Medical Engineering and Physics 37 (2015) 759–766

Contents lists available at ScienceDirect

Medical Engineering and Physics

journal homepage: www.elsevier.com/locate/medengphy

Biomechanical properties of the Marfan's aortic root and ascending aorta before and after personalised external aortic root support surgery

S.D. Singh[a], X.Y. Xu[a,*], J.R. Pepper[b,c], T. Treasure[d], R.H. Mohiaddin[b,c]

[a] Department of Chemical Engineering, Imperial College London, South Kensington Campus, London SW7 2AZ, UK
[b] Royal Brompton and Harefield NHS Foundation Trust, Sydney Street, London SW3 6NP, UK
[c] National Heart and Lung Institute, Imperial College London, London SW7 2AZ, UK
[d] Clinical Operational Research, Department of Mathematics, University College London, 4 Taviton Street, London WC1H 0BT, UK

ARTICLE INFO

Article history:
Received 11 August 2014
Revised 16 February 2015
Accepted 9 May 2015

Keywords:
Marfan syndrome
Aortic root dilatation
Finite element modelling
Vascular prosthetics

ABSTRACT

Marfan syndrome is an inherited systemic connective tissue disease which may lead to aortic root disease causing dilatation, dissection and rupture of the aorta. The standard treatment is a major operation involving either an artificial valve and aorta or a complex valve repair. More recently, a personalised external aortic root support (PEARS) has been used to strengthen the aorta at an earlier stage of the disease avoiding risk of both rupture and major surgery. The aim of this study was to compare the stress and strain fields of the Marfan aortic root and ascending aorta before and after insertion of PEARS in order to understand its biomechanical implications.

Finite element (FE) models were developed using patient-specific aortic geometries reconstructed from pre and post-PEARS magnetic resonance images in three Marfan patients. For the post-PEARS model, two scenarios were investigated—a bilayer model where PEARS and the aortic wall were treated as separate layers, and a single-layer model where PEARS was incorporated into the aortic wall. The wall and PEARS materials were assumed to be isotropic, incompressible and linearly elastic. A static load on the inner wall corresponding to the patients' pulse pressure was applied.

Results from our FE models with patient-specific geometries show that peak aortic stresses and displacements before PEARS were located at the sinuses of Valsalva but following PEARS surgery, these peak values were shifted to the aortic arch, particularly at the interface between the supported and unsupported aorta. Further studies are required to assess the statistical significance of these findings and how PEARS compares with the standard treatment.

1. Introduction

Marfan syndrome (MFS) is a heritable systemic connective tissue disorder with manifestations in the cardiovascular, ocular and skeletal systems [1]. Cardiovascular complications of MFS are the major cause of death in patients with this disease [2]. MFS is linked to mutations in the fibrillin 1 gene (FBN1), which is responsible for the synthesis of normal fibrillin glycoprotein. This protein is a major component of microfibrils [3]. In MFS, the structural microfibril abnormalities not only result in inherently weakened aortic connective tissue, but also in failure of the normal maintenance and repair processes. The interplay of aortic biomechanics and the abnormal aortic wall connective tissue is conducive for the formation of aortic aneurysm [4]. Normally, elastic fibres enable the aorta to distend during the cyclic increase of blood pressure and then recover fully to its original state upon removal of the pressure load. However, fragmentation of the elastic fibres prevents full recovery from the cyclic distending pressure. This results in a thinned aortic wall which exhibits progressive aortic dilatation and decreased distensibility with heightened risks of aneurysm formation and dissection throughout the length, but mainly at the root [5,6]. Dilated aortic root in MFS is typically characterised by increases in diameter across the sinuses of Valsalva and the sinotubular junction with cranial displacement of the origin of the coronary arteries and often incompetent aortic valve [6]. Currently, for patients with MFS exhibiting dilating aortic root and ascending aorta, the threshold for intervention has fallen between 45 and 50 mm diameter, especially if progressive dilatation is observed [6].

Various surgical techniques have been used to repair the dilated aortic root, aorta and the leaking aortic valve in MFS. The standard surgical approach (known as the Bentall procedure) is the composite root replacement in which a mechanical prosthetic valve is sewn into

* Corresponding author: Tel.: +44 207 594 5588; fax: +44 207 594 1989.
E-mail address: yun.xu@imperial.ac.uk (X.Y. Xu).

http://dx.doi.org/10.1016/j.medengphy.2015.05.010
1350-4533/

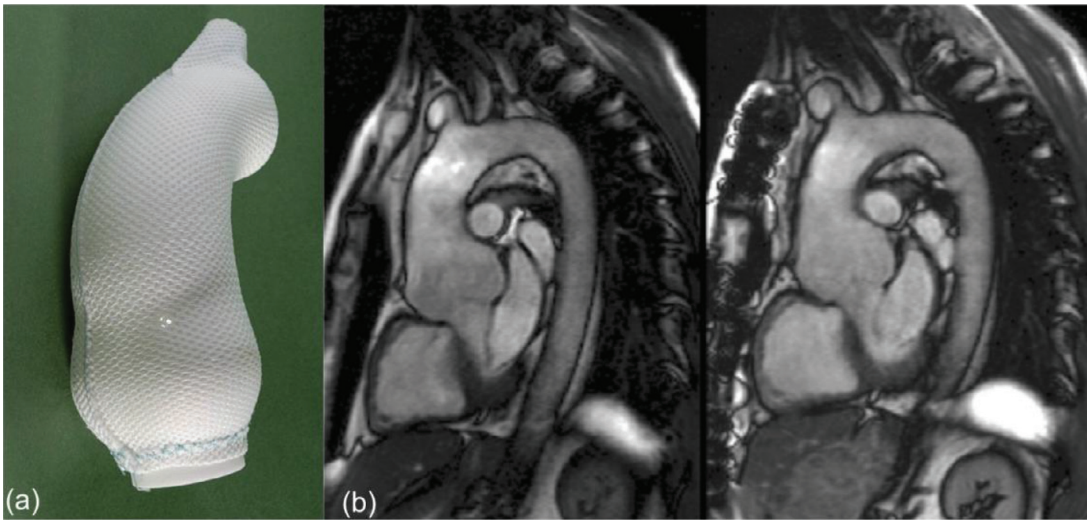

Fig. 1. (a) Aortic model wrapped in the personalised external aortic root support (PEARS) which is manufactured from a medical grade mesh; (b) Magnetic resonance imaging of the aorta before (left) and after (right) insertion of the PEARS in the first patient [11].

the proximal end of a Dacron tube graft [7]. The diseased aortic root and ascending aorta are replaced by a tube graft and the coronary ostia anastomosed to the side of the graft. Another option is the valve sparing root replacement which involves radical excision of the aortic root down to, but not including, the valve leaflets [8]. This is a more difficult operation requiring considerable operative skill and judgement [5,9]. More recently, a less invasive surgical technique has been pioneered and evaluated [10]. A personalised external aortic root support (PEARS) (shown in Fig. 1) is used to reinforce the ascending aorta while leaving the native aortic valve intact.

Early clinical results of PEARS indicated that there is no further dilatation of the aortic root after insertion of the PEARS, although the long term outcome cannot be predicted based on such early and limited experience [11,12]. Additionally, the structural status of the aortic wall after PEARS is uncertain [13]. To address these uncertainties, a macroscopic and histological evaluation was performed by wrapping polytetrafluoroethylene (PTFE) mesh, as used for the PEARS, around the carotid artery of sheep [14]. It was shown that the mesh became incorporated in the periadventitial tissue of the artery and there was a significant increase in the tensile strength of the carotid artery/mesh composite compared with the unwrapped carotid artery. One of the concerns associated with implantation of the PEARS is that the increasing stiffness of the supported aorta will affect the working load of the heart, mechanics of the valve and arterial pressures [14]. Additionally, the aorta distal to the support is unprotected and can be vulnerable to dilatation, a limitation shared by the Bentall procedure [12].

The combination of cardiovascular magnetic resonance imaging and finite element (FE) analysis offer the opportunity for detailed assessment of the biomechanical changes of the aortic root and ascending aorta before and after insertion of PEARS. Previous FE studies of the dilated aortic root include work done by Auricchio et al. [15] to reproduce aortic root pathology for assessment of aortic valve incompetence [15,16] to determine the mechanisms of aortic valve incompetence by applying radial forces to the root. However, none of these studies employed patient-specific geometries. One of the most important components of FE analysis is the selection of an appropriate constitutive model and the corresponding material properties. So far, several *in vivo* studies have reported the distensibility of the Marfan aorta [17–21] but these data do not give any information about the strength of the tissue. Okamoto et al. [22] determined the mechanical properties of dilated ascending aorta, particularly in patients with Marfan syndrome and bicuspid aortic valves, and applied these to a simplified model of the aorta [23]. The present study is not only the first attempt to evaluate the effects of the PEARS on the biomechanics of the Marfan aorta using patient-specific data, but also the first attempt at evaluating the biomechanics of the native Marfan aorta. Data from three patients were acquired before and after implantation of the PEARS and detailed analysis of stress patterns and displacements were carried out.

2. Methodology

2.1. MR image acquisition

Electrocardiographic-gated MR images of three Marfan patients, before and after implantation of the PEARS, were acquired from using a 1.5 Tesla scanner (Avanto, Siemens, Erlangen, Germany). Anatomical images used for segmentation of the aortic root and thoracic aorta were acquired in diastole, at the same point in the cardiac cycle. The images covered the ascending aorta, aortic arch and proximal descending aorta in three orthogonal planes (see Table 1 for imaging parameters) and were stored in a Digital Imaging and Communications in Medicine Data (DICOM) format. The study was approved by the local ethics committee, and complied with the Declaration of Helsinki.

2.2. Reconstruction of patient-specific ascending aorta

These DICOM images were imported into Mimics® (Materialise, Louvain, Belgium) segmentation software where a semi-automatic procedure was used for reconstruction. Two-dimensional (2D) region-growing method was used to detect the aortic lumen by defining seed-points in the region of interest and the lower and upper grey-level thresholds. The patient-specific 3D aortic lumen was then reconstructed by stacking 2D contours. The resulting geometry was smoothed to remove any noise from the surface, which might have resulted in artificial stress concentrations.

Two models describing the post-PEARS geometry were constructed, as illustrated in Fig. 2:

(i) A bilayer model, which was developed to simulate conditions immediately after insertion of the PEARS. It was assumed that the PEARS lay on the outer surface of the aortic wall upon its implantation. This was recreated by adding another layer corresponding to the thickness of PEARS from the aortic root to the base of the brachiocephalic artery of the pre-PEARS geometries.