Medical Engineering & Physics 35 (2013) 1282–1289

Contents lists available at SciVerse ScienceDirect

Medical Engineering & Physics

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

Importance of material model in wall stress prediction in abdominal aortic aneurysms

Stanislav Polzer[a,*], T. Christian Gasser[b], Jiri Bursa[a], Robert Staffa[c], Robert Vlachovsky[c], Vojtech Man[a], Pavel Skacel[a]

[a] Institute of Solid Mechanics, Mechatronics and Biomechanics, Brno University of Technology, Czech Republic
[b] Department of Solid Mechanics, Royal Institute of Technology, Stockholm, Sweden
[c] 2nd Department of Surgery, St. Anne's University Hospital, Faculty of Medicine, Masaryk University, Brno, Czech Republic

ARTICLE INFO

Article history:
Received 26 April 2012
Received in revised form
14 November 2012
Accepted 27 January 2013

Keywords:
Material model
Pre-stressing
Abdominal aneurysm
Wall stress
FE analysis

ABSTRACT

Background: Results of biomechanical simulation of the abdominal aortic aneurysm (AAA) depend on the constitutive description of the wall. Based on in vitro and in vivo experimental data several constitutive models for the AAA wall have been proposed in the literature. Those models differ strongly from each other and their impact on the computed stress in biomechanical simulation is not clearly understood.
Methods: Finite element (FE) models of AAAs from 7 patients who underwent elective surgical repair were used to compute wall stresses. AAA geometry was reconstructed from CT angiography (CT-A) data and patient-specific (PS) constitutive descriptions of the wall were derived from planar biaxial testing of anterior wall tissue samples. In total 28 FE models were used, where the wall was described by either patient-specific or previously reported study-average properties. This data was derived from either uniaxial or biaxial in vitro testing. Computed wall stress fields were compared on node-by-node basis.
Results: Different constitutive models for the AAA wall cause significantly different predictions of wall stress. While study-average data from biaxial testing gives globally the same stress field as the patient-specific wall properties, the material model based on uniaxial test data overestimates the wall stress on average by 30 kPa or about 67% of the mean stress. A quasi-linear description based on the in vivo measured distensibility of the AAA wall leads to a completely altered stress field and overestimates the wall stress by about 75 kPa or about 167% of the mean stress.
Conclusion: The present study demonstrated that the constitutive description of the wall is crucial for AAA wall stress prediction. Consequently, results obtained using different models should not be mutually compared unless different stress gradients across the wall are not taken into account. Highly nonlinear material models should be preferred when the response of AAA to increased blood pressure is investigated, while the quasi-linear model with high initial stiffness produces negligible stress gradients across the wall and thus, it is more appropriate when response to mean blood pressure is calculated.

1. Introduction

A diameter exceeding 5.5 cm is the most commonly accepted criterion for elective surgical repair of abdominal aortic aneurysm (AAA) [1,2]. There is, however, a need for other predictors for rupture, since aneurysms with a diameter less than 5.5 cm can rupture [3,4] and 60% of larger aneurysms do not rupture [5]. According to the biomechanical rupture risk assessment an aneurysm will rupture if the mechanical stress exceeds the local strength of the wall. Consequently, it has been suggested that the peak wall stress (PWS) [6,7] and peak wall rupture risk (PWRR) [8,9] could possibly identify rupture-prone AAAs better than the maximal diameter criterion.

Biomechanical indices like PWS and PWRR require the computation of wall stress and typically using the finite element method (FEM). The sites of PWS and PWRR may not coincide [39], and hence an accurate prediction of the whole stress field is needed for the reliable computation of PWRR. Several factors influence wall stress computations, and it has been generally accepted that the individual AAA geometry is the most important one.

While most FE models use the patient-specific (PS) AAA geometry, they rely on available study-average data on tissue properties, the impact of which remains poorly understood. Using an idealized model of AAA and varying material model properties based on uniaxial tensile testing within 95% confidence interval (CI) revealed

* Corresponding author at: Institute of Solid Mechanics, Mechatronics and Biomechanics, Brno University of Technology, Technicka 2896/2, 616 69 Czech Republic. Tel.: +420 777 236 456.
E-mail address: polzer@seznam.cz (S. Polzer).

1350-4533/$ – see front matter © 2013 IPEM. Published by Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.medengphy.2013.01.008

only a 5% change in PWS [16]. Other studies reported that PWS was higher [25] or lower [38] when a nonlinear material model was used instead of a linear one.

Most comprehensive data was derived from planar biaxial tensile testing [26,35] and led to an improved constitutive description of the aneurysm wall. Specifically, the nonlinearity of the AAA wall was more pronounced under biaxial than under uniaxial testing. The biomechanical consequences of that finding were investigated with the conclusion that constitutive models fitted to biaxial data exhibit higher PWS than models fitted to uniaxial data [40,43].

Although averaged results of biaxial tests show a rather small anisotropy [26,35], the PS behavior of aneurysmal tissue can be significantly anisotropic. With anisotropy taken into account, higher stresses were obtained in comparison with isotropic wall models [37,40,43] an effect that might be difficult to distinguish from the influence of nonlinearity detailed below. However, current anisotropic models follow a purely phenomenological approach and a sound structural background is still missing to consider the distribution of e.g. collagen fibers.

Generally all studies in the literature compared single stress values (PWS or mean stress) and therefore could not provide a comprehensive picture of the impact of modeling assumptions on the wall stress distribution. In summary, more sophisticated analysis methods are required that involve the whole stress field and allow us to draw valuable conclusions regarding the impact of FE modeling assumptions. Therefore, in order to analyze the reliability of wall stress predictions through several state-of-the-art biomechanical models, the aim of this study was to compare AAA wall stresses predictions based on different wall constitutive descriptions. To this end PS stress–strain laws for the AAA wall were considered in this study, based on biaxial tensile testing of wall samples that were collected during surgical AAA repairs. They were then used as reference models for comparison of stresses all over the aneurysmal aorta with wall models suggested in the literature.

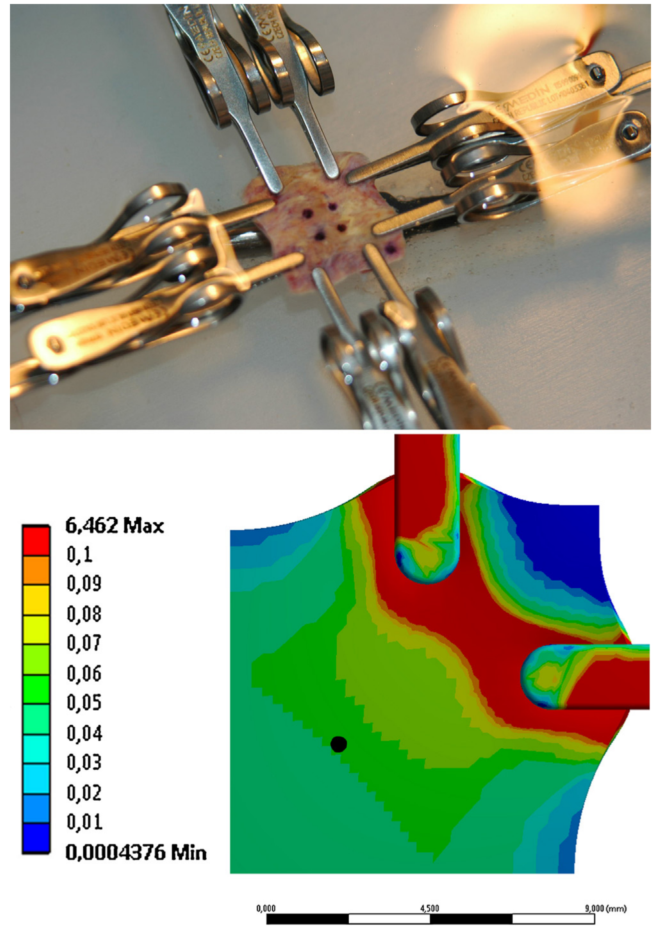

Fig. 1. Abdominal aortic aneurysm (AAA) wall specimen located in the planar biaxial testing system and immersed in physiological saline solution (upper part). Stress concentrations induced by presence of the clamps (lower part). Black dot represents the position of the marker.

2. Methods

2.1. Specimen acquisition and biaxial mechanical testing

During elective surgical AAA repair a sample of the anterior aneurysm wall was taken from male patients with asymptomatic ($n = 6$) and symptomatic ($n = 1$) AAAs. Within 3 h post surgery the mechanical properties of the harvested AAA wall samples were identified through biaxial mechanical testing. To this end a test specimen (18 mm × 18 mm) was clamped in a custom made planar biaxial tensile testing device (Camea s.r.o, Czech Republic), see Fig. 1. Four markers (ink dots) were placed in the middle of the specimen (measurement area) allowing contactless measuring of tissue strain with a CCD camera at a resolution of 0.02 mm/pixel. Further details on the testing device and the methodology are reported elsewhere [28,42]. The use of human tissue for this project was approved by the local ethic committee.

The specimen was tested using displacement-controlled protocols, where the ratio u_x:u_y was kept constant between the clamp displacements in circumferential and axial directions, respectively. Note that a constant ratio of the clamp displacements does not imply a constant strain ratio in the testing area. In vitro testing aims at reflecting the in vivo loading conditions as closely as possible, and a priori it is not clear, if a stress or strain-controlled experiment would be more appropriate. Blood pressure translates directly into wall stress, and hence a stress-based protocol would be recommended. However, in vivo the axial expansion of the AAA is constrained, which would motivate to control the axial strain during biaxial testing.

In order to flatten the test specimen and to avoid bending during biaxial testing, it is typically slightly pre-stressed [26,35]. Although in the literature lower pre-stress is reported, all our test specimens were pre-stressed in the circumferential and axial directions by 0.2N to avoid any bending effects during biaxial testing. Test specimens were preconditioned by four equi-displacement cycles that resulted in roughly 12% strains in the testing area [34], i.e. the preconditioning is similar to that reported earlier for biaxial testing of the AAA wall [26,35]. Each specimen was then removed from the testing machine, placed on a glass plate and covered with another one to ensure its planeness. Then the (virtually) unstressed specimen was pictured to define its reference configuration, i.e. to define the reference for the following biaxial testing. Thereafter, the specimen was placed back to the testing machine and stress and stretch data were recorded for displacement ratios of u_x:u_y = 1:1, 1:2, 2:1 and at a displacement rate of 0.167 mm/s, i.e. such that the test can be regarded as quasi-static. It is noted that the specimen's reference configuration should be stress-free per definition, and removing the specimen from the testing machine avoids a pre-stressed reference configuration as used by previous experimental studies [17,26,35]. Such a pre-stressed reference configuration is highly questionable and the level of pre-stress largely influences the data.

Fixation of the test specimen with clamps, as with hooks, induces stress concentrations, which must not affect the measurement area. Protocol development of our biaxial testing considered FE simulations to define the optimal clamp positions. Specifically, a sufficiently homogenous stress field in the measurement area was