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Over length quantification of the multiaxial mechanical properties of the ascending, descending and abdominal aorta using Digital Image Correlation

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ABSTRACT

In this paper, we hypothesize that the biaxial mechanical properties of the aorta may be dependent on arterial location. To demonstrate any possible position-related difference, our study analyzed and compared the biaxial mechanical properties of the ascending thoracic aorta, descending thoracic aorta and infrarenal abdominal aorta stemming from the same porcine subjects, and reported values of constitutive parameters for well-known strain energy functions, showing how these mechanical properties are affected by location along the aorta.

When comparing ascending thoracic aorta, descending thoracic aorta and infrarenal abdominal aorta, abdominal tissues were found to be stiffer and highly anisotropic. We found that the aorta changed from a more isotropic to a more anisotropic tissue and became progressively less compliant and stiffer with the distance to the heart. We observed substantial differences in the anisotropy parameter between aortic samples where abdominal samples were more anisotropic and nonlinear than the thoracic samples.

The phenomenological model was not able to capture the passive biaxial properties of each specific porcine aorta over a wide range of biaxial deformations, showing the best prediction root mean square error $\varepsilon = 0.2621$ for ascending thoracic samples and, especially, the worst for the infrarenal abdominal samples $\varepsilon = 0.3780$. The micro-structured model with Bingham orientation density function was able to better predict biaxial deformations ($\varepsilon = 0.1372$ for ascending thoracic aorta samples). The root mean square error of the micro-structural model and the micro-structured model with von Mises orientation density function were similar for all positions.

1. Introduction

Aorta mechanical properties vary along the aortic tree, generally agreeing that aortic stiffness increases with increasing distance from the heart (Guo and Kassab, 2003; Hang and Fung, 1995; Kim et al., 2013; Peña et al., 2015). Parameters such as aortic wall thickness, moisture content, and the location of the specimen along the aorta may influence the mechanical response (Sokolis, 2007). The fact that vessels differ so significantly in terms of anatomic characteristics is commonly attributed to the heterogeneity of blood flow within their territories during the arterial tree development phase (Dinardo et al., 2014). Determining the effect of position on gross mechanical properties has both experimental and clinical applications (García et al., 2011). Specifically, inflation (Lillie et al., 2012; Kim and Baek, 2011), planar biaxial (Zeinali-Davarani et al., 2013; Kamenskiy et al., 1998; Polzer et al., 2015) and uniaxial (Lally et al., 2004; Silver et al., 2003; Peña et al., 2015) testing are preferable in-vitro mechanical test protocols for vascular tissue. The aorta has been studied with great interest partially due to its large size, and partially due to its propensity to develop disease such as atherosclerotic process, dissection, and aneurysm. Here, animal models remain popular in clinical hypothesis testing, where specifically the pig aorta has a central role. In some cases, the validation of these models based only on uniaxial test data is inappropriate as biological and biomaterial membranes generally develop multiaxial stress states during real-life loading conditions. However, despite numerous studies on aortic properties, there is still little quantification of this effect by biaxial tests. Research to date has been limited by equibiaxial tests of descending aorta (Zeinali-Davarani et al., 2009; Peña et al., 2015), which found that distal thoracic samples are stiffer than proximal ones and anisotropy was more remarkable in lower thoracic aorta. There is limited data on the mechanical properties of ascending (Vorp et al., 2003; Guo and Kassab, 2004; Choudhury et al., 2009) and abdominal aorta (deGeest et al., 2004; Haskett et al., 2010; Kamenskiy et al., 1998). However, only Haskett et al. (2010) compared the ascending, descending and abdominal aorta biaxial mechanical properties.

To reproduce the mechanical behavior of these kinds of material,

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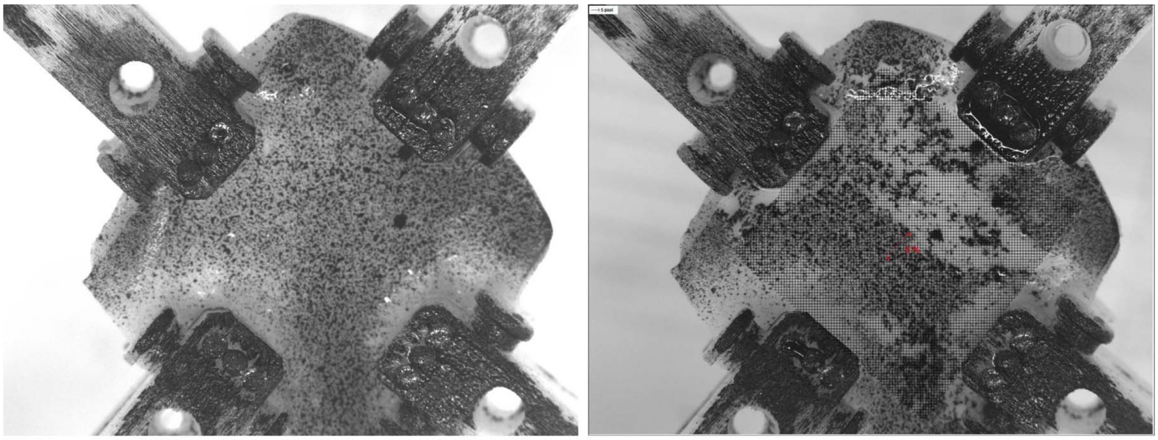

(a) Biaxial setup (b) Biaxial DIC grid

Fig. 1. (a) Representative image of the specimen mounted in a biaxial tensile testing device after the application of a pre-load. (b) Application of a grid on the surface of the vessel and the lengths between the two markers in each direction were measured by a Digital Image Correlation (DIC) Strain Master LaVision System.

many constitutive models have been proposed for soft tissues (Fung, 1993; Holzapfel et al., 2000; Humphrey, 2002; Weiss et al., 1996). The preferred methodology to describe and reproduce its complex mechanical response is the definition of a strain energy function (SEF) from which the stress response is derived, see e.g. (Alastrué et al., 2009; Holzapfel et al., 2000; Zullinger et al., 2004; Gasser et al., 2006; Holzapfel and Ogden, 2010; Sokolis, 2010) and references therein. Although phenomenological models may reproduce the biomechanical properties of the vascular tissue, their material parameters lack a clear physical meaning. Moreover, these models are unreliable for predictions beyond the strain range used in parameter estimation (Polzer et al., 2015). Most these constitutive models simplify the micro-structure and assume fibers to be set out symmetrically relative to vessel axis, with a preferred orientation, yielding macroscopic orthotropic constitutive law for each layer (Rhodin, 1980). The response of fibers are typically assumed to be governed by exponential functions (Holzapfel et al., 2000, 2005). However, structurally-motivated material models may provide increased insights into the underlying mechanics and physics of arteries and could overcome this drawback (Weisbecker et al., 2015). The work by Gasser et al. (2006) included micro-structural information in the model by means of the assumption of a fiber orientation von Mises distribution function. Other models which assume the geometrical features of fibers follow a typical continuous distribution such as β-distribution with primarily planar array (Lanir, 1979; Hollander et al., 2011); more recently, models including fiber dispersion from a micro-structurally based approach have been proposed using axially symmetric von Mises orientation distribution function (ODF) around two preferred mean direction (Alastrué et al., 2009). More recently, Alastrué et al. (2010) proposed the use of the Bingham ODF for the incorporation of anisotropy in the micro-structurally based models. One of the main advantages of the Bingham ODF is the possibility of considering three different concentration parameters in three orthogonal directions of the space. These orientations can be easily correlated with the three main directions of a blood vessel: circumferential, radial and axial. Experimental studies have demonstrated that the non-symmetric Bingham ODF is more suitable to model aneurysms (Gasser et al., 2012), carotid (Sáez et al., 2016) and aorta (Polzer et al., 2015).

We hypothesized that the ascending aorta exhibits more isotropic biomechanical responses than descending and abdominal aorta with similar stiffness on circumferential and longitudinal directions to the artery. This behavior is more difficult to reproduce with the classical phenomenological strain energy functions used in the literature, and the micro-structurally based models fitted the experimental data very well. The aim of this study is to employ biaxial test methods to identify and quantify the effect of aortic region on the mechanical characteristics of the artery. Furthermore, our aim is (a) to investigate if changes to the mechanical properties are dependent on position and (b) to quantify these differences by estimation of the mechanical constitutive parameters by least-square fitting the recorded in-vitro biaxial test results. Since pigs are often used as models for cardiovascular studies, we designed the present study to analyze the mechanical behavior of porcine aortas.

2. Experiments

Porcine aortas (n = 7) were harvested postmortem from approximately 3.5 ± 0.6 months-old female pigs, sacrificed for other studies that did not interfere with the aorta or the circulation system. The experiments on these swines were approved by the Ethical Committee for Animal Research of the University of Zaragoza and all procedures were carried out in accordance with the “Principles of Laboratory Animal Care” (86/609/EEC Norm). After artery harvesting and cleaning by removing excess connective tissue, they were kept frozen at − 20°C until testing. Once defrosted, samples were preserved in ion-free PSS (0.9% NaCl) at $4\,[°C]$ until preparation of testing samples was carried out. The aorta was subdivided into three parts: ascending thoracic (ATA), descending thoracic aorta (DTA) and infrarenal abdominal aorta (IAA). For this study, the analyzed specimens were obtained from the proximal region of each considered part (Peña et al., 2015). Samples were inspected for potential damage during slaughtering or harvesting.

Square specimens, approximately 25×25 [mm], were cut from the ATA, DTA and IAA using a punch cutter and a scalpel. The specimens were prepared with their sides aligned in the circumferential and axial directions of the artery Fig. 1a. A Mitutoyo Digimatic micrometer was used to measure the length, width and thickness of the samples using the average of three measurements for each sample. Kim and Baek (2011); Kim et al. (2013) reported that the arterial thickness and stiffness are significantly different at locations particularly varying in the circumferential direction. For this reason, during the measurement of the thickness, samples in which noticeable thickness variations were observed (10%) were rejected.

2.1. Mechanical testing

Tests were carried out in a high precision drive system adapted for biological specimens Instron BioPuls™ low-force planar-biaxial testing system. Square specimens were mounted in the planar-biaxial machine by connecting four carriages by noddles clamps, immersed in a bath filled with PBS and maintained at 37 °C by a heater-circulation (Peña