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BIOMECHANICAL PROPERTIES OF HUMAN DILATED ASCENDING AORTA

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Aneurysms of ascending aorta are dilatation of the first part of the human aorta. They commonly show no clinical symptoms. This condition increases the risk of aorta dissection, which is a life-threatening condition. In this study we attempted to elucidate the changes in the biomechanical properties that occur in the dilated human ascending aorta. Fourteen specimens of ascending aorta wall were mechanically tested under a uniaxial tensile test. Two specimens from each ascending aorta anterior region were cut in longitudinal and circumferential directions. The samples were stretched until rupture of the sample occurred. The obtained experimental data were processed to determine maximal stress, maximal strain and the tangential modulus of elasticity in the linear part of the stress-strain curve. The obtained results showed a remarkable anisotropy of the ascending aorta tissue. We found higher strength of the tissue in the circumferential direction than in the longitudinal direction. There were no statistically significant differences between the strains of the samples. Tangential modulus of elasticity of the aortic samples in the longitudinal direction was significantly lower than the elastic modulus of the samples in the circumferential direction. The tissue in the circumferential direction is stronger and stiffer than in the longitudinal direction.

Key words: *ascending aorta, aneurysm, mechanics, uniaxial tensile test, elastic modulus.*

INTRODUCTION

Aneurysm of the ascending aorta is a progressive and localised dilatation of the first part of the aorta and presents a special challenge to primary care physicians, internists, and cardiac surgeons, because they remain asymptomatic until they present with either dissection or rupture, which is a severe life-threatening condition (Evangelista, 2010; Lavall *et al*., 2012).

The incidence of aortic dissection is difficult to determine, as many cases remain undiagnosed. As known, incidence is about 2.9 cases per 100 000 inhabitants per year, with at least 7000 new cases per year in the United States. However, the actual incidence could be even greater in the range of 6–10 cases per 100 000 inhabitants per year. Most often aortic dissection presents after the age of sixty, according to the International Registry of Acute Aortic Dissection (IRAD). The average age of patients is 62; men suffer twice as often as women (68% and 32%) and at younger age (Mészáros *et al*., 2000; Erbel *et al*., 2014).

The most common risk factors associated with aortic dissection are: hypertension, up to 70%, aortic aneurysm — 14%, bicuspid aortic valve — 3%, and Marfan syndrome — 5% (Januzzi *et al*., 2004).

Although often in a histological analysis of the aortic wall only age-specific changes are revealed, aortic dissection is rarely observed in people with a completely normal aortic media layer. Any disease or condition characterised by inadequate or damaged elastic fibres or muscle cells in the media layer increases the risk of aortic dissection. This would definitely include unclear media necrosis, Marfan syndrome, Eller-Danlo syndrome, and other genetically altered changes in connective tissue that may initially lead to a dilatation of the diameter of the aorta and aneurysm formation (Erbel *et al*., 2014).

Nowadays, the only method of treatment for ascending aorta aneurysm is surgical replacement of the dilated part. Despite the development of modern surgical techniques, the risk of surgery is relatively high. Consequently, it is necessary to individually assess the risks associated with possible aneurysm rupture and surgical replacement risks (Elefterides, 2002; Elefteriades and Farkas, 2010).

It is known that the risk of aortic dissection increases significantly with increasing diameter of ascending aorta. Therefore, it is considered that an ascending aorta diameter greater than 5.5 cm is an indication for surgical replacement. However, this criterion may not always be correct, as it is known that the aortic dissection may also occur at a lower ascending aorta diameter, as well as in the case of comorbidities, and thus the limit value could be decreased to 4.5 cm (Pape *et al*., 2007; Elefteriades and Farkas, 2010).

The absolute size of ascending aorta is a predicting tool for an unwanted event, but probably there could be a better indicator for early surgery. Devies *et al*. (2006) described the aortic size index, which is the ratio between the maximum diameter of the ascending aorta and the body surface area. They recommend elective surgery when the aortic size index is greater than 2.75 cm/m^2 (Devies *et al*., 2006).

It has been described that remodelling of elastin and collagen fibres in the aortic wall tissue occurs as a result of the dilatation of the ascending aorta. These changes have a remarkable effect on tissue mechanical properties, which induce increased wall stress and/or decreased wall ultimate strength (Okamoto *et al*., 2003; Ferrara *et al*., 2016).

So far, there is not much data about the biomechanical changes and structural changes in the case of a dilated ascending aorta.

Analysis of biomechanical properties of ascending aorta tissue and other clinical predictors can help to better understand the development of ascending aorta dilatation stages, and in the future aid in predicting or even avoiding possible dissection or rupture of ascending aorta.

MATERIALS AND METHODS

Fourteen patients treated at the Pauls Stradiņš Clinical University Hospital and undergoing elective ascending aorta surgery were selected for this study. Specimens of ascending aorta were collected from each patient, according to planned volume of each operation. The study protocol was approved by the Ethics Committee of Rīga Stradiņš University and conducted in accordance with the principles stated in the Declaration of Helsinki.

Mean age of the patients was 62.43 years (SD = 8.35). There were nine male and five female patients. Mean weight of the patients was 88.43 kg (SD = 12.92) and mean height was 1.75 m (SD = 0.09). Mean body mass index was 28.87 kg/m^2 (SD = 3.88) and mean body surface area using Do Bois formula was 2.04 m^2 (SD = 0.18).

Computed tomography angiography was performed on each patient to determine the maximum size of ascending aorta. Mean maximum size of ascending aorta was 5.82 mm (SD = 0.44). We also calculated the aortic size index (ASI) according to Davies *et al.* (2006), as maximum ascending aorta diameter (cm) divided by body surface area (m^2). Mean aortic size index was 2.88 cm/m^2 (SD = 0.38).

Before testing, the materials were stored in frozen isotonic physiological saline at –20 ± 1 °C. It has been shown in experiments with soft biological tissue (arteries, heart valves), which were previously frozen and stored at low temperatures, that such storage conditions do not change the biomechanical properties of materials (Stemper *et al*., 2007; O'Leary *et al.*, 2014; Chow *et al*., 2011).

Samples of ascending aorta above the sinotubular junction (Fig. 1) were prepared using a special stamp with two parallel razor blades. Two specimens from each ascending aorta anterior region were cut in the longitudinal and circumferential directions. The sample length was 30–35 mm, and their width was 5 mm. Each specimen was cleaned, but the intima and adventitia were left intact. Specimens of ascending aorta were investigated under a uniaxial tensile test. Tensile test equipment Zwick/Roell (Germany) BDO-FB0.5TS was used. This testing machine was equipped with a load cell of 50.0 ± 0.1 N and was used in combination with the testing software testXpert 2 for control and data processing. Before the testing of the samples their thickness was measured, using an optical cathetometer MK-6 (LOMO, Saint Petersburg, Russia). The measurement accuracy of the thickness was ± 0.01 mm. The samples were stretched at a speed of 5 mm/min until rupture of the sample occurred (Fig. 2). All tests were conducted at room temperature 21 ± 1 °C. During the experiment, the specimen was kept wet by spraying of isotonic physiological solution to prevent tissue drying. The obtained experimental data were processed using testXpert 2 software to determine

Fig. 1. Image of an excised part of dilated ascending aorta from which samples were obtained. (A) anterior region.

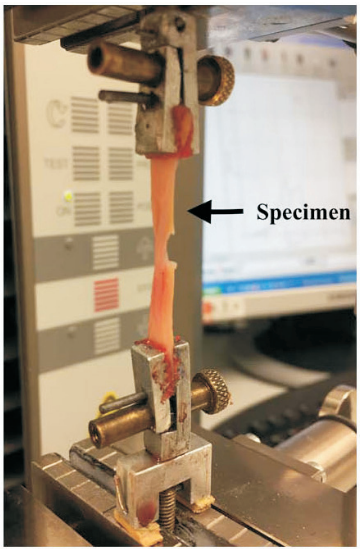

Fig. 2. Image of a ruptured tissue specimen.

maximal stress, maximal strain and the tangential modulus of elasticity.

The tangential modulus of elasticity (E) characterises the stiffness of the tissue, and a higher value indicates stiffer tissue. The tangential modulus was expressed as a tangent of the angle between the strain axis and tangential line on the linear portion of the stress–strain relationship (Fig. 3), where all load-bearing wavy collagen fibres are straight. This approach is commonly used to determine the tangent modulus of elasticity of soft biological tissues (Barber *et al.*, 2001).

The strain of the samples was calculated as:

$$\varepsilon = [(l - l_0) / l_0] \times 100\ \%,$$

where l – the deformed length of the sample, l_0 – the original length of the sample.

The stress was calculated as:

$$\sigma = F/A,$$

where F – axial force, A – actual cross sectional area of the sample, calculated assuming that the tissue is incompressible.

The incompressibility of the aortic wall material due to the high liquid content was established in Lawton (1954), and confirmed in Carew *et al.* (1968). It means that the volume of the sample during deformation is the same as in the original (not deformed) volume of this sample. Based on this, the actual cross section of the sample is calculated as:

$$A = A_0 / (1+\varepsilon),$$

where A_0 – the original cross section area of the sample.

Statistical analysis. Statistical data analysis, calculation and all graphs were made using GraphPad PRISM version 6.0e (GraphPad Software Inc., San Diego, California, USA). Unequal SD comparison of medians between different groups was performed with the Mann–Whitney test. All

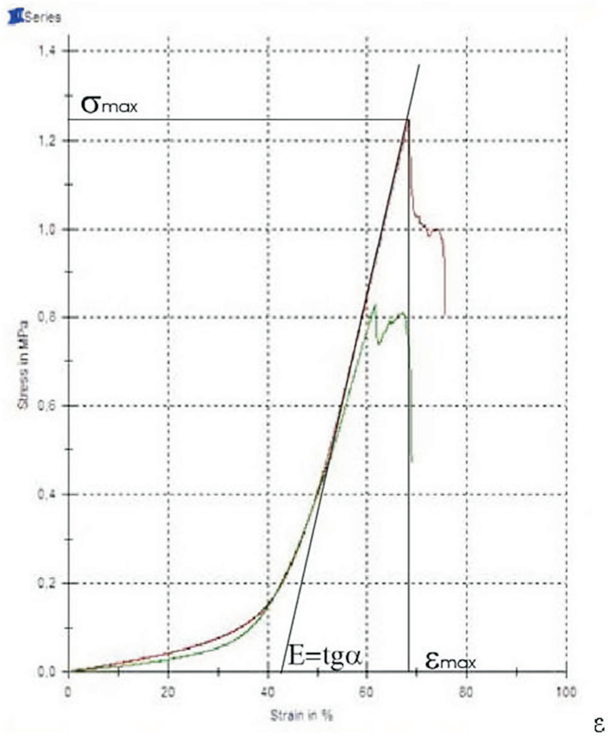

Fig. 3. Typical view of the stress–strain relationship for samples of ascending aorta: σ_{max} and ε_{max} – maximal stress and strain respectively, E – tangential modulus of elasticity.

biomechanical parameters were presented as medians (*Md*) with interquartile range (IQR). Two values were considered as statistically significantly different if *p*-value was less than 0.05 ($p < 0.05$).

RESULTS

The thickness of samples (Fig. 4) in the longitudinal direction was *Md* = 2.35 mm (2.11–2.80) and in the circumferential direction was *Md* = 2.34 mm (1.93–2.94). There were no statistically significant differences between the thicknesses of the aortic wall in both directions ($p = 0.28$).

The maximal stress for samples (Fig. 5) in the longitudinal direction was *Md* = 0.42 MPa (0.33–0.60) and in the circumferential direction was *Md* = 0.61 MPa (0.42–0.84). There was a statistically significant difference between the

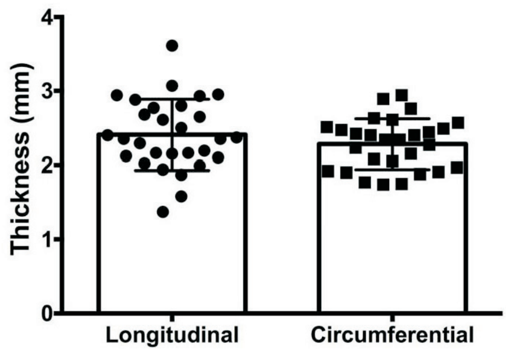

Fig. 4. Thickness of the aortic samples in the longitudinal and circumferential directions (there was no statistically significant difference between the two groups, $p = 0.28$).

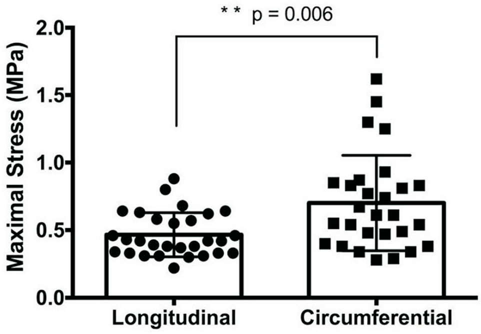

Fig. 5. Maximal stress for the aortic samples in the longitudinal and circumferential directions.

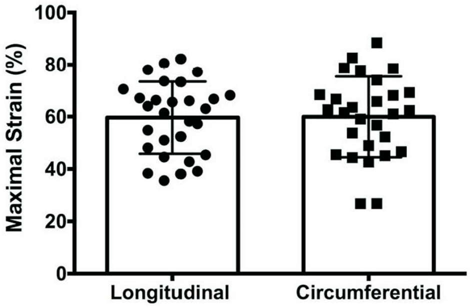

Fig. 6. Maximal strain for the samples of the aortic wall in the longitudinal and circumferential directions (there was no statistically significant difference between the two groups, $p = 0.90$).

maximal stress for the samples of the aortic wall in the longitudinal and in the circumferential directions ($p = 0.006$).

There was no statistically significant difference between the maximal strain of the samples in the longitudinal and in the circumferential directions (Fig. 6). The maximal strain for samples in the longitudinal direction was *Md* = 63.01% (46.73–69.36) and in the circumferential direction was *Md* = 61.98% (47.20–69.03), respectively ($p = 0.90$).

Tangential modulus of elasticity (Fig. 7) of the aortic samples in the longitudinal direction *Md* = 1.76 MPa (1.16–2.42) was significantly lower ($p = 0.002$) than the elastic modulus of the samples in the circumferential direction *Md* = 2.33 MPa (1.95–3.76).

DISCUSSION

The study investigated biomechanical properties of dilated human ascending aorta. Specimens cut from the anterior region of excised dilated aortic portion from patients undergoing elective cardiac surgery were tested and analysed in circumferential and longitudinal directions.

Our results showed that there was no significant difference between the thicknesses of the aortic wall tissue in both directions. Also there was no significant difference between the maximal strain for samples in the longitudinal and in the circumferential directions.

The results confirmed the anisotropy of dilated ascending aorta tissue. Values of the maximal stress for samples in the

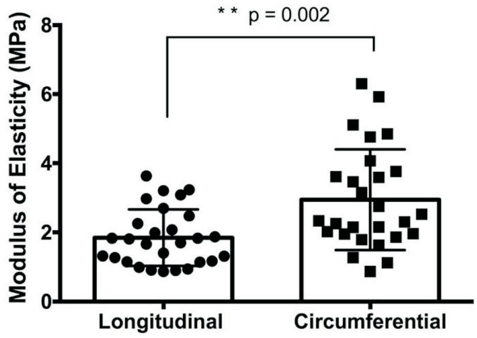

Fig. 7. Tangential modulus of elasticity the aortic samples in the longitudinal and circumferential directions.

longitudinal direction were lower than in the circumferential direction. Also, tangential modulus of elasticity in the longitudinal direction was significantly lower than in the circumferential direction. These results are consistent with studies available in the literature (Duprey *et al.*, 2010; Pham *et al.*, 2013; Ferrara *et al.*, 2015).

It is very important to conduct further research to analyse structural changes of ascending aorta tissue and the possible role of clinic-pathological risk factors like aortic valve type (bicuspid valve or tricuspid valve), ageing, hypertension and others on these processes. This could help to better understand mechanisms and causes of biomechanical changes in dilated ascending aorta.

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DILATĒTAS CILVĒKA ASCENDĒJOŠAS AORTAS BIOMEHĀNISKĀS ĪPAŠĪBAS

Ascendējošās aortas aneirisma ir cilvēka aortas pirmās daļas dilatācija. Visbiežāk tā nerada klīniskus simptomus. Ascendējošās aortas dilatācija ievērojami palielina aortas atslāņošanās risku, kas ir dzīvībai bīstams stāvoklis. Pētījumā autori cenšas izskaidrot biomehānisko īpašību izmaiņas, kas rodas dilatētas cilvēka ascendējošās aortas gadījumā. Četrpadsmit dilatētas ascendējošās aortas sieniņas tika mehāniski testētas ar ierīci vienass noslogojuma pētījumu veikšanai. No katras ascendējošās aortas priekšējās sienas tika izveidoti divi paraugi cirkulārā virzienā un divi paraugi gareniskā virzienā. Paraugi tika stiepti līdz paraugu plīsumam. Iegūto eksperimentu dati tika apstrādāti, lai noteiktu paraugu maksimālo elasticitāti, maksimālo deformāciju un tangencionālo elastības modeli. Iegūtie rezultāti parādīja nozīmīgu ascendējošās aortas sienas audu anizotropiju. Lielāka audu izturība tika novērota cirkulārā virzienā, salīdzinot ar garenvirzienu. Audu paraugu deformācijai nav statistiski nozīmīga atšķirība abos virzienos. Iegūtais aortas paraugu tangenciālais elastības modulis gareniskā virzienā bija ievērojami zemāks par iegūto elastības moduli cirkulārā virzienā. Audi cirkulārā virzienā ir stiprāki un cietāki, salīdzinot ar audiem gareniskā virzienā.