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Comparison Study of the Viscoelastic Properties of Light and Heavy Hernia Meshes

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Abstract

The purpose of this study is to investigate and compare viscoelastic mechanical properties of pristine surgical meshes with the viscoelastic properties of human fascia.

One-dimensional tensile relaxation experiments with heavy and light commercially available hernia meshes, Surgimesh, Tecnomesh, Surgipro, Vypro II and Parietex were performed. Mesh density, initial and equilibrium stresses, stress ratio, and stress reduction during relaxation are determined as basic parameters. All investigated meshes revealed orthotropic mechanical properties with a level of orthotropy of 1.76–3.35 for heavy meshes and 0.18–0.85 for light meshes. The analysis of the results showed that initial stress $0\text{–}\sigma_0$ is between 0.09-0.529 MPa and stress reduction parameter $\Delta\sigma$ is in the range 19%-29% for light meshes and 40-52% for heavy weight meshes. The long-term mechanical compatibility between human fascia and hernia meshes was accessed also. The stress reduction of Surgimesh increases 25% in longitudinal direction two years after expiration date while stress reduction of Tecnomesh decreases with 15 % in both directions 5 years after expiration date.

The results presented in this article are important for evaluating the mesh ability to match abdominal viscoelasticity at the moment of implantation and over a period of time.

Key words: *Hernia Meshes; Human Fascia; Uniaxial Relaxation Tests; Viscoelastic Properties*

Introduction

Hernia meshes ensure mechanical stability of abdominal wall in case of herniation and all types of female stress incontinence in sling surgery. A rapid growth in the variety of meshes leads to difficulty in choosing the most suitable one because of differences in their structure and mechanical properties [1, 2, 3]. The synthetic meshes have been used as a hernia repair material since late 50s but very little attention has been payed to their viscoelastic properties. Most of the authors investigated structural characteristics and the elastic properties of hernia meshes [1, 2]. There are recommendations about values of ultimate tensile strength and deformability of hernia meshes based on theoretical application of law of Laplace in case of normal and obese patients [l, 3]. All these results are used in the process of selection of hernia meshes but they do not consider the processes of mesh relaxation.

In the repair of herniated abdominal wall its layers and meshes are combined, which requires to know not only the material properties of hernia meshes but the properties of abdominal layers as well. The human abdominal wall is a subjected to intra-abdominal pressure and dynamic loads during jumping, coughing or lifting heavy objects [4]. In everyday life the cases of increased intra-abdominal pressure or dynamic loads predisposes the subsequent stress relaxation. In order to include the viscous effects of the abdominal wall in computational simulations, the viscoelastic behavior of the wall layers need to be determined. The viscoelastic mechanical properties of the abdominal wall in an animal model of rabbits, pigs or rats are investigated in the works of Hernandez et al, Sun et al. and Van Loocke et al. [5, 6, 7, 8]. The time dependent behavior of different human muscles have been studied, including skeletal muscles, oblique muscle and sternocleidomastoideus muscle [9, 10, 11]. Kirilova studied the viscoelastic properties of human abdominal fascia at three different strain levels [12]. The viscoelastic properties of hernia meshes are very important because may impact the mesh function in vivo. The necessity to learn more about viscoelasticity of hernia meshes and tissues which they substitute, stimulate our interest towards the problem.

The aim of this work is twofold: to investigate the relaxation behavior of heavy and light commercially available hernia meshes and to compare the properties of these meshes with the viscoelastic properties of human abdominal fascia.

Materials and methods

Uniaxial stress relaxation tests on mesh specimens from three heavy weight (HW) and two lightweight (LW) mesh brands were performed. Polypropylene knitted hernia meshes Surgimech (Aspi Medical, France), Tecnomesh (TecnoMedic GmbH, Germany), Surgipro (USSC,USA) with thickness in the range 0.57- 0.6 mm and maximum pore size 0.5- 0.96 mm, as well as VyproII (Ethicon, Inc., Somerville, NJ, USA) and Parietex (Covidien, France) with thickness 0.32- 0.5 mm and maximum pore size 1.15-3.5 mm were investigated. The density of the meshes is as follows: for light meshes 35-37 g/m^2, while for heavy meshes 81-110 g/m^2. Surgimech(SM) , Tecnomesh(TM) and Surgipro(SP) are heavy meshes while VyproII(VP) and Parietex(PX) are light meshes. The mesh and fascia specimens were cut to 10mm × 70mm rectangular samples. The samples were tested

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using a device FU1000/e (Germany), with load cell 500 N, , minimal value of the load of 20 g and minimal value of the displacement of 0.1 mm. The mesh specimens were cut parallel to the column of loops (direction L) and along the rows of loops (direction T) . For each brand ten samples were studied in both orthogonal directions.

The results from relaxation experiments with human abdominal fascia were obtained from previously published results [13]. The experiments were approved by the Ethical committee of the Bulgarian Academy of Sciences.The samples of fascia transversalis (FT) and fascia umbilicalis (UF) were cut parallel to the fiber bundles (direction L) and orthogonal to the them (direction T). All experiments were performed at 5% deformation at 1.26 mm/s rate of elongation. During relaxation tests the extension of the specimen was kept constant while the load was recorded. The duration of every test was 600s because the preliminary tests showed that a fascia reached relaxation state after 600s. After mechanical testing load and displacement data were converted to a Lagrangian stress as a function of time (Lagrangian stress is the total load divided by the cross-sectional area of the sample in its initial unloaded state). From the stress - time curves the initial stress σ_0 at t=0 and the equilibrium stress σ_{eq} at t=600s were determined. The modulus at initial strain strain E_0 ($E_0 = \sigma_0 / \varepsilon$, (ε =5%), as well as the modulus at equilibrium state - E_{eq} ($E_{eq} = \sigma_{eq} / \varepsilon$) were calculated. The relaxation process was characterized also by the reduction of the stress during relaxation process $\Delta\sigma$, defined as $\Delta\sigma = \dfrac{(\sigma_0 - \sigma_{eq})}{\sigma_0}\,100\%$ and the ratio of calculated Lagrangian stress σ_T/σ_L which is an indicator for the orthotropy of the material. The stress ratio σ_T/σ_L was calculated also at t =0s and 600s.

The long-term changes of relaxation behavior of chosen hernia meshes were evaluated. The samples of Tecnomesh and Surgimesh were investigated at two and five years after expiration date (ED). The changes of the stress reduction parameter and stress ratio were described.

The comparison between viscoelastic properties of the meshes and human abdominal fascia was presented. The connection between mesh density and stress reduction parameter as well as stress ratio and relaxation time were demonstrated.

Statistical analysis was conducted using Statistica version 13 Software.

Results are represented as mean ± SD. The differences between parameters were investigated by applying a nonparametric Mann-Whitney test because sets of samples include no more than five samples. A significance level of 0.05 was chosen.

Results

Tensile stress relaxation tests with heavy and light hernia meshes were performed in which fifty mesh samples and eighteen abdominal fascia samples were investigated and compared. For each direction mean stress according to applied constant strain was plot. The obtained mean relaxation curves are presented in [Figure 1 and 2] There is a pronounced difference in stress relaxation values for light and heavy meshes in L direction only. The curves match for Surgipro and Tecnomesh in the same direction shows that the relaxation properties of chosen heavy meshes are very close.

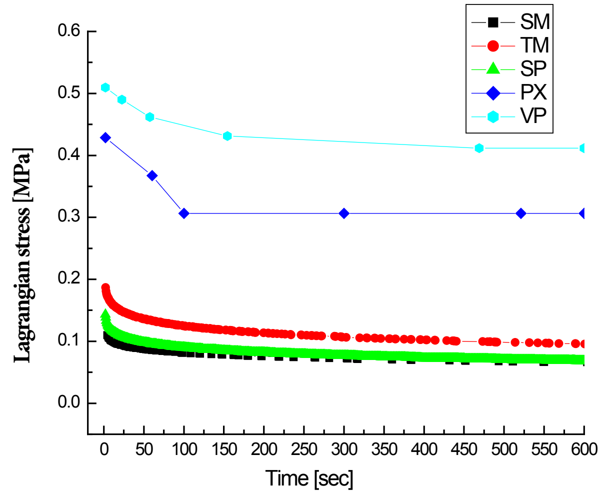


Figure 1: The mean stress relaxation curves of investigated hernia meshes in longitudinal direction. The difference in relaxation behavior of heavy meshes (SM, TM, and SP) and light meshes (PX, VP) were revealed.

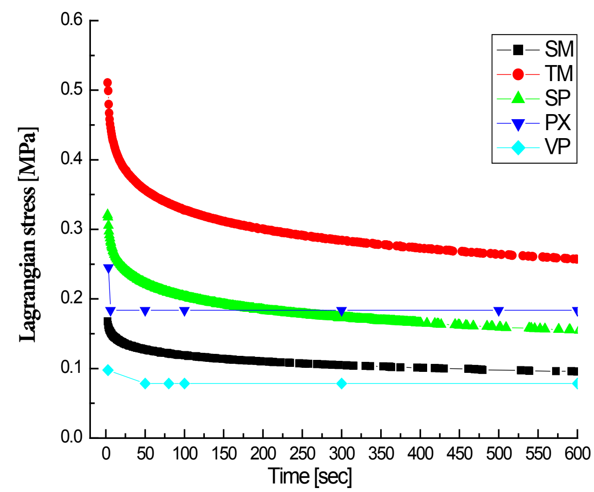


Figure 2: The mean stress relaxation curves of investigated hernia meshes in transversal direction.

The mean values of the model parameters are listed on Table 1. The initial stress σ_0 in L direction is in the range 0.11- 0.17 MPa for a HW meshes and 0.39-0.53 MPa for light meshes.

The mean values of the model parameters are listed on Table 1. The initial stress σ0 in L direction is in the range 0.11- 0.17 MPa for a HW meshes and 0.39-0.53 MPa for light meshes. The values for initial stress in T direction exceed 0.17 MPa for HW and 0.098 MPa for LW meshes. Performing statistical analysis we found significant differences between values of initial stress for longitudinal and transversal directions of Tecnomesh ($p<0.5$) Surgipro ($p<0.5$) and Vypro ($p<0.5$).

The parameter σ_T/σ_L is an indicator for the orthotropy of the materials. It was used to compare orthotropy between the two main groups of meshes and within every group. The stress ratio was calculated at two points at the beginning of the relaxation process t=0 s and at the end of the test (t= 600s). The results for orthotropic level of meshes and fascia are presented in [Figure 3] . None of the meshes possess isotropic properties (with stress ratio nearly 1). The stress ratio is between 0.18–0.85 for light meshes and 1.72–3.35 for heavy meshes [Table 1, Figure 3]. The highest level of the orthotropy has Tecnomesh

Table 1: The values of mechanical parameters for investigated meshes.

Brand of mesh	**σ_0 [MPa] t=0**	**$\Delta\sigma$[%] at t=600s**	**σ_T/σ_L t=0**	**σ_T/σ_L t=600s**	**E_0 [MPa]**	**E_{eq} [MPa]**
SM-L	0.115±0.05	40±4.4	1.92±0.86	1.76±0.62	2.3±0.01	1.32±0.66
SM-T	0.174±0.04	43.11±4.2			3.48±0.8	1.92±0.48
TM-L	0.171±0.06	48.39±4.5	3.35±1.09	2.99±0.96	3.42±1.2	1.92±0.8
TM-T	0.524±0.04	51.88±2.6			10.84±0.8	5.14±0.26
SP-L	0.145±0.029	52.45±2.7	2.38±0.81	3.06±1.1	2.86±0.58	1.36±0.48
SP-T	0.339±0.12	51.71±9.2			6.78±2.4	3.1±1.3
PX-L	0.397±0.04	28.504±8.5	0.62±0.04	0.85±0.13	7.94±0.8	4.28±2.6
PX-T	0.245±0.02	25.31±5.1			4.9±0.4	3.66±0.02
VP-L	0.529±0.24	19.05±9.8	0.18±0.11	0.19±0.08	10.58±4.8	8.24±3.88
VP-T	0.098±0.03	19.17±1.4			1.96±0.6	1.57±0.03
FT-L	0.389±0.27	38.15±15.8	2.11±1.1	2.33±1.2	7.78±.1.4	4.6±1.04
FT-T	0.71±0.28	40.46±2.2			14.2±5.6	8.6±3.7
UF-L	0.76±0.16	51.36±9	0.355±0.1	0.376±0.1	15.53±3.88	8.49±3.82
UF-T	0.27±0.11	47.42±4			5.35±2.18	3.02±1.33

and Surgipro over 3. There is no clear trend for impact of time on stress-ratio. For Surgimesh and Tecnomesh the orthotropy level decreases, for Surgipro, Parietex and fascia the value of σ_T/σ_L increases. The values of stress ratio σ_T/σ_L for FT are 2.11±1.1 at the beginning of the relaxation and 2.33±1.2 after 600s. For umbilical fascia the obtained results are 0.355±0.14 versus 0.376±0.11. Thus according to the results only Surgimesh possess the orthotropy close to the orthotropy of fascia transversalis.

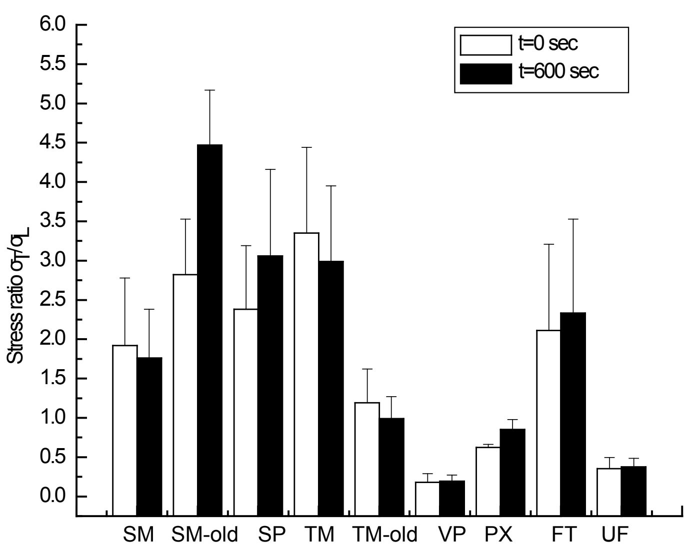
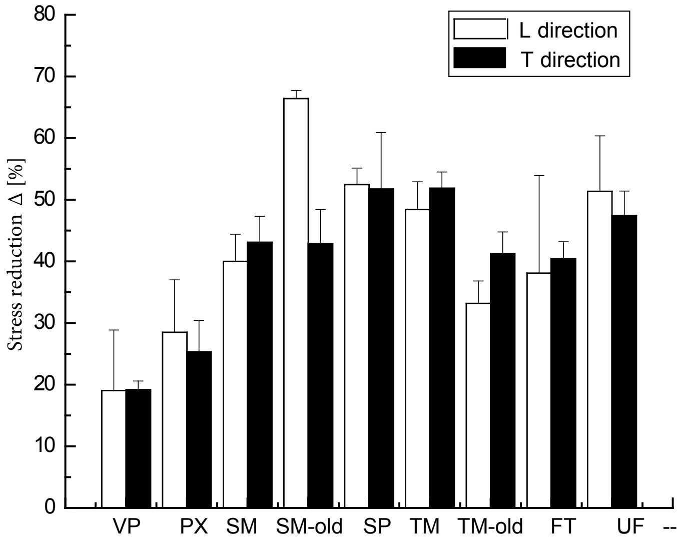


Figure 3: The orthotropic level of investigated meshes and fascia.The stress ratio σ_T/σ_L is presented at the beginning of the relaxation process (t=0s) and at the end of the test (t=600s). Two years after ED the level of orthotropy of SM is far from the stress ratio of the fasia, while the level of orthotropy of the TM five years after ED is much closer.

A characteristic of the time-dependent changes in the meshes is the stress reduction parameter $\Delta\sigma$. The results are plotted in [Figure 4] . It differed in magnitude according to the brand of mesh, loading direction and relaxation time. The amount of stress reduction varied with respect to the loading direction about 2–7% for every mesh except Vypro II. The comparison of the values of the stress-reduction parameter at chosen time points showed that the parameter changes in the range of 40–52% for heavy meshes and 19-28% for light meshes. It was obtained that stress reduction of Surgimesh is close to $\Delta\sigma$ for fascia transversalis and that the same conclusion can be done for Surgipro, Tecnomesh and umbilical fascia [Figure 4] . There are no considerable differences between the values of the parameter according to direction of loading. We did not find significant differences between mean values of stress reduction for heavy and light meshes despite pronounced differences between values for $\Delta\sigma$ for two groups (p =0.2).

The results about mesh density and stress reduction are presented in [Figure 5]. They demonstrated that there is a logarithmic relationship between the mesh density and stress reduction parameter. Density is proportional to stress reduction with regression coefficient R^2= 0.95.

The long-term mechanical compatibility between human fascia and hernia meshes was also accessed. The study demonstrated that the level of orthotropy and stress reduction of investigated meshes is greatly variable. Long-term stress ratio results are presented in [Figure 3]. After five years the orthotropy level of TM decreased from 3.35 to 1.19 and became close to orthotropy level of umbilical fascia. The stress reduction of Surgimesh increases 25% in longitudinal direction two years after expiration date while stress reduction of Tecnomesh decreases with 10-15% in both directions 5 years after expiration date [Figure 4].



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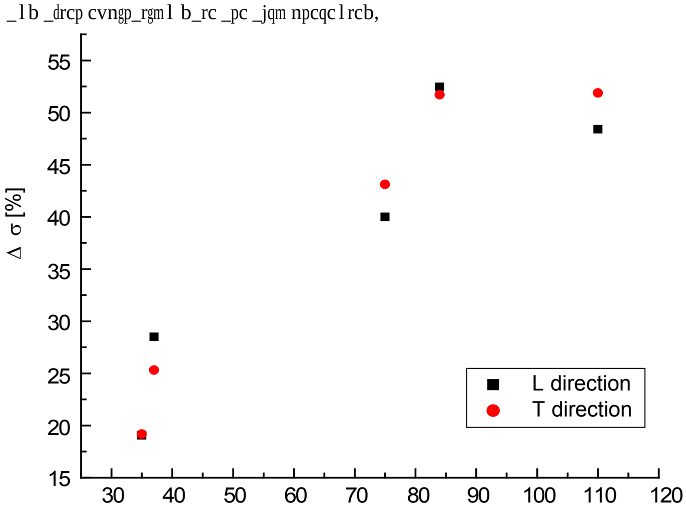

Figure 5: The relationship between mesh density and stress reduction parameter Δσ. The most appropriate regression curve is logarithmic curve with R^2 value 0.95.

The changes of relaxation behavior of chosen hernia meshes were evaluated using the moduli E_0 and E_{eq} [Figure 6]. It is seen that for heavy meshes the range of E_0 is 2-4 MPa for L direction and 3-11 MPa for T direction. The trend for light meshes is an opposite they have high values of E_0 in longitudinal direction and relatively low values for this modulus in transversal direction. The same tendency is presented for E_{eq} (not shown) but the values for E_{eq} are lower. The comparison of the results for meshes and fascia demonstrated that the properties of these meshes are far from the properties of the fascia.

Discussion

The proper mesh material needs to possess appropriate tensile and relaxation mechanical properties. In order to evaluate the resistance of meshes their tensile strength are usually tested. In everyday life however,

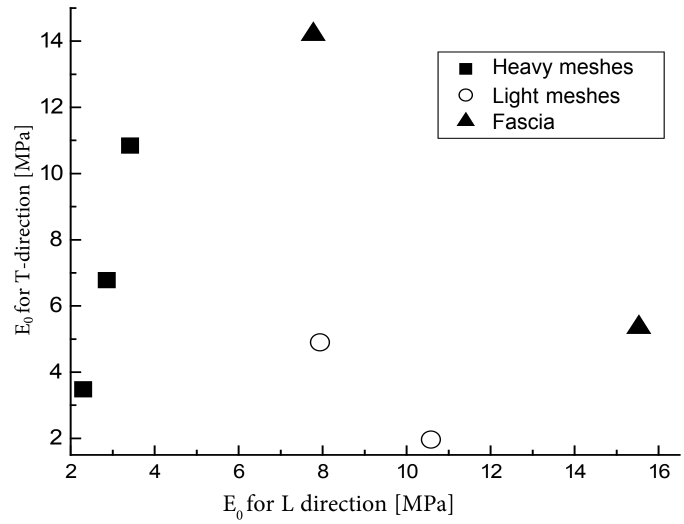

Figure 6: Comparison of moduli at initial stress for heavy and light meshes.

their tensile strength are usually tested. In everyday life however, the cases of dynamic loads during physical activity lead to stress relaxation of abdominal wall. This fact imposes the investigation of wall and mesh properties using tensile relaxation experiments. The relaxation testing regime depicts the stresses that abdominal wall and implanted meshes undergo within the body during conditions when a constant strain is applied. Actually data of the viscoelastic properties of hernia meshes with regard to stress reduction and orthotropy are lacking. This implied the performance of current study.

Viscoelastic properties of heavy and light weight meshes were investigated and compared. A big diversity of the results was obtained according to the mesh brand.

The values of the parameters in transverse direction are higher than those in longitudinal direction for heavy meshes, while the parameters for light meshes revealed the opposite trend.

The analysis of the results for hernia meshes showed that initial stress σ_0 is between 0.09-0.529 MPa. Stress reduction parameter Δσ are in the range 19%-52%. The values of stress ratio vary between 0.18-3.35. E_0 is in the range 1.96-10.84 MPa and E_{eq} is between 1.32 – 8.24 MPa.

The anisotropic behaviour of hernia meshes has been documented by uniaxial tensile testing and now the same response was revealed with relaxation tests [14]. Our previous investigations showed that TM and SP possess orthotropic elastic properties and only SM exhibits isotropic mechanical properties at a physiological range of deformation [14]. The level of orthotropy obtained at tensile tests is less than the level obtained at relaxation tests [15]. The stress ratio at tensile tests is between 0.8–1.91 for heavy hernia meshes and 0.23–0.35 for fascia while the level of orthotropy of testing materials during relaxation experiment is in the range 0.18–3.35 for hernia meshes and 0.355-2.11 for fascia.The information about the level of orthotropy of hernia meshes is given by Sabersky but he used tensile experiments [16]. (For HW meshes the obtained value is 0.43 while for LW – 0.085.)

The abdominal wall is subjected to different type of loads and the discrepancy between the level of orthotropy of hernia meshes and abdominal layers could lead to increase of tension at the place of implantation and in some cases to a re-operation. The results described that stress ratio for FT is close to this of Surgimesh while orthotropic level of UF is similar to those of Vypro [Figure 3]. The statistical analysis showed that the level of orthotropy does not depend on the relaxation time but depend on the age of the material.

The stress reduction $\Delta\sigma$ of the meshes was established. The difference between values of $\Delta\sigma$ for both directions is about 2-4% for fascia and 0-7% for meshes. Separating the results for heavy and light hernia meshes we found that the values of the stress reduction $\Delta\sigma$ for light meshes is two times less than the stress reduction for heavy meshes. The stress reduction for fascia transversalis is close to stress reduction of Surgimesh, while stress reduction of UF is close to stress reduction of Surgipro and Tecnomesh. The results supposed that it is necessary to work on improvement of stress reduction parameters for implanted meshes. Despite the widespread acceptance of the hernia meshes their long-term properties are not studied in details. The alterations of the mesh properties can cause serious discomfort and reduction of the quality of patients' life.

Our investigation of the long-term viscoelastic behavior of Surgimesh and Tecnomesh described that the stress reduction of Surgimesh increases 25% two years after ED while stress reduction of Tecnomesh decreases about 10% in 5 years after ED [Figure 4]. In the literature there are reports about the cracked surfaces of polypropylene meshes detected by scanning electron microscopy and routine microscopy [17, 18]. The alterations in the chemical structure of polypropylene are responsible for material embrittlement [18]. The possible reasons for these changes are aging and fatigue of the material.

The trend of elastic modulus for hernia meshes before ED and up to four years after ED was presented in [19]. TM and SM became more elastic in both directions while SP does not change significantly its elasticity. The secant modulus E(5) for SM and TM decreases about 30% in direction parallel to the column of loops but along the rows of loops (transversal direction) only modulus of TM decreases significantly more than 2 times from 12.63 MPa to 5.45 MPa. The preliminary study of the resorbable mesh Vypro showed pronounced stiffening after 1.5 years.

We compared the properties of unused materials with human fascia in order to examine how successfully the meshes match the properties of native tissues. It is known that the elasticity of human abdominal wall is higher in the longitudinal direction than in the transverse direction by approximately 2:1 in proportion [20]. This requirement is met in the design of TM and SP but after years their modulus of elasticity changes the secant modulus of TM decreases in both direction, the secant modulus of SM decreases in L direction, while SP elasticity remain nearly constant [19]. Thus the stress ratio after three years became for SM 1.18, for TM 1.56, and for SP 1.86 [19]. In case of relaxation experiments the ratio for SM is 0.66 and for TM is 0.33. After 2-5 years the values of these ratios are 0.38 and 0.88.

The present study was limited to the investigation of the one-dimensional relaxation properties of hernia meshes. Future bi-axial experiments experiments should be aimed to reveal their mechanical

properties of native tissues. It is known that the elasticity of human abdominal wall is higher in the longitudinal direction than in the transverse direction by approximately 2:1 in proportion [20]. This requirement is met in the design of TM and SP but after years their modulus of elasticity changes the secant modulus of TM decreases in both direction, the secant modulus of SM decreases in L direction, while SP elasticity remain nearly constant [19]. Thus the stress ratio after three years became for SM 1.18, for TM 1.56, and for SP 1.86 [19]. In case of relaxation experiments the ratio for SM is 0.66 and for TM is 0.33. After 2-5 years the values of these ratios are 0.38 and 0.88.

Conclusion

The results presented in this article are important for evaluating the mesh ability to match abdominal viscoelasticity at the moment of implantation and over a length of time. The comparison of the viscoelasctic properties of light and heavy hernia meshes revealed the differences in their material properties. It was established that the stress reduction increases with density of the meshes. The level of orthotropy of investigated meshes is nearly constant and does not depend on the relaxation time but depend on the age of material. The initial and equilibrium moduli vary in the similar range 1-10 MPa. The differences in material properties between hernia meshes and human abdominal fascia were also revealed. The stress reduction for fascia transversalis is close to stress reduction of Surgimesh, while stress reduction of UF is close to stress reduction of Surgipro and Tecnomesh. All other tested meshes exhibited mechanical properties very different from those of the fascia.

The obtained data about meshes will be a useful step towards the convergence of the mechanical properties of synthetic meshes and tissue layers.

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