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Research Paper

Evaluating ascending aortic aneurysm tissue toughness: Dependence on collagen and elastin contents

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ABSTRACT

Ascending thoracic aortic aneurysms (ATAAs) can lead to a dissection or rupture of the aorta, causing death or disability of the patients. Surgical interventions used to treat this disease are associated with risks of mortality and morbidity. Several studies have investigated the rupture mechanisms of ATAAs; however, underlying reasons behind aortic rupture (failure) have not been fully elucidated and further investigations are necessary. The rupture of pathological aortic tissue is a local phenomenon resulting from defects or tears in the vessel wall. In this work, the toughness-based rupture properties of ATAAs have been examined.

The toughness, biaxial tensile properties, and histological properties of aneurysmal and control human ascending thoracic aortas (ATAs) were characterized from four quadrants of surgically excised aortic rings. The aneurysmal tissue population included aortas from patients with bicuspid aortic valves (BAV) and tricuspid aortic valves (TAV). The toughness, incremental modulus, and thickness properties of the aortas were determined and compared regionally. Additionally, to further explore the rupture propensity of ATAAs, the inter-correlation of the toughness properties with histological characteristics have been explored. We found no correlation between toughness and incremental modulus. However, toughness decreased significantly with the amount of

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collagen. In the outer curvature, there was an increase in incremental modulus with collagen+elastin content, but a decrease in toughness. These results suggest tissue remodeling could affect toughness and stiffness differently in ascending aortic aneurysms.

1. Introduction

An aneurysm is a life-threatening cardiovascular disease in which the wall of an artery grows and dilates permanently. Ascending aortic aneurysms put patients at high risk of aortic dissection and/or rupture (Elefteriades and Farkas, 2010). The occurrence of thoracic aortic aneurysms (TAAs) and acute aortic dissection are reported as 10.4 and 3.5 cases per 100,000 in the general population each year, respectively (Clouse et al., 1998', 2004; Golledge and Eagle, 2008). Most TAAs and the thoracic aortic dissections occur at the ascending thoracic aorta (Milewicz et al., 2008).

Surgery is used to manage these diseases and to save patients' lives. Cardiac surgery carries a risk of mortality and can cause postoperative complications (Davies et al., 2002; Tremblay et al., 2009). Hence, careful considerations are needed to select appropriate criteria to guide surgical interventions. Current clinical criteria for surgical decision-making are predominately based on size of the ATAA, however, the ability of these criteria to predict thoracic aortic dissection and rupture (TAD) propensity of all ATAAs has been questioned (Elefteriades and Farkas, 2010; Verma and Siu, 2014). Several studies have investigated the failure mechanism of the ATAAs and the aortic dissection yet the reasons for TAD are not fully understood.

Biological and biomechanical factors interact with each other and, in combination, contribute to the progression of TAD (Lasheras, 2007). ATAs remodel and regenerate in order to retain their integrity (Lasheras, 2007) although, during the progression of ATAAs, the artery does not properly remodel and regenerate causing permanent dilation. The aneurysmal remodeling can adversely affect the functionality of the aorta through the formation of localized tissue defects and micro-damages. Aortic dissections are mainly associated with intimal tears in the aortic circumferential (transverse) direction (Hirst et al., 1958; Thubrikar et al., 1999). The cyclic stresses imported on the ATA by blood flow and contraction of the heart, could gradually grow local tissue defects and cause an aortic dissection or rupture (the concept of fatigue failure). Toughness is defined as the energy needed to open a crack of a certain area. To better understand the failure mechanisms associated with TAD requires knowledge of aortic toughness (resistance to cutting).

In this study, the toughness and tensile properties of ATAAs removed at surgery were evaluated and compared with histological data. To the best of authors' knowledge, this is the first study characterizing the regional toughness property of human ATAAs and comparing it with its macroscopic tissue structure and modulus.

2. Materials and methods

A group of aneurysmal ATAs with BAV and TAV were collected and tested during aortic replacement surgery under informed consent and in accordance with the ethical approval of the Montreal Heart Institute, and Royal Victoria Hospital in Montreal, Quebec, Canada.

Table 1 presents the characteristics of the patient population with the average age and ex-vivo diameter of 68 ± 12 years and 36 ± 5 mm, respectively. The toughness and the biaxial tensile tests were performed in all quadrants of the aortic ring. Fig. 1 illustrates the locations of these quadrants around the aortic rings and are listed as the following: inner curvature (IC), anterior wall (Ant), outer curvature (OC), posterior wall (Post).

2.1. Biaxial tensile tests

2.1.1. Experimental procedure

Biaxial tensile testing was conducted with an EnduraTec ELF 3200 (Bose, Minnesota, USA). This mechanical tester has two axes, perpendicular to each other, containing a 1 kg load-cell (Model 31, Sensotec Honeywell) and a displacement transducer. The apparatus is equipped with a black-and-white CCD-camera video-extensometer (Watec America LCL 902C camera with Computer TEC55 Lens), allowing the automatic tracking of gauge marks.

After tissue collection, the specimens were kept refrigerated in buffer solution and were tested within 24 h. Tissue sections of $15 \times 15\ mm^2$ from each quadrant were collected

Table 1 – Characteristics of the patients' population. The population is categorized based on the aortic valve types, including: BAV ($N=6$), TAV ($N=8$).

Sample #	Gender	Age (year)	Aortic Diameter (mm)	Valve type
7	M	67	32	BAV
8	M	75	45	BAV
9	M	65	34	BAV
10	M	45	32	BAV
11	M	81	48[a]	BAV
12	M	60	50[a]	BAV
19	M	75	38	TAV
20	M	73	38[a]	TAV
21	M	67	33	TAV
22	M	69	30	TAV
23	M	76	40	TAV
24	M	68	35	TAV
25	M	46	43	TAV
26	F	85	50[a]	TAV

[a] In-vivo diameter.