Uniaxial Tensile Test and Constitutive Modelling of Human Perivascular Adipose Tissue

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Abstract
All the human blood vessels are surrounded by adipose tissue. Therefore in biomechanics of blood vessels, it is important to deal not only with the constitutive modelling of blood vessels as such but also with the mechanical properties of surrounding tissue. In this study, mechanical response of human perivascular adipose tissue that surrounds the abdominal aorta is concerned. From the performed uniaxial tensile tests, a representative experimental curve was selected to be fitted by hyperelastic models. The experiments showed nonlinear behavior of the tissue with gradual stiffening at higher deformations. Constitutive models Ogden, Gent, Fung were used. The material parameters estimated by nonlinear regression analysis are μ = 0.001 MPa and α = 28, μ = 0.026 MPa and J_m =0.067, μ = 0.018 MPa and b = 31.834, respectively. It was concluded that all applied mathematical models predicted material behavior satisfactorily with coefficient of determination 0.995, 0.981, 0.994, respectively.

Keywords
Abdominal aorta, constitutive modelling, Fung model, Gent model, hyperelasicity, incompressibility, isotropy, Ogden model, perivascular adipose tissue, uniaxial tensile test.

1. Introduction

Blood vessels are surrounded by adipose tissue which creates interface between vessels and organs. In contrast to arteries, constitutive models of fat tissue are studied only rarely. However, surrounding tissue affects mechanical state of arteries. To fill this gap, present paper deals with constitutive modelling of human perivascular adipose tissue.

The adipose tissue consists of mature, lipid-filled adipocytes, lipid-free preadipocytes, endothelial cells, nerve fibers and monocytes/macrophages. The studies demonstrated significant differences between subcutaneous and intraabdominal fat. Visceral adipose tissue contains more blood vessels, nerve fibres, and monocytes/ macrophages [1 - 3].

The fat cells (adipocytes) produce proteins such as adiponectin, leptin, adipokines and cytokines. Adiponectin regulates metabolism of sacharides and lipids and stimulates transport of glucose and free fatty acids into muscles, liver and fat cells. Leptin contributes to a regulation of body weight [1 - 8]. Adipokines and cytokines are inflammatory proteins which may diffuse from surrounding adipose tissue into the arterial wall, where subsequently may cause endothelial dysfunction, hypercoagulability and proliferation of smooth muscle cells [1].

Fat tissue serves as storage for energy in the form of triglycerides and protects organs from trauma [1, 2].

The paper presents constitutive parameters obtained by fitting three different mathematical models to uniaxial tensile test data of human perivascular adipose tissue surrounding abdominal aorta.

2. Materials and methods

2.1 Material

The specimen of human abdominal aorta with surrounding perivascular adipose tissue was obtained from the Faculty Hospital Královské Vinohrady in Prague and was excised during the authopsy of man aged 29. Our study has been approved by the Ethics Committee of the Faculty Hospital Královské Vinohrady. The sample was transported to the laboratory and subsequently manually separated from aortic wall using a scalpel and cut to approximately rectangular shape (Fig. 1a, Fig. 2). Axis of specimen was parallel with axis of abdominal aorta. The fat tissue was tested 38 hours after removal from a deceased donor and that is consistent with the fact that the mechanical properties of biological tissues does not change significantly up to 6 days when stored in cold [9].

2.2 Uniaxial tensile test protocol

The multipurpose testing machine (Zwick/Roell, Ulm, Germany) was used for measurement of mechanical response of perivascular tissue (Fig. 1b). Dimension of the deformed sample was determined by built-in video extensometer by means of the distance of transverse marks on the sample surface (Fig. 1a). Current force (U9B, ± 25 N, HBM, Darmstadt, Germany) and video extensometer data were recorded into the controlling computer. Four loading cycles were realized at constant velocity of the clamp 0.2 mm/s. The specimen of fat tissue was tested in air and at room temperature.

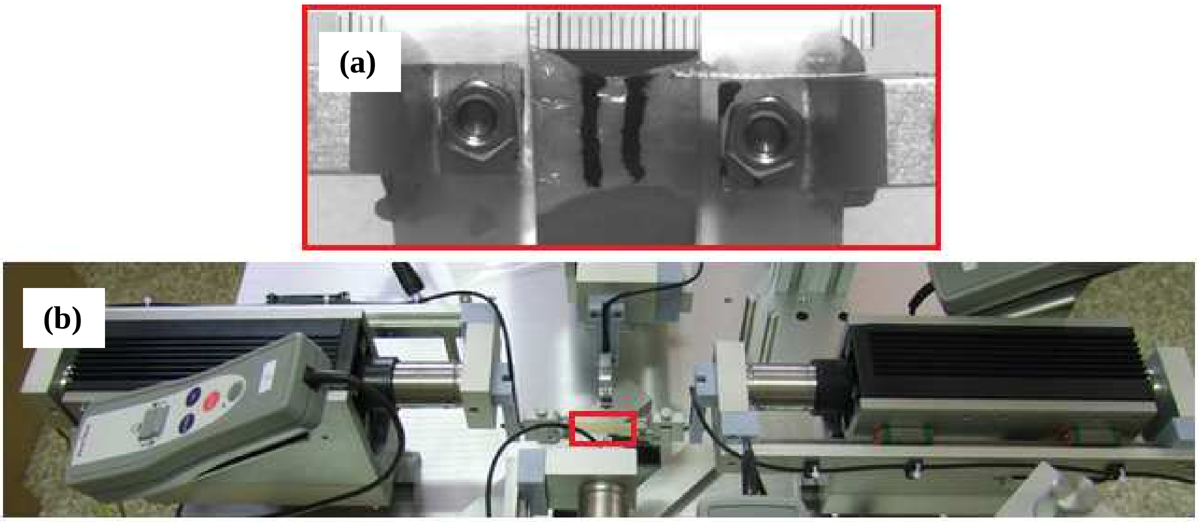

Fig. 1. (a) *The tested specimen of human perivascular tissue in the jaws of the multipurpose testing machine with transverse marks for the strain measurement.*
(b) *The used multipurpose testing machine for uniaxial tensile test.*

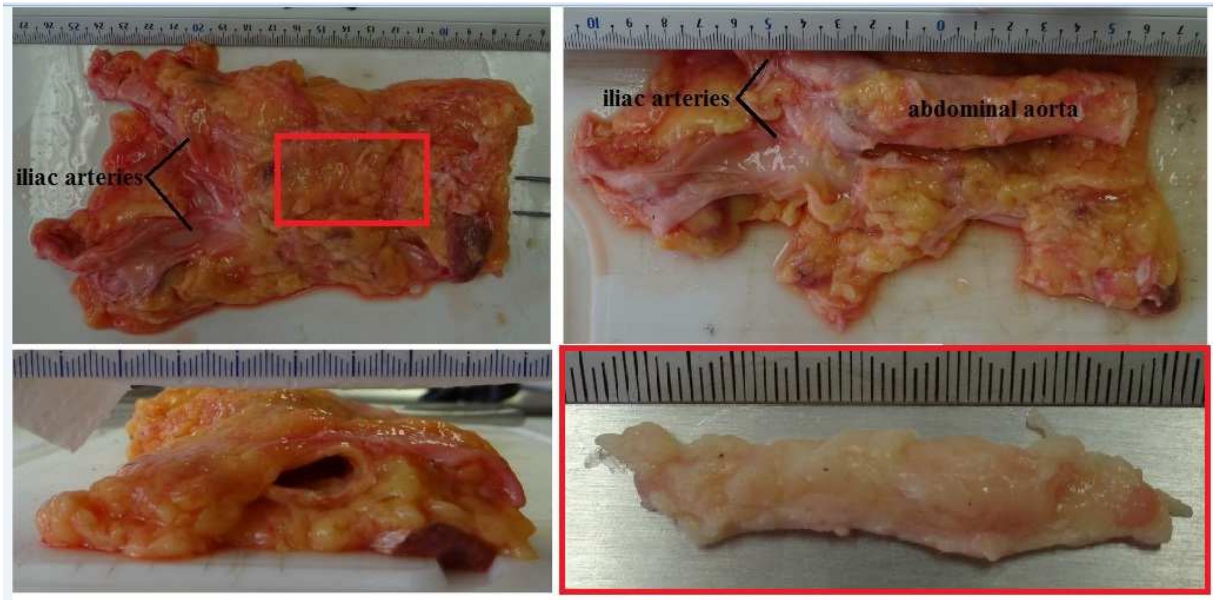

__Fig. 2.__ Sample of the human abdominal aorta, iliac arteries and perivascular adipose tissue.

2.3 Data analysis and constitutive modelling

The strain energy density function for the hyperelastic Ogden [10], Gent [11], and Fung [12] model is expressed as

$$W_{\text{Ogden}} = \frac{\mu}{\alpha}(\lambda_1^{\alpha} + \lambda_2^{\alpha} + \lambda_3^{\alpha} - 3), \tag{1}$$

$$W_{\text{Gent}} = -\frac{1}{2}\mu J_m ln\left(1 - \frac{I_1 - 3}{J_m}\right), \tag{2}$$

$$W_{\text{Fung}} = \frac{1}{2}\frac{\mu\left(e^{b(I_1-3)} - 1\right)}{b}, \tag{3}$$

where λ_1, λ_2, λ_3 are the principal stretches and $I_1 = \lambda_1^2 + \lambda_2^2 + \lambda_3^2$ is the first invariant of the right Cauchy-Green strain tensor. μ, α, J_m, b are material parameters. μ is positive stress-like material parameter corresponding at infinitesimal strain in shear modulus. α, J_m, b are dimensionless material constants which indicate strain stiffening of material.

The Cauchy stress tensor for incompressible material is given by constitutive equation

$$\boldsymbol{\sigma} = \mathbf{F}\frac{\partial W}{\partial \mathbf{F}} - p\mathbf{I}, \tag{4}$$

where $\mathbf{F}$ is the deformation gradient, $\mathbf{I}$ is the unit tensor and p is the Lagrange multiplier, which is interpreted as the hydrostatic pressure resulting from the incompressibility condition [10].

In case of incompressible material can be expressed

$$\det \mathbf{F} = \lambda_1\lambda_2\lambda_3 = 1, \tag{5}$$

where index 1 indicates direction of the loading force, λ_2 and λ_3 are transversal stretches.

For an isotropic material during uniaxial tensile test can be written the following relationship

$$\lambda_2 = \lambda_3. \tag{6}$$

From equation (5) and (6) implies

$$\lambda_2 = \frac{1}{\sqrt{\lambda_1}}. \tag{7}$$

The Cauchy stress acting in the direction of axial force during uniaxial tensile loading for incompressible material can be express by equations (8) for Ogden, (9) for Gent, and (10) for Fung model

$$\sigma_{\text{mod}}^{\text{Ogden}} = \mu\lambda_1^{\alpha} - \mu\left(\frac{1}{\sqrt{\lambda_1}}\right)^{\alpha}, \tag{8}$$

$$\sigma_{\text{mod}}^{\text{Gent}} = \frac{\mu J_m\left(\lambda_1^3-1\right)}{J_m\lambda_1+3\lambda_1-\lambda_1^3-2}, \tag{9}$$

$$\sigma_{\text{mod}}^{\text{Fung}} = \frac{\mu}{\lambda_1}e^{\frac{b(\lambda_1+2)(\lambda_1-1)^2}{\lambda_1}}\left(\lambda_1^3-1\right). \tag{10}$$

The Cauchy stress can be express using loading force and current cross-section

$$\sigma_{\exp} = \frac{f}{a}, \tag{11}$$

where f is applied force and a is current cross-sectional area of the specimen [13].

Assuming incompressible behavior of the adipose tissue, current cross-sectional area can be expressed as

$$a = \frac{LA}{l} = \lambda_1^{-1}A, \tag{12}$$

where l and L are current and reference lengths between the transverse marks, respectively. A is the reference cross-sectional area. $\lambda_1 = 1 + \varepsilon = 1 + \frac{l-L}{l}$ is the stretch ratio in the direction of applied load. ε is engineering deformation.

Combining equations (11) and (12) gives the Cauchy stress

$$\sigma_{\exp} = \lambda_1\frac{f}{A}. \tag{13}$$

The material parameters have been determined by means of nonlinear least squares regression method using Maple (Maplesoft, Waterloo, Canada). The global minimum of the objective function Q is given by expression

$$Q^2 = \sum_{i=1}^{n}\left(\sigma_{\exp_i} - \sigma_{\text{mod}_i}\right)^2, \tag{14}$$

where n is the number of data points.

3. Results

Reference dimensions of the geometrically non-uniform sample (width, thickness and cross-section area) are in Table 1. Geometrical characteristics were determined as mean value of six measurements. Observation data fitted by models (8), (9), (10) are displayed in Fig. 3. Material parameters determined from uniaxial tensile test are α = 28 and μ = 0.001 MPa, J_m =0.067 and μ = 0.026 MPa, b = 31.834 and μ = 0.018 MPa (Table 2). The goodness of fit of the nonlinear regression analysis is indicated by the coefficients of determination which are included in Table 2.

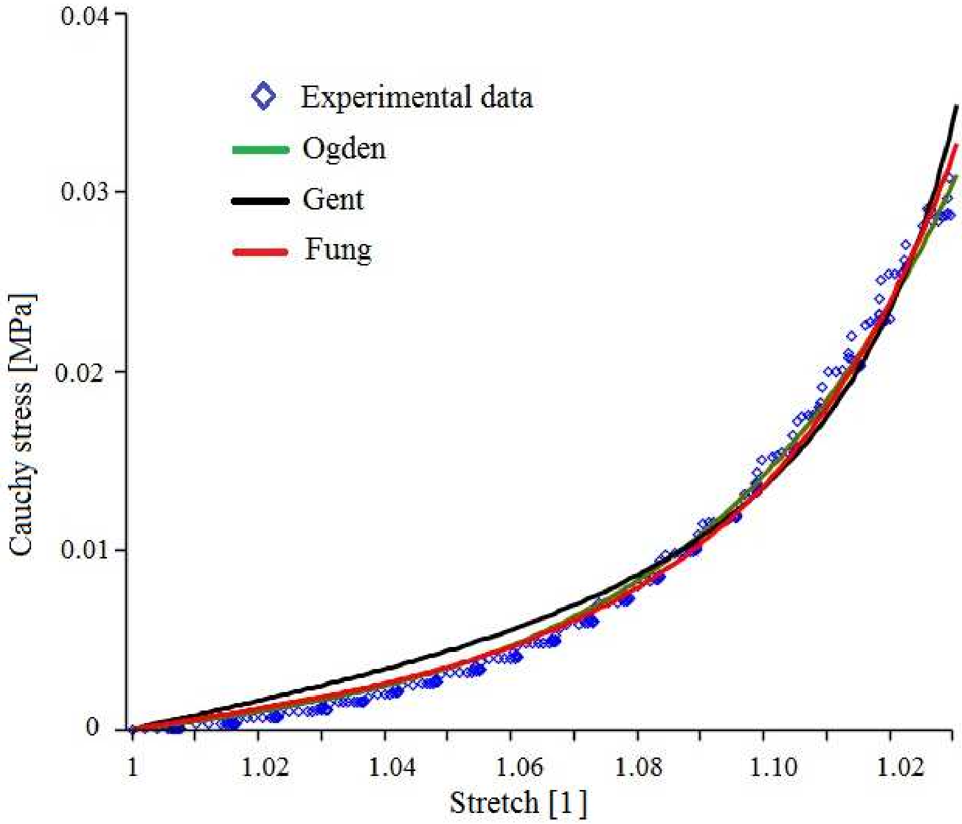

***Fig. 3** Results of the nonlinear regression analysis.*

***Table 1.** – Reference geometry of the sample (mean ±SD).*

Donor	Excesion site	Type of sample	Reference thickness ± SD [mm]	Reference width ± SD [mm]	Reference cross-section [mm^2]
M29	Abdominal aorta	Longitudinal	7.998 ± 0.295	6.456 ± 0.456	51.640

***Table 2.** – Material parameters obtained from Ogden, Gent and Fung model and coefficient of determination.*

Hyperelastic model	Material parameter μ [MPa]	Material parameter α, J_m, b [-]	Coefficient of determination
Ogden	0.001	28	0.995
Gent	0.026	0.067	0.981
Fung	0.018	31.834	0.994

4. Discussion and Conclussion

One representative sample of human perivascular adipose tissue surrounding the abdominal aorta from 29 year-old male donor (M29) was subjected to uniaxial tensile test at postmortem interval of 38 hours (Fig. 1a, 1b). The abdominal aorta, iliac arteries and perivascular tissue harvested of retroperitoneal space in the human body are in Fig. 2.

This article dealt with the constitutive modeling of human perivascular adipose tissue surrounding abdominal aorta. Material parameters were estimated from three nonlinearly elastic models (8), (9), (10). The hyperelastic models showed good fit to experimental data (Fig. 3).

Material models are part of commercial FEM software, therefore the results of our study could be included in stress analysis of the human abdominal aorta surrounding perivascular adipose tissue.

Acknowledgement

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Nomenclature

W	strain energy density function	(MPa)
μ	constitutive model parameter	(MPa)
α	constitutive model parameter	(1)
J_m	constitutive model parameter	(1)
b	constitutive model parameter	(1)
λ_1	first principal stretches	(1)
λ_2	second principal stretches	(1)
λ_3	third principal stretches	(1)
I_1	first invariant of the right Cauchy-Green strain tensor	(1)
$\boldsymbol{\sigma}$	Cauchy stress tensor	(-)
$\mathbf{F}$	deformation gradient	(-)
p	Lagrange multiplier	(MPa)
$\mathbf{I}$	unit tensor	(-)
σ_{mod}	Cauchy stress	(MPa)
σ_{exp}	Cauchy stress	(MPa)
f	applied force during experiment	(N)
A	reference cross-sectional area	(mm^2)
a	current cross-sectional area	(mm^2)
L	reference lengths between the transverse marks	(mm)
l	current lengths between the transverse marks	(mm)
ε	engineering deformation	(1)
Q	objective function	(MPa^2)

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