

IN VITRO INVESTIGATION OF LONG-TERM PROPERTIES OF HERNIA MESHES

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ABSTRACT: The study aims to investigate the influence of aging on the mechanical properties of non-resorbable and resorbable surgical meshes as well as heavyweight and lightweight meshes.

Nine types of meshes were characterized before and after their expiration date. The maximum tensile stress, stretch at maximum stress, and elastic secant modulus of the mesh at 5% strain were calculated from derived stress- stretch curves for each specimen.

The results indicate that the maximum tensile stress and elastic secant modulus of non-resorbable and lightweight meshes decrease after the expiration date. The stretch at maximum stress of non-resorbable meshes increases after the expiring date, while in other subgroups the behaviour of this parameter depends on the direction of loading.

KEY WORDS: Hernia meshes; Mechanical properties; Experimental study; Long-lasting follow-up.

1 INTRODUCTION

Surgical meshes were used to improve the outcome of operations, but not all possible aspects of the problems concerning implantation have been investigated. Evaluation of the mechanical properties of hernia meshes is particularly important to understand the conditions related to complications and reoperations after surgical procedures.

More studies focus mainly on the tensile mechanical characterization of hernia meshes and particularly on the strength and stiffness of biomaterials because the main purpose for using meshes in hernia repair is mechanical support [1–5]. Some studies are focused on the compatibility of meshes and abdominal layers at the time of implantation [6–9] but information about long-term changes in the mechanical properties of meshes after implantation is rare.

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The meshes exposed to physiological conditions demonstrate failure load, stiffness, and extension that are different from those of pristine materials. Synthetic meshes provoke complications that require long-lasting follow-up. Their long-term behaviour can be characterized by *in vivo* or *in vitro* experiments. *In vivo* experiments give realistic results after non-invasive measurements by optical techniques or ultrasound imaging, combined electromyography and ultrasound measurements, or intra-abdominal pressure measurement [10, 11].

In the case of *in vitro* tests samples of meshes are placed in the chamber of the thermostatic bath full of buffer solution or water. Other tests are the comparison of the mechanical behaviour of meshes before and after their expiration date (ED) or the testing of explanted meshes.

The mechanical properties of the implanted polypropylene (PP) or polyester (PE) meshes depend on the age of implantation [12]. It was reported about erosions of PP, polyethylene terephthalate (PET), polytetrafluorethylene (PTFE), or polyvinylidene fluoride (PVDF) used for incontinence and prolapse [13]. It is proved that PTFE is not influenced by hydrolysis and oxidation, while PVDF shows excellent resistance to aging and does not increase its stiffness [13–16]. The results of explanted mesh specimens were reported in [17, 18]. The authors analyzed only the tissue reaction to mesh samples.

Mechanical alterations of human mesh explants made of polyester were investigated using a uniaxial tensile test and a relaxation test. The tensile strength post implantation changed in the transversal direction. The elastic modulus in the same direction increased two times [19]. Lu et al. published results about polypropylene mesh degradation after up to 13 years of implantation. The study characterized changes in surface oxidation, crystallinity, and mechanical properties. According to the authors, the main factor affecting changes in mesh stiffness was infection [20].

Ryncevic et al. [21] compared pristine control samples with mesh specimens placed in alkaline and acid mediums at 37°C during 42 and 90 days. The authors analyzed meshes in terms of their weight loss and thickness changes. The results showed that the greatest weight loss and thickness reduction were suffered by Ultrapro mesh [21]. Mechanical aspects of the degradation process of partially absorbable composite hernia meshes Ultrapro and Vypro placed in a digital thermostatic bath full of buffer solution for 90 days (Vypro II) and 120 days (Ultrapro) were reported in [22]. Statistically significant differences between values before and after degradation for maximum tensile stress $T_{\max}$, and stretch at maximum stress $\lambda_{\max}$ for VyproII mesh in both directions were proved. The mechanical properties of three commercially available hernia meshes Microval, TiO2 Mesh, and VyproII soaked in PBS solution for 70 days were compared by Pashkouleva et al. [23]. It was proved that the changes that occur with aging, affect their mechanical properties.

Investigation of the long-term mechanical response of surgical meshes before and after their expiration date is not a commonly used method. As far as we know, the only work describing some results in this direction is our previous study [24]. To overcome the lack of available data on the mechanical properties of the explanted meshes we focused on unused meshes of various polymer materials and densities to assess the effect of aging of chosen meshes over a long period.

The study aims to examine the long-term mechanical behaviour of polypropylene (non-resorbable) and resorbable hernia meshes used in surgical practice as well as the difference in the mechanical behaviour of heavyweight and lightweight meshes. Our hypothesis was that the meshes change their properties significantly after their expiration date.

2 MATERIALS AND METHODS

Nine commercially available hernia meshes – seven non-resorbable and two resorbable meshes were investigated (Table 1). The non-resorbable meshes, namely Microval, Optilene, Parieten, Surgimesh, Surgipro, TechnoMesh, and TiO2 are made from polypropylene. The resorbable meshes combine polypropylene/polyglactin 910 (Vypro II) and polypropylene/polyglecaprone (Ultrapro). The data from the product sheets furnished by the manufacturers is presented in Table 1.

For the uniaxial tensile tests, 10 rectangular samples were cut from every mesh. Each sample was 70 mm long $\times$ 10 mm wide. Five samples along the loop columns (L direction) and five samples across the loop columns (T direction) were tested.

The strips of the tested meshes were gripped with the jaws of a universal testing machine (Fu1000e, Germany, 500 N load cell). The distance between the jaws was 40 mm. A constant rate of 0.13 mm/s was used during the tests. The force F [N] and the extension L [mm] were recorded from the system software. The relationship between the Lagrangian stress T_L and stretch ratio λ of each specimen was obtained, where T_L was defined by dividing the applied force F by the initial cross-section area S_0 . Stretch ratio λ was defined as the ratio of the obtained displacement L to the initial testing length L_0 . From the stress-stretch curves, maximum tensile stress $T_{\max}$, stretch at maximum stress $\lambda_{\max}$, and elastic secant modulus of mesh E_5 (defined as a ratio of the Lagrangian stress T_L and 5% strain) were calculated. The average values of the parameters for every mesh in both directions were obtained.

The mechanical properties of the meshes were studied in the interval 49 months before and 101 months after the expiration date (ED). The origin of a coordinate system coincides with ED. All non-resorbable meshes except Optilene were tested once before ED. Surgipro and Parietene were tested once after ED, while all other non-resorbable meshes were tested between two – and five times after ED (mean value – 3.5 times). The mean density of two subgroups of meshes was determined –

Table 1. A list of the tested meshes

Brand name	Manufacturer	Type of Material	Weight [g/m ²]
Microval 2D Mesh	MICROVAL, France	Polypropylene (non-resorbable)	90 (HW)
Optilene	B-Braun, Germany	Polypropylene (non-resorbable)	36 (LW)
Parietene	Sofradim Production, France	Polypropylene (non-resorbable)	87 (HW)
Surgimesh	Aspide Medical, France	Polypropylene (non-resorbable)	85 (HW)
Surgipro	USSC, USA	Polypropylene (non-resorbable)	87 (HW)
TecnoMesh	TecnoMedicGmbH, Germany	Polypropylene (non-resorbable)	90 (HW)
TiO ₂ Mesh	BioCerEntwicklungsGmbH, Germany	Polypropylene/ Titanium dioxide layer (non-resorbable)	47 (LW)
Ultrapro	Ethicon, Johnson&Johnson, USA	Polypropylene/ Polyglecaprone 25 (resorbable)	54 (LW)
Vypro II	Ethicon, Johnson&Johnson, USA	Polypropylene/ Polyglactin 910 (resorbable)	50 (LW)

heavyweight meshes (HW) (mean density 93 g/m²) and lightweight meshes (LW) (mean density 41 g/m²).

The values of parameters $T_{\max}$, $\lambda_{\max}$, and E_5 characterizing the main trends of long-term mesh mechanical properties were separated according to directions of loading in the following subgroups: non-resorbable (PP) and resorbable meshes according to the type of the material and heavyweight and lightweight meshes according to the density of meshes. The durability of the follow-up period was different for every mesh, and the mean value of durability for subgroups was calculated. The meshes were compared between the subgroups and within the subgroups according to the direction of loading. The mean value of every parameter before and after ED was calculated also.

All statistical tests were made using a statistical software package (MedCalc

17.9.7 Software). Quantitative data are represented as mean $\pm$ standard error of the mean. The comparison between the average values of parameters was accomplished by a procedure that calculates the difference between the observed means in two independent groups. A significance level of $p < 0.05$ was chosen. The mean values of mechanical parameters before and after ED for resorbable meshes were not compared because of a shortage of data.

3 RESULTS

The mean values of mechanical parameters for the subgroups are presented in Table 2, while the mean values of mechanical parameters within the subgroups are presented in Table 3 and Table 4.

The subgroups were tested as follows: non-resorbable meshes were tested in the period 34 months before ED – 101 months after ED, resorbable meshes from 49 months before ED to 18 months after ED), HW meshes were tested in the interval 30 months before ED – 101 months after ED and LW meshes were tested 34 before ED up to 60 months after ED.

Table 2. Basic parameters of the investigated baseline meshes for all period

Para- meters	Direc- tion	Mean values non-resorbable meshes $n = 23$	Mean values resorbable meshes $n = 6$	p	Mean values HW mesh $n = 16$	Mean values LW mesh $n = 7$	p
$T_{\max}$ [MPa]	T_L	6.82 $\pm$ 2.25	8.38 $\pm$ 4.24	0.22	7.51 $\pm$ 1.68	5.26 $\pm$ 2.73	0.02
	T_T	7.81 $\pm$ 2.85	1.72 $\pm$ 1.86	0.001	8.23 $\pm$ 1.53	6.87 $\pm$ 4.74	0.30
E_5 [MPa]	E_L	5.78 $\pm$ 4.11	6.76 $\pm$ 5.89	0.64	4.7 $\pm$ 0.87	9.69 $\pm$ 5.85	0.0009
	E_T	8.15 $\pm$ 6.27	2.03 $\pm$ 1.34	0.02	6.71 $\pm$ 2.6	11.47 $\pm$ 10.43	0.09
$\lambda_{\max}$	λ_L	1.91 $\pm$ 0.48	1.49 $\pm$ 0.24	0.04	2.19 $\pm$ 0.21	1.26 $\pm$ 0.07	0.001
	λ_T	1.79 $\pm$ 0.33	1.53 $\pm$ 0.05	0.06	1.98 $\pm$ 0.31	1.35 $\pm$ 0.13	0.0001

3.1 COMPARISON OF NON-RESORBABLE AND RESORBABLE MESHES

The values of $T_{\max}$ for non-resorbable meshes are in the interval 3.34–16.69 MPa, and for resorbable meshes are in the interval 0.18–13.44 MPa. Figure 1a,b presents changes in $T_{\max}$ according to a direction of loading for PP and resorbable meshes. The values of $T_{\max}$ are higher in the L direction for resorbable meshes (8.38 $\pm$ 4.24 MPa vs. 6.82 $\pm$ 2.25 MPa) and lower in the T direction (1.72 $\pm$ 1.86 MPa vs. 7.81 $\pm$ 2.85 MPa) (Fig. 1a,b). The difference between mean values is statistically significant in the T direction ($p = 0.001$) (Table 2).

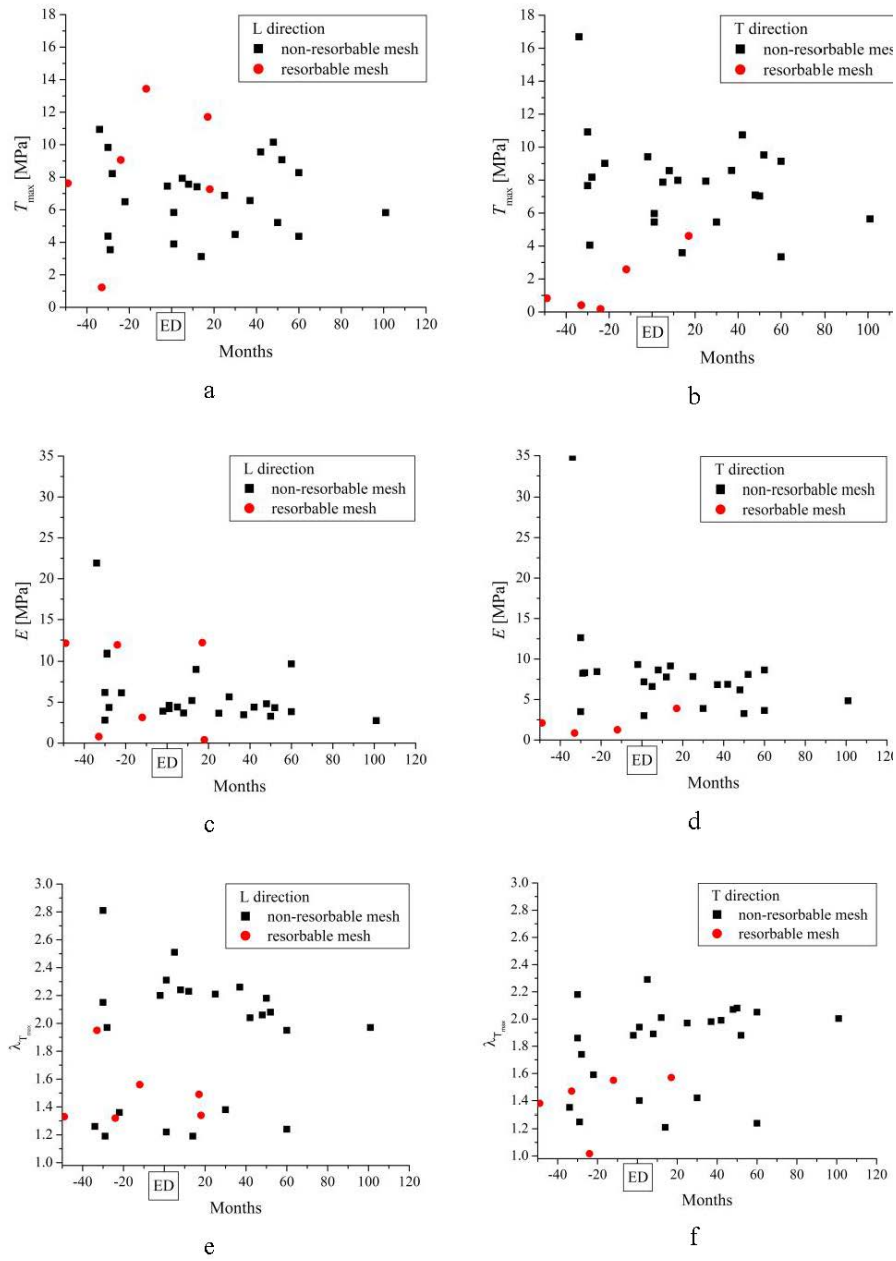


Fig. 1. The comparison of parameters for non-resorbable and resorbable meshes.

The values of E_5 for non-resorbable meshes are between 2.8–34.8 MPa. Figure 1c,d shows that the values of modulus E_5 for non-resorbable meshes in the L direction are in the interval 0.4–12.8 MPa, which are the minimum and maximum values of E_5 for resorbable meshes. The values of E_5 are higher in the T direction for non-resorbable meshes (mean values: 8.15 ± 6.27 MPa vs. 2.03 ± 1.34 MPa). The difference between mean values is statistically significant ($p = 0.02$) (Table 2).

The values of stretch ratio $\lambda_{\max}$ are between 1.19–2.51 for non-resorbable meshes and 1.01–1.95 for resorbable meshes. In the L direction, the mean values for non-resorbable meshes are 1.91 ± 0.48 , and for the T direction, 1.79 ± 0.33 . In the case of resorbable meshes, mean values of $\lambda_{\max}$ in the L direction are 1.49 ± 0.24 , and for the T direction, 1.53 ± 0.05 (see Fig. 1e,f). The mean values of the stretch ratio for non-resorbable meshes are higher than those of resorbable meshes in both directions. There was a statistically significant difference between mean values in the L direction ($p = 0.04$) (Table 2).

3.2 COMPARISON OF HEAVYWEIGHT AND LIGHTWEIGHT MESHES

Figure 2 presents the comparison of investigated parameters for heavyweight (mean density 93 g/m^2) and lightweight meshes (mean density 41 g/m^2). Maximum tensile stress is higher for HW meshes than for LW meshes in both directions.

In the L direction, $T_{\max}$ is 7.51 ± 1.68 vs. 5.26 ± 2.73 MPa, ($p = 0.02$). In the T direction, $T_{\max}$ is 8.23 ± 1.54 vs. 6.87 ± 4.74 MPa ($p = 0.3$). For elastic modulus the trend is the opposite – the mean values of E_5 are higher for lightweight meshes than for heavyweight meshes in both directions 9.69 ± 5.85 vs. 4.07 ± 0.87 in the L direction, and 11.47 ± 10.43 vs. 6.71 ± 2.6 ($p = 0.0009$ for L direction, Table 2.)

Comparing the values of stretch ratio for HW and LW meshes, we obtained that the elongation of heavyweight meshes is higher in both directions. (2.19 ± 0.2 vs. 1.26 ± 0.07 in the L direction and 1.98 ± 0.13 vs. 1.35 ± 0.13 in the T direction).

This trend is clear from Fig. 2e,f. The difference is statistically significant in both directions (< 0.05 , Table 2).

3.3 COMPARISON OF PARAMETERS BEFORE AND AFTER THE EXPIRATION DATE

Tables 3 and 4 compare parameters before and after ED in every subgroup and direction of loading. Evaluating the trend of parameters before and after ED for non-resorbable, HW, and LW groups, it was obtained that the values of $T_{\max}$ for non-resorbable meshes and light meshes decrease after ED. The values of E_5 for non-resorbable heavyweight and lightweight meshes also decrease.

The values of $T_{\max}$ for non-resorbable meshes before ED range from 3.34 to 16.69 MPa. The values of $T_{\max}$ after ED range from 3.12 to 10.74 MPa. $T_{\max}$ decreases after ED in both directions. The results are not statistically significant.

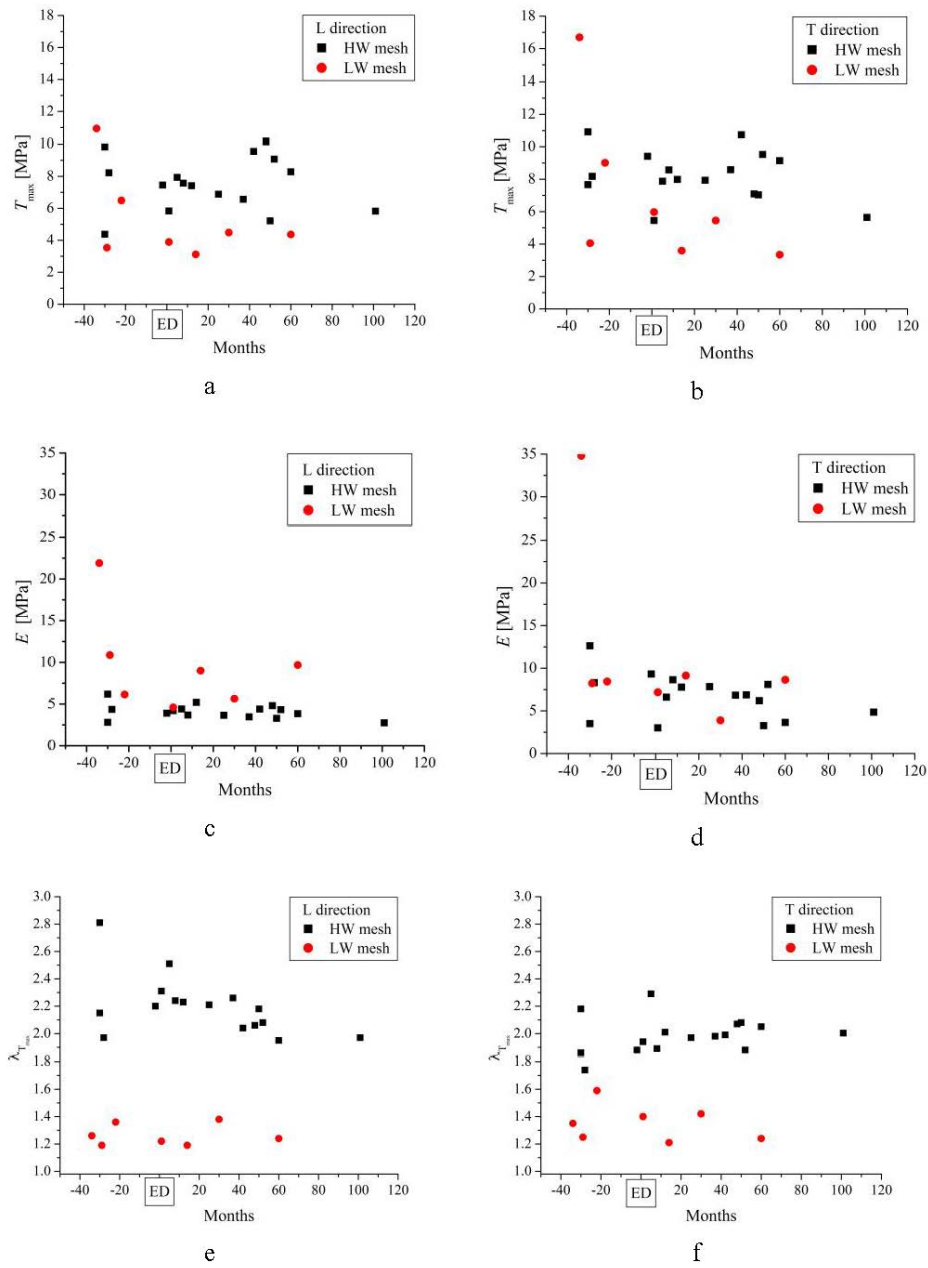


Fig. 2. The comparison of parameters for heavyweight and lightweight meshes.

Table 3. The mean values of mechanical parameters for non-resorbable (PP) and resorbable meshes

Para- meters	Direc- tion	PP mesh before ED $n = 7$	PP mesh after ED $n = 16$	p	Resorbable mesh before ED $n = 4$	Resorbable mesh after ED $n = 2$
$T_{\max}$ [MPa]	T_L	7.26±2.7	6.63±2.09	0.55	7.84±5.05	9.48±3.14
	T_T	9.42±3.84	7.12±2.08	0.07	1±1.08	4.61(n=1)
E_5 [MPa]	E_L	8.02±6.65	4.81±1.91	0.08	6.98±5.87	6.29±8.32
	E_T	12.17±10.32	6.40±2.05	0.04	1.41±0.64	3.9(n=1)
$\lambda_{\max}$	λ_L	1.84±0.6	1.94±0.43	0.65	1.54±0.29	1.42±0.11
	λ_T	1.69±0.32	1.84±0.33	0.32	1.35±0.23	1.57(n = 1)

The values of $T_{\max}$ for resorbable meshes are in the interval 0.18–13.44 MPa. The values of parameters before ED are in the interval 0.18–13.44 MPa. The values of the $T_{\max}$ after ED are in the interval 4.61–11.71 MPa. $T_{\max}$ increases after ED in both directions. Statistical analysis for this subgroup was not applied because of the small number of samples in the resorbable meshes subgroup.

The opposite trend was observed for the stretch behaviour at maximum stress $\lambda_{\max}$ plotted in Fig. 1 and Fig. 2. The stretch ratio in the non-resorbable group increases after the expiration date. Its trend depends on the direction of loading in other subgroups. The results are not statistically significant.

The difference between the results before and after ED for non-resorbable, HW, and LW meshes is not statistically significant ($p > 0.05$). Only the values of elastic moduli in the transversal direction before and after ED differed significantly ($p = 0.04$, Table 2).

Table 4. The mean values of mechanical parameters for heavyweight and lightweight meshes

Para- meters	Direc- tion	HW mesh before ED $n = 4$	HW mesh after ED $n = 12$	p	LW mesh before ED $n = 3$	LW mesh after ED $n = 4$	p
$T_{\max}$ [MPa]	T_L	7.47±2.29	7.52±1.55	0.96	6.99±3.73	3.96±0.62	0.40
	T_T	9.04±1.45	7.96±1.52	0.23	9.91±6.36	4.59±1.32	0.65
E_5 [MPa]	E_L	4.31±1.41	3.99±0.68	0.54	12.97±8.08	7.24±2.48	0.19
	E_T	8.44±3.77	6.13±1.97	0.13	17.15±15.27	7.21±2.36	0.89
$\lambda_{\max}$	λ_L	2.28±0.36	2.17±0.15	0.38	1.27±0.08	1.26±0.08	0.99
	λ_T	1.92±0.18	2.01±0.11	0.24	1.39±0.14	1.31±0.11	0.65

Although the meshes demonstrated orthotropic properties, there are no statistically significant differences between the mean values of maximum tensile stress $T_{\max}$ in both directions for non-resorbable meshes (7.47 ± 2.29 vs. 9.04 ± 1.45 , $p = 0.24$ – before ED) and (7.53 ± 1.55 vs. 7.96 ± 1.52 , $p = 0.51$ – after ED) (Table 4). The differences between the mean values of elastic secant modulus of mesh E_5 and stretch ratio $\lambda_{\max}$ between the directions of loading before and after ED were also compared. The results were not statistically significant. Only the values of secant modulus for heavyweight meshes after ED differ significantly ($p = 0.0018$).

4 DISCUSSION

Large numbers of mesh brands are available in surgical practice, and particular attention is required when choosing a hernia mesh. It is known that many factors like structure, type of polymer, density, pore size, or thickness of the material influence the outcome of a hernia operation.

We investigated unused meshes of various polymer materials and weights before and after ED, hypothesizing that the changes in their mechanical properties over a long period will reveal the main aging trends. We characterized the long-term performance of mesh materials by investigating the maximum tensile stress $T_{\max}$, the elongation at the maximum tensile stress, and the elastic secant modulus of mesh E_5 . We expected the results to shed light on the dynamics of the processes after implantation.

The present study is a part of a long-lasting follow-up of hernia meshes. An experimental investigation of the long-term behaviour of three polypropylene hernia meshes was accomplished and reported some years ago [24]. The parameters trend demonstrates the influence of age on the strength and elasticity of investigated meshes, but the results were too individual. TechnoMesh becomes more elastic in both directions, Surgimesh becomes elastic in the L direction, and Surgipro does not change significantly its elasticity [24].

The best method to investigate the long-term mesh properties is testing of explanted meshes. These studies describe the inflammatory infiltrate, connective tissue on meshes, or structural alterations like shrinkage, expansion, adhesion formation, or degradation of the explanted hernia meshes [16]. Costello et al. and Burns-Heffner reported that explanted heavyweight PP meshes increased stiffness while Ultrapro decreased stiffness. The average tensile stiffness of Ultrapro mesh decreased by 59.1% [25, 26]. We obtained that the elastic modulus of polyester increased after implantation [19]. Unfortunately, access to explanted meshes is not easy, and we tested mesh materials before and after ED.

The results showed that non-resorbable, heavy weight PP meshes lose their elasticity and strength after the ED – $T_{\max}$ and E_5 for non-resorbable meshes decrease

in both directions while values of stretch ratio increase. The conclusions for resorbable and lightweight meshes are not clear because of the insufficient number of tested samples – between two and four. We should increase the number of investigated resorbable and lightweight mesh samples to guarantee the generality of the results.

The study revealed that the trend of non-resorbable, heavyweight PP mesh behaviour years after ED is opposite to those described in [25, 26], although the mean density of this subgroup is 93 g/m^2 – close to the density of the mesh Composix E/X, investigated from Costello et al. and Burns-Heffner. Composix E/X is knitted monofilament PP heavyweight mesh, sewn to thin ePTFE layer with a density of 95 g/m^2 . Probably the reason is the physiological conditions to which the explanted meshes were subjected. According to Costello, it is possible that oxidation is responsible for these changes in material properties [25].

The study has some limitations. The number of investigated resorbable and lightweight mesh samples should be increased. Meshes for all subgroups should be tested more times after ED for confirmation of conclusions. The experimental protocol can be enlarged, adding more parameters to describe the mechanical behaviour of meshes.

5 CONCLUSIONS

The long-term changes in the mechanical characteristics of nine commercially used surgical meshes were investigated. The results revealed that the changes of parameters with age showed different trends depending on the type of investigated meshes.

Maximum tensile stress and elastic secant modulus of meshes decrease after the expiration date for the non-resorbable meshes and lightweight meshes. The stretch at maximum stress λ_{max} of non-resorbable meshes increases after the expiring date, while the behaviour of this parameter depends on the direction of loading in other subgroups.

A clear understanding of the mechanical properties of hernia meshes is important for the outcomes of operations. The results may shed light on the safety of meshes and can be useful for clinical recommendations. Continuous progress in the technologies will contribute to further understanding of the long-term behaviour of the hernia meshes.

REFERENCES

- [1] P. POTT, M. SCHWARZ, R. GUNDLING, K. NOWAK, P. HOHENBERGER, E. ROESSNER (2012) Mechanical properties of mesh materials used for hernia repair and soft tissue augmentation. *PLOS ONE* 7(10) e46978.
- [2] C.R. DEEKEN, M.S. ABDO, M.M. FRISSELLA, B.D. MATTHEWS (2011) Physicome-

- chanical evaluation of polypropylene, polyester, and polytetrafluoroethylene meshes for inguinal hernia repair. *Journal of the American College of Surgeons* **212**(1) 68-79.
- [3] L. ZHU, P. SCHUSTER, U. KLINGE (2015) Mesh implants: An overview of crucial mesh parameters. *World Journal Gastrointestinal Surgery* **7**(10) 226-236.
 - [4] L. MIAO, F. WANG, L. WANG, T. ZOU, G. BROCHU, R. GUIDOIN (2015) Physical characteristics of medical textile prostheses designed for hernia repair: a comprehensive analysis of select commercial devices. *Materials* **8**(12) 8148-8168.
 - [5] A. CODA, R. LAMBERTI, S. MARTORANA (2012) Classification of prosthetics used in hernia repair based on weight and biomaterial. *Hernia* **16** 9-20.
 - [6] M. KIRILOVA (2010) About mechanical compatibility of some hernia meshes and abdominal wall layers. *Series on Biomechanics* **25**(1-2) 134-139.
 - [7] M. MAURER, B. ROHRNBAUER, A. FEOLA, J. DEPREST, E. MAZZA (2014) Mechanical biocompatibility of prosthetic meshes: A comprehensive protocol for mechanical characterization. *Journal of the Mechanical Behavior of Biomedical Material* **40** 42-58.
 - [8] W. HE, G. CAO, X. GAN, Y. FAN, B. PEI, X. LI (2021) Evaluation methods for mechanical biocompatibility of hernia repair meshes respective characteristics application scope and future perspectives. *Journal of Materials Research and Technology* **13** 1826-1840.
 - [9] C. DEEKEN, S. LAKE (2017) Mechanical properties of the abdominal wall and biomaterials utilized for hernia repair. *Journal of the Mechanical Behavior of Biomedical Materials* **74**(10) 411-427.
 - [10] K. SZEPIETOWSKA, M. TROKA, M. LICHODZIEJEWSKA-NIEMIERKO, M. CHMIELEWSKI, I. LUBOWIECKA (2023) Full-field in vivo experimental study of the strains of a breathing human abdominal wall with intra-abdominal pressure variation. *Journal Mech Behav Biomed Mater* **147** e106148.
 - [11] S. SPADONI, S. TODROS, P. PAVAN (2024) Numerical modeling of the abdominal wall biomechanics and experimental analysis for model validation. *Frontiers in Bioengineering and Biotechnology* **12** e1472509.
 - [12] G. STERNSSCHUSS, D. OSTERGARD, H. PATEL (2012) Post-implantation alterations of polypropylene in the human. *Journal of Urology* **188**(1) 27-32.
 - [13] R. KIRSCHNER-HERMANN, U. KLINGE, B. KLOSTERHALFEN, B. BREHMER, A. HEIDENREICH (2010) What can we learn from explanted slings and meshes in pelvic floor surgery? *Journal of Urology* **183**(4) 686-687.
 - [14] B. BOYCE (1982) Physical characteristics of expanded polytetrafluoroethylene grafts. In: J.C. Stanley (ed) "Biologic and Synthetic Vascular Prostheses, Philadelphia" PA: Grune and Stratton, pp. 553-561.
 - [15] M. BINNEBOSEL, K. TROTHA, P. JANSEN, J. CONZE, P. NEUMANN, K. JUNGE (2011) Biocompatibility of prosthetic meshes in abdominal surgery. *Seminars in Immunopathology* **33**(3) 325-343.
 - [16] P. BRACCO, V. BRUNELLA, L. TROSSARELLI, A. CODA (2005) Comparison of polypropylene and polyethylene terephthalate (Dacron) meshes for abdominal wall hernia repair: A chemical and morphological study. *Hernia* **9** 51-55.

- [17] B. KLOSTERHALFEN, K. JUNGE, U. KLINGE (2005) The lightweight and large porous mesh concept for hernia repair. *Expert Review of Medical Devices* **2**(1) 103-117.
- [18] B. KLOSTERHALFEN, U. KLINGE (2013) Retrieval study at 623 human mesh explants made of polypropylene impact of mesh class and indication for mesh removal on tissue reaction. *Journal of Biomedical Materials Research Part B* **101**(8) 1393-1399.
- [19] M. KIRILOVA-DONEVA, D. PASHKOULEVA, S. SOPOTENSKI, G. PETROVA (2020) Comparison of pre- and post-implantation mechanical behavior of composite hernia meshes. *Journal of Theoretical and Applied Mechanics (JTAM) Poland* **58**(3) 769-778.
- [20] X. LU, M. HARMAN, B. HENIFORD, V. AUGENSTEIN, B. MCIVER, W. BRIDGES (2022) Analyzing material changes consistent with degradation of explanted polymeric hernia mesh related to clinical characteristics. *Surgical Endoscopy* **36** 5121-5135.
- [21] R. RYNKEVIC, P. MARTINS, F. PEREIRA, N. RAMIAO, A. FERNANDES (2017) In vitro study of the mechanical performance of hernia mesh under cyclic loading. *Journal Materials Science: Materials in Medicine* **28**(11) 176-183.
- [22] D. PASHKOULEVA, M. KIRILOVA-DONEVA (2022) Mechanical aspects of the degradation process of partially absorbable composite hernia meshes. *Series of Biomechanics* **36**(1) 98-104.
- [23] D. PASHKOULEVA, M. KIRILOVA-DONEVA (2024) Experimental investigation of long-term mechanical response of surgical meshes. *Journal of Theoretical and Applied Mechanics, Sofia* **54**(2) 147-158.
- [24] M. KIRILOVA-DONEVA, D. PASHKOULEVA (2019) Long-term mechanical compatibility of polypropylene surgical meshes. *Journal of Mechanics in Medicine and Biology* **19**(6) e1950056.
- [25] C. COSTELLO, L. BACHMAN, B. RAMSHAW, S. GRANT (2007) Materials characterization of explanted polypropylene hernia meshes. *Journal of Biomedical Materials Research. Part B: Applied Biomaterials* **83**(1) 44-49.
- [26] C. BURNS-HEFFNER (2014) Development of Explant Registry and Mechanical Testing of Pristine and Explained Surgical Mesh. PhD thesis, Clemson University.