortas in order to understand the haemodynamics associated with this disease, as well as to investigate the implications associated with PEARS implantation. Pre- and post-operative geometries for three Marfan patients were reconstructed using MR images, and physiologically realistic inflow and boundary conditions were imposed. Blood flow patterns, helicity flow indices and WSS in the pre- and post-PEARS aortas were compared.

2. Materials and methods

2.1. MR imaging

Electrocardiographic-gated MR images for three patients pre- and post-PEARS were obtained using a 1.5 T scanner (Avanto, Siemens, Erlangen, Germany). The images covered aortic root, ascending aorta, aortic arch and proximal descending aorta in three orthogonal planes. They were acquired in diastole, at the same point in the cardiac cycle. Phase contrast (PC) mapping with a fast gradient echo sequence was also performed to obtain pixel-based time-varying velocities from each patient at locations just above the aortic valves. Details of the patients' demographic data are given in Table 1. All patients had no significant aortic valve regurgitation. The study was approved by the local ethics committee, and complied with the Declaration of Helsinki.