journal of the mechanical behavior of biomedical materials 17 (2013) 126–136

Available online at www.sciencedirect.com

SciVerse ScienceDirect

www.elsevier.com/locate/jmbbm

Research Paper

# Characterization of fracture toughness exhaustion in pig aorta

Boby Chu[a], Emmanuel Gaillard[a,*], Rosaire Mongrain[a,1], Steven Reiter[a], Jean-Claude Tardif[b]

[a]Department of Mechanical Engineering, McGill University, 817 Sherbrooke Street West, Montreal, QC, Canada H3A 2K6
[b]Montreal Heart Institute, 5000 Bélanger Street, Montreal, QC, Canada H1T 1C8

ARTICLE INFO

*Article history:*
Received 17 May 2012
Received in revised form
10 August 2012
Accepted 20 August 2012
Available online 7 September 2012

*Keywords:*
Aortic rupture
Fracture toughness exhaustion
Aortic wall stiffness

ABSTRACT

*Background:* Spontaneous rupture of the aorta (SRA) without aneurysm, dissection, inflammation or infection of the aortic wall can be of two types: traumatic and non-traumatic. SRA is most of the time a fatal event. Consequently, it is important to understand the conditions which lead to the aortic rupture, and, in the case of non-traumatic SRA, to predict the temporal likelihood of rupture.

*Method of approach:* The present work incorporates the temporal aspect by examining the effects of fatigue on aortic wall properties, and adopts an energy approach, based on fracture toughness, to evaluate the aorta's resistance to rupture. Fracture toughness characterization is a destructive testing process and as a consequence cannot be implemented as a clinical tool. However, using concepts in damage mechanics, in theory, it should be possible to indirectly assess fracture toughness from other mechanical properties, such as aortic wall stiffness. Tissue samples from non-aneurysmal porcine aortas were fatigued and were subjected to both biaxial and guillotine tests to assess wall stiffness variations and fracture toughness exhaustion, respectively.

*Results:* The experiments reveal that aortic wall stiffness variations and fracture toughness exhaustion decreased as a function of loading cycles and can be modeled with exponential functions. After one million loading cycles, the stiffness ratio between the non-fatigued sample and the fatigued sample, dropped to about 0.85, while the fracture toughness ratio counterpart fell to about 0.80.

*Conclusion:* Consequently, the changes in both stiffness and fracture toughness as a function of applied fatigue cycles can be measured in aortic tissues. Moreover, these results suggest the possibility to use fracture toughness exhaustion curves as a fatigue criterion.



## 1. Introduction

Spontaneous rupture of the aorta (SRA) without aneurysm, dissection, inflammation or infection of the aortic wall can be of two types: traumatic and non-traumatic. Spontaneous traumatic rupture of the aorta (STRA) is usually caused by high speed impacts such as those that occur in vehicle collisions and serious falls (Gammie et al., 1998). By far, the largest percentage of patients diagnosed with STRA have

*Corresponding author. Tel.: +1 514 588 7489.
E-mail addresses: boby.chu@mail.mcgill.ca (B. Chu), emmanuel.gaillard@mcgill.ca (E. Gaillard), rosaire.mongrain@mcgill.ca (R. Mongrain), Steven.reiter@mail.mcgill.ca (S. Reiter), Jean-claude.tardif@icm-mhi.org (J.-C. Tardif).
[1] Tel.: +1 514 398 1576.

1751-6161/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jmbbm.2012.08.007

suffered automobile related trauma (Gammie et al., 1998). Spontaneous non-traumatic rupture of the aorta (SNTRA) without aneurysm, dissection, inflammation or infection of the aortic wall is rare (al Moussarih et al., 1998; Aoyagi et al., 1991). Nevertheless, the risk of SNTRA is considerably increased by the practice of vigorous exercise at young individuals and adults (Thompson et al., 2007).

SRA is most of the time a fatal event due to the profuse bleeding that results from the rupture (Fabian et al., 1997; Gammie et al., 1998). Consequently, it is important to understand the conditions which lead to the rupture, and, in the case of non-traumatic SRA, to predict the temporal likelihood of rupture.

To permit prediction of SRA on a temporal basis, there is a need to introduce a time parameter linked to the mechanics within the aortic wall. Given the cyclical nature of the loading conditions, a logical choice is fatigue. Fatigue is the progressive weakening of a part of a structure through cyclical loading. Each cycle imparts a certain amount of damage to the structure or part until the latter's failure due to the total accumulated damage. In the present study, the temporal aspect will be incorporated by examining the effects of fatigue on aortic wall properties.

Moreover, a fracture mechanics (FM) approach was used to evaluate the aorta's resistance to rupture. Fracture toughness is defined as an inherent property which describes the ability of a material to resist propagation of a crack from an existing flaw. It corresponds to the critical stress intensity at the tip of the flaw which allows crack propagation under plane-strain conditions (Ferracane et al., 1995). An energy approach was used in this study to analyze crack growth.

The rupture of the aorta can be considered as a catastrophic fracture occurring when its mural strain energy per unit area exceeds the threshold level determined by the overall fracture toughness of the aortic wall in a damaged state.

Fracture toughness characterization is a destructive testing process and as a consequence cannot be implemented as a clinical tool. However, using concepts in damage mechanics, in theory, it should be possible to indirectly assess fracture toughness from other mechanical properties, such as aortic wall stiffness for which non-invasive measurements methods and tools already exist, like optical coherence elastography (OCE) (Khalil et al., 2005; Sun et al., 2011). According to Lemaître, damage in a given material manifests itself as alterations to the material's macroscopic physical properties (Lemaître, 1996). This assertion implies that both the fracture toughness as well as the stiffness of a piece of ascending aortic tissue are separately governed by the amount of cumulative damage present internally, and in a purely fatigue-driven environment, the latter can be expressed in terms of the number of fatigue cycles applied to the tissue. Consequently, it should be possible to track the variations in fracture toughness in the tissue by observing the changes in the material's stiffness.

The energy approach has also been employed in many fields, especially in characterizing the fracture behaviour of soft thin materials, biological or otherwise. Most of the work featured the slicing of test samples using an instrumented cutting implement like a guillotine (Atkins and Mai, 1979), a blade (Lake and Yeoh, 1978), or a pair of scissors (Sim et al., 1993). In haptics, fracture mechanics have enabled the modelling of the forces required to cut through soft tissue with scissors (Mahvash et al., 2008). Related to biomechanics, Pereira et al. (1997) have ranked the fracture toughness of various mammalian soft tissues using a scissor testing rig. Oyen-Tiesma and Cook (2001) determined fracture resistance of cultured neocartilage using energy based method. Adeeb et al. (2004) studied the fatigue behavior of tendon tissue using a stress intensity approach for fracture mechanics. Shergold and Fleck (2005) looked at the deep penetration of human skin by the means of both a sharp punch and a flat-bottom punch. Particular to vascular mechanics, fatigue was the main area of focus. Gilpin cyclically loaded porcine coronary arteries and plotted the variation of circumferential ultimate tensile stress as a function of both fatigue cycles and load amplitude (Gilpin, 2005). Sacks and Smith subjected prosthetic bovine heart valves to accelerated testing that cycled samples up to 500 million times and observed signs of fatigue-induced damage accumulation (Sacks and Smith, 1998). In terms of fracture toughness, Purslow (1983a) performed both "trouser" tearing tests and uniaxial tensile tests on samples of porcine descending aortas, and found that toughness, stiffness, and ultimate tensile strength varied distally along the descending aorta.

Nevertheless, to our knowledge, no study has been led to determine if the fracture toughness of soft tissues, as aorta, is sensitive to the fatigue damage process. A few works have shown that the fracture toughness is affected by fatigue but only in the case of metals or composite materials (Cadenas-Herrera et al., 2010; Sriram et al., 1995; Ye and Wang, 2001; Ye and Zheng, 2008).

Consequently, the main objective of this study was to assess the feasibility of tracking the variation of both stiffness and fracture toughness of porcine aortic tissue as a function of fatigue. Tissue samples from 14 non-aneurysmal porcine aortas were fatigued and subjected to both biaxial and guillotine tests to assess stiffness variations and fracture toughness exhaustion, respectively.

## 2. Materials and methods

### 2.1. Tissue preparation

14 non-aneurysmal porcine aortas producing 28 samples after processing were used. The time elapsed between the aortas harvesting and the measurements was lower than 48 h and allowed to keep fresh tissues.

Two 1-cm-wide rings were excised from each ascending aorta: ring A starting immediately above the sinuses, and ring B right above ring A (Fig. 1).

Rings were then sliced open, forming strips. A-strips (obtained from the rings A) were kept away from any moving parts and taken as control. B-strips (obtained from the rings B) were assigned to be fatigued by a particular number of fatigue cycles, being either 0, 1000, 10,000, 100,000 or 1 million.

The Bose EnduraTec ELF 3200 universal tester (Bose Corporation, Framingham, USA) was at the core of the experimental setup as it served to actuate all the moving components of the