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Inflation Tests of Vena Saphena Magna for Different Loading Rates

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Abstract— **The aim of the study was to verify whether constitutive model parameters obtained from quasistatic inflation-extension test could be used for *in-vivo* computational simulation of venous graft used as bypass at arterial conditionns. Inflation tests of human *vena saphena magna* at three loading rates were performed: a quasistatic (slow), moderate, and fast, which was similar to human heart rate. The experimental data were fitted by hyperelastic nonlinear anisotropic constitutive model (Holzapfel-Gasser-Ogden) in order to obtain material parameters. It was found that parameters differ significantly with respect to loading rate. Especially the parameter related to large strain stiffening (k_2) increased with loading rate. The results suggest that constitutive parameters are strongly influenced by experimental conditions which we interpret as viscoelasticity of the vein grafts.**

Keywords— **inflation test, saphenous vein, constitutive model, CAGB, loading rate**

I. INTRODUCTION

The number of coronary-artery and peripheral-artery-bypass grafts using the saphenous vein as a replacement is increasing [1]. After bypass surgery, the vein is subjected to arterial conditions (pulsations) which are different from venous one. The change of the mechanical environment initiates remodeling process. The most studied effect of graft adaptation is the development of intimal hyperplasia [2]. Large attention was paid to flow conditions and wall sheer stress which are suspected to be responsible for hyperplasia which may cause the graft failure (see e.g. [3], [4]). Varicose veins were also studied from the mechanical and histological point of view [5], [6].

However, papers dealing with biomechanics of the graft wall and constitutive modeling are rare in the literature. Probably the most detailed study dealing with mechanics of saphenous veins was performed by Donovan and coworkers [7]. They carried out uniaxial tensile test with 45 saphenous veins and described their mechanical properties in terms of material and structural parameter: vessel diameter, tensile stiffness, failure and ultimate forces, and tensile modulus, failure stress, and strain. Pressure-diameter data from inflation tests with saphenous veins from upper and lower limbs were published in [8], but without identification of constitutive parameters.

The material parameters are necessary for computations (e.g. FEA) to obtain stress and strain field. To the best of our knowledge there is only one paper describing behavior of coronary-artery bypass in terms of constitutive parameters [2]. The aim of this preliminary study was to extend the available set of material parameters.

II. METHODS

The sample of human vena saphena magna was harvested during coronary-artery bypass graft surgery in the General University Hospital in Prague. The usage of the biological material was approved by the Ethics committee of the Hospital. The vein was immediately stored in the physiological solution and tested within four hours after the excision.

A. Inflation tests

The specimen was mounted in the setup for inflation-extension test (Fig. 1) and inflated by internal pressure as follows. The sample of vena saphena was inflated four times up to approx. 4kPa (vein pressure) and then four times up to approx. 16kPa (systolic pressure).

The sample of the vein underwent pressurization cycles at three loading rates which can be characterized by the frequency of pulsations (Fig. 2). The frequency of loading-unloading cycle (0-16-0 kPa) was:

A. quasistatic slow loading – frequency 0.04 Hz

B. moderate loading – frequency 0.5 Hz

C. fats loading - frequency 1 Hz, which is similar to a heart rate.

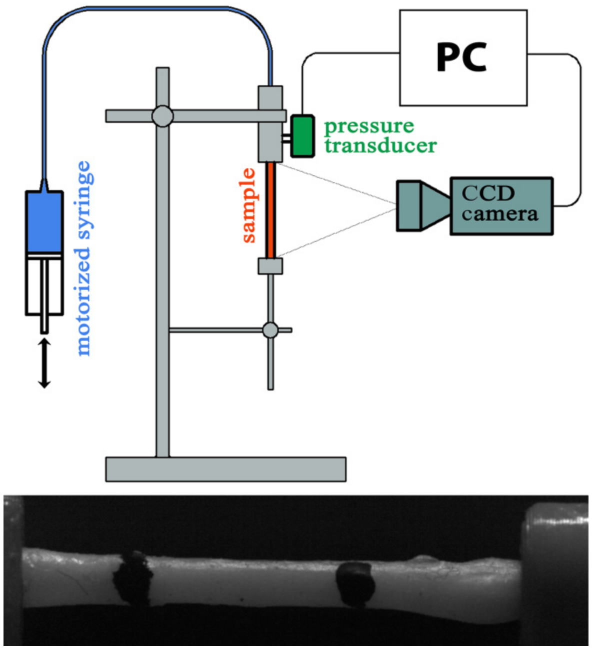

Fig. 1 Up: Inflation test set-up. Down: Photograph of the sample in front of contrasting background from CCD camera. Black markers were used to evaluate the longitudinal deformation of the sample.

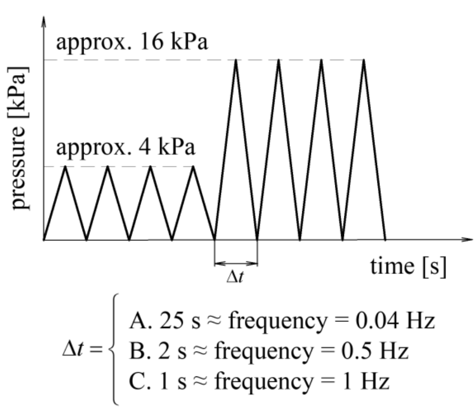

Fig. 2 The loading protocol during inflation tests.

The intraluminal pressure was recorded during the test by the pressure transducer (Cressto, Cressto s.r.o. Czech Republic). Sample was recorded by the CCD camera during the loading. The longitudinal (λ_z) and circumferential (λ_t) deformations of the tube were evaluated using the edge detection method and computed via equations (1) and (2) assuming the incompressibility of the venous wall expressed by equation (3).

$$\lambda_t = \frac{2\pi r_m}{2\pi R_m} \tag{1}$$

$$\lambda_t = \frac{l}{L} \tag{2}$$

$$\lambda_r = \frac{1}{\lambda_t \lambda_z} \tag{3}$$

Here r_m and R_m are middle radii of the tube in deformed and reference geometry. l and L is longitudinal distance of marks in deformed and reference geometry and λ_r is the radial deformation.

The reference geometry and the distance of longitudinal marks are listed in Table 1.

Table 1 Reference geometry of the sample

Outer radius	*Ro*	2.77 mm
Thickness	*H*	0.80 mm
Distance of axial marks	*L*	11.20 mm

The experimental circumferential (σ_{tt}) and longitudinal (σ_{zz}) stress during the loading was computed adopting presumption of the thin-wall geometry with closed ends which results in Laplace's Law (4), (5).

$$\sigma_{tt}^{EXP} = P\frac{r_m}{h} = P\frac{R_m \lambda_t^2 \lambda_z}{H} \tag{4}$$

$$\sigma_{zz}^{EXP} = \frac{\sigma_{tt}}{2} \tag{5}$$

Here P is intraluminal pressure, H is the reference thickness of the sample.

B. Numerical model

The data for each loading rate were fitted separately. The hyperelastic Holzapfel-Gasser-Ogden (HGO) nonlinear anisotropic constitutive model [10] was used to fit the experimental data. The strain energy density function is expressed by equation (6).

$$W = \frac{C}{2}(I_1 - 3) + \frac{k_1}{k_2}\left(e^{k_2(I_4-1)^2} - 1\right) \tag{6}$$

In (6) C and k_1 are stress-like parameters, k_2 is dimensionless parameter. I_1 is the first invariant of the right Cauchy-Green strain tensor and I_4 is additional invariant arising from material anisotropy and has the meaning of square of the stretch in preferred (fiber) direction. I_1 and I_4 are defined in (7) and (8).

$$I_1 = \lambda_r^2 + \lambda_t^2 + \lambda_z^2 \tag{7}$$

$$I_4 = \lambda_t^2 \cos^2\beta + \lambda_z^2 \sin^2\beta \tag{8}$$

In (8) β defines preferred direction within the material measured from circumferential axis of the tube in cylindrical configuration of the vein. Parameter β was considered to be the same for all loading rates.

According to [9], the stress in the sample is then computed using W using equations (9), (10), (11).

$$\sigma_{rr}^{MOD} = \lambda_r \frac{\partial W}{\partial \lambda_r} - p \tag{9}$$

$$\sigma_{tt}^{MOD} = \lambda_t \frac{\partial W}{\partial \lambda_t} - p \tag{10}$$

$$\sigma_{zz}^{MOD} = \lambda_z \frac{\partial W}{\partial \lambda_z} - p \tag{11}$$

Here p is the Lagrange multiplier which plays a role of the reaction to incompressibility constrain. The equation (9) was combined with $\sigma_{rr}=-P/2$ (radial equilibrium equation) and then used to eliminate p. p is substituted into (10) and (11).

Objective function Q in (12) was minimized and the constitutive parameters of the model were calculated in Maple 16 (Maplesoft, Canada).

$$Q = \sum_{\substack{i=t,z \\ k=1..n}} \left(\sigma_{ii}^{EXP} - \sigma_{ii}^{MOD}\right)_k^2 \tag{12}$$

III. Results

Pressure-stretch (P-λ) and stress-stretch (σ-λ) curves are plotted to illustrate the effect of the loading rate in Fig. 3. It is shown that increasing loading rate is manifested as the shift of the curves to the left. This can be interpreted in the way that material stiffens with increasing loading rate. Estimated parameters of HGO constitutive model for each inflation rate are listed in Table 2. Considering results in Table 2 parameter k_2 depend strongly on loading rate (the higher the rate, the higher k_2). Parameter C is slightly increasing and k_1 is slightly decreasing with pressurizing rate but it should be noted that W depends linearly on them.

Table 2 Parameters of HGO model for different loading rates

loading frequency	C [kPa]	k_1 [kPa]	k_2 [-]	β [rad]
A. 0.04 Hz	4.93	3.43	19.13	0.75
B. 0.5 Hz	7.66	0.28	46.82	0.75
C. 1 Hz	13.04	0.24	60.30	0.75

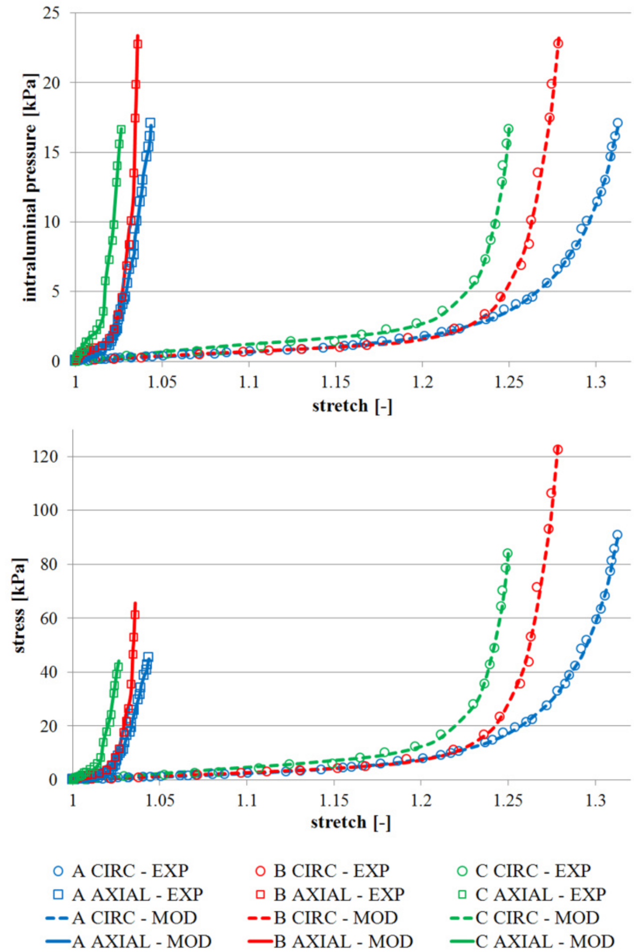

Fig. 3 Experimental data and computed model curves for the sample of vena saphena magna. CIRC and AXIAL denote circumferential and longitudinal direction, EXP and MOD denote experimental and model data.

IV. Discussion and Conclusios

The inflation tests of human vena saphena magna at different loading rates were performed. The experimental data were fitted by anisotropic HGO constitutive model to obtain material parameters for different pressurizing rates. As shown in Table 2 the model parameters differ significantly, especially parameter k_2 which appears in the exponent of the strain energy density function. The results suggest that constitutive parameters are strongly influenced by experimental conditions which we interpret as viscoelasticity of the vein grafts.

The limitation of this preliminary study is related to the number of tested specimens. Only one sample obtained from one donor was tested. More samples from donors of different age and pathology should be studied. We are evaluating other inflation-extension tests in order to extend the available set of material parameters of vena saphena magna.

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References

1. Krasiński Z, Biskupski P, Dzieciuchowicz L, Kaczmarek E et al. (2010) The influence of elastic components of the venous wall on the biomechanical properties of different veins used for arterial reconstruction. Eur J Vasc Endovasc 40:224-229
2. Horny L, Chlup H, Zitny R et al. (2009) Constitutive modelling of coronary artery bypass graft with incorporated torsion. Metalurgia 49:273-277
3. Tran-Son-Tay R, Hwang M, Garbey M et al. (2008) An experiment-based model of vein graft remodeling induced by shear stress. Ann Bimed Eng 36:1083-1091
4. Fernandez MC, Goldman DR, Jiang Z et al. (2004) Impact of shear stress on early vein graft remodeling: A biomechanical analysis. Ann Bimed Eng 32:1484-1493
5. Clarke GH, Vasdekis SN, Hobbs JT, Nicolaides AN (1992) Venous wall function in the pathogenesis of varicose veins. Surgery 111:402-408
6. Wali MA, Dewan M, Eid RA. (2003) Histopathological changes in the wall of varicose veins. Int Angiol 22:188-193
7. Donovan DL, Schmidt SP, Townsend SP et al. (1990) Material and structural characterization of humansaphenous vein. J Vasc Surg 12:531-537
8. Stooker W, Gok M, Sipkema P et al. (2003) Pressure–diameter relationship in the human greater saphenous vein. Ann Thorac Surg 76:1533–1538
9. Holzapfel GA, Gasser TC, Ogden RW (2000) A new constitutive framework for arterial wall mechanics and a comparative study of material models. J Elast 61:1–48

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