Medical Engineering & Physics xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Medical Engineering & Physics

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

Imaging and finite element analysis: A methodology for non-invasive characterization of aortic tissue

Vittoria Flamini[a,b], Arthur P. Creane[b], Christian M. Kerskens[c], Caitríona Lally[b,*]

[a] New York University Polytechnic School of Engineering, Brooklyn, NY, United States
[b] School of Mechanical & Manufacturing Engineering, Dublin City University, Dublin, Ireland
[c] Trinity College Institute of Neuroscience, Trinity College Dublin, Ireland

ARTICLE INFO

Article history:
Received 27 November 2013
Received in revised form 8 September 2014
Accepted 10 October 2014

Keywords:
Medical imaging
Magnetic resonance imaging
Finite element analysis cardiovascular
Constitutive model

ABSTRACT

Characterization of the mechanical properties of arterial tissues usually involves an invasive procedure requiring tissue removal. In this work we propose a non-invasive method to perform a biomechanical analysis of cardiovascular aortic tissue. This method is based on combining medical imaging and finite element analysis (FEA). Magnetic resonance imaging (MRI) was chosen since it presents relatively low risks for human health. A finite element model was created from the MRI images and loaded with systolic physiological pressures. By means of an optimization routine, the structural material properties were changed until average strains matched those measured by MRI. The method outlined in this work produced an estimate of the *in situ* properties of cardiovascular tissue based on non-invasive image datasets and finite element analysis.

1. Introduction

Notwithstanding all the advances in medical technology and engineering, techniques available to investigate the structure and the mechanical behaviour of human tissue are very limited in that they are highly invasive and consist mainly of histology [1–3] and mechanical testing [3].

These techniques are not only invasive, since they need the tissue to be harvested, but they also represent the material property of a tissue *ex vivo*, *i.e.* when tissue physiological three-dimensional shape is altered, initial strain and residual stresses are removed, and physiological loading is absent [2,4,5].

Recently, there has been a lot of interest in obtaining realistic numerical models of human tissue in order to use these models to do preclinical testing of novel medical devices [6]. In order to be effective, these models need to be based on estimates of *in vivo* mechanical behaviour. Non-invasive imaging techniques that can be used to gather *in vivo* information include ultrasound, and in particular the latest developments in terms of 3D strain echo imaging and speckle tracking [7–12], and magnetic resonance imaging (MRI) [13,14].

The only tissue information that can be obtained non-invasively, however, is tissue loading (*i.e.* pressure, flow, weight) and tissue deformation (*i.e.* strain). Procedures aimed at characterizing the constitutive relationship of a biological tissue using knowledge of loading and deformation only involve an inverse analysis, in which an optimization routine is required to iterate until the desired match between loading and deformation is obtained [15].

To date, this approach has been applied successfully to tissues where the loading conditions are well defined or cyclic, such as the loading produced on the liver by the heart [16], for example.

Typically, these inverse analyses rely on dynamic displacements obtained by time-resolved imaging and passive constitutive information obtained from literature or mechanical testing [16].

In this paper a non-invasive approach for the *in vivo* determination of aortic mechanical behaviour is presented. This approach is based on MRI for the collection of tissue structural information and tissue deformation, and on an optimization routine for the inverse analysis. In particular, we focussed on two particular MRI techniques, diffusion tensor imaging (DTI) and phase contrast magnetic resonance imaging (PC-MRI). The first gives information of tissue structure and in particular on tissue anisotropy and fibrous content [17,18], whilst the second enables measurement of the velocities and therefore the strain rate of the tissue [19].

* Corresponding author at: School of Mechanical and Manufacturing Engineering, Dublin City University, Collins Avenue, Glasnevin, Dublin 9, Ireland.
Tel.: +353 01 700 7608.
E-mail address: triona.lally@dcu.ie (C. Lally).

http://dx.doi.org/10.1016/j.medengphy.2014.10.006
1350-4533/

2. Materials and methods

Porcine tissue used in this study was sourced from a local abattoir under licensing of the Irish Minister for Agriculture (number: Res 0007). Thoraco-abdominal sections of porcine aortas were harvested from pigs aged between 5 and 6 months and placed into a custom-designed cylindrical chamber, see Fig. 1A. The chamber was filled with water and placed in a 7 T Biospec® (Brucker Biospin, Germany) scanner for imaging. Each imaging protocol was completed within 24 h of slaughter.

2.1. Estimate of structural parameters for the constitutive model

Diffusion tensor imaging (DTI) was used to analyse the structural properties of porcine aortas [14]. The imaging protocol was characterized by the use of a whole body coil and by the following parameters: spin echo sequence; matrix 128 × 128 pixel; slice thickness 0.5 mm; inter-slice spacing 0.1 mm; number of slices 16; echo time 20.3 s; field of view 28 mm × 28 mm. Diffusion tensor images were acquired for different levels of diffusion sensitivity (200, 400, 600, 800, 1200 and 1600 s/mm^2). Fibre tractography was performed using MedINRIA (Sophia-Antipolis, France) and a custom Matlab® (Natick, MA) routine was used for post-processing fibre information; further details on fibre tracking and post-processing of diffusion tensor images can be found in Flamini et al. [20,21].

Fibre distribution plots obtained from the analysis of DTI data were employed to estimate the mean fibre angle and the fibre dispersion. In fact, these two quantities represent the structural properties to be used in the arterial tissue constitutive model proposed by Gasser et al. [22]:

$$\Psi(I_1, I_{4,i}) = \frac{c}{2}(I_1 - 3) + \sum_{i=1}^{2} \frac{k_1}{2k_2}\{\exp[k_2(\kappa I_1 + (1-3\kappa)I_{4,i} - 1)^2] - 1\}$$
$$I_1 = tr(\mathbf{C}); \quad I_{4,i} = (\mathbf{CM}) \cdot \mathbf{M} \tag{1}$$

In which Ψ is the strain energy function, I_1 is the first invariant of the left Cauchy tensor $\mathbf{C}$, $I_{4,i}$ is an invariant dependent on the mean fibre direction $\mathbf{M}$ (unit vector oriented along the fibre angle γ), κ is a dispersion parameter ($\kappa \in [0, 1/3]$, where 0 is maximum anisotropy and 1/3 is isotropy) [23], and c, k_1 and k_2 are material parameters. The quantities indicated by γ and κ will be referred to as structural parameters, since they are used to characterize the fibrous structure of the tissue.

Finally, the structural properties estimated from DTI were used as an input for a non-linear regression routine coded in Labview® (Austin, TX). This routine was used to determine the material constants c, k_1, k_2 by fitting the model described in Eq. (1) to porcine aorta uniaxial tensile test data performed on five porcine aortas sourced from the same local abattoir [24]. Porcine aortas for uniaxial tensile tests were prepared by cutting the thoracic aorta along the intervertebral arteries line. Specimens for the tests were die-cut using a custom dog-bone shaped die (gauge length 20 mm and width 4 mm) in the longitudinal and in the circumferential direction of the aorta. With this procedure we produced 10 sets of aortic strips cut in the longitudinal and in the circumferential direction, respectively, for a total of 20 samples. In order to be able to record strain measurements a black marker was used to draw two parallel lines along the centre of the specimen prior to testing. Tests were performed using a Zwick/Roell Z005 testing machine (Zwick GmbH, Ulm, Germany) supplied with a 20 N load-cell, custom nylon grips, and a video-extensometer to record the strain (MESSPHYSIK Material Testing, Furstenfeld, Austria). Hydration was maintained by keeping specimens in PBS (Sigma–Aldrich) up to specimen mounting, and by irrigating specimens with PBS using a pipette right before testing. Mechanical testing was performed using this protocol within 24 h from of slaughter.

The non-linear regression analysis performed on the uniaxial tensile tests stress–strain curves led to the definition of an estimate on the material properties of the tissue based on structural information obtained in a non-invasive way from MRI images.

2.2. Non-invasive characterization of tissue deformations

Phase contrast magnetic resonance imaging (PC-MRI) was employed to measure the circumferential strain in the porcine tissue when loaded with a physiological pulsatile waveform.

For PC-MRI a custom set-up was built consisting of a pulsatile pump for large animals (HP-553305 by Harvard Apparatus, Holliston, MA) to generate a continuous physiological pulsatile waveform, see Fig. 1B, and a pressure transducer (TA-100 by CWE, Ardmore, PA) to measure the pressure inside the porcine aorta and to trigger the MRI scanner to acquire images every 0.10 s. This system pumped water from the pump to the custom-built chamber containing the porcine aorta. PC-MRI images were acquired using the following protocol: matrix 256 × 256 pixel; slice thickness 1.5 mm; number of slices 9; echo time 10 ms; field of view 28 mm × 28 mm, velocity encoding 4.6 cm/s.

Afterwards, phase contrast (PC) images were post-processed following the steps described in [25–28] using a custom-built Matlab® routine, described in Table 1. Post-processing included the

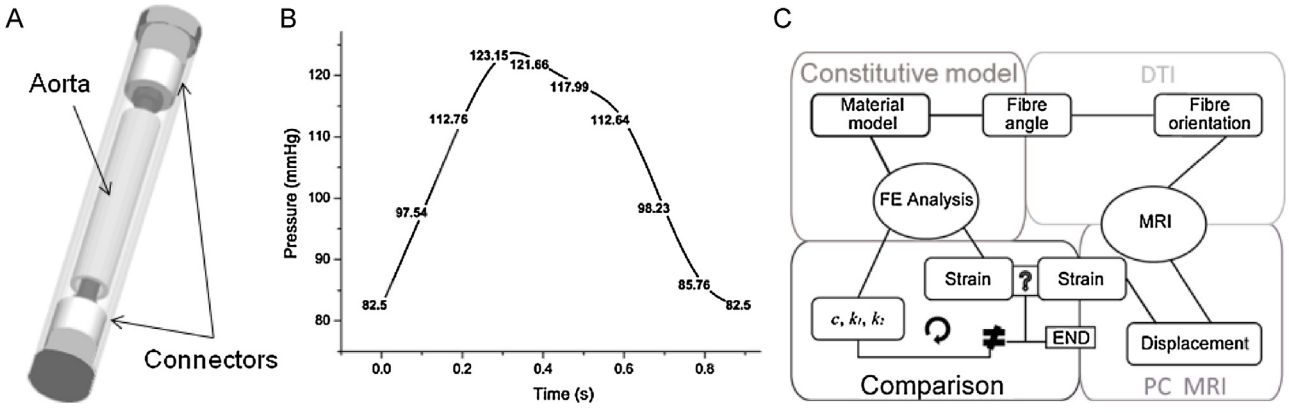

Fig. 1. (A) Computer aided drawing of the custom chamber used in the MRI studies; (B) relationship between pulsatile pressure and time produced by the pump used in the PC-MRI part of the study; (C) optimization routine workflow.

Please cite this article in press as: Flamini V, et al. Imaging and finite element analysis: A methodology for non-invasive characterization of aortic tissue. Med Eng Phys (2014), http://dx.doi.org/10.1016/j.medengphy.2014.10.006