Mechanical Strength Variety of Orthodontic Polymeric Chains

In vitro assessment and mathematical model

OLIMPIA BUNTA[1], VLAD MURESAN[2], MARIANA PACURAR[3]*, MIHAELA BACIUT[4], DORIN NENOVICI[4], CRISTINA MOLNAR VARLAM[3], VIORICA TARMURE[1]

[1]Iuliu Hatieganu Univertity of Medicine and Pharmacy, Faculty of Dental Medicine, Orthodontics Department, 31 Avram Iancu Str., 400083, Cluj Napoca, Romania

[2]Technical University of Cluj-Napoca, Automation Department, 26-28 Baritiu Str., 400027 Cluj Napoca, Romania

[3]Targu Mures Univertity of Medicine Pharmacy, Science and Technology, Faculty of Dental Medicine, Orthodontics Department, 38 Gheorghe Marinescu Str., 540139, Targu Mures, Romania

[4]Iuliu Hatieganu Univertity of Medicine and Pharmacy, Faculty of Dental Medicine, Department of Maxillofacial Surgery and Implantology, 16 Mihai Eminescu Str., 400033, Cluj Napoca, Romania.

Elastomeric chains, as means of force delivery, are one of the most studied elements of the orthodontic field. Effects on tooth movement are closely related to force degradation degrees of these polymers. Unfortunately, due to varied manufacturing techniques and materials, different brands of elastomeric chains offer different initial force values and different force decay, with direct impact on tooth movement duration and effectiveness and quality of orthodontic treatments.

Key words: elastomeric chains, orthodontic treatment, polymer, memory chains

Elastomeric chains are often used in orthodontic treatments, especially with the purpose of closing existing or extraction spaces. Due to elastomeric properties and individual particularities, movement amplitude of the interested teeth and duration of tooth movement vary. In this context, over time, multiple studies have been conducted in order to assess the mechanical properties of these elastomeric chains, with the ultimate goal of determining the degree and duration of orthodontic tooth movement, in hope of a more rapid and efficient treatment [1,2]. Therefor the aim of this paper is to providing independent and original results of an in-vitro comparison experiment between plastic and memory elastomeric chains, by generating a mathematical model of the force evolution and degradation.

Elastomers, as defined by the International Union for Pure and Applied Chemistry (IUPAC), are polymers that exhibit rubber-like elasticity [3]. Their introduction in the orthodontic field, has led to the development of the frictional systems frequently used at the moment, especially in extraction cases. So, in other words, orthodontic elastomeric chains are polyurethanes, thermosetting polymer products of a step-reaction polymerization process, possessing a –(NH)-(C=O)-O-unit [4,5]. The various time-dependent force loss of the orthodontic elastomeric chains available at this time on the market are the result of different manufacturing processes and chemical composition, variation of manufacturing techniques and morphology and dimensional characteristics [6,7]. Based on the manufacturing technique, the orthodontic elastomeric chains can be thermoplastic or thermoset. The thermoplastic elastomers are moldable at high temperatures and made of plastic. It has been demonstrated by in-vitro studies that they present more force loss and require less pre-stretching than the thermoset ones [8,9]. Thermoset chains are cured irreversibly during fabricating and present less force loss in vitro [10].

In terms of materials, elastomeric chains used in orthodontics can be made from natural or synthetic latex. There are three types of chains: closed, short, long. Depending on the type used, the amount of force generated varies. The closed chains offer the greatest amount of force, as long chains offer the smallest [11]. Mechanical properties of elastomeric chains have been an issue of interest for the orthodontic field starting the 1970s, with the published research of Andresen and Bishara [12,13]. The use of orthodontic elastomeric chains in conjunction with fixed appliances - braces, offer an amount of advantages, including: full control over tooth positioning, precise use of forces, reduced risk of intraoral trauma and accidents, do not require patient compliance and are not very expensive [14-17]. There are disadvantages as well in the use of orthodontic elastomeric chains, including: different amounts of force loss over time, difficulties in oral hygiene, plaque retention, coloring with food pigments or loss of color [10,13].

The technique used in orthodontics, in order to achieve tooth movement, implies stretching the elastomeric chains, obtaining instantaneous elastic deformation [4]. The effects of these chains are correlated with the changes that occur in the dimensions of the material, as a portion of the mechanical work of the elongation that occurs in the stretch state is dissipated as heat, while other parts produce molecular reorientation, and permanent deformation of the elastomer [5]. Elastomeric chains manufactured by different producers generate various initial force levels when stretched the same amount [7,17].

Experimental part

A wood jig with 28 pairs of steel nails placed 22 mm apart was constructed. Two types of elastomeric chains, Long Plastic (plastic material - PM) and Long Memory American Orthodontics (elastic material- EM), were compared. Two 3-unitS of each elastomeric chain, with natural length of 12mm - PM, respectively 14 mm - EM, were stretched between the 22 mm apart nails of the wood jig (Fig. 1).

An NK-20 Analog Force Gauge (Fig. 2) was used to measure the initial forces exhibited by all 3-units of both elastomeric chains at the beginning of the experiment-day 1, and daily for a time interval of 28 weeks.

*email: marianapac@yahoo.com

Fig. 1. Wood jig constructed for the in-vitro experiment

Fig. 2. NK-20 Analog Force Gauge

A mathematical model of the force evolution in time, for both PM and EM chains, is proposed, as follows:

$$Y_1(s) = y_{1in} - \left(\frac{K_1}{T_1 \cdot s + 1} \cdot U(s)\right) \qquad (1)$$

$$y_1(t) = L^{-1}\{Y_1(s)\} \qquad (2)$$

respectively,

$$Y_2(s) = y_{21in} - \left(\frac{K_2}{T_2 \cdot s + 1} \cdot U(s)\right) \qquad (3)$$

$$y_2(t) = L^{-1}\{Y_2(s)\} \qquad (4)$$

Results and discussions

As shown in Table 1, the mean initial force of the PM 3-unit chain measured with the force gauge is 450 g force [gf]. According to our in-vitro experiment, the PM chain lost 20% of its' initial value, reaching 360 gf, after only one day. At the end of day 7, the PM chain expressed a force of 210 gf, losing 53.33% of its' initial value. For day 14 the force loss represented 64.44% of the initial force value, for day 21 68.88%, and at the end of day 28 the force loss represented 71.11% of the initial force value.

Given these results, our in-vitro experiment contradicts most data in the orthodontic literature [7,11,12,17-22], and only partially confirming the results generated by the study of Kardach et all [9,13].

The mean initial force of the EM 3-unit chain measured with the force gauge at the beginning of the experiment was 347 grams force [gf]. From table 1, the 25.07% force degradation after only one day can be observed, as well as the degradation rates of 45.24%, 59.65%, 62.53% respectively 65.41% for the time moments of day 7, 14,21 respectively 28. These results contradict the findings of Kardach et all and other authors [9,10,18].

The graphical evolution of the PM's force degradation over a 28 days period of time is exposed in figure 3, the graphical evolution of the EM's force degradation over the same period of time is exposed in Fig. 4, and the graphical comparison between the two experimental responses is presented in figure 5.

Table 1

FORCE DEGRADATION OF THE PM AND EM ORTHODONTIC CHAINS (GRAMS FORCE)

	Initial force	*Day 1*	*Day 7*	*Day 14*	*Day 21*	*Day 28*
Force expressed by PM chain	450	360	210	160	140	130
Force expressed by EM chain	347	260	190	140	130	120

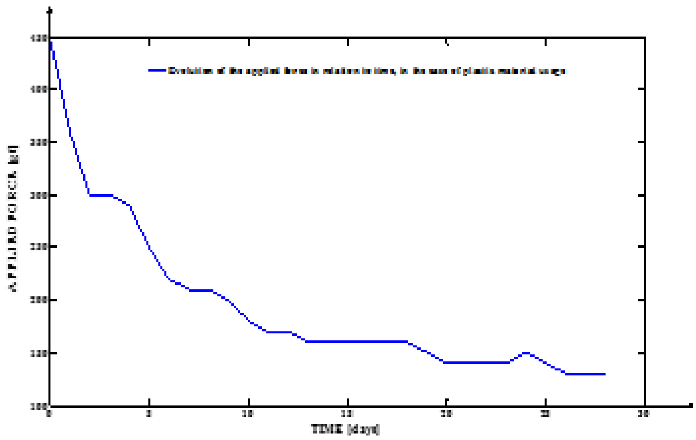


Fig. 3. Experimental response in the case of plastic material usage

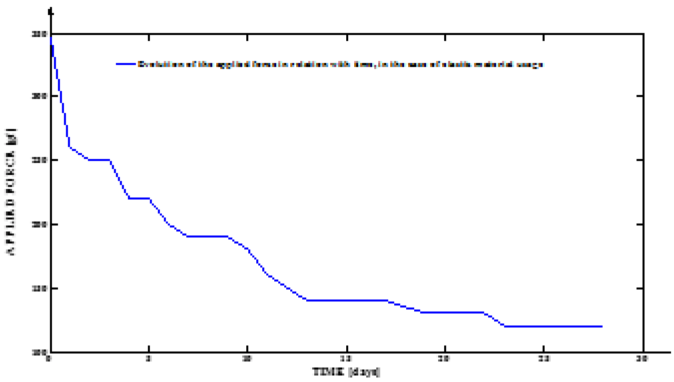


Fig. 4. Experimental response in the case of elastic material usage

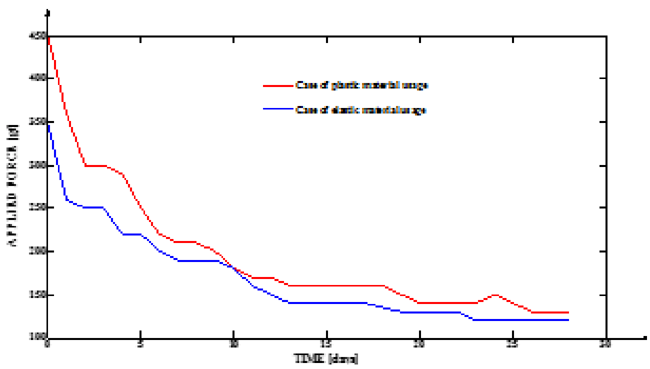
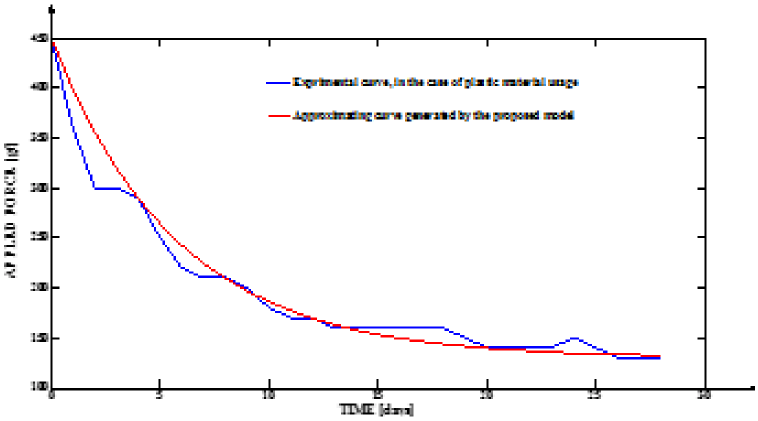


Fig. 5. Comparative graph between the two experimental responses



g. 6. Comparative graph between the experimental onse and the response generated by the proposed model, in the case of plastic material usage

The proposed mathematical model for the applied force dynamics, in the case of plastic material usage (1), uses the y_{1in} = 450 gf coefficient which represents the initial value of the applied force, $K_1 = y_{1in} - y_{1st}$ is the proportionality constant of the model (y_{1st} = 130 gf represents the steady state value of the applied force) and T_1 = 5.75 days is the time constant of the model. Also, U(s) is the model input unit step signal expressed using the Laplace transform and $Y_1(s)$ is the model output signal (the applied force) expressed using the Laplace transform. $H_1(s) = \frac{K_1}{T_1 \cdot s + 1}$ is the model transfer function. The T_1 time constant is determined using an iterative mathematical procedure which has as main scope to minimize the mean square error (MSE) between the experimental response and the response generated by the proposed model. In order to obtain the output signal written in time domain we apply the inverse Laplace transform according to relation [4]. The obtained MSE in this case, computed on 28 pairs of samples of the experimental response, respectively of the response generate by the proposed model is MSE_1 = 15.6035 gf. The relatively small error value and the acceptable fitting between the two curves presented in figure 6 proves the high quality of the identified model.

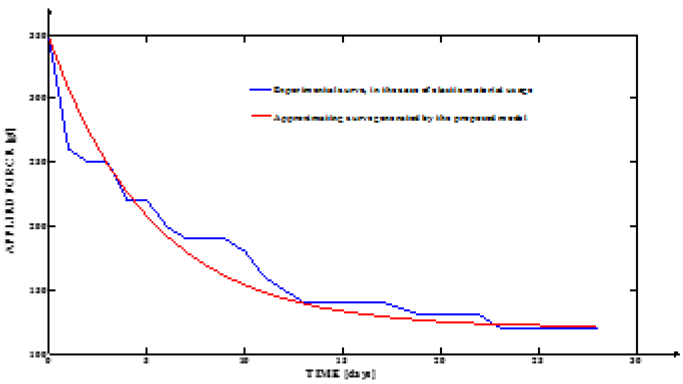


Fig. 7. Comparative graph between the experimental response and the response generated by the proposed model, in the case of elastic material usage

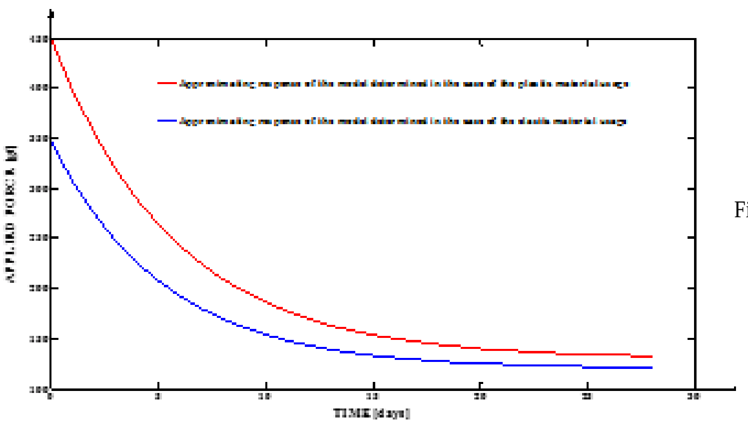


Fig. 8. Comparative graph between the response generate by the two proposed models

Using a similar procedure, the mathematical model for the applied force dynamics, in the case of elastic material usage is presented in relations (3) and (4), where y_{2in} = 347 gf is the initial value of the applied force, $K_2 = y_{2in} - y_{2st}$ is the proportionality constant of the model (y_{2st} = 120 gf represents the steady state value of the applied force) and T_2 = 5.25 days is the time constant of the model. Also, U(s) is the model input unit step signal expressed using the Laplace transform and $Y_2(s)$ is the model output signal (the applied force) expressed using the Laplace transform. $H_2(s) = \frac{K_2}{T_2 \cdot s + 1}$ is the model transfer function. The T_1 time constant is determined using a similar procedure as in the previous case. $y_2(t)$ represents the output signal written in time domain. The obtained MSE in this case, computed on 28 pairs of samples of the experimental response, respectively of the response generate by the proposed model is MSE_2 = 14.2349 gf (Fig. 7, Fig. 8). Conclusions are the same as in the previous case.

It can be remarked that $T_2 < T_1$, resulting the fact that the applied force decreases faster in the case of usage the elastic material, but, when analyzing the plastic material, the applied force decreases more significantly than in the case of using the elastic material (y_{1in}/y_{1st} = 0.2889 < y_{2in}/y_{2st} = 0.3458). The two ratios represent the proportions of the remnant forces in relation to the initial applied forces, for the two approached cases.

Most orthodontic elastomeric chains present a force loss of 50%-70% in the first 24 h , then stabilize until the end of the assessed period- usually 4 weeks [7,11,12,17-22]. Of course, force decay may be influenced by factors like temperature and *p*H levels. It has been demonstrated that in vitro, simulating an oral environment with a basic pH level of 7.26, force decay occurs more rapidly than in an acidic pH level of 4.95 or in air [7,11,23,24].

As it has already been demonstrated, elastomeric chains tend to lose force in time, in different temperature and pH levels. An in vitro study, evaluating the effects of elastomeric chains submerged in 37°C artificial saliva, demonstrated that plastic chains lost almost 50% of their initial force values in only a week, compared to the memory chains that presented a decrease in force of only 20% in the first week [10]. Another study on the behavior of elastomeric chains and NiTi closed springs, showed that after being submerged in 36.6°C artificial saliva, the elastomeric chains presented a substantial force loss in the first 24 hours, and after 28 days the force loss was 34±1.3% - 53.86±2% [25]. Comparing the force decay of the thermoplastic and the thermoset elastomeric chains on a period of 8 weeks, in 37°C artificial saliva with *p*H levels of 6.75, the study conducted by Masaud et al. [8] showed a 20% more force degradation of the thermoplastic chains. When investigating the differences between several brands of elastomeric chains, with or without memory, in 37°C distilled water, the study conducted by Mirhashemi et al. [25] showed that the chains without memory had a substantial force loss in the first hour and only 30-40% of the initial force was retained after 4 weeks. The memory chains retained 60% of the initial force at the end of the 4 week time interval. Another study comparing different brand chains demonstrated that AO-Memory and Ormco chains maintained most of their initial force at the end of the 4 week interval tested [26].

In the literature, multiple studies have been conducted with the purpose of analyzing elastomeric chains. As it appears, after thoroughly analyzing multiple studies regarding the biomechanical properties of elastomeric chains, results show very different values of force degradation in the same way as archwires [7,23]. Some authors reported that received coated archwires have significantly lower values of ultimate tensile strength and modulus of elasticity when compared to the as received regular NiTi wires [26].

Conclusions

Determination of the amount of force generated by elastomeric chains and more importantly, their force degradation in the oral cavity, are of great importance, in terms of bodily tooth movement and effectiveness and rapidness of the treatment.

The force degradation of plastic elastomeric chains is more pronounced than that of the memory elastomeric chains, even in the range of the same producer.

We can conclude that thermoset elastomeric chains with memory are by far more stable. Of course further investigation of this aspect is needed, especially in vivo.

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