JOURNAL OF THE MECHANICAL BEHAVIOR OF BIOMEDICAL MATERIALS 46 (2015) 229–243

Available online at www.sciencedirect.com
ScienceDirect
www.elsevier.com/locate/jmbbm

Research Paper

Effects of aneurysm on the directional, regional, and layer distribution of residual strains in ascending thoracic aorta

*Dimitrios P. Sokolis**

Laboratory of Biomechanics, Biomedical Research Foundation of the Academy of Athens, Athens, Greece

ARTICLE INFO

Article history:
Received 9 November 2014
Received in revised form
15 January 2015
Accepted 28 January 2015
Available online 21 February 2015

Keywords:
Opening angle
Zero-stress state
Heterogeneity
Vascular remodeling
Aortic dissection
Stress distribution

ABSTRACT

Stress analyses in ascending thoracic aortic aneurysms require measurement of the stress-free state of tissue, for which there is limited information. The true reference configuration can also be difficult to delineate with opening angle measurements, due to (a) the variability in aneurysmal shape and (b) layered wall structure, suggesting spatial dependency of the residual strain field, and (c) the non-consideration of axial residual strains. The present study was designed to overcome these difficulties, by providing extensive data about the consequences of aneurysm on the directional, regional, and layer distribution of residual strains in the ascending thoracic aorta. We demonstrate that the opening angle of rings cut-open anteriorly correlated positively with age, diameter, degree of atherosclerosis, and circumferential residual strain at the external wall and negatively with that at the internal wall. As anticipated from the highly curved and non-axisymmetric geometry, the opening angle of ascending thoracic aortic aneurysms from tricuspid aortic valve patients declined notably, from ~240 to 190 deg, along a relatively short vessel length and residual strains varied strongly from one layer to another, being compressive in the intima and tensile in the media and adventitia, and depended also on circumferential position and direction. Smaller opening angles were found in aneurysms from bicuspid aortic valve patients and non-aneurysmal aorta, but differences were only significant for the latter that also showed less pronounced axial decline and smaller layer-specific residual strains. Dimensional data of the aortic layers obtained via histology support the association between opening angle change and non-uniform tissue remodeling, with the greater cross-sectional area of the intima and media in the wall of tricuspid aortic valve aneurysms explaining the increase of opening angle in this patient class compared to control.

---

*Tel.: +30 210 6597370; fax: +30 210 6597365.
E-mail address: DimitrisSokolis@ath.forthnet.gr

http://dx.doi.org/10.1016/j.jmbbm.2015.01.024
1751-6161/© 2015 Elsevier Ltd. All rights reserved.

Table 1 – ATAA patient and autopsy demographics.

Experiment type	Tissue type	Sample no.	Age (years)	ATAA Diameter (cm)
Single strip measurements	BAV	10	65±4	6.0±0.5
	BAV Male	7	64±6	5.6±0.1
	BAV Female	3	68+8	6.8±1.6
	TAV	19	65±2	5.7±0.3
	TAV Male	11	64±4	5.5±0.2
	TAV Female	8	67±3	6.1±0.7
	Control	4	67±8	–
	Control Male	2	59±0	–
	Control Female	2	73±10	–
Histological analysis	BAV	10 per quadrant	65±4	6.0±0.5
	BAV Male	7	64±6	5.6±0.1
	BAV Female	3	68+8	6.8±1.6
	TAV	19	65±2	5.7±0.3
	TAV Male	10	64±4	5.5±0.2
	TAV Female	9	67±3	6.1±0.7
	Control	10	64±2	–
	Control Male	6	60±2	–
	Control Female	4	69±3	–
Axial variation measurements	BAV	6 per region	54±3	5.9±0.4
	BAV Male	4	58±2	6.1±0.6
	BAV Female	2	47±7	5.5±1.0
	TAV	11	61±2	5.6±0.1
	TAV Male	9	62±2	5.5±0.1
	TAV Female	2	56±7	5.9±0.3
	Control	9	58±2	–
	Control Male	6	56±2	–
	Control Female	3	61±4	–
Layer-specific residual stretches	BAV	5 per quadrant and direction	52±4‡#	5.2±0.1
	BAV Male	5	52±4	5.2±0.1
	BAV Female	0	–	–
	TAV	5	62±3#	5.0±0.3
	TAV Male	5	62±3	5.0±0.3
	TAV Female	0	–	–
	Control	7	71±3	–
	Control Male	7	71±3	–
	Control Female	0	–	–

Symbols ‡ and # indicate significant difference against Control and TAV, respectively. Note that the differences in age and male/female ratio among BAV and TAV patients, and autopsy subjects were non-significant in the first three experiment types, as were those in ATAA diameter between BAV and TAV patients.

1. Introduction

Ascending thoracic aortic aneurysm (ATAA) is the gradual expansion of the proximal aortic region, affecting 5–10 patients per million population each year, most often men between the ages of 50 and 70 years old (Olsson et al., 2006). It is related with significant morbidity and mortality; 50% of patients who experience rupture die before reaching the hospital with emergency surgery of ruptured ATAA carrying a dramatic 97–100% mortality (Johansson et al., 1995), as opposed to a <5% operative mortality when they are electively treated. Elective repair for asymptomatic ATAA is effective in improving survival and is indicated when the risk of surgery is less than the risk of negative events, i.e. death, dissection, or rupture for a particular aneurysm size (Elefteriades, 2002). Prediction of these complications is non-trivial, with current clinical risk assessment typically based on the maximum ATAA diameter. Since these complications represent, to a large extent, mechanical failures of the aortic wall, it is important to examine them with a biomechanical approach, so as to interpret the underlying mechanisms driving dissection or rupture.

Biomechanical stress–strain analyses across wall thickness and in different ATAA locations are most pertinent under both physiologic and supra-physiologic (i.e. near-failure) conditions, but current finite element analyses, e.g. (Pasta et al., 2013), have hypothesized vanishing residual stresses, likely leading to inaccurate assessments of local stress distributions. Information on the zero-stress wall configuration is critical, as postulated independently by Vaishnav and Vossoughi (1983) and Fung (1984) for healthy arterial tissue some thirty years ago, with the existence of circumferential residual strains in the no-load state (when lumen pressure and external tethering forces are removed) leading to a more uniform through-thickness distribution of