Acta Biomaterialia 42 (2016) 273–285

Contents lists available at ScienceDirect

Acta Biomaterialia

journal homepage: www.elsevier.com/locate/actabiomat

Full length article

Biaxial rupture properties of ascending thoracic aortic aneurysms

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ARTICLE INFO

Article history:
Received 25 February 2016
Received in revised form 11 May 2016
Accepted 22 June 2016
Available online 23 June 2016

Keywords:
Aneurysm
Human thoracic aorta
Bulge inflation test
Rupture properties
Extensibility

ABSTRACT

Although hundreds of samples obtained from ascending thoracic aortic aneurysms (ATAA) of patients undergoing elective surgical repair have already been characterized biomechanically, their rupture properties were always derived from uniaxial tensile tests. Due to their bulge shape, ATAAs are stretched biaxially in vivo. In order to understand the biaxial rupture of ATAAs, our group developed a novel methodology based on bulge inflation and full-field optical measurements. The objective of the current paper is threefold. Firstly, we will review the failure properties (maximum stress, maximum stretch) obtained by bulge inflation testing on a cohort of 31 patients and compare them with failure properties obtained by uniaxial tension in a previously published study. Secondly, we will investigate the relationship between the failure properties and the age of patients, showing that patients below 55 years of age display significantly higher strength. Thirdly, we will define a rupture risk based on the extensibility of the tissue and we will show that this rupture risk is strongly correlated with the physiological elastic modulus of the tissue independently of the age, ATAA diameter or the aortic valve phenotype of the patient.

Statement of Significance

Despite their medical importance, rupture properties of ascending thoracic aortic aneurysms (ATAA) subjected to biaxial tension were inexistent in the literature. In order to address this lack, our group developed a novel methodology based on bulge inflation and full-field optical measurements. Here we report rupture properties obtained with this methodology on 31 patients. It is shown for the first time that rupture occurs when the stretch applied to ATAAs reaches the maximum extensibility of the tissue and that this maximum extensibility correlates strongly with the elastic properties. The outcome is a better detection of at-risk individuals for elective surgical repair.

1. Introduction

Ascending thoracic aortic aneurysms (ATAA), described at tissue level by medial degeneration and biomechanical weakening of the aneurysmal wall [1,2], are a life-threatening pathology causing a permanent dilation associated with a high risk of aortic rupture or dissection and death of the patient. ATAA affects approximately 10 out of 100,000 persons per year [3] and is the 17th most common cause of death [4].

ATAAs are treated by replacing them with synthetic grafts when the aortic diameter exceeds 5.5 cm [5]. However the rupture or the dissection of ATAAs remains rather unpredictable on a patient-specific basis. Even if the yearly risk of dissection or rupture rises from 3% to 7% with aneurysms >6 cm, rupture of ATAAs has been documented to occur at diameters less than 4.5 cm [6]. Factors other than the aneurysm diameter that may affect the predisposition to rupture are age, hypertension, aortic valve phenotype (bicuspid or tricuspid) or the presence of genetic disorders (Marfan syndrome, Ehler-Danlos syndrome).

Rupture of an ATAA occurs when the stress applied to the aortic wall locally exceeds its capacity to sustain stress. Finite-element analyses can be used to estimate the local distribution of the stress applied by the blood pressure onto the aortic wall [7–9]. An open

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http://dx.doi.org/10.1016/j.actbio.2016.06.028
1742-7061/

question is to estimate the patient-specific strength, which can vary from a few tenths of MPa to a few units of MPa from one individual to another [10,11]. Another open question is that mean physiological wall stresses acting on pathologic aortas were found to be far from rupture, with factors of safety (defined as the ratio of tensile strength to the mean wall stress) larger than six [12].

Another equivalent definition of rupture can be stated when the stretch applied to the tissue exceeds its extensibility. For instance, Martin et al. [13] defined a diameter risk, which is the ratio between the current diameter of the aneurysm and the rupture diameter. The authors show that the diameter risk increases significantly with the physiological elastic modulus of the artery. Indeed, if the aortic wall is stiff, a rather large increase of pressure can be induced by a small increase of volume.

In vitro mechanical characterization of ATAA rupture on specimens, obtained from ascending aorta tissue of patients undergoing elective surgical repair, has been instrumental to improve the understanding of the aortic wall properties and the potential risk for rupture of ATAAs [14]. Several authors have focused on elastic properties of ATAAs [9,15–17]. They showed that ATAAs have altered collagen fiber architecture in the medial plane and have significantly less elastin than healthy tissue. The tissue is generally stiffer in the circumferential direction than in the longitudinal direction and the elastic properties vary regionally [16]. Stress-strain analyses also aided in determining material properties [18–20]. Kim and Baek showed significant spatial variations of mechanical properties in a porcine thoracic aorta using optical full-field measurements and inflation-extension tests [21].

Despite the interest of these studies on elastic properties, we will focus on the rupture properties of ATAAs. At least 11 papers reported rupture properties of ascending thoracic aortas and ATAAs in uniaxial tension (Table 1). In these studies, the strength was always determined in uniaxial tension, except for a few samples that were reported in the second paper of Mohan and Melvin where they performed bulge inflation tests [22].

Due to their bulge shape, aneurysm tissues are stretched biaxially in vivo [23], and there is no guarantee that results obtained from a uniaxial test can be applied to a biaxial state. The lack of rupture analysis in biaxial tension can be explained by the fact that biaxial testing is less suitable for strength assessment, due to attachment techniques and the square shape of the specimen, which may prevent failure of the specimen in the gauge area.

Bulge inflation test is another technique for investigation of biaxial mechanical behavior, which has been applied in the past to the study of human and pig aortas [22,24] as well as other soft tissues [25]. The basic testing protocol consists in obtaining square specimens from an excised cylindrical aortic tissue laid flat. These are clamped in the inflation device forming a hermetically sealed cavity in which a fluid (water) is injected at a controllable rate while simultaneously measuring pressure.

Our group recently conducted bulge inflation tests on human ATAA tissues [26–28], to test media/adventitia samples as well as complete layers. Stereo-digital image correlation (SDIC) was used to obtain the strain field of the entire inflated membrane. Video-based tracking techniques can allow simultaneous evaluation of material parameters for constitutive modeling purposes and of localized stress in the area that eventually ruptures, providing a powerful experimental tool to characterize the mechanical properties of vascular tissues [17,26,29–32].

The objective of the current paper is threefold. Firstly, we will review the failure properties (maximum stress, maximum stretch) obtained by bulge inflation testing on a cohort of 31 patients undergoing elective surgical repair and compare them with failure properties obtained by uniaxial tension in a previously published study. Secondly, we will investigate the relationship between the failure properties and the age of patients. Thirdly, we will define a rupture risk based on the brittleness of the tissue and investigate the correlation between this rupture risk and the physiological elastic modulus of the tissue.

2. Methods

2.1. Materials for bulge inflation tests

ATAA samples for bulge inflation tests were obtained from patients undergoing elective surgery to replace the pathological segment of aorta with a synthetic graft. The collection of the aortic

Table 1
Published studies reporting uniaxial rupture properties of ascending thoracic aortas and ATAAs.

Reference	Tests	Main conclusions
Mohan and Melvin (1982)	34 aortas in uniaxial tension	Failure properties of human aortic tissue at quasi-static and dynamic strain rates
Okamoto et al. (2002)	25 ATAAs tested up to failure in uniaxial tension	Age clearly influences the measured elastic and strength properties in ATAA
Vorp et al. (2003)	36 ATAAs and 10 non aneurysmal ascending thoracic aortas	ATAA samples are stiffer and approximately 30% weaker than healthy samples
Sokolis et al. (2012)	Uniaxial tensile tests on intima, media and adventitia	Similar extensibility for all the layers but larger strength for the adventitia
Iliopoulos et al. (2009a)	Tensile tests on ATAAs sample of 12 patients	Inverse correlations of failure stress with thickness and direct correlations with peak elastic modulus
Iliopoulos et al. (2009b)	Uniaxial tensile tests on 26 ATAAs and 15 non aneurysmal ascending thoracic aortas	ATAA display smaller failure strain, smaller elastin content and higher peak elastic modulus. Circumferential specimens show higher failure stress and peak elastic modulus but equal failure strain
Forsell et al. (2014)	Uniaxial tensile tests on 24 ATAAs, 14 patients with bicuspid aortic valve (BAV) and 10 with tricuspid aortic valve (TAV)	The strength was almost two times higher in BAV samples. Collagen related stiffness was significantly increased in BAV samples whereas elastin related stiffness was similar in both groups
Pichamuthu et al. (2013)	Uniaxial tensile tests on 38 ATAAs, 23 from BAV patients and 15 from TAV patients	Circumferential and longitudinal tensile strengths were higher for BAV ATAAs than TAV ATAAs. Uniform collagen content between groups
García-Herrera et al. (2012)	Uniaxial tensile tests on 26 ATAAs (12 BAV and 14 TAV) and 23 non aneurysmal ascending thoracic aortas	Age causes a major reduction in the mechanical parameters of healthy ascending aortic tissue, no significant differences between the mechanical strength of aneurysmal TAV or BAV aortic specimens and the corresponding age-matched control group
Pham et al. (2013)	Uniaxial tensile tests on 35 ATAAs (20 BAV and 15 TAV) and 20 non aneurysmal ascending thoracic aortas	No difference of failure properties between the groups. Moderate medial degeneration characterized by elastin fragmentation, cell loss, mucoid accumulation and fibrosis. The ultimate tensile strength decreases with age
Sokolis and Iliopoulos (2014)	Uniaxial tensile tests on 35 ATAAs (20/15 male/female ratio)	Male ATAAs are stronger but equally extensible in the circumferential axis compared to female ones. Longitudinally, instead, gender differences at each region are insignificant