

DEVELOPING MATERIALS FOR BIODEGRADABLE OTOLARYNGOLOGICAL STENTS

Marta Razimowicz¹, ✉, Przemysław Gnatowski¹, Paweł Szarlej¹, Edyta Piłat¹,
Maciej Sienkiewicz¹, Justyna Kucińska-Lipka¹

<https://doi.org/10.23939/chcht17.01.024>

Abstract. Materials for otolaryngological stents have to be characterized by good tensile strength, wear resistance, biocompatibility, and specific degradation time. This work aimed to synthesize polyurethanes based on various biodegradable polyol blends. Their biodegradability and mechanical properties were tested and compared to commercial BIOFLEX material.

Keywords: polyurethane, biodegradation, stents, vascular scaffold, drug delivery systems.

1. Introduction

The first application of the bioresorbable vascular scaffold was carried out about 20 years ago for the treatment of narrowing in the blood vessels of the lower extremities. Bioresorbable stents are designed to clear a clogged vessel, release the drug substance, and restore the proper functioning of the damaged tissue segment, after which it undergoes absorption (slow degradation). Stents are also used in the treatment of otolaryngological diseases, such as thrombosis of the cerebral venous sinuses or chronic nosebleeds.¹

An important aspect is that the stent as well as the products resulting from its degradation in human body fluids were biocompatible. A group of synthetic polymers, including polyurethanes, has proven to be a suitable candidate for a bioresorbable stent material. Biodegradable macromolecular compounds are characterized by good tensile strength and wear resistance, they do not interact with the organism, and most importantly, their modifications make it possible to obtain polyurethane with a specific degradation time. These features contributed to the growing interest in this material and the possibility of using it in the production of biodegradable stents.²

The research focused on the synthesis and characterization of polyurethanes suitable for usage as otolaryngological stents using commercially available substrates. Their mechanical properties were characterized and compared with the use of various research techniques, and the degradation time of the obtained polyurethanes in solutions stimulating human body fluids was investigated.

2. Experimental

2.1. Synthesis

Polyurethanes (PUR) were synthesized using a two-step reaction. The example synthesis scheme: The urethane prepolymer (8 wt % of free isocyanate groups) was obtained in the reaction of poly(ϵ -caprolactone) with 1,6-hexamethylene diisocyanate (HDI, Sigma Aldrich, Poznań, Poland) in a three-necked glass reactor. Polyol was first degassed and dehydrated for 3 h at 353 K. Hexamethylenediisocyanate (HDI, Sigma Aldrich Chemistry, Poland) was added to the reactor and a prepolymerization reaction was carried out at 353 K for 3 h. As a result of this process, a urethane prepolymer, called pre-PUR PCL, was obtained with 6.19 % of unreacted NCO groups. In the second stage, the prepolymer at 353 K was mixed using a mechanical stirrer with one droplet of the dibutyltindilaurate catalyst. In the next step, the calculated 1,4-butanediol amount was added to extend the PUR chain. The whole mixture was transferred to a vacuum vessel to degas the mixture and then was poured onto a metal mold placed on a heating plate at 353 K. After 24 h of annealing, PUR PCL was obtained. Other syntheses with different polyols proceeded similarly. In the case of two polyol systems, the mass ratio between them was 1:1. Five syntheses were carried out based on different polyol blends: poly(ϵ -caprolactone) (PCL, CAPA 2000, Sigma Aldrich Chemistry, Poland), poly(ethylene glycol) (PEG, CAPA 400, BASF SE, Poland), α,ω -oligo(ethylene-butylene adipate)diol (POLES 55/20, CAPA 2000, ZACHEM S.A., Bydgoszcz). The polyurethanes were obtained: PCL,

¹ Department of Polymer Technology, Faculty of Chemistry, Gdansk University of Technology,

11/12 Narutowicza St., Gdansk, 80-233, Poland

✉ s176461@pg.edu.pl

© Razimowicz M., Gnatowski P., Szarlej P., Piłat E., Sienkiewicz M., Kucińska-Lipka J., 2023

PEG:POLES (1:1) (two polyurethanes with different NCO:OH ratio, 1 – 1:2, 2 – 1:1.1), POLES and POLES:PCL (1:1). BIOFLEX (natural color, 1.75 mm, F3D Filament, Poland) filament was used as received. Fig.1 shows a scheme for the preparation of polyurethane-based on PCL.³

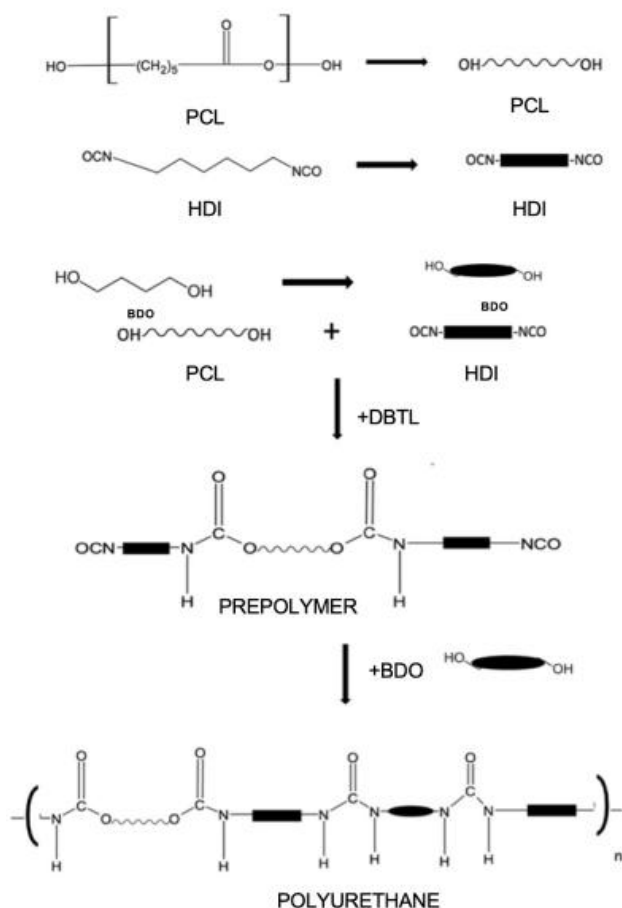


Fig. 1. Two-step method of obtaining polyurethane PCL

2.2. Degradation Test

The degradation time of the synthesized polyurethanes and BIOFLEX filament was investigated by measuring the weight loss of the samples placed at 310 K in 2 M HCl, 5 M NaOH, and 0.01 M phosphate buffer solution (PBS) stimulating degradation in human body fluids. Chosen media allow studying both short-term and long-term (accelerated due to media high concentrations) degradation behavior. The evaluation of changes in the microstructure of polyurethanes was examined using the Delta Optical MET-1000-TRF optical microscope using a MTR3CMOS20000KPA camera and a ToupView program. Pictures were taken before and after the degradation test.

2.3. Modification with the Active Substance

The modification using Corhydron 25 was carried out on the previously synthesized polyurethane PEG:POLES 2 and on the biodegradable BIOFLEX filament. Materials were immersed in 1 wt % solution of Corhydron 25 in DMSO for 5 min at 333 K. Samples were then immersed in 0.01 M PBS and placed in an oven at 310 K. After a definite time droplets of solution were placed on a microscopic glass and dried. The images were then obtained using a Delta Optical L-1000 microscope with an epifluorescence kit equipped with a ToupTek Photonics model: SCCCD01400KPA camera and Toup View software. The G filter for the active substance solution and the U filter for the remaining samples were used to take the pictures.

2.4. Tensile Test

The strength test was carried out on a Zwick/ROELL Z020 universal testing machine at room temperature according to the ISO 37 standard. The tensile speed was 50 mm/min. The static tensile test consisted of uniaxial stretching of the oars at a constant speed. For the obtained results, the standard deviation was calculated using the function: *standard deviation* in MS Excel as the average deviation of the value of a given parameter from its arithmetic mean, which was calculated from five measurements made for the samples of each type.

2.5. Fourier-Transform Infrared Spectroscopy

The analysis of the molecular structure in the modified polyurethane samples was performed using FTIR spectroscopy. The FTIR spectroscopy method uses variable infrared energy for sample analysis. The infrared radiation beam passes through the sample and interferes with the beam that has the same source (reference beam) but has not passed through the tested object. The bonds in the molecule oscillate with different energies and thus absorb different wavelengths of this radiation. The spectrum picture consists of numerous absorption bands. FTIR spectroscopy allows testing the compatibility of raw materials, intermediates, or end products. The analysis of the molecular structure of all polyurethane samples as well as samples after modification and release was performed on the Nicolet IS10 apparatus in the range of 500-4000 cm⁻¹ with a resolution of 16 cm⁻¹ and 128 scans.

3. Results

3.1. Degradation – the Influence of Factors on the Obtained Polyurethane Compounds

Biodegradable polyurethanes should be characterized by an optimal degradation time under the influence of factors corresponding to body fluids in the human body. PUR samples based on various polyols were tested for biodegradability (Fig. 2). The degradation time was determined by the weight loss of the samples in three solutions (2 M HCl, 5 M NaOH, and 0.01 M PBS). The tested materials in an acidic environment (Fig. 2a) showed greater susceptibility to degradation, as exemplified by

PEG:POLES 1 and PEG:POLES 2 polyurethanes, which completely degraded after 14 days of incubation in 2 M HCl. A significant decrease in weight was also observed for PUR:POLES, after 28 days it was about 80 %, although up to 3 days the weight loss was slight. The smallest changes showed BIOFLEX (~30 % weight loss) and PCL (~50 % weight loss). The acidic environment causes greater mass losses of polyurethanes obtained from polyesters because they contain a large number of ester bonds, which are attacked primarily by hydrochloric acid. The degradation rate in the alkaline environment was relatively linear (Fig. 2b). The exception was POLES-based PUR, which after 28 days of incubation showed a significant decrease in weight (almost 80 %). Ester bonds were hydrolyzed, which resulted in the formation of shorter chains in the polyurethane.

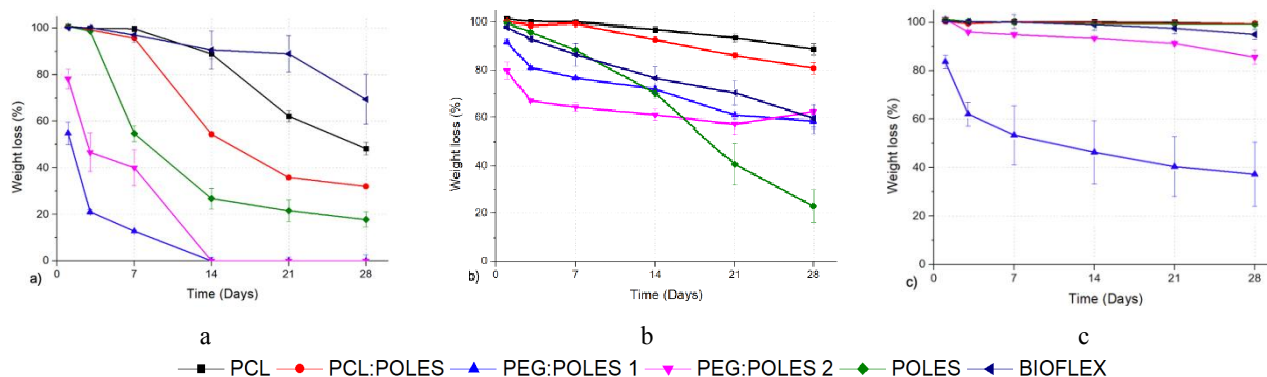


Fig. 2. Degradation results: 2 M HCl (a), 5 M NaOH (b), 0.01 M PBS (c)

As a result of the buffer solution, the number of crystalline phases in the polyurethane samples is reduced and the appearance of their structure changes. As a last resort, there are noticeable changes on the surface of the samples and a significant increase in their roughness. Such changes were noticed for the polyurethane sample PEG:POLES 2 and PEG:POLES 1 after 7 days (Fig. 2c). The greatest weight loss was observed for PUR PEG:POLES 1 (about 45 %), which means that the resulting PUR has a low resistance to degradation. Hydrolytic activity is due to the presence of numerous ester bonds. PEG:POLES 2-based polyurethane began to degrade after 14 days, its weight loss was approx. 19 % (Fig. 2c). This is due to the high molecular weight of the polycaprolactone used in the PUR PCL synthesis.

The analysis of microscopic photos allows us to determine the homogeneity of the obtained polyurethanes. Fig. 3 presents pictures of the microstructure of samples of the obtained polyurethanes before and after the degradation process under 5 \times magnification, and Fig. 4 under 20 \times magnification. Before the degradation, the surface of the samples was flat, with no visible cracks and

no major defects in the structure. Only numerous scratches were observed. After the degradation in sodium hydroxide, the PUR PCL sample shows deep cracks, although the sample did not disintegrate. On the other hand, the samples after incubation in HCl showed unevenness and delamination in the structure. Minor defects and surface porosity were noticed for the samples that were in the PBS solution. After degradation in hydrochloric acid, the samples broke and remained whole in the buffer solution.

For the samples of PCL:POLES-based polyurethane placed in hydrogen chloride, clearances and serious delamination in the structure were observed, which made it impossible to take a photo of the sample at higher magnification (too high height differences on the sample surface). An extensive network of cracks was noted for the samples that degraded in an alkaline environment, while for the samples in PBS solution, no changes were noted on the surface. The hydrogen chloride disintegrated the material into small pieces, and the samples in NaOH and PBS remained unchanged. Significant changes in the structure were noted for the PEG:

POLES 1 samples after incubation in all three environments. The highest delamination was observed for the sample immersed in a buffer solution, and the smallest was in HCl. The samples fell to pieces after incubation in NaOH, while in HCl and PBS they crumbled to fine a powder. These solutions penetrated deeply into the structure of the samples. For the samples with PUR PEG: POLES 2, numerous surface irregularities caused by sodium hydroxide were observed. Considerable cracks and delamination were noted for the samples in the buffer solution. The samples in the HCl solution crumbled to a fine powder and it was not possible to take sharp pictures. After the period of degradation in HCl and PBS, the samples partially disintegrated. For the POLES samples in the acidic environment, the structure disintegrated into parts, the edges of which were not frayed and looked like sugar cubes. Wide cracks and delamination were noticed on the surface of the samples after incubation in NaOH solution. They were very similar in structure to the samples in HCl. The samples immersed in PBS had an uneven surface in the form of stuck sticking each other (20× magnification). The buffer solution penetrated deep into the sample and crystallized, but it did not disintegrate the

sample. The samples from POLES disintegrated into powder after incubation in HCl. The smallest changes were noted for the samples from Bioflex. Apart from scratches and porous structure, there were no major deformations on the surface of BIOFLEX in individual places.

3.2. Modification with the Active Substance

Fig. 5a shows the microstructure of the evaporated PBS solution. For this sample, no fluorescence was observed in any of the available filters. The image was taken with a U filter and a small amount of white light to show the structure of the PBS crystals. Fig. 5b shows the microstructure of the evaporated solution of the active substance with the G-type filter used without white light. The active substance does not show fluorescence in this range, so it can be easily seen as black spots in the picture. The red color, on the other hand, is a matrix made of polyurethane and BIOFLEX, which were partially dissolved during the modification process. Using the U filter, the entire sample glowed and it was not possible to distinguish the places with the more active substance.


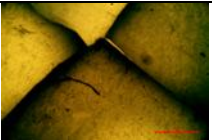
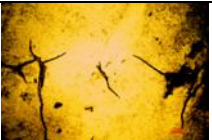













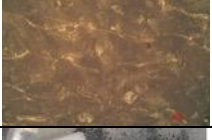




Sample	Neat Sample	HCl (2 M)	NaOH (5 M)	PBS (0.01 M)
PCL				
PCL:POLES				
PEG:POLES 1				
POLES				
PEG:POLES 2		_*	_*	
BIOFLEX			**	

Fig. 3. Microscopic photos of the samples before and after degradation under 5× objective magnification

* Failed to capture a sharp image of the sample due to high roughness

** Failed to capture a sharp image of the sample due to the small size of the sample


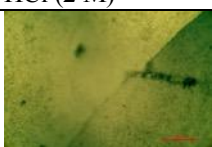

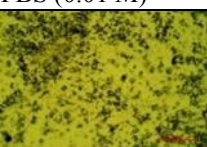


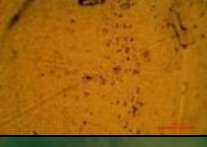

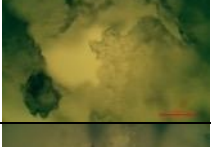
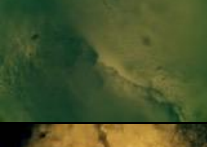



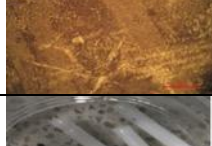





Sample	Neat Sample	HCl (2 M)	NaOH (5 M)	PBS (0.01 M)
PCL				
PCL:POLES		_*		
PEG:POLES 1		_*		
POLES		_*		
PEG:POLES 2		_*		
BIOFLEX			_**	

Fig. 4. Microscopic photos of the samples before and after degradation under 20× objective magnification

* Failed to capture a sharp image of the sample due to high roughness

** Failed to capture a sharp image of the sample due to the small size of the sample

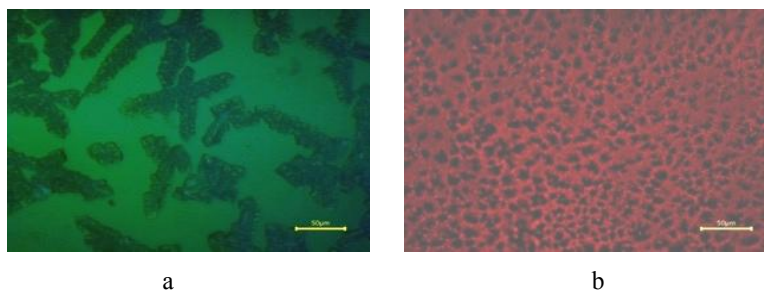


Fig. 5. Microstructure of evaporated solutions: PBS (a), active substance (b)

In BIOFLEX, the active substance (Fig. 6) was released in a large amount into the solution and crystallized with the PBS solution (Figs. 7, 8). The U filter was used for the photos, which show the active substance released in the solution in blue. There is a visible increase in the intensity of the crystals glow with the duration of the release process.

For the samples made of PEG:POLES 2 polyurethane, the active substance penetrated deeply into the polymer and was released slowly. For the sample after 1 day of release (Fig. 9), the phenomenon of fluorescence was visible in a few places, e.g., on the edge of the sample. In the case of the sample after 3 days of release, the phenomenon of fluorescence was observed in more

places, but still, most of the sample did not show any light (Fig. 10). The situation changed after 7 days of release (Fig. 11) – the whole sample showed the phenomenon of fluorescence, but with a much lower intensity than in the case of BIOFLEX samples. PUR PEG:POLES 2 was also partially degraded, the photos show pieces of polymer shining with a celadon-colored light (Fig. 11), as in the case of the entire BIOFLEX degradation solution after 7 days. The use of a fluorescence microscope confirmed the effectiveness of the selected surface modification method and the ability of both selected polymers to release the active substance in the PBS solution, simulating the environment of body fluids.

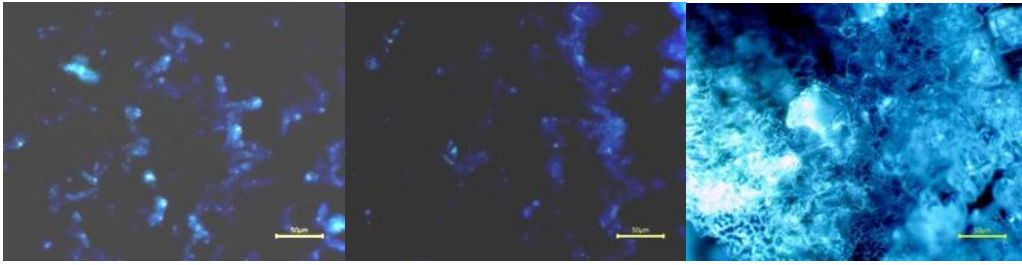


Fig. 6. Release of an active substance in the samples – images of microstructure in several shots: Bioflex after 1 day

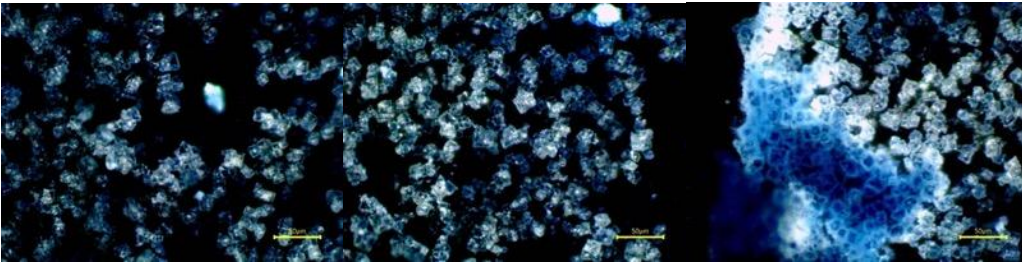


Fig. 7. Release of an active substance in the samples – images of microstructure in several shots: Bioflex after 3 days

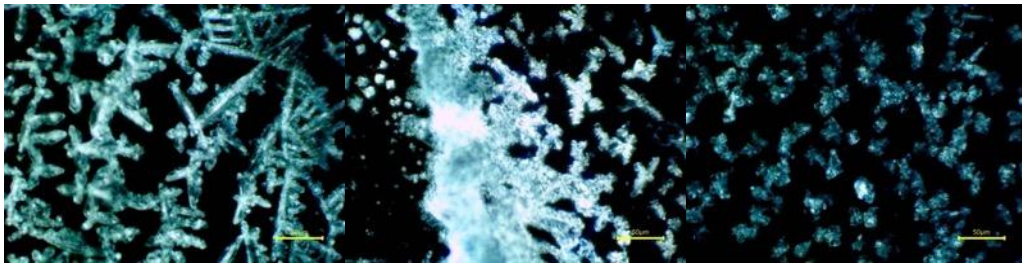


Fig. 8. Release of an active substance in the samples – images of microstructure in several shots: Bioflex after 7 days



Fig. 9. Release of an active substance in the samples – images of microstructure in several shots: PEG:POLES 2 after 1 day

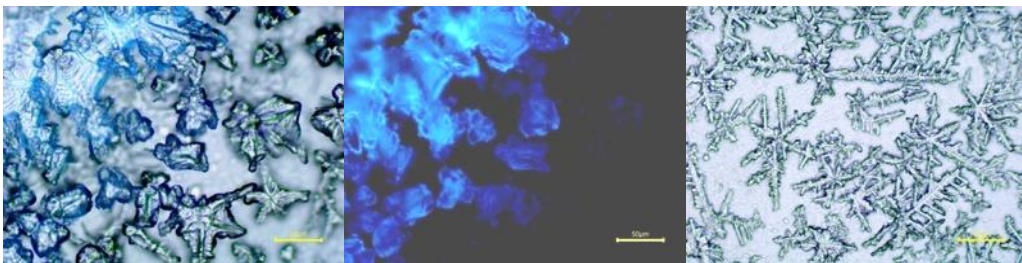


Fig. 10. Release of an active substance in the samples – images of microstructure in several shots: PEG:POLES 2 after 3 days

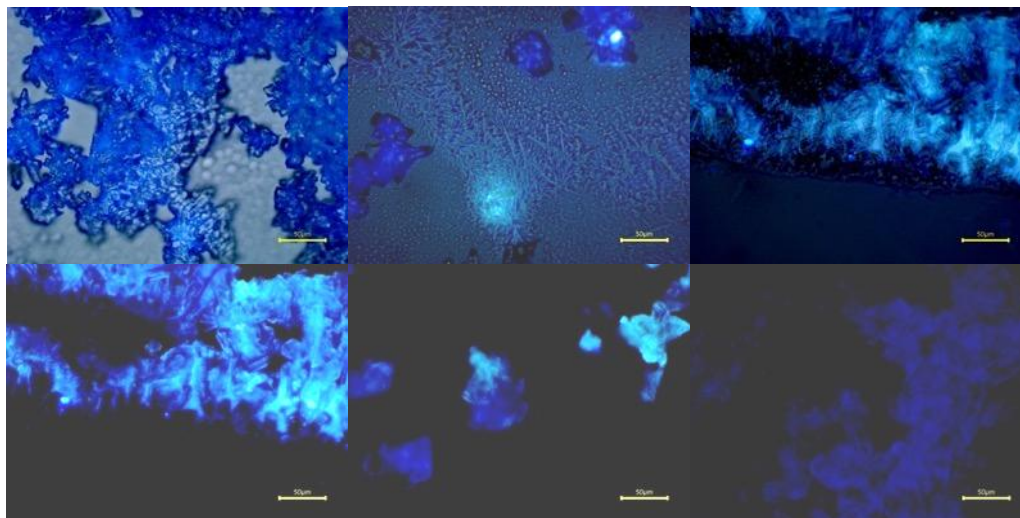


Fig. 11. Release of an active substance in the samples – images of microstructure in several shots: PEG:POLES 2 after 7 days

3.3. Mechanical Properties

The samples from the obtained polyurethanes, except for PEG:POLES 1, were subjected to the strength test, because they had too high brittleness and stiffness, and the paddles were unstable and broke during cutting. The remaining samples were tested in a static tensile test. Paddles made of PCL:POLES showed the highest permanent deformation (60.9 ± 3.0 %) with a maximum stress of 33.5 ± 3.2 MPa (Table 1). The Young's modulus for this compound was 37.6 ± 4.5 MPa. Samples made of PCL polyurethane showed lower tensile strength than PCL:POLES (8.64 ± 0.96 MPa), and lower permanent deformation (49 ± 15 %), which indicates that PUR PCL showed greater flexibility. Moreover, for PCL-based polyurethane, Young's modulus was 32.3 ± 1.4 MPa, which means that it was deformed to a greater extent than PCL:POLES. The POLES polyurethane paddles were characterized by a maximum stress of 6.0 ± 0.46 MPa and a permanent deformation after fracture of 3.7 ± 4.7 %. Low deformation and high Young's modulus indicate that the sample was very flexible and underwent small deformation, as exemplified by PEG:POLES 2, the permanent deformation of which was 1.4 ± 1.2 % and the modulus was 43.1 ± 3.7 MPa. The highest elongation at break was recorded for PUR PCL:POLES, and the lowest one was for PUR POLES.

3.4. Fourier-Transform Infrared Spectroscopy

Fig. 12 shows the results of FTIR tests of synthesized PUR and the commercial polymer BIOFLEX. For all samples, local maxima of about 2940 and 2860 cm^{-1} were observed, corresponding to the stretching

vibrations of C-H bonds. In the case of all polyurethanes, a maximum is visible at approx. 3300 cm^{-1} , corresponding to the stretching vibrations of the N-H bonds. For all samples at approx. 1725 cm^{-1} , a maximum was observed coming from C=O stretching vibrations attributed to the ester group. For the polyurethane samples, the maxima were also observed at approx. 1685 cm^{-1} , which probably corresponds to the stretching vibrations of the C=O bonds in the N=C=O group. Other signals appearing only in the case of polyurethanes are signals at approx. 1540 cm^{-1} bending vibrations of the N-H bonds. Another signal that can be observed is the signal at approx. 1250 cm^{-1} , which corresponds to the vibration stretching the C-O bonds in the ester group.⁴ The maximum at approx. 1100 cm^{-1} can be attributed to the tensile vibrations of the ether bonds in the case of BIOFLEX and PEG-based polyurethanes. The last signal considered is the maximum at 728 cm^{-1} , which is visible only for BIOFLEX and may come from C-H vibrations in the aromatic ring.⁵ In conclusion, the presence of N-H bonds and ester bonds was confirmed for all polyurethanes. In the case of PEG-based polyurethanes, the presence of ether bonds has also been observed. In the case of BIOFLEX, the manufacturer does not specify the chemical structure of the polymer but based on the FTIR test, it can be concluded that the chemical structure of this polymer contains both ester and ether bonds and probably aromatic rings, while the content of nitrogen-related groups can be excluded: amide, amine, and urethane.

Fig. 13 shows the results of FTIR BIOFLEX tests, before modification, after modification, and after 1, 3, and 7 days of degradation. The graph shows no major differences between the samples, except for a small maximum at about 800 cm^{-1} , which can be attributed to the substituted aromatic rings derived from the active substance.⁵



Table 1. Static tensile test results for the obtained polyurethanes

Sample	σ_b [MPa]	ε_b [%]	E_y [MPa]	ε_p [%]
PCL	8.64±0.96	306±64	32.3±1.4	49±15
POLES	6.00±0.46	136±12	41.9±2.5	3.7±4.7
PEG:POLES 2	3.89±0.64	48.7±6.5	43.1±3.7	1.4±1.2
PCL:POLES	33.5±3.2	1387±126	37.6±4.5	60.9±3.0

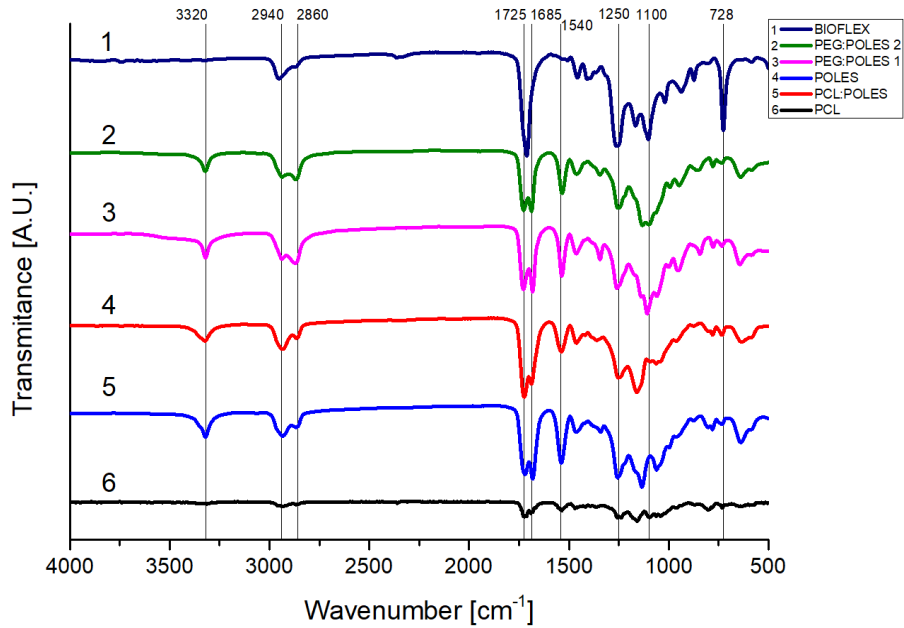


Fig. 12. FTIR test results for the obtained PUR and for Bioflex

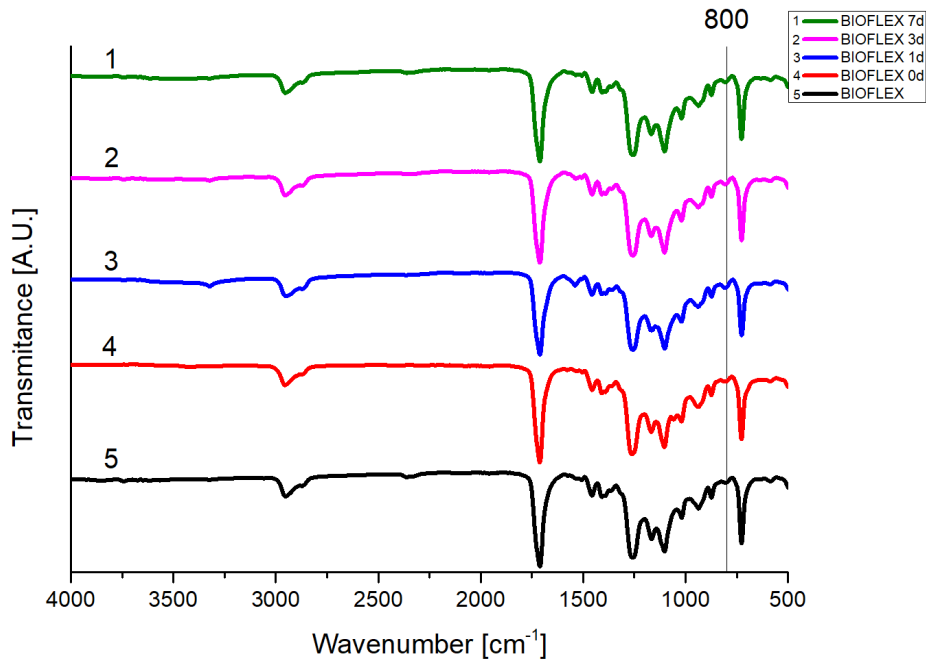


Fig. 13. FTIR test results for Bioflex

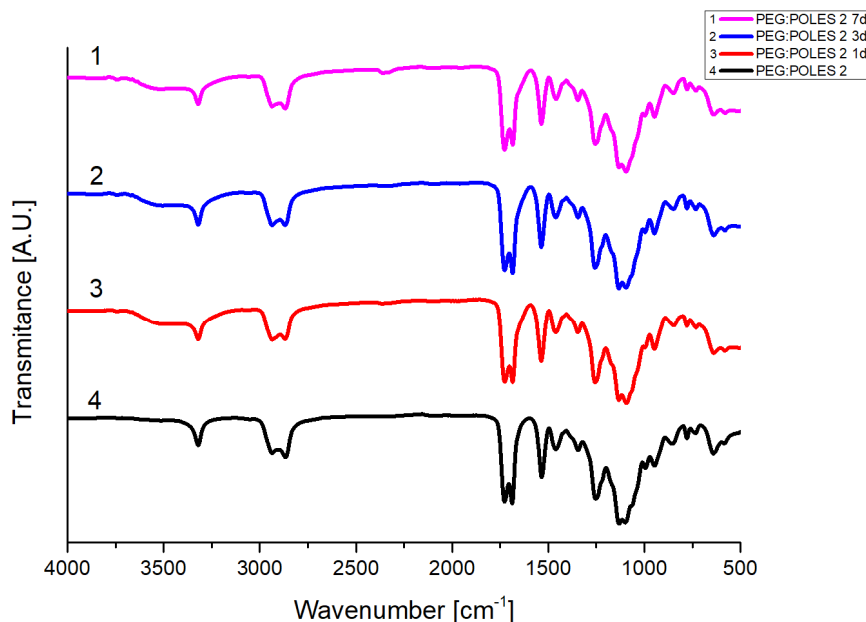


Fig. 14. FTIR test results for PEG:POLES 2

Fig. 14 shows the results of FTIR PEG:POLES 2 tests, before modification and after 1, 3, and 7 days of degradation. The chart shows no major differences between the samples.

When analyzing the FTIR spectra of samples after modification, it should be remembered that the modification process was focused only on the modification of the sample surface. The amount of active substance that was present on the surface of the samples was probably below the FTIR test capability. For these samples, other structural analyzes, *e.g.*, NMR, would be desirable.

4. Discussion

The chemical structure of the obtained biomedical polyurethanes as well as their mechanical properties, final form, and shape must be properly adapted to the environment in which they will stay. Fourier-transform infrared spectroscopy (FTIR) was used to determine the chemical structure of the synthesized bioresorbable polyurethanes. The analysis of absorption spectra confirmed the presence of N-H bonds and ester bonds for all polyurethanes. In the case of PEG-based polyurethanes, the presence of ether bonds has also been observed. However, for BIOFLEX, the presence of ester and ether bonds and probably aromatic rings were confirmed. The mechanical properties of biodegradable polyurethanes were tested in a static tensile test. For PUR PCL: POLES, the highest permanent deformation ($60.9 \pm 3.0\%$) was recorded at the maximum stress of 33.5 MPa. This means that the material was very flexible. Its elongation at break was

1387%, and Young's modulus was one of the lowest among all polyurethanes, *i.e.*, 37.6 ± 4.5 MPa. Similar parameters were shown by PCL-based polyurethane, elongation at break was equal to $306 \pm 64\%$ and Young's modulus – 32.3 ± 1.4 MPa. The most deformed samples were PUR PCL. PEG-based polyurethane: POLES 2 had the lowest deformation after fracture of $1.4 \pm 1.2\%$, because the presence of PEG in the material increased its viscosity, so its maximum stress was only 3.89 ± 0.64 MPa. PUR POLES obtained a similar permanent deformation as PUR PEG:POLES 2, in the order of $3.7 \pm 4.7\%$ with a maximum stress of 3.89 ± 0.64 MPa. PEG:POLES 1-based PUR, which could not be tested in the strength test due to its high level of brittleness, turned out unfavorably.

Materials for bioresorbable stents should be characterized by optimal distribution in solutions similar to those found in the human body. For this purpose, the obtained polyurethanes were subjected to 4-week degradation in solutions with different pH: acidic, alkaline, and buffer. The rate of PUR degradation was measured by measuring the weight loss. The greatest loss of mass and susceptibility to degradation in an acidic environment was shown by PEG-based materials: PEG:POLES 1 and PEG:POLES 2, which almost completely degraded after 14 days of incubation in HCl. The reason for faster degradation may be the high content of ester bonds, which are attacked primarily by hydrochloric acid, which makes them break down faster. The smallest weight loss was recorded for BIOFLEX (about 30%), PCL (about 50%), and PCL: POLES (about 57%). In the alkaline environment, the degradation rate of all polyurethanes was

linear, except for PUR POLES, where 80 % weight loss was recorded after 28 days. It happened because of the high content of ester bonds that were subject to hydrolysis. After 4 weeks of incubation in the buffer solution, no changes were noticed for PCL and PCL:POLES. A significant increase in roughness and weight loss (about 61 %) was demonstrated by PUR based on PEG:POLES 1.

The greatest changes in the microstructure were observed for PEG:POLES 2 in the form of numerous porosity, delamination, and cracks for samples placed in NaOH and PBS solutions. The smallest changes were observed on polyurethane samples based on PCL:POLES after the degradation process in a buffer solution. The PUR PCL sample showed deep cracks after being degraded in NaOH, but the sample did not disintegrate. On the other hand, the samples after incubation in HCl showed unevenness and delamination in the structure. After degradation in hydrochloric acid, the samples were broken and remained whole in the buffer solution. The samples of polyurethane PCL:POLES placed in hydrogen chloride showed clearances and serious delamination in the structure. An extensive pattern of cracks was noted for the alkaline degrading samples but was not noticed in the PBS solution. In HCl, the samples looked like crumbs, and the samples in NaOH and PBS were unchanged. On the surface of the PEG:POLES 1 samples, changes were noted in all three environments. The highest delamination had the sample in PBS and the lowest one it had in hydrochloric acid. The samples fell to pieces after incubation in NaOH, while in HCl and PBS they fell to powder. For the samples with PUR PEG:POLES 2, numerous porosities were observed due to the action of sodium hydroxide and numerous cracks and delamination on the samples in the buffer solution. On the other hand, the samples disintegrated into powder after incubation in HCl. After degradation in HCl and PBS, the samples partially disintegrated. The structure of POLES samples resembled sugar cubes, which had crystallized. Wide cracks and delamination were noticed on the surface of the samples after incubation in NaOH solution. The samples immersed in PBS had an uneven surface in the form of balls stuck to each other. The buffer solution penetrated deep into the sample and crystallized, but this did not disintegrate the sample, whereas the POLES samples disintegrated into powder after incubation in HCl. For comparison, the tests were carried out on the commercial BIOFLEX material, which, apart from scratches and porous structure, did not show any deformations on its surface.

A fluorescence microscope was used to determine the active substance's release rate from the surface of

modified polyurethanes with the PBS solution. In the samples based on PEG:POLES 2, the active substance penetrated deeply into the polymer and was released slowly. After 1st day of release, the phenomenon of fluorescence was noticeable only in some places, mainly at the edges of the sample. The situation changed after the 7th day of release, when the fluorescence phenomenon was visible on the entire surface, unfortunately, the release intensity decreased and the sample was partially degraded. In the case of BIOFLEX samples, after 7 days the active substance was released in large amounts into the PBS solution and crystallized with it. Nevertheless, the release intensity was greater compared to the PEG:POLES 2 samples. The noticeable increase in glow intensity of the crystals increases with the length of the release process. Such an effect is desirable in materials intended for otolaryngological stents due to the possibility of the drug faster delivery to the vessel.

5. Conclusions

The properties of the synthesized bioresorbable polyurethanes and their subsequent use in biomedical implants depend primarily on the chemical composition of the material, manufacturing technology, and the selection of its parameters. Polycaprolactone-based polyurethane (PCL) is the most promising material for otolaryngological stents. It is distinguished by a permanent deformation ($49 \pm 15\%$), with a maximum stress of 8.64 ± 0.96 MPa. Moreover, it has an optimal degradation time in an environment with different pH. Cracks were observed on the sample of PUR PCL after the degradation in NaOH, although the sample remained intact. The samples after incubation in HCl showed unevenness and delamination in the structure, which resulted in broken samples. In contrast, the PCL samples remained whole in the buffer solution and no major changes were noted.

The observed properties may allow the drug substance to be delivered before it is completely dissolved in human body fluids, so far in a period not longer than 4 weeks. To investigate its total degradation time, an additional series of studies should be carried out, including extending the incubation in solutions corresponding to the fluids in the human body and checking for pharmacokinetics, *i.e.*, all release parameters of the active substance.

The properties of new polyurethane materials presented in the work constitute the basis for further research on the use of the synthesized materials in 3D printing. The next step would also be to test the obtained materials from the biological point of view – possible bactericidal properties or cell survival.



Acknowledgements

Research financed under the IDUB GUT RADIUM LEARNING THROUGH RESEARCH PROGRAMS number 13/Radium/2022 is highly appreciated.

References

- [1] Vert, M.; Doi, Y.; Hellwich, K.-H.; Hess, M.; Hodge, P.; Kubisa, P.; Rinaudo, M.; Schué, F. Terminology for Biorelated Polymers and Applications (IUPAC Recommendations 2012). *Pure Appl. Chem.* **2012**, *84*, 377-410. <https://doi.org/10.1351/PAC-REC-10-12-04>
- [2] Velasco, M.A.; Narváez-Tovar, C.A.; Garzón-Alvarado, D.A. Design, Materials, and Mechanobiology of Biodegradable Scaffolds for Bone Tissue Engineering. *Biomed Res. Int.* **2015**, *2015*, 729076. <https://doi.org/10.1155/2015/729076>
- [3] Hung, K.-C.; Tseng, C.-S.; Hsu, S.-H. 3D Printing of Polyurethane Biomaterials. In *Advances in Polyurethane Biomaterials*; Elsevier, 2016; pp 149-170. <https://doi.org/10.1016/B978-0-08-100614-6.00005-6>
- [4] Zubyk, H.; Mykhailiv, O.; Papathanassiou, A.N.; Sulikowski, B.; Zambrzycka-Szelewa, E.; Bratychak, M.; Plonska-Brzezinska, M.E. A Phenol-Formaldehyde Polymeric Network to Generate Organic Aerogels: Synthesis, Physicochemical Characteristics and Potential Applications. *J. Mater. Chem. A* **2018**, *6*, 845-852. <https://doi.org/10.1039/C7TA08814K>
- [5] Bratychak, M.; Bratychak, M.; Brostow, W.; Shyshchak, O. Synthesis and Properties of Peroxy Derivatives of Epoxy Resins Based on Bisphenol A: Effects of the Presence of Boron Trifluoride Etherate. *Mater. Res. Innov.* **2002**, *6*, 24-30. <https://doi.org/10.1007/s10019-002-0157-7>

Received: June 13, 2022 / Revised: September 06, 2022 / Accepted: December 08, 2022

РОЗРОБЛЕННЯ МАТЕРІАЛІВ ДЛЯ БІОДЕГРАДАБЕЛЬНИХ ОТОЛАРИНГОЛОГІЧНИХ СТЕНТІВ

Анотація. Матеріали для отоларингологічних стентів повинні мати хорошу міцність на розрив, зносостійкість, біосумісність і певний час деградації. Ця робота стосується синтезу поліуретанів на основі різних біодеградабельних сумішей поліолів. Досліджено їхню біодеградабельність і механічні властивості та порівняно з комерційним матеріалом BIOFLEX.

Ключові слова: поліуретан, біодеградація, стенти, судинні каркаси, системи доставки ліків.