Physical behavior of pre-strained thermoset and thermoplastic orthodontic chains

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The physical properties of pre-strained (50% and 100%) thermoset (TSU) and thermoplastic (TPU) elastic chains of four different manufacturers (n=120) were determined after storage in different environments. The in vitro force-decay was investigated after storage in the media air, distilled water and artificial saliva at 37°C. The modified pull test was performed with a universal testing machine Model 4444 and load cell 2530-427. The initial and residual forces (after 1 h, 2 h, 4 h, 8 h, 24 h, 7 days, 21 days) were used to calculate the relative force. All chains show a force decay that is greatest in the first hour regardless of pre-strain or storage media. Over the entire incubation period, a significant difference between the providers was found. The paired comparisons showed no difference between the relative forces of chains made from TPU nor between the chains made from TSU. Yet, a highly significant difference between these two groups was found.

Keywords: Thermoset, Thermoplastic, Pre-strain, Force decay, Orthodontic chains

INTRODUCTION

Elastic power chains play an important part of daily treatment in orthodontics when using fixed appliances. They have a large number of different indications such as closure of gaps between teeth, derotation and tipping of teeth or correction of midline discrepancies. The advantages of elastic chains are their low production costs and the fact that they do not require patients’ adherence. Furthermore, they are easy to apply and comfortable to wear. One disadvantage is the poor hygiene capability due to additional dirt niches and plaque accumulation points. This makes it even harder for the patient to maintain proper oral hygiene with a fixed appliance. In addition, forces of elastic chains are difficult to regulate and to estimate. The greatest weakness of elastic chains is seen in their inability to maintain the initially applied force constantly over a long period of time, especially when space closure takes places.

One can distinguish between two basic types of action of elastic power chains. On the one hand, there is the effect of low applied forces, which do not exceed capillary pressure. This causes direct bone resorption and physical tooth movement. On the other hand, there are strong applied forces that are associated with tilting movements and lead to ischemia and indirect bone resorption. Indirect resorption can cause root resorption and negative effects on tooth movement. Several studies have shown that the application of small forces can achieve the desired therapeutic goal. However, in many clinical cases the actual applied force is higher than systolic blood pressure and is therefore higher than necessary.

Almost every orthodontic manufacturer offers elastic chains. They can be distinguished by their shape and chemical composition. Each type of chain has a different molecular chemical structure which results in different chemical and physical properties. Thermoset polyurethane (TPU) or thermoset polyurethane (TSU). TPU has a special molecular chemical characteristic: it combines thermoplastics and elastomers and is referred to as a hybrid. At room temperature, TPU is comparable to elastomers and therefore is highly elastic. However, it is plastically deformable under heat input, which justifies its classification as a thermoplastic. TPU combines the technology of thermoplastics with the properties of elastomers. Elastic chains of TPU are claimed to be less suitable, because they are not rigid enough and cannot maintain their force for the required period of time. That is why elastic chains made of TSU are often used instead. TSU consists of highly branched polymers that are closely linked to each other by strong covalent bonds. This explains their high tensile strength.

The force decay of elastic chains over time, the consequences of pre-strain and the general impact of the environment on the force delivered by orthodontic chains have been examined. Yet, there are conflicting results with regard to the effect of different incubation media on force decay. To our knowledge, less light has been shed on the force decay due to the difference in the properties of TPU and TSU themselves (Table 1). So far their fabrication procedure and the chemical makeup has been assessed with regard to containing latex or not. In direct comparison, thermoset chains

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Color figures can be viewed in the online issue, which is available at J-STAGE.

Received May 20, 2020; Accepted Sep 24, 2020
doi:10.4012/dmj.2020-192  JOI JST.JSTAGE/dmj/2020-192
Table 1 Chemical and physical properties of different materials used for orthodontic chains

| Characteristics   | Thermoplastics polyurethane (TPU) | Elastomers | Thermosets (TSU) |
|-------------------|-----------------------------------|------------|------------------|
| Cross-linking     | Amorphous or semi-crystalline structure | Weakly cross-linked | Highly cross-linked |
| Swellable         | Swellable-dissolvable            | Swellable  | Not swellable    |
| Tensile strength  | Low                               | Low        | High             |
| Stress relaxation | Yes                               | Yes        | Minor-No         |

Table 2 The materials used in this study

| Material                  | Manufacturer                  | Composition            | Lot No.  |
|---------------------------|-------------------------------|------------------------|----------|
| Plastic Chain             | AO, Sheboyan, WI, USA         | Thermoplastic polyurethane | C67298   |
| Elastic Power Chain       | Forestadent, Pforzheim, Germany | Thermoplastic polyurethane | 32303684 |
| Energy Chain              | RMO, Denver, CO, USA          | Thermoset polyurethane  | 05103    |
| Power Chain Generation II | Ormco, Orange, CA, USA        | Thermoset polyurethane  | 15H46    |
| Artificial saliva         | Local pharmacy                | According to NRF 7.5: 0.12 g KCl; 0.085 g NaCl; 0.25 g Na2HPO4* 12H2O; 0.015 g CaCl2* 2H2O; 0.005 g MgCl2* 6H2O; 0.1 g sorbic acid; 0.5 g carmellose sodium 400; 4.3 g sorbitol solution 70%; 1 g ad 100.0 mL H2O purif. |}

Information according to the manufacturer unless otherwise specified.

performed better than thermoplastic chains and thus a clear distinction between the two should be made.

Thus, the aim of this study was to simulate the clinical application of thermoset and thermoplastic elastic orthodontic chains and to measure their force decay over 21 days. The effect of "pre-strain" on force decay is discussed controversially in the literature. Therefore, two different pre-strain levels were also considered. Hence three hypotheses were examined. The null hypotheses were defined as follows: (1) The distribution of the relative forces at the respective measurement points (h) is statistically identical over the category of chain pre-strain. (2) The distribution of the relative forces at the respective measurement times is statistically identical across the category of the storage medium (artificial saliva; air and water as controls). (3) The distribution of the relative forces at the respective measuring points (h) is statistically identical across the category of the chain suppliers.

MATERIALS AND METHODS

Materials

Four different elastic closed chain types (i.e. no intermodular link) were tested in this study. Artificial saliva was prepared by a local pharmacy according to “Deutsches Arzneimittel-Codex®/Neues Rezeptur-Formularium® (DAC/NRF)” formula 7.5 (Table 2).

Procedures

In this study, the clinical situation to measure the force decay of elastic orthodontic chains in the patient’s mouth was simulated in vitro. The composition of human saliva shows individual and physiological fluctuations. As such, artificial saliva of a defined composition was used. The media “water” and “air” were additionally included, to enable comparability with published studies and as control groups. We simulated 21 days as this resembles the clinical time before chain renewal. As such, the setup was created to (1) test two different pre-stains and (2) incubate simultaneously with three different media at 37°C (Fig. 1).

The orthodontic chains were each stretched on the metal pins with 50% pre-strain and 100% pre-strain. A total of 120 orthodontic chains were examined to characterize the force behavior. To incubate the pre-strained chains under different conditions, six acrylic plates with the dimensions 19×14×10 cm were made (Fig. 2). To mount orthodontic chains (12 each), 24 holes were drilled into each acrylic plate with a milling machine. The drill holes were arranged pairwise with a within pair distance of 13 cm. Afterwards, corrosion-resistant stainless-steel pins were inserted into each drill hole. The force behavior of the chains was investigated in three different media: air, distilled water and artificial saliva.

On each acrylic plate eight chains were mounted. The acrylic plates were divided according to the three media and the two different pre-expansions. At both ends of an orthodontic chain two additional rings were left, which were marked with black, water-insoluble ink (Fig. 2). This facilitated the removal of the chains from
the pins and to reposition after tensile testing.

Ten chains of each manufacturer were placed on acrylic plates; five with 50% pre-expansion and five with 100% pre-expansion. Their force behavior was examined in three different media: artificial saliva, distilled water, and air (Fig. 1). The initial force was determined directly after the chains were pulled onto the pins (baseline, i.e. hour 0). Further measurements were taken after one hour, two hours, four hours, eight hours, 24 h, one week, and after three weeks. Between the measuring times, the acrylic plates were placed in the respective media in an incubator (APT.line BB E2; Binder, Tuttlingen, Germany) at 37°C representing the temperature in the oral cavity.

The modified pull test for residual forces was performed with a universal testing machine (Model 4444, Instron, Norwood, MA, USA) and load cell 2530-427 (Instron) and was in line with the specifications of ISO standard 21606:2007. The orthodontic chains were attached to two hooks on the machine with the same distance they had on the acrylic plates (13 cm) (Fig. 3).
An initial measurement of forces was done at this point. After that, the measuring machine moved to 6.5 cm distance between the hooks (50% of the initial distance) with a speed of 2.5 mm/s before moving back to its initial position. During this movement, a force-deflection value pair was generated at a scanning rate of 50 Hz. Finally, the orthodontic chain was removed from the hooks and placed back on the acrylic plate to be stored in its corresponding medium again.

The measured data was processed with the Bluehill 3 program (3.63.3617; Instron). The highest value, at 130 mm chain length, was extracted from the data set and used for the results, since this value reproducibly represents the force without mechanical deformation.

Statistical analysis
Statistical analysis was performed using IBM SPSS Statistics Version 25 (IBM, Armonk, NY, USA). In addition to descriptive statistics, pairwise comparisons were made using the Mann-Whitney U-Test ($p<0.05$). For multiple comparisons the Kruskal-Wallis test was used. Post-hoc tests were calculated, if the result was significant and the significance level was corrected for multiple testing. The results were presented as relative forces, with reference to the initial value of the respective absolute force at the beginning (hour 0).

RESULTS

Incubation in artificial saliva
The relative force loss is significantly lower for Ormco and RMO chains (thermoset) than for AO chains ($p<0.001$) at a pre-strain of 50% regardless of the time of incubation (Tables 3 and 4). The relative force loss at a pre-strain of 100% is significantly lower for Ormco and RMO chains than for Forestadent chains ($p<0.001$). Still, there is no statistically significant difference between AO and Forestadent chains nor between RMO and Ormco chains regardless of the time of incubation and strain condition.

After 21 days, the relative force of AO and Forestadent chains are only 35% or 36%, while the relative force of Ormco and RMO chains is still 70% or 75% respectively ($p<0.001$) (Table 4). In a comparison of relative forces between 50% and 100% pre-strain, only Ormco chains showed a significant difference ($p=0.003$). With all other manufacturers, the relative forces of the chains did not differ at 50% and 100% pre-strain (Table 5). Therefore, the measurements at 50% and 100% pre-strain of the chains of AO, Forestadent and RMO will be summarized in the further evaluation.

Incubation in distilled water
The relative force loss is significantly lower for Ormco

| Pre-strain | Medium     | Relative forces (%)–Median [Min; Max] | p-value | KW |
|------------|------------|--------------------------------------|---------|----|
| 50%        | Artificial saliva | 62.8 [61.4; 66.0]A | 64.9 [63.6; 68.0]AB | 83.4 [82.7; 85.1]A | 84.4 [83.7; 85.4]A | 0.001 |
|            | Distilled water  | 64.1 [61.9; 68.8]B | 66.5 [63.6; 68.6]AB | 85.6 [83.3; 87.0]A | 87.3 [83.6; 88.3]A | 0.002 |
|            | Air         | 80.1 [74.4; 81.2]A | 81.7 [80.5; 83.1]AB | 89.1 [87.4; 91.3]A | 90.2 [88.8; 92.7]A | 0.001 |

Homogenous subgroups were calculated with post-hoc correction according to Bonferroni after Kruskal-Wallis test and carry identical super-script letters. Within each row values with a differing superscript letter are statistically different.

| Pre-strain | Medium     | Relative forces (%)–Median [Min; Max] | p-value | KW |
|------------|------------|--------------------------------------|---------|----|
| 100%       | Artificial saliva | 65.9 [62.7; 68.4]AB | 59.1 [56.2; 60.6]AB | 88.2 [85.6; 89.7]A | 86.7 [85.1; 90.3]A | 0.001 |
|            | Distilled water  | 65.1 [57.6; 65.7]AB | 57.1 [55.6; 57.7]AB | 82.4 [81.0; 85.2]A | 85.5 [82.6; 87.6]A | 0.001 |
|            | Air         | 80.9 [79.9; 85.1]AB | 76.7 [75.1; 77.4]AB | 91.0 [90.3; 93.0]A | 89.1 [88.4; 90.3]A | 0.001 |

Homogenous subgroups were calculated with post-hoc correction according to Bonferroni after Kruskal-Wallis test and carry identical super-script letters. Within each row values with a differing super-script letter are statistically different.
and RMO chains (thermoset) than for AO chains ($p<0.001$) after $1$ h regardless of the pre-strain (Table 3). The same homogenous sub-groups can be found at a pre-strain of $100\%$ after $21$ days (Table 4). The relative force loss at a pre-strain of $50\%$ after $21$ days is significantly lower for Ormco and RMO chains than for Forestadent chains ($p<0.001$). Still, there is no statistically significant difference between AO and Forestadent nor between RMO and Ormco chains regardless of the time of incubation and strain condition.

After $21$ days, the relative force of AO and Forestadent chains is only $49\%$ and $46\%$, respectively, while the relative force of Ormco and RMO chains is $72\%$ and $75\%$ ($p<0.001$) (Table 4). When comparing the relative forces between $50\%$ and $100\%$ pre-strain, only the Forestadent chains showed a significant difference ($p=0.021$). For all other manufacturers, the relative forces of the chains did not differ between $50\%$ and $100\%$ pre-strain (Table 5). Therefore, the measurements at $50\%$ and $100\%$ pre-strain of the chains of AO, Ormco and RMO will be summarized in the further evaluation.

**Comparison of the media**

For the comparison of the relative force with the different media water, air and saliva, data could be partially combined, as no differences in the pre-expansions were found. The results show that air differs significantly from water and saliva (Table 6). In contrast, no difference between saliva and water can be found. For the chains of the manufacturers AO, Forestadent and Ormco, there were significant differences in the relative forces for the different media ($p<0.001$). The relative forces of RMO chains showed no significant difference when incubated in the three media ($p=0.093$).

**Comparison of the chain providers: Influence of aqueous media on relative force**

Since there was no significant difference between the media saliva and water, the data sets of the providers were combined. This resulted in $n=20$ for AO, Forestadent and RMO and $n=15$ for Ormco (Fig. 4). When comparing the relative forces of the chains averaged over the entire incubation period, a significant difference between the providers was found (Kruskal-Wallis test, $p<0.001$). The paired comparison of the chain providers shows that the thermoplastic chains of American Orthodontics and Forestadent ($p_{adj}=1.000$) or the thermoset chains of Ormco and RMO ($p_{adj}=0.720$) did not differ from each other, but that there is a highly significant difference between these two groups ($p_{adj}<0.001$).

### Table 5 Relative forces (%) averaged over the entire incubation period with pairwise comparisons ($n=80$) at $50\%$ and $100\%$ pre-strain given as Median [Min; Max]

| Medium         | Manufacturer | 50% Pre-strain | 100% Pre-strain | $p$-value | Sig. level |
|----------------|--------------|----------------|-----------------|-----------|------------|
| Artificial saliva | AO           | 54.2 [33.8; 100.0] | 54.0 [34.4; 100.0] | 0.696 | n.s.            |
|                | Forestadent  | 55.5 [35.8; 100.0] | 50.0 [33.9; 100.0] | 0.115 | n.s.            |
|                | Ormco        | 79.0 [67.9; 100.0] | 83.9 [72.7; 100.0] | 0.003 | *              |
|                | RMO          | 81.2 [68.0; 100.0] | 83.1 [72.2; 100.0] | 0.129 | n.s.            |
| Distilled water | AO           | 50.6 [31.6; 100.0] | 53.0 [31.7; 100.0] | 0.620 | n.s.            |
|                | Forestadent  | 54.4 [35.3; 100.0] | 50.6 [34.1; 100.0] | 0.095 | n.s.            |
|                | Ormco        | 80.2 [69.1; 100.0] | 80.0 [71.3; 100.0] | 0.675 | n.s.            |
|                | RMO          | 82.0 [69.1; 100.0] | 82.5 [73.0; 100.0] | 0.904 | n.s.            |
| Air            | AO           | 72.0 [48.3; 100.0] | 69.2 [46.1; 100.0] | 0.547 | n.s.            |
|                | Forestadent  | 73.9 [44.3; 100.0] | 64.7 [42.6; 100.0] | 0.021 | *              |
|                | Ormco        | 83.0 [70.8; 100.0] | 84.3 [76.6; 100.0] | 0.438 | n.s.            |
|                | RMO          | 84.3 [72.3; 100.0] | 83.2 [75.2; 100.0] | 0.479 | n.s.            |

* $50\%$ pre-strain versus $100\%$ pre-strain ($p<0.05$)
Table 6  Relative forces (%) averaged over the entire incubation period in the media air, artificial saliva and water with pairwise comparisons of the media

| Medium                                      | Relative force (%)–Median [Min; Max] |
|---------------------------------------------|--------------------------------------|
|                                             | AO        | Forestadent | Ormco     | RMO       |
| Air (50% pre-strain; n=40)                  | n.a.      | 73.9 [44.3; 100.0] B | n.a.      | n.a.      |
| Air (100% pre-strain; n=40)                 | n.a.      | 64.7 [42.6; 100.0] B | n.a.      | n.a.      |
| Air (n=80)                                  | 71.6 [46.1; 100] B | n.a.      | 83.6 [70.8; 100.0] B | 83.8 [72.3; 100.0] A |
| Artificial saliva (50% pre-strain; n=40)    | n.a.      | n.a.        | 79.0 [67.9; 100.0] A | n.a.      |
| Artificial saliva (100% pre-strain; n=40)   | n.a.      | n.a.        | 83.9 [72.7; 100.0] B | n.a.      |
| Artificial Saliva (n=80)                    | 54.2 [33.8; 100] A | 52.8 [33.9; 100] A | n.a.      | 81.7 [68.0; 100.0] A |
| Distilled water (n=80)                      | 52.0 [31.6; 100] A | 52.6 [34.1; 100.0] A | 80.1 [69.1; 100.0] A | 82.3 [69.1; 100.0] A |

KW p-value
<0.001  <0.001  <0.001  0.093

Homogenous subgroups were calculated with post-hoc correction according to Bonferroni after Kruskal-Wallis test and carry identical super-script letters. Within each column values with a differing super-script letter are statistically different. (n.a.: not applicable)

Fig. 4  Relative forces (%) of the orthodontic chains stored in aqueous media over time. Note the difference between chains made from TSU (orange and green) and TPU (red and blue).

DISCUSSION
The measured, absolute forces varied between the chains from the different manufacturers over the whole measurement period. Material properties such as elastic modulus and Poisson’s ratio of the chains’ material were unknown, relative forces were used for comparison. In our study, a 100% pre-strained chain showed a greater absolute force compared to an identical 50% pre-strained chain. Nevertheless, the relative force decay over time is comparable between 50% and 100% pre-strain. This effect was noted mainly in the first hour and questioned the clinical value of pre-strain an elastic chain. Still, there is no thread of potential initial permanent deformation, which was an issue with the introduction of elastic chains.

Our results show that the force decay can be described mathematically as a hyperbolic function, while the decrease is most prominent in the first hour. Over time the function becomes almost linear. These results are in line with the results of earlier studies. Until now, force decay of elastic chains over 21 days or longer periods was assessed in a few studies only. Forces did not change at later measuring points and the elastic...
chains showed similar force ranges after more than 21 days. Hence, we have chosen this duration as maximum incubation period for our experimental setup.

Thermoplastic elastic chains showed a greater force decay being incubated in water than in air. This result was to be expected since thermoplastic polyurethane has easily swellable properties as soon as it encounters liquids. The swelling causes a negative change in the chemical structure and composition, which means that the elastic chains can no longer effectively maintain their power. The decrease in force of thermoplastic elastic chains stored in distilled water and artificial saliva were comparable. This effect may be attributed to the similarity of both fluids. The artificial saliva used in our study is an aqueous solution and therefore consists mainly of water molecules. These molecules then again have the possibility to integrate themselves into the chain structures\textsuperscript{39}. Elastic chains made from thermoset polyurethane showed comparable force behaviors in all media, which means that they are more resistant to water absorption. This statement is supported by the basic chemical structure of these plastics: due to the three-dimensional cross-linking of the molecules, the individual water molecules cannot integrate themselves into the chain structure. This is certainly a positive property of thermoset elastic chains, as their force decay is less\textsuperscript{39,40}.

In the medium air, we suppose that the difference between TSU and TPU is due to greater stress relaxation or creep in TPU chains. Stress relaxation or creep describes a time-dependent decrease in stress under a constant strain. Orthodontic chains made from polyurethane show viscoelastic behavior that depends on deformation history\textsuperscript{39} and is thus time-dependent. Earlier studies have shown a decrease in stress due to pre-strain and tooth movement and an increase in permanent deformation\textsuperscript{39}.

The in-vitro set up allows for better standardization and is beneficial when comparing force behavior. In previous studies the storage in aqueous liquids was found to be similar to the behavior of orthodontic chains in the oral cavity\textsuperscript{39,40}. Still the in vivo behavior of orthodontic elastic chains may differ from our test parameters. The presence of the oral flora\textsuperscript{20}, enzymes\textsuperscript{13} and plaque accumulation cannot be simulated in vitro and potentially have a detrimental effect on polyurethane. Further studies simulating clinical conditions are therefore necessary.

A precise force application is required for an efficient biological tooth movement without pathological side effects. Future developments on orthodontic chains should allow a better force adjustment.

**CONCLUSIONS**

Depending on the properties of the chains examined, force and relative force decay varied over time. The following conclusions were drawn:

1. In general, in all chains tested the relative force decay is highest in the first hour regardless of pre-strain or storage media.
2. In comparison to chains made from TSU, chains made from TPU showed significantly greater force decay. In aqueous media, we suppose, that this is due to the absorbance of water molecules by thermoplastic material. In air, this might be due to greater stress relaxation in TPU chains.
3. TPU chains showed a higher force decay. Therefore, in clinical applications these chains should be replaced at shorter intervals.
4. Elastic power chains made from TSU are preferable to increase treatment effectiveness. Further studies are necessary to substantiate this claim.

**ACKNOWLEDGMENTS**

The authors wish to thank Dr. Staphner (Physistas, Department of Orthodontics) and Mr. Aust (Master Precision Engineer, Department of Physics, LMU Munich) for their support of the experimental setup.

**CONFLICTS OF INTEREST**

This study did not receive any specific grant from funding agencies in the public, commercial, or non-profit sectors. The authors declare no conflict of interest.

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