An investigation into UV light exposure as an experimental model for artificial aging on tensile strength and force delivery of elastomeric chain

Siti Waznah Wahab*, Dirk Bister** and Martyn Sherriff***

*Orthodontic Unit, National Dental Centre, Brunei, **Department of Orthodontics, Guy’s and St Thomas’ Dental Hospital, London, ***School of Oral & Dental Sciences, University of Bristol, UK

Correspondence to: D. Bister, Department of Orthodontics, King’s College London Dental Institute, 22nd Floor, Tower Wing, Guy’s Hospital, Great Maze Pond, London SE1 9RT, UK. E-mail: dirk.bister@kcl.ac.uk

SUMMARY This study investigated the effect of ultraviolet type A light (UVA) exposure on the tensile properties of elastomeric chain. UVA light exposure was used as model for artificial aging, simulating prolonged storage of elastomeric chain.

Tensile strength (n = 60) was measured after exposing Ormco, Forestadent and 3M chains to UVA light for 0, 2, 3, and 4 weeks.

Force decay was measured (n = 60) using chain exposed for 5, 10, and 14 days. The chains were subsequently stretched at a constant distance and the resulting forces measured at 0, 1, 24 hours and 7, 14, 21, and 28 days. This test simulated a clinical scenario of pre-stretching and subsequent shortening of elastomeric chain.

Tensile strength had statistically significant difference and was directly related to the duration of ultraviolet light exposure. Forestadent chain, which had the second highest value for the ‘as received’ product, showed the most consistent values over time with the lowest degradation. Ormco showed the lowest values for ‘as received’ as well as after UV exposure; 3M chain had the highest loss of tensile strength.

Force decay was also significantly different. UV light exposure of 10 days or more appears to mark a ‘watershed’ between products: 3M had most survivors, Forestadent chain had some survivors, depending on the time the chain was stretched for. None of the Ormco product survived UV light exposure for more than 5 days.

UVA light exposure may be used as a model for artificial aging as it reduces force delivery and tensile strength of exposed chains.

Introduction

The aim of this study was to investigate the effect of UV light exposure on the tensile properties of elastomeric chain and compare its effect with the new ‘as received’ product. UV light exposure was used as model for artificial aging, simulating prolonged storage of elastomeric chain. This model should enable researchers/manufacturers to investigate the effect of aging on elastomeric elements without the necessity of awaiting natural aging. Three different chains from three manufacturers were exposed to UV light for a variety of time intervals to investigate whether the length of exposure affects the mechanical properties of elastomeric chain differently.

Elastomeric elements are used in orthodontics in a variety of forms, such as separators, ligatures, and elastomeric chain. Latex rubber has been replaced by synthetic elastomers for the manufacture of those elements because of their improved characteristics and also as a precaution as there appears to be a rise in incidence of latex allergies among patients and health workers (Jacobsen and Hensten-Pettersen, 1989).

In orthodontics, space closure is often achieved by using auxiliaries that can be metal based (Nickel Titanium Coil - Spring) or elastomeric (Elastomeric chain, O-links, Power-chain, etc.). Superelastic coil springs have the advantage over elastomers because of better physical characteristics such as superior elasticity and less force degradation. However, elastomers are still widely used because these are more cost efficient and close space both in straight line and along the arc and without impinging the mucosa (Andreasen and Bishara, 1970; Young and Sandrik, 1979; De Genova et al., 1985; Lu et al., 1993; Josell et al., 1997).

Most current synthetic elastomers are made of polyurethane, which is an organic polymer first discovered in 1937 by Otto Bayer and co-workers in Germany. The polymer is easily stretched and regains most of its shape on relaxation under normal conditions; however, it is not completely inert. It suffers from aging affects, and this may result in change of its properties such as colour and shape. Such speed of this aging phenomenon is affected by one or
more environmental factors such as heat, light, exposure to chemicals (ozone), tension, and storage condition. In air, the free oxygen radicals readily degrade polyurethane over time.

Many synthetic polymers are readily degraded by exposure to UV radiation, e.g. ambient light. The materials may crack, disintegrate, and/or discolor depending on extent and degree of exposure. Pigments and dyes integrated in the elastomers may also be affected. The UV degradation process involves the tertiary carbon chain that forms a free radical, which reacts with oxygen in the atmosphere, producing a carbonyl group. Intra-orally, the product ages and weakens further as it is exposed to saliva and its mineral contents, pH and temperature fluctuations, ingress of microorganisms and its by-products, plaque formation, food, chewing forces, and abrasion during tooth brushing.

Artificial aging or accelerated aging can be simulated by enhanced exposure to environmental factors. Polymers are very sensitive to the effect of free-radical-generating systems, notably, ozone and UV light. Thus, manufacturers add antioxidants and antiozonates in their elastomeric product to extend its shelf-life.

Numerous investigations on mechanical properties of polyurethane-based elastomeric chains have been undertaken. Previous studies investigated the efficiency of tooth movement for both in vivo and in vivo situations (Ash and Nikolai, 1978; Kuster et al., 1986; Eliades et al., 1999; Eliades, 2004), as well as the effect of different environments on the elastic properties of the chains (De Genova et al., 1985; Ferriter et al., 1990; Lew, 1990; Stevensen and Kusy, 1995). A number of environmental effects on the mechanical property of chains were investigated, such as the impact of storage media (Huget et al., 1990; Jeffries and Von Fraunhofer, 1991; von Fraunhofer, 1992; von Fraunhofer et al., 1992), exposure to foodstuffs (Nattrass et al., 1998), and the effect of ageing (Eliades et al., 2005). Baty et al. (1994), noted the impact of light exposure and suggested to keep the chains in the container provided by the manufacturer for protection from direct sunlight.

To our knowledge no investigator has systematically reviewed the effect of exposure of UV light type A (UVA) on the properties of elastomeric chain. Bulk purchase is often used in orthodontic practice to reduce prices, and long-term storage may become necessary. Orthodontists need to be reassured that products function reliably, and our investigation was designed to study the effect of artificial aging (UVA exposure) on the properties of elastomeric chains. We chose tensile testing to investigate the overall effect of UVA exposure of the final force level before fracture in the first instance and further tried to simulate the clinical scenario by measuring force decay levels of pre-stretched chain over various lengths of time.

Materials and methods

UVA light was used, which is the mildest form of UV light commercially used for tanning skin. Two units of the ‘LAMPADA UVA’ light cure boxes (Bracon Limited, West Sussex) were used in this study and each unit was specifically allocated for exposure for either force decay or tensile strength samples. The chains were laid flat in the box

Figure 1  Plots of the estimated marginal means and 95 % confidence intervals for Ormco. Tensile force and ultraviolet type A (UVA) light exposure time before fracture.
and regularly turned over. The UV-irradiation was produced by 4 units of fluorescent 9 Watt power lamps, which were ordered new from the supplier.

For the experiments, elastomeric chains from three different companies were used:

1. Ormco Generation II Power Chain—Ormco 1332 South Lane Ormco 1332 South Lane Hill Avenue, Glendora CA 91740
2. Forestadent Happy Elastics ‘normal’—Forestadent USA 2315 Weldon Pkwy
3. 3M Unitek C-1 short chain—Monrovia, CA 91016 USA

Clear chains were used to eliminate the effect of pigmentation on the elastic property of the material (Lu et al., 1993; Baty et al., 1994).

The elastomeric chains from each company were prepared by a single operator (SW). Ten and 12 links were used.

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**Figure 2**  Plots of the estimated marginal means and 95% confidence intervals for Forestadent. Tensile force and ultraviolet type A (UVA) light exposure time before fracture.

**Figure 3**  Plots of the estimated marginal means and 95% confidence intervals for 3M Unitek. Tensile force and ultraviolet type A (UVA) light exposure time before fracture.
in the force decay and tensile strength test, respectively. In both tests, only the middle six links of the specimens were stretched (Eliades et al., 2004) to 40 mm as this imitates the average width of an upper labial segment.

The tensile force test was undertaken first and the chains were stretched to their limits immediately after the exposure to UV light for 14, 21, and 28 days. The force decay samples were exposed to UV light for 5, 10, and 14 days. These samples were subsequently labelled and stretched and mounted on the jigs, which were stored in dry and dark conditions (a large cardboard box) for the designed amount of time before testing immediately afterwards.

Forces were measured using an Instron Universal Testing Machine (Model No. 1195, Instron Limited, High Wycombe, Bucks., UK) with 50 N tension load cell (type: 2511/1111). The testing was carried out at room temperature throughout the experiment.

**Tensile strength test**

A total of 60 elastomeric chains were tested for each product. Fifteen were as-received \((n = 15)\), aged for 2 \((n = 15)\), 3 \((n = 15)\), and 4 weeks \((n = 15)\). In this test, the middle six links were subjected to stretching, and the three loops at each end were not used as to alleviate the excessive stress concentration on the terminal loops (Eliades et al., 2004).

The first and sixth links of the mid section were hooked to the 1.0 mm stainless steel pin attached to the fixed and movable crosshead of the Instron machine. The two crossheads were positioned at the distance equal to the original length of test specimen. The chains were stretched at crosshead speed of 100 mm per minute, until the specimen fractured. The force at breakage was recorded for each specimen.

**Force decay test**

A total of 60 sample chains from each product were tested. Ten were used as controls, 30 taken from samples aged for 14 days, 10 from 10 days, and 10 from 5 days. The force delivered by each samples were recorded at the initial stretch after 1 and 24 hours and 7, 14, 21, and 28 days. The chains were stretched at fixed length of 55.5, 54.0 and 57 mm for product 1, 2, and 3, respectively. These distances were made constant by storing the elements on a jig, of which three were used simultaneously. Each jig was made from two acrylic blocks of \(1.5 \times 1.5 \times 20.0\) cm held at a fixed distance \(3 \times \) original length of tested elastomeric chains) by two stainless steel screws (see Figure 4). On each block, 30 stainless steel tubes (1.2 mm diameter) were positioned in place at 5 mm interval to each other. When not tested, the stretched chain was kept on the jig and stored in a cardboard box in dark and dry conditions and at room temperature.

![Figure 4](https://academic.oup.com/ejo/article-abstract/36/1/47/715223)
For the initial force value, the samples were first manually extended to three times its original length. Using the extra two loops at both ends as engagement points during stretching eliminated additional stresses created by squeezing the material. The chains were then transferred to the Instron machine, without changing the length. The samples were then extended to four times their original length at a rate of 100 mm per minute and then held at that distance for 5 seconds. The specimens were then returned to three times their original length, and this length was maintained for another 30 seconds. In the end, the resulting force was recorded. The stretched length were then transferred to the storage jig again and kept at constant length for the rest of the experiment.

For the remaining testing at 1 and 24 hours and 7, 14, 21, and 28 days, the same specimen were transferred from the storing jig to the testing jigs, and forces were measured as described above.

Data analysis

Data were analysed using Stata 12.0 with significance pre-determined at $\alpha = 0.05$. The null hypothesis was that there was no significant effect of treatment or time on the force decay.

The experimental design had repeated measures and was balanced for each time and treatment. Univariate summary statistics are shown in Table 1, and it can be seen that there were a large number of failures resulting in empty cells, which complicates the data analysis. As a consequence the data were analysed separately for each system using linear mixed models, Stata xtmixed, and the effects of treatment were compared using contrasts with Sidak’s method to adjust for multiple comparisons. Plots of the estimated marginal means and 95 per cent confidence intervals are shown more clearly.

Results

Tensile strength test

Table 1 shows results of the tensile strength test for all chains. The results demonstrate reduction in tensile strength of aged elastomers from all products. Sites of weakening and fracture were commonly found in the cracks that are perpendicular to the direction of applied stress. This has also been referred to as ‘ozone crack’ (Eliades et al., 1999; Eliades et al., 2003). From observation, the most frequent fracture sites for Ormco and 3M Unitek were found in the intermodular link. Forestadent chains exhibited sites of tearing in the loop itself. The differences in the findings were associated with the structural shape and dimension of the elastomers.

Results showed generalized reduction in the tensile strength of artificially aged chain. The effect of UV Light in degrading the polymer resulted in reduced stress resistance of the chain; the longer the exposure, the weaker they became. Sidak’s method for multiple comparisons for each time period and each system are shown in Table 2. It demonstrated that the differences between all combinations were statistically significant, except for 2 week aging and 3 week aging for Forestadent. Overall, the Forestadent chain showed the least relative reduction of tensile strength followed by 3M Unitek and Ormco (see Figures 1–3). Please note that the time scale on the x-axis of the figures is not proportionate but is equally spaced so that the differences are shown more clearly.
Force decay test

The numbers of samples that survived aging and initial stretching to three times the original length were subsequently used. The failure or fracture of chain in the initial stage was associated with the first stretch to 300 per cent of the original length, when placing them on the test jigs. Subsequent failure during the pre-stretching to 400 per cent the original length also occurred and is included in the figures.

After 5 days of aging some of the Ormco samples failed to mechanical stresses of stretching during the initial loading on to the test jig. The results showed consistently lower numbers of survival with increasing duration of exposure to UV light. Only half the chain aged for 5 days survived the initial stretch for up to 24 hours. From 24 hours to 7 days the number of chain reduced to 40 per cent, followed by 30 per cent at 14 days and 20 per cent at 21 days. None of the chain survived the initial stretching for chains aged 10 and 14 days. Double aging in the form of UV exposure and mechanical stress of stretching does not agree with this product.

Some of ‘as received’ (control, before UVA exposure) chain from Forestadent demonstrated failure after 7 days of loading: 10 per cent of the stretched chain fractured and only 60 per cent of the chain survived until 28 days. Test chain aged for 5 days demonstrated 40 per cent survival after 24 hours; then all failed when stretched for more than 7 days. Chain aged for 10 days showed better survival than chain exposed to 5 days, but this was not statistically significant: 40 per cent survival after 24 hour, which then reduced to 20 per cent at 14 days, and none were left at 21 days. For chains aged for 14 days, 12 out of 30 survived the initial stretch, which then reduced to four after 1 hour followed by 100 per cent failure at 24 hours.

Sample chains from 3M Unitek demonstrated 100 per cent survival throughout test period for both ‘as received’ and 5 day aging. The 10 day aged chain showed 100 per cent survival for 24 hours and this reduced to 80 per cent after stretching for 14 days and beyond. After 14 days of aging 14 out of 30 survived the initial stretch of 300 per cent original length; this number was reduced to 3 when stretched between 7 and 21 days and all failed thereafter.

Particular difficulties arise in the interpretation of the above data because of two sources of variability: within and between samples. Within each sample, the forces measured differ because they were taken at different times. Furthermore, inconsistency of the number of ‘survived’ samples at various time points made it impossible to analyse the overall force decay. However, the available data were still analysed and significance was pre-determined when probability is greater than 0.05. The analyses indicated a complex situation where all main terms (time point, aging condition and elastomeric chain type) and interactions were significant, so each elastomeric chain was analysed separately to evaluate the effect of time and interaction of aging and time.

Figures 1–3 show the effect of time for all conditions of chains. Analyses showed that there is statistically significant interaction between ‘as received’ and Ormco chain, which survived 5 day aging. The percentage of force that remained after 24 hours was between 60 and 75 per cent of the initial force.

There was no significant difference between the ‘as received’ and 10 day aged Forestadent chain. The remaining
force found after 24 hours was between 65 and 79 per cent for the survivor from ‘as received’, 5 day aged, and 10 day aged chain.

3M Unitek chain showed a significant effect between the ‘as received’, 5 day aged, and 10 day aged chain. But there was no significant difference between 14 day aged chain and the previous three. About 60–75 per cent of initial force remained after 24 hours of stretching.

Discussion

The results of this study have shown that polymers degrade after experimental UVA light exposure; tensile strength is affected as well as force decay after pre-stretching.

The tensile strength of all exposed chains demonstrated a lower maximum load. Ormco chain had the lowest tensile strength compared with the other two elastomers tested. The material had become brittle after aging for 2 weeks or more.

Tensile strength of chain from Forestadent showed least reduction in tensile strength after aging. Interestingly there was no difference in strength of chain aged for 2 or 3 weeks. This phenomenon may be attributed to irregularities during production of the chain or method error inherent in this study, the latter being less likely than the former.

Aged 3M Unitek chain had lower tensile strength than Forestadent chain, despite its good performance in the force decay test. This finding may be explained by the different chemical composition of the chain (such as antiozonates). Aging for 2 weeks or more is, at least theoretically, a critical length of time before the antiozonate of the material fails to protect the molecular structure.

Differences in force decay and tensile strength of different brands of chains can be attributed to either variations in manufacturing technique (die stamping or injection molding), differences in the constituent of basic polyurethanes, various incorporated additives, and in morphology / dimensional characteristics such as ellipsoidal or circular shapes or presence or absence of an intermodular links (Eliades et al., 2005).

The Ormco chain demonstrated highest vulnerability to the aging process despite sufficient force delivery (above 1 N after force relaxation), it had the highest failure rate: 50 per cent of chain that had been exposed to UV light for 5 days or more fractured.

Chains from Forestadent exhibited a mixture of failure and survival for all conditions, including ‘as received’ and aged conditions. The observed failure of the chain from ‘as received’ samples indicate the unfavourable response to stretching of more than three times its original length. It appears that at this distance (or more), the chains had reached its limit of elasticity/transition point (Rock et al., 1985). While pre-stretching up to two times its original length is often performed clinically, the effects of mechanical stretching of more than three times its original length had a profound effect on this chain. Rock et al. (1985) investigated 13 commercially available elastomeric products. They looked at the strength / stiffness / initial force of each elastomeric chain when stretched to 100 per cent of its original length. The authors suggested that 50–75 per cent of extension should be sufficient to generate reliable orthodontic force. However, Andreasen and Bishara (1970) suggested stretching up to four times the original length would be necessary to counteract the effect of force decay associated with the material and aging effect of intra-oral environment.

3M Unitek chain aged for 5 days behaved similarly to the ‘as received’. All chains survived pre-stretching. This material hence performed best in terms of mechanical and environmental stress and the same holds for all other exposure times.

A study by Eliades et al. (2004) showed no correlation in tensile strength with ‘as received’, stretched in air and samples retrieved from intra-oral environment. However, our study found that the tensile strength is affected by artificial environmental aging: chains exposed to UVA light have significantly lower tensile strength than ‘as received’ chains. The differences in findings may be due to the differences of applied strain: stretching the material to different lengths and different aging methods.

Previous studies have shown the effect of thermal cycling on elastomeric properties. De Genova et al., (1985) demonstrated that elastomeric properties of chains subjected to thermal cycling (15 and 45°C) over a 3 week period had less force decay than those stored at 37°C. We recognized that we were unable to hold the temperature of our samples constant at room temperature when the chains were exposed to the UVA light. However, the temperature in the ‘LAMPADA UVA’ light cure boxes was identical for all products and should have hence had little effect on the results of our study.

Conclusions

1. Exposure of elastomeric chain to UVA light ages elastomeric chain as it had a significant impact on force decay and tensile strength of the three products tested. Different makes of elastomeric chains were affected in different ways.

2. For tensile strength tests we found statistically significant differences, which were related to the duration of UV light exposure. The Forestadent chain that had the second highest value for the ‘as received’ product showed the most consistent values over time with the lowest degradation of tensile strength. The Ormco product showed the lowest values at ‘as received’ as well as after UV exposure, while the 3M product had the highest net force decay over time.

3. For the force decay test results were complex: after 5 days of aging all of the Ormco chain fractured after they had been stretched for more than 3 weeks. Forestadent...
chain should not be pre-stretched more than three times their original length as this induced failure even for ‘as received’ products; after 5 days of exposure all chains had fractured after 1 week of stretching; for the 3M product, however, all samples survived 5 days of exposure. The results for 10 days of aging were as follows: all Ormco chains failed; some of the Forestadent chain survived initial stretch but all eventually failed after 3 weeks of stretching; again the 3M product did best with 80 per cent survivors even after more than 3 weeks of stretching. After 10 days of UVA exposure all Ormco chains had fractured, 60 per cent of the Forestadent chain survived initially, but all remained failed after 14 days of stretching, only the 3M products showed a somewhat better survival with 80 per cent surviving even 28 days of stretching. After 14 days of aging only 3M showed any noteworthy survival, but no chain survived more than 3 weeks of stretching.

4. Force delivery of the ‘survivors’ of the force decay test showed that there was little further force decay after the initial force decay until failure occurred. In other words, the chains will deliver reasonably constant force delivery once they have survived pre-stretching.

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