STRESS RELAXATION PHENOMENA IN POLYMERIC ORTHODONTIC LIGATURES

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Abstract

Elastomeric products are applied in orthodontics mainly as elastic ligatures or chains and have become an alternative to wire ligation made of titanium alloy or stainless steel. Despite their popularity among the dentists and undoubtful advantages, some essential warnings are being raised regarding the degree of load loss. This relaxation phenomenon seems to be a dominant feature in the time-dependent behaviour of those elements in orthodontic procedures, such as dentition corrections or teeth extrusions. The aim of the paper was to examine and analyse the rheological properties of biocompatible orthodontic elastomeric ligatures. Five different polymeric orthodontic ligatures were examined in the following experiments: a simple relaxation test, relaxation simulating orthodontic extrusion and the two-steps relaxation process, which stands for so-called 'secondary tightening', resulting in the increase of the orthodontic force. The results of the relaxation experiments proved that among various descriptions of that phenomenon, the power-law descriptions fit the best time-dependent behaviour during orthodontic procedures. Power-law models give the most intensive initial relaxation, which is characteristic for elastomeric ligatures. The obtained results and analyses allow precise control of the treatment progress in the orthodontic extrusion procedure.

Keywords: *orthodontic extrusion, polyurethane ligatures, stress relaxation, rheological models*

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Introduction

Orthodontics is a part of dentistry which deals with the layout, arrangement, shape, and appearance of teeth in the oral cavity. Orthodontic treatment improves both the aesthetic image and the quality of dentition functioning. The controlled orthodontic extrusion induces the natural eruptive movement of the tooth towards the occlusal plane. This is achieved through the additional forces caused by polymeric flexible links as well as by fixed or movable metallic braces. Through the tooth, these forces affect both the periodontium and the alveolar bone, stimulating them to change and remodel [1-3]. Extrusion is also used as an auxiliary method preparing the teeth for endodontic treatment and further prosthetic procedures [4]. In the case of subgingival hard tissue cavities, it is an alternative to the tooth extraction. This method allows to keep the patient's own root and associated periodontal ligaments.

Elastomeric products, mainly elastic ligatures and chains, are applied in orthodontic treatments in order to improve the aesthetic image and the quality of dentition functioning. For the first time, they were used in orthodontics several years ago as an alternative for a wire ligation made of stainless steel. They also replaced flexible teeth retraction appliances which were made of latex rubber and required daily replacement by the patient [5]. Despite their popularity among dentists and the undoubtful advantages, some essential warnings are being raised mainly concerning the degree of load loss due to the relaxation features in polymeric ligatures [6,7].

The aim of the paper was to examine and analyse the strength and rheological properties of biocompatible orthodontic elastomeric ligatures. Proper assessment of their rheological properties will enable dentists to predict the degree of load/stress loss due to the relaxation phenomenon in elastomeric ligatures. Finally, it will allow for precise control of the treatment progress in various orthodontic procedures.

Materials and Methods

Ligatures and chains are made of polyurethanes, which are elastomers able to bind under the influence of temperature, having - (NH) - (C = O) - O - as a structural unit and undergoing a sequential condensation polymerization reaction. Ligatures of the 0.2-0.36 mm diameter range are commonly used in dentistry [3]. Polymers characterized with rubber-like elasticity have a long chain and a poorly cross-linked structure. Elastic behaviour results from the entropy reduction associated with the twisting of the macromolecular chain from its most likely conformation. Nevertheless, the local movements of the chain segments must be limited to let polymer to return to its original shape, since the irreversible chains movement causes constant distortion of the material with each subsequent movement. Cross-linkages between the chains must be relatively few in order to facilitate high stretching without any breakage of the base bonds [8,9]. The glass transition temperatures (*Tg*) of biomedical polyurethanes range from about -50 to -80°C [4].

The main advantages of polyurethane links are following: easy fixing, lower transferred loads, aesthetic image, and the possibility of fluorine release [3]. Elastomeric ligatures are the main element supporting and maintaining wire arches in the channel of an orthodontic lock. Five most commonly used polymeric orthodontic ligatures produced by *Dentaurum*® were chosen for the tests. Three of them were of a chain type (denoted in the experiments as A, B, C); the next two were of a string type (D and E) – FIG. 1. The thickness of all chain ligatures was 1 mm, while the surface area in the thinnest place, for example, between the two "eyes", was 1 mm^2 for the A and B types and 1,4 mm^2 for the C ligature. For string ligatures, the values of the surface areas were 2.1 and 1.1 mm^2 for the D and E types, respectively.

Depending on the value and duration of the applied loading, two types of extrusion procedures are used in a clinical practice, so-called slow and fast or rapid. In the slow extrusion the total force applied to a one-root tooth should not exceed 30 G (approx. 0.3 N) and the total root displacement should be less than 1 mm per week – FIG. 2. For the fast extrusion, the load can be increased to 50 G (approx. 0.5 N). The procedure usually lasts for 4-8 weeks. Rapid extrusion is commonly used prior to further prosthetic treatment [3,10].

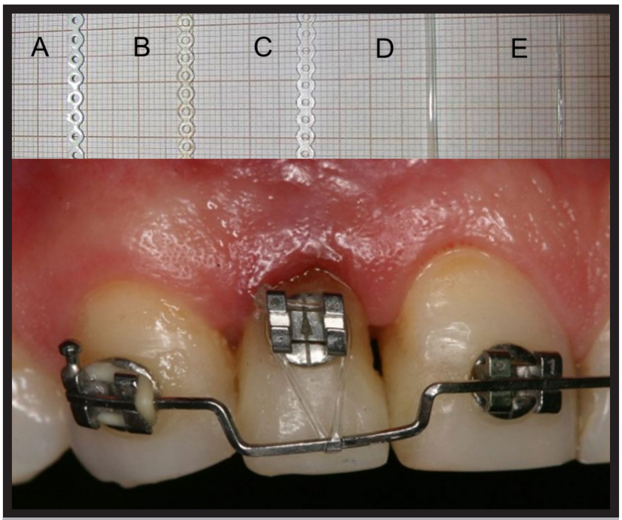

FIG. 1. Examples of the chain and string elastomeric ligature and their application in an orthodontic lock used in the extrusion treatment.

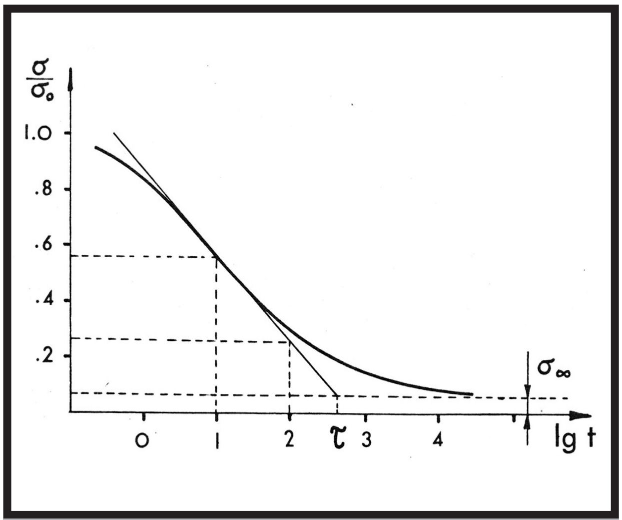

FIG. 3. Determination of the relaxation process parameters for the exponential models.

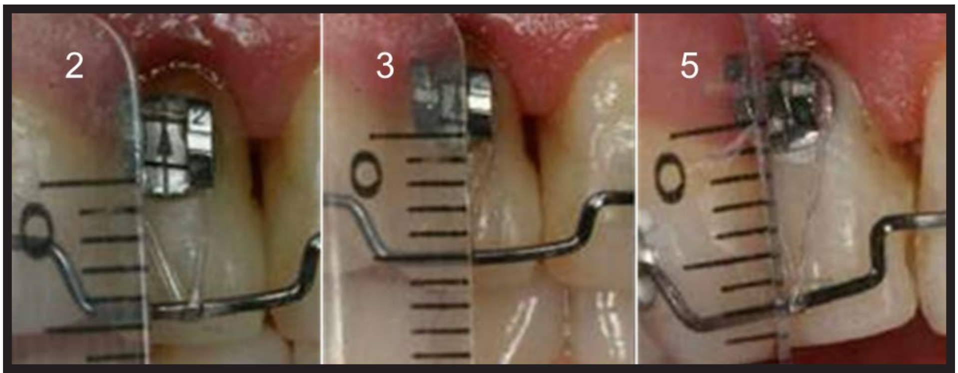

FIG. 2. Results of the orthodontic extrusion after 2, 3 and 5 weeks of the treatment.

Various rheological models were used to describe the stress relaxation behaviour of polyurethane ligatures: linear mechanical models, models based on the continuous distribution of relaxation time spectra, power-law models, exponential and cooperative models [11-13]. As the rheological properties of polyurethane elastomers are nonlinear, the paper presents the extrapolation fittings of the experimental curves in the power-law and exponential models.

The stress relaxation kinetics in polymers is often represented in terms of the stress dependent thermal activation, known also as the 'site model' theory [14,15]. The theory governs the dependencies of the relaxation times τ_{rel} upon the structural molecular changes, both conformational and chemical:

$$\tau_{rel} = \tau_0 \exp\left(-\frac{\Delta H}{kT}\right) \tag{1}$$

or

$$\tau_{rel} = \tau_0 \exp\left[\frac{(\Delta H - V\sigma)}{kT}\right], \tag{2}$$

where τ_0 is the basic atomic net thermal vibrations period, *ΔH* is the apparent activation energy of the process, *T* is the thermal energy, *k* is the Boltzmann constant, *V* is the elementary volume of the activation process, called also the 'free volume', and *σ* is the effective stress. The exponential law describes the stress relaxation in the following way:

$$\frac{d\sigma}{dt} \sim \exp\left(\frac{V\sigma}{kT}\right). \tag{3}$$

According to this rule, two types of the equations are commonly used for a wide range of polymeric materials [13]:

$$\frac{d\sigma}{dt} = -b\, sh\left(\frac{\sigma}{F}\right) \tag{4}$$

and

$$\frac{d\sigma}{dt} = -b\left[\exp\left(\frac{\sigma}{F} - 1\right)\right], \tag{5}$$

where *b* and *F* are the parameters. The first model is known as Eyring's model, while the second stands for Kubat's model. The parameter *F* represents the maximal slope (in the inflection point) of the relaxation curve plotted in the logarithmic time scale and the normalized stress (σ/σ_0) system of coordinates – FIG. 3. The parameter *b* is taken as $b = F/\tau$.

Power-law models generally undergo the rule $d\sigma/dt \sim \sigma^n$. The most commonly used model is known as Hook-Norton's law [14] which in terms of stress relaxation leads to the following relation:

$$\frac{d\sigma}{dt} = k\,\sigma^n, \tag{6}$$

where *k* and *n* are the parameters. The parameter *k* is proportional to the Young modulus of the polymer and is responsible for the stress relaxation course along the time axis, while the parameter *n* controls the slope of the relaxation curve. Based on the Hook-Norton's law, the American standards (ASTM) for the stress relaxation description suggest the following formula:

$$\sigma(t) = \frac{\sigma_0}{(1+\frac{t}{b})^a}, \tag{7}$$

with the *a* and *b* parameters. The ASTM stress relaxation representation corresponds to the Hook-Norton's law and the parameters $a \rightarrow 1/n$ and $1/b \rightarrow nk\sigma_0$. In that representation, for many thermoplastic polymers, the values of the *a* and *b* parameters take approximate values in the ranges (1.8-2.2) and (0.15-0.18), respectively.

Results and Discussions

Both the strength tests in the uniaxial stress state and the relaxation experiments for polyurethane ligatures were performed using the universal strength machine Instron 4465 – FIG. 4. The tensile tests were done for five samples in each group of ligatures. The medium values of the strength properties and the standard deviations for tensile stress for different polymeric ligatures in stress-strain test are shown in TABLE 1.

TABLE 1. Comparison of the strength properties of the examined polymeric ligatures in tensile tests.

Ligature type	Ultimate force [N]	Tensile stress [MPa]	SD	Maximal strain [%]
A	24	24.0	0.63	304
B	34	34.0	1.14	326
C	26	18.6	0.38	489
D	48	22.8	0.27	354
E	14	12.7	0.21	375

FIG. 4. A stand for tensile and relaxation tests of polyurethane ligatures.

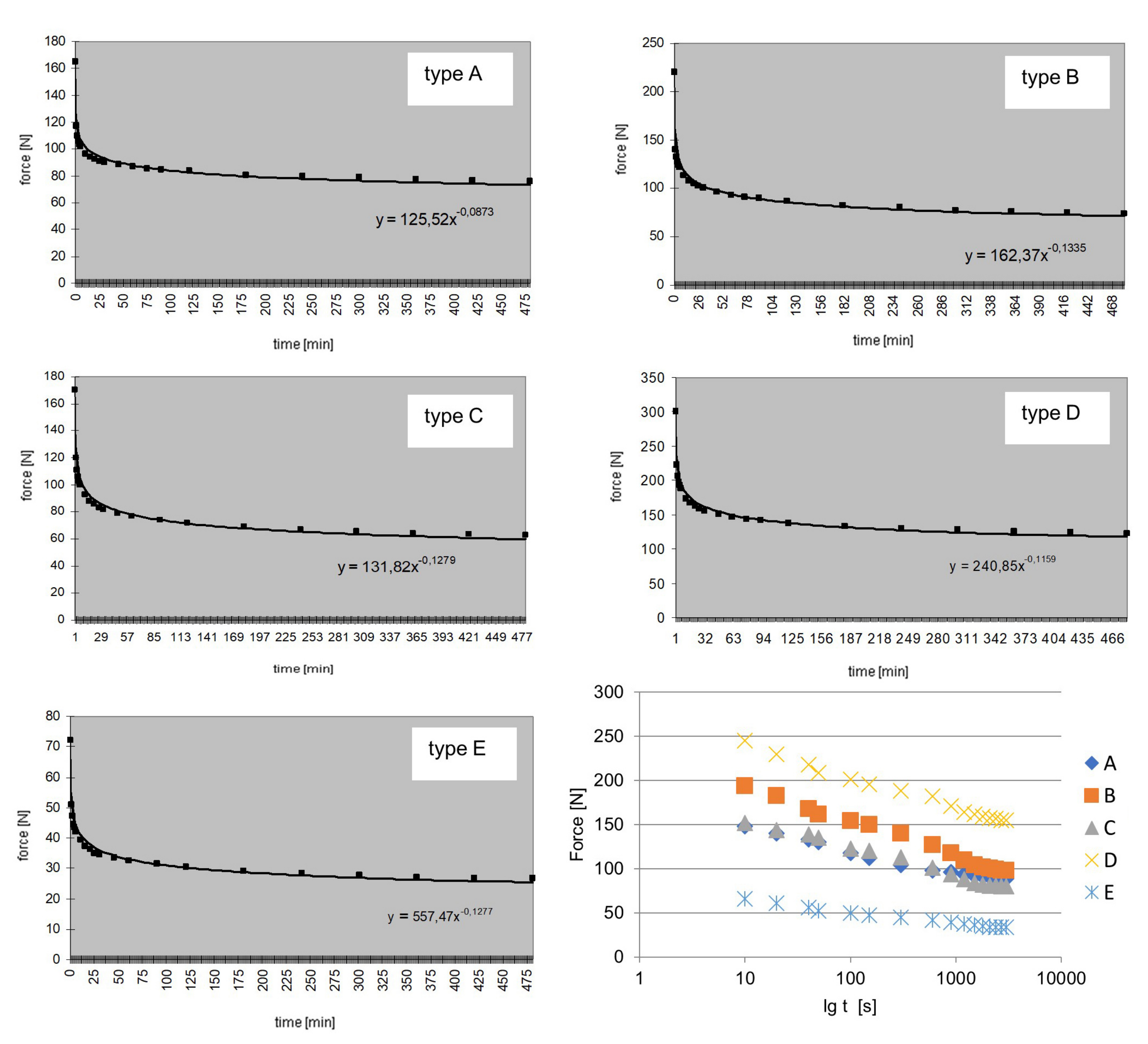

FIG. 5. Examples of the relaxation course for each group of the elastomeric ligatures.

Relaxation phenomenon seems to be a dominant feature in the time-dependent behaviour of those elements in orthodontic procedures, such as dentition corrections or teeth extrusions. Rheological properties of the elastomeric ligatures were examined in the relaxation tests in the uniaxial stress state for a set of 10 parallel arranged ligatures at room temperature and standard humidity.

FIG. 5 presents the examples of the relaxation course in each group of the polyurethane ligatures for approx. 8 hours of the experiments. TABLE 2 gives a set of the medium values of the relaxation percentage in all examined groups of ligatures after one week of the test. As the one-week stress relaxation tests are very time-consuming, three research trials were conducted in each group. Each experiment in a given research group was very comparable, especially with regard to the equilibrium relaxation determination, so no standard deviation analysis was done. Additionally, FIG. 5 presents a comparison of relaxation courses for all ligatures plotted in a logarithmic time scale. Regardless of the type of ligature, the basic relaxation time corresponding to the inflection point of the curve varies between 50 and 100 seconds, so that is why only the initial parts of the relaxation courses are presented.

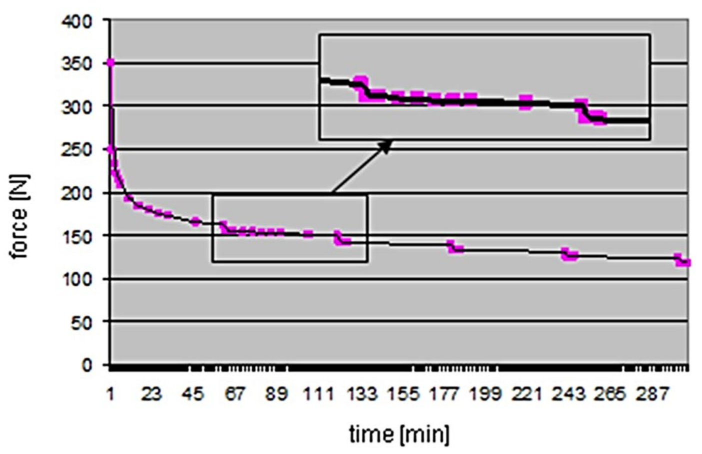

FIG. 6. The relaxation course in the type D elastomeric ligature in the simulated increase of tooth extrusion in orthodontic procedure.

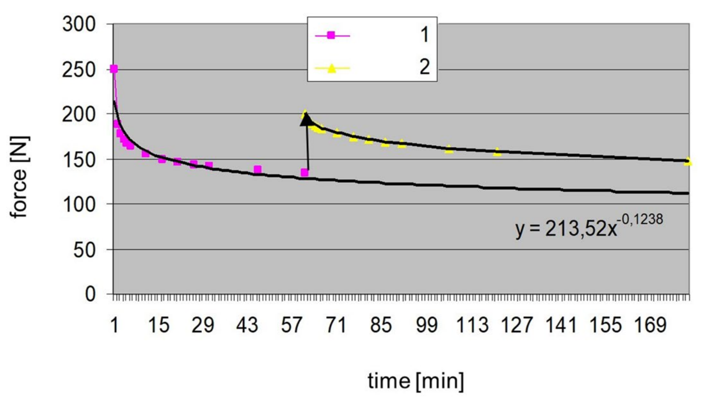

FIG. 7. The relaxation course in the type D elastomeric ligature in the two-steps process simulating the orthodontic force increase.

TABLE 2. Comparison of the relaxation percentage in the examined polymeric ligatures after one week (168 hours).

Time [h]	Relaxation of ligature type [%]				
	A	B	C	D	E
168	34	22	24	28	24

The experiments proved that regardless of the type of ligature, the relaxation processes were relatively very fast. More than 50% of the initial force/stress disappeared after the first hour of relaxation. After one day, no more than 35% of the initial force/stress remained, while after a week it was approximately 25%. Starting from the second day, the daily force/stress decrease in the ligature ranged from 3 to less than 1%. The obtained regularities confirmed that the power-type relationship should only be used for low stress levels rheological processes. For all types of ligatures, the stress relaxation curves produced the similar exponent constant of the power-law model in the range -0.08 to -0.13. However, the proportional parameters were different, i.e. for chain ligatures the values varied in the 120-163 range and 240-560 for string ligatures, respectively.

The exponential models were excluded from further analyses as they were characterized with too fast final relaxation.

In clinical practice, both dentists and patients, during orthodontic extrusion report the uncontrolled decrease of the orthodontic force that leads to treatment failure. To simulate that undesirable phenomenon, the following experiment was carried out: five times, every hour, the displacement value (kinematic control) corresponding to the initial force of the relaxation force was reduced by 1 mm. The results of the experiments are presented in FIG. 6. To compensate for this disadvantage, dentists often use so-called ‘secondary tightening’ [16]. FIG. 7 presents the relaxation course in the elastomeric ligature in a two-steps relaxation process simulating the increase of orthodontic force in the secondary tightening. The first curve is an extrapolated plot of the D-type ligature relaxation for the initial force of 250 N. An hour later, the sample is restretched again to a ligature force of 200 N, which produces the relaxation given by curve no 2. The two-steps relaxation changes the value of the equilibrium stress. The asymptote of the first function is around 110 N, while the second is around 150 N, which provides the proper conditions for orthodontic extrusion.

The proper orthodontic extrusion assumes that the tooth should descend towards the occlusal line for about 0.15 mm per day. Correlations between stress-strain curves and stress relaxation characteristics estimate the therapeutic force that should be applied to the treated tooth in order to provide the extrusion phenomenon following the recommendations, i.e. at a rate of about 1 mm per week.

Regardless of the type of ligature, starting from the second day of the treatment comparable decrease values of both processes, i.e. the orthodontic extrusion force and the relaxation phenomenon, were registered. During the next two days, the decrease in force associated with the phenomenon of relaxation was approximately three times smaller than the decrease in force associated with the phenomenon of extrusion. Over the week, that difference was already of a smaller magnitude.

Conclusions

The most important conclusions from the research are as follows:

• the relationship between the strength and the elongation increments in biocompatible polyurethane ligatures is almost linear;

• the relaxation process runs most rapidly in the first phase of the phenomenon;

• a secondary increase in the ligature tension slows down the relaxation process and increases the asymptote value by about half of the difference between the primary and secondary tightening;

• after a day, the influence of the extrusion process on the decrease in strength begins to outweigh the influence of the relaxation process.

However, the exponential law which is based on the theory of rheological processes thermal activation is assumed in the literature to describe the best the relaxation behaviour of polymers. The results of relaxation experiments in elastomeric ligatures prove that, among various descriptions of that phenomenon, the power-law descriptions fit the best the time-dependent behaviour during orthodontic procedures. The power-law model gives the most intensive initial relaxation, which is characteristic for elastomeric ligatures.

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