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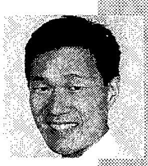

DEFORMATION OF ORTHODONTIC ARCHWIRES OVER TIME

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Most previous studies of archwire deformation over time (hereafter referred to as "time-dependent deformation of orthodontic wires") have been conducted at a constant room temperature. In the clinical situation however, arch wires are exposed to 37°C as well as to periods of temperature increase when hot foods or fluids are ingested. The effects of the latter on time-dependent behaviour are largely unknown. Since the introduction of direct electric resistance heat treatment to superelastic nickel titanium wires, there have been no reports on its effect on time-dependent deformation. This study investigated the effects of repeated temperature increases (70°C) on stainless steel, nickel titanium and beta titanium wires. The wires were deflected by approximately 3 and 5 mm on two jigs for periods of 1 minute, 1,7,14 and 28 days. Permanent deformation was measured optically with a measuring microscope and the amount of time-dependent deformation was calculated. Beta titanium wires demonstrated the greatest amount of time-dependent deformation; followed by non-superelastic nickel titanium, stainless steel, and superelastic nickel titanium. Exposure to repeated temperature (70°C) increases and direct electric resistance heat treatment of superelastic nickel titanium did not affect time-dependent behaviour.

Key Words
Archwires, time-dependent deformation, direct electric resistance heat treatment, temperature increase.

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Introduction

In order to move teeth, an orthodontic appliance needs to exert force over a period of time. The archwire is one component of the orthodontic appliance which provides stored energy required for tooth movement. In the clinical situation, forces exerted by the wire may vary with time because of tooth movement and stress relaxation in the wire. Stress relaxation occurs when stress decreases over time at a constant amount of total strain (Fig. 1).[1] This is associated with the conversion of elastic strain into plastic strain which can be measured as an increase in permanent deformation over time: that is, time-dependent information (Fig. 1).[1] Stress relaxation also results in a decrease in stored energy (resiliency) in the wire. Clinically, a decrease in force and stored energy may lead to a decrease in the amount of tooth movement.

Literature Review

Stress relaxation behaviour of orthodontic wires has been studied by measuring the decrease in stress or the increase in permanent deformation over time.[2-8]

Twelftree *et al*[2] in 1977 demonstrated stress relaxation by applying a tensile load to stainless steel and cobalt-chrome-nickel alloys over a period of three days. They reported varying amounts of stress relaxation in different wires. Stainless steel wires made by Wilcock had much less stress relaxation compared with other brands of stainless steel and cobalt-chrome-nickel wires. Lebsack *et al*[3] found that, when using Begg uprighting springs, force decay was dependent on the type of wire, number of coils in the helix design and the bracket/archwire angulation. Hazel *et al*[4] designed an apparatus to measure the

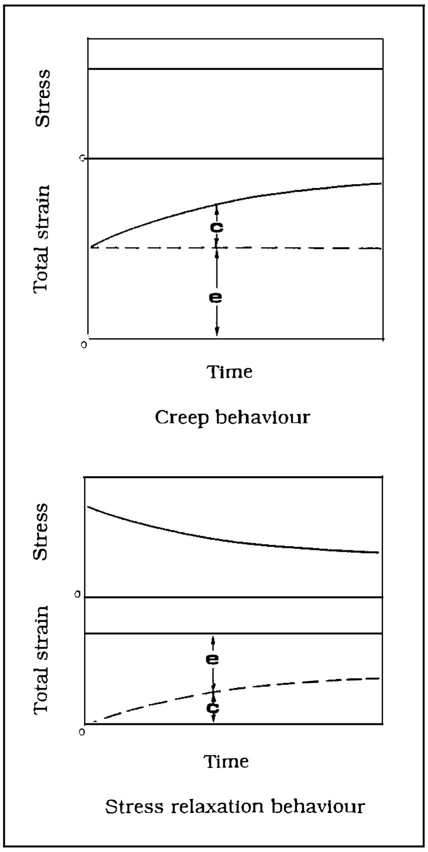

Fig 1. Difference between creep and stress relaxation behaviour. c = creep strain, e = elastic strain.

force relaxation of tip-back bends in orthodontic archwires over a 28 day period. It was shown that stainless steel, cobalt-chrome-nickel and Nitinol[*] wires stress relaxed at 21°C; no relaxation was observed in Nitinol at 37°C.

In 1979, Lopez *et al*[5] demonstrated time-dependent deformation of Nitinol wires with a cantilever system (ADA specification No.32). A 60 degree angle was bent into the test wires and maintained for 0, 1, 5, 20, 40, and 60 minutes. Unused Nitinol wires deformed an additional 5 degrees (8 per cent) over the 60 minute period and 11 degrees (18 per cent) after 48 hours.

During the 60 minute period, most of the deformation occurred during the first 5 minutes.

In 1982, Barrowes[6] investigated arch wire flexibility and deformation by ligating various archwires into a malaligned typodont arch. Nitinol wires which had been ligated for 8 weeks showed an additional 6 per cent distortion at 5 mm activation.

In a study of Chinese NiTi, Burstone *et al*[7] observed time-dependent deformation in Nitinol after three days, but not in stainless steel and Chinese NiTi. The wires were deflected in a three bracket system with the centre bracket representing a malaligned tooth in the occluso-gingival direction. There was no quantification of results.

More recently, Hudgins *et al*[8] in 1990 investigated time-dependent deformation of nickel titanium, TMA and stainless steel wires over a four week period. This was the only study that was conducted in a 37°C environment. The wires were deflected by 5 mm over periods of 1 day, 14 days and 28 days. Nitinol had the greatest increase in permanent deformation of 4.4 per cent after 28 days. However, as the first measurement was taken after one day, it may have given an inaccurate result; Lopez *et al*[5] reported that a large amount of time-dependent deformation occurs within the first five minutes.

In the clinical situation, archwires are exposed to periods of temperature increase when hot foods or fluids are ingested. No information has been found on the effects of exposure to temperature increase on time-dependent behaviour.

Direct electric resistance heat treatment was proposed by Miura *et al*[9] in 1988 to create bends in superelastic Japanese NiTi** and to control the force level exerted by the wire. The effect of direct electric resistance heat treatment on time-dependent deformation of superelastic nickel titanium has not been published in the literature.

Therefore, the aims of this study were to:

1. Investigate the time-dependent deformation of nickel titanium, beta titanium and stainless steel archwires in a 37°C environment.
2. Determine if time-dependent deformation is influenced by:
   (i) exposure to periods of temperature increase (70°C);
   (ii) direct electric resistance heat treatment of superelastic nickel titanium.

Materials and Methods

The wires used in this study are listed in Table 1. All the wires were rectangular 0.406 x 0.558 mm (0.016 x 0.022") in cross-section and were obtained in straight sections. One cross-sectional size was chosen to maintain a uniform amount of play between the wire and slot.

To test the effects of direct electric resistance heat treatment, Neo Sentalloy** wires were heat treated to 500°C using a heating machine†† before testing. This was done according to the manufacturer's instructions.

The test jig represents a three bracket system with the middle bracket acting as a malaligned tooth in the occluso-gingival direction. This method of testing is similar to that used by Burstone *et al*[7]. With this design, no ligation was needed to secure the wire in the slot. Hence, it eliminated the influence of the litigation method on the deformation of wire.

The jig consisted of: (i) two side bars with slots which act as 'supports'; (ii) a middle bar (also with slots) to deflect the wires; and (iii) a base to which the bars were fixed (Fig. 2 and 3). The middle bar was mounted 0.7 mm higher than the side bars to allow simpler loading of the wires into the jig (Fig. 3). Two brass jigs were made: one deflected the wires by 2.9 mm and the other by 5.1 mm (Fig. 2). This was to test the effect of deflection on time dependent information.

The test jigs deflected wires over a 14 mm span (Fig. 3). Each bar was 4 mm wide to simulate the width of a twin bracket. Slots of 0.457 x 1.549 mm

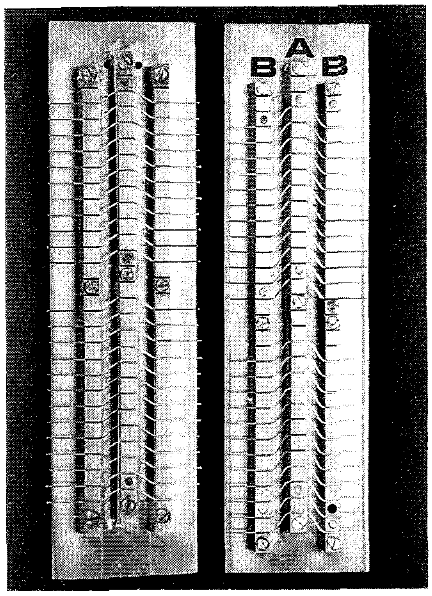

Fig. 2. The two test jigs loaded with wire specimens. Wires were deflected by 2.9 mm in the jig on the left, and 5.1 mm in the jig on the right. A, middle bar; B, side bar.

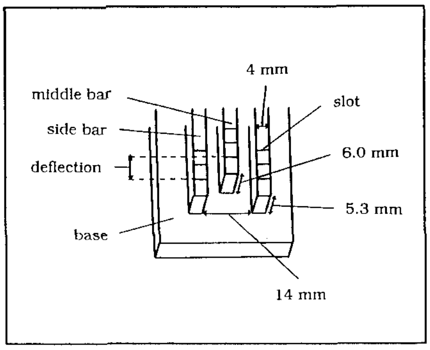

Fig. 3. Diagram of a test jig showing its components and measurements of various dimensions.

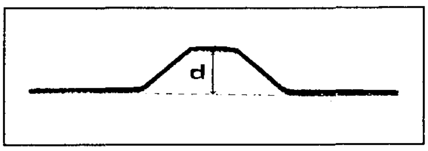

Fig. 4. Schematic drawing of a wire specimen after removal from a test jig (not to actual dimensions). The amount of permanent deformation (d) was measured at the middle of the span.

Table 1. List of wires tested.

Wire Trade Name	Material	Condition
Tru-Chrome§	Stainless Steel	AR Steel
TMA‖	Beta Titanium	AR
Nitinol¶	Nickel Titanium *Non-superelastic*	AR
Neo Sentalloy** (F80)	Nickel Titanium *Superelastic*	AR
Neo Sentalloy** (F80)	Nickel Titanium *Superelastic*	DERHT
Sentalloy** (Medium)	Nickel Titanium *Superelastic*	AR

AR As received from the manufacturer.
DERHT Direct Electric Resistance Heat Treatment.

(0.018 x 0.061") were cut into the bars to accommodate 0.406 x 0.558 mm (0.016 x 0.022") wires edgewise. The distance between each wire was 4 mm.

Each wire specimen was cut to 40 mm in length and tested in the following manner. To load the wire into the jig, the wire was firstly placed in the middle slot. With the aid of a ligature director[††], the ends of the wire were deflected and placed into the side slots one at a time. Fine ink marks were made on the wire precisely where it emerged from the inner edge of the side slot. These marks were used as reference points to measure the permanent deformation in the wire (as shown in Fig. 4). To unload the wire from the jig, the wire was lifted from the side slots prior to the middle slot.

Permanent deformation of the wire was measured optically with a measuring microscope[§§] with an accuracy of 0.001 mm (as determined by the manufacturer). The amount of permanent deformation of the wire was measured at the middle of the span as shown in Fig. 4.

A short period of operator training was conducted to standardise the experimental technique prior to commencement of the experiment. The reliability of the technique was assessed by loading and unloading 10 stainless steel wires in two separate trials. For each trial the mean, standard deviation, and standard error of the mean deformation were calculated. No significant difference in permanent deformation between the first and second trial was found (T-test, $P<0.05$).

This method of reliability testing accounted for:

(i) errors in construction of the jig (i.e. in deflection);

(ii) intra-operator variability in loading and unloading independent wire samples;

(iii) intra-operator variability in measurement using the microscope; and

(iv) the possibility of variation in properties within a batch of wires.

For each condition (wire, time and deflection), four new wires were tested. This made each test wire independent of the others. The jigs were loaded with 24 wires each and placed in a dry oven[|||] at 37± 1°C. Wires were deflected for periods of 1 minute, 1, 7, 14 and 28 days. The 1 minute time interval, which is equivalent to 0.00069 days, was given

Table 2. Summary of the experimental design

Factor	Number of Levels	Levels
Wire	6	Tru-Chrome, TMA, Nitinol, Sentalloy, Neo Sentalloy, Neo Sentalloy (DERHT)
Time Interval	5	0 day (1 minute), 1 day, 7 days, 14 days, 28 days
Deflection	2	2.9 mm, 5.1 mm

an approximate value of 0 day. The shortest time interval of 1 minute was selected as it allowed sufficient time for the temperature of the wire to reach 37°C before unloading. If insufficient time was given, the Neo Sentalloy and Sentalloy wires showed large deformations. This is because superelastic nickel titanium wires do not demonstrate the shape memory effect below the "transition temperature".[10] The longest period of 28 days was chosen as it has been shown that no additional deformation occurred after this time interval.[8] A summary of the experimental design is shown in Table 2.

After unloading from the jigs, the wires were left on a bench for one hour at room temperature (23±2°C) prior to the measurement of permanent deformation. This allowed the recovery of creep strain.

The absolute magnitude and percentage of creep deformation (time-dependent deformation) were calculated for all the materials over the 28 day period.

$$[\text{Creep deformation}] = \text{deformation}_{28\,\text{day}} - \text{deformation}_{0\,\text{day}}$$

$$\text{Creep deformation \%} = \frac{[\text{creep deformation}]}{\text{deflection}} \times 100$$

where deflection is either 2.9 mm or 5.1 mm

The second part of this study investigated the effects of repeated temperature increase on time-dependent deformation. As described in the previous section, four of each type of wire were loaded into the 5.1 mm jig and placed in a dry oven at 37°C for a period of 7 days. In addition, the wires were placed in another oven[¶¶] set at 70°C for 10 minutes a day. By keeping the variables constant, apart from the increase in temperature, these results could be compared with the baseline data obtained in the previous experiment.

All statistical analyses were performed using the SPSS/PC+ Studentware package. To evaluate the effects of wire, time and deflection on permanent deformation, analysis of variance (ANOVA) with factorial design was used. The significance level (α) chosen was 0.05. With the factorial design, the effects of each individual factor and the interaction between factors were analysed. To analyse the effect of temperature increase on permanent deformation, t-test was performed for each of the six brands of wire. A two-way ANOVA was not used as it would not assess the effect of temperature increase on the wire individually. To overcome the deficiency of using multiple t-tests, the α significance level was adjusted by 0.05/6 = 0.008.

Results

Table 3 lists the means and standard deviations of permanent deformation for the various wires, time intervals and deflections. These results are presented graphically in Figs. 5 and 6. After a 1 minute (0 day) interval, there was a large range of deformation values among the different wires. The Neo Sentalloy and Sentalloy, including those heat treated, experienced no permanent deformation. However, the other wires showed significant amounts of deformation in decreasing order: Tru-Chrome, TMA and Nitinol. This order was maintained for all the other time intervals.

For both the 2.9 mm and 5.1 mm deflections, all the wires demonstrated an increase in permanent deformation with time (i.e. creep deformation). In general, most of the increase in permanent deformation for Tru-Chrome, TMA and Nitinol occurred during the 14 day period. More specifically, TMA and Nitinol (tested at 2.9 mm deflection) appeared to experience most time-dependent deformation within the first day. Between 14 and 28 days, Tru-Chrome, TMA and Nitinol showed little increase in permanent deformation. Neo Sentalloy and Sentalloy (including the heat treated Neo Sentalloy) experienced only very small amounts of permanent deformation after 7 days (0.041 to 0.045 mm).

Table 3. Means and standard deviations of permanent deformation for various wires tested at 2.9 mm and 5.1 mm deflection after various time intervals.

Wire	Deflection (mm)	Permanent Deformation (mm) 0 day	1 day	7 days	14 days	28 days
Tru-Chrome (AR)	2.9	2.192± 0.048	2.226± 0.024	2.268± 0.045	2.272± 0.036	2.289± 0.013
	5.1	4.290± 0.008	4.350± 0.042	4.378± 0.023	4.473± 0.028	4.483± 0.018
TMA (AR)	2.9	1.326± 0.024	1.668± 0.071	1.781± 0.092	1.828± 0.018	1.840± 0.039
	5.1	3.162± 0.022	3.643± 0.018	3.765± 0.045	3.920± 0.048	3.945± 0.024
Nitinol (AR)	2.9	0.160± 0.014	0.369± 0.009	0.465± 0.038	0.497± 0.032	0.501± 0.018
	5.1	1.418± 0.061	1.628± 0.021	1.862± 0.082	2.073± 0.022	2.083 0.013
Neo Sentalloy (AR)	2.9	0.000± 0.000	0.000± 0.000	0.000± 0.000	0.000± 0.000	0.014± 0.011
	5.1	0.000± 0.000	0.000± 0.000	0.041± 0.006	0.051± 0.009	0.059± 0.007
Neo Sentalloy (DERHT)	2.9	0.000± 0.000	0.000± 0.000	0.000± 0.000	0.000± 0.000	0.011± 0.014
	5.1	0.000± 0.000	0.000± 0.000	0.045± 0.005	0.043± 0.009	0.057± 0.007
Sentalloy (AR)	2.9	0.000± 0.000	0.000± 0.000	0.000± 0.000	0.000± 0.000	0.000± 0.000
	5.1	0.000± 0.000	0.000± 0.000	0.041± 0.008	0.059± 0.009	0.071± 0.006

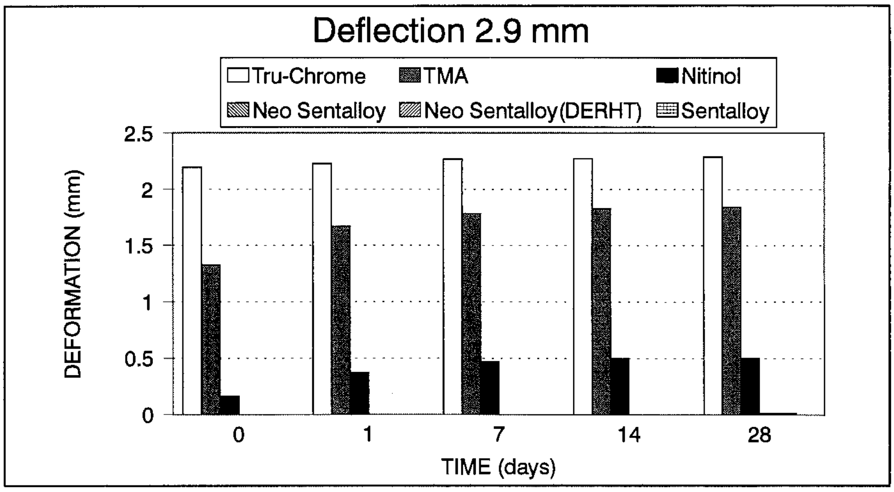

Fig. 5. Mean deformations observed in test wires subjected to 2.9 mm deflection after various times.

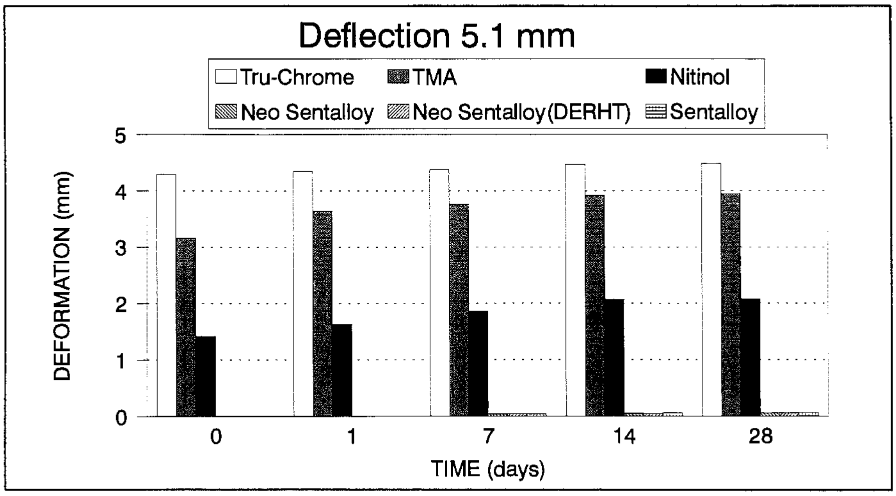

Fig. 6. Mean deformations observed in test wires subjected to 5.1 mm deflection after various times.

When individual factors were analysed separately, the 3-way ANOVA indicated that there were statistically significant differences in permanent deformation among different wires, time intervals and deflections. There were also highly significant interaction effects between: wire and deflection, wire and time, deflection and time, and wire, time and deflection. Table 4 shows the mean amount of time-dependent deformation over the 28 day period for the different wires and deflections. Comparing the wires deflected by 5.1 mm, TMA demonstrated the largest amount of time dependent deformation of 15.38 per cent. This was followed by Nitinol (13.06 per cent), Tru-Chrome (3.79 per cent), Sentalloy (1.39 per cent), Neo Sentalloy (1.16 per cent) and heat treated Neo Sentalloy (1.12 per cent).

The effects of initial deflection on time-dependent deformation can also be observed from these results. All the wires that were subjected to 5.1 mm of deflection demonstrated larger absolute magnitudes of creep deformation compared with those subjected to 2.9 mm of deflection. A similar trend was observed when comparing the percentage of creep deformation; except for the TMA wires. However, the difference in creep deformation values between the two deflections was small.

The results of subjecting the wires to repeated temperature increase (70°C) over a 7 day period are summarised in Table 5. These are shown graphically in Fig. 7. It can be seen that there was generally very little difference in permanent deformation between the wires that had been stored at a constant 37°C and those that had been subjected to periods of temperature increase. The t-tests support that there was no significant effect on Tru-Chrome, TMA, Nitinol, Neo Sentalloy and heat treated Neo Sentalloy. Although Sentalloy showed a statistically significant difference, it is doubtful if this is meaningful as the deformation values were so small.

Discussion

The amount of permanent deformation experienced by the wire after 1 minute of deflection gives an indication of its working range. The larger the permanent deformation, the smaller the working range. In this study it was observed that nickel titanium had the largest working range, followed by beta titanium and then stainless steel. Similar findings have been reported in

Table 4. Mean creep deformation over the 28 day period.

Wire	Deflection (mm)	Creep Deformation (mm)	Creep Deformation (%)
Tru-Chrome	2.9	0.097	3.33
(AR)	5.1	0.193	3.79
TMA	2.9	0.514	17.66
(AR)	5.1	0.783	15.38
Nitinol	2.9	0.341	11.72
(AR)	5.1	0.665	13.06
Neo Sentalloy	2.9	0.014	0.48
(AR)	5.1	0.059	1.16
Neo Sentalloy	2.9	0.011	0.38
(DERHT)	5.1	0.057	1.12
Sentalloy	2.9	0.000	0.00
(AR)	5.1	0.071	1.39

Table 5. Means and standard deviations of permanent deformation for wires tested under the two conditions for 7 days.

Wire	Permanent Deformation (mm) Condition A	Condition B	T-Value
True-Chrome (AR)	4.378 ± 0.023	4.385 ± 0.055	- 0.23
TMA (AR)	3.765 ± 0.045	3.769 ± 0.050	- 0.10
Nitinol (AR)	1.862 ± 0.082	1.901 ± 0.030	- 0.91
Neo Sentalloy (AR)	0.041 ± 0.006	0.045 ± 0.004	- 1.00
Neo Sentalloy (DERHT)	0.045 ± 0.005	0.056 ± 0.007	- 2.44
Sentalloy (AR)	0.041 ± 0.008	0.069 ± 0.003	- 6.62**

Condition A: Temperature at 37°C constant.
Condition B: Temperature at 37°C plus periods of 70°C.
** $P \leq 0.01$, i.e. Reject H_0

previous studies.[8, 11-14] The zero permanent deformation in Neo Sentalloy and Sentalloy wires after a 5 mm deflection observed in this study is in agreement with findings by Lipshatz.[15]

The increase in permanent deformation observed over time is due to stress relaxation in the material. Although there was no uniform pattern in time-dependent deformation among the different wires, the graphs of deformation versus time for Tru-Chrome, TMA and Nitinol suggest the decelerating nature of creep deformation. These results indicate that very little additional permanent deformation occurred after 14 days. Hudgins *et al*[8] observed no further increase in permanent deformation after 28 days. The high rate of creep deformation during the first day for TMA and Nitinol (at 2.9 mm deflection) relates to the 'primary creep' phenomenon.[16]

For Neo Sentalloy and Sentalloy wires, only very small values of permanent deformation (0.041-0.045 mm) were detected after 7 days. With such small mean values, the standard deviations are large in relation to the mean values. This may be due to the difficulty and inaccuracy associated with recording very small measurements. The clinical significance of such minute amounts of deformation is doubtful.

Most of the values of time-dependent (creep) deformation observed in this study are greater than those reported by Hudgins *et al*[8]. Several factors may account for this. The first measurement of a permanent deformation was recorded after 1 minute of deflection in this study compared with 1 day in the study by Hudgins *et al.*[8] Lopez *et al*[5] observed that a large proportion of creep deformation occurs during the first 5 minutes of deflection. Studies of stress relaxation have demonstrated an initial transient period where a large proportion of stress relaxation occurs.[2-4] This may also explain why the greatest amount of time-dependent deformation was recorded for TMA in this study. As shown in Figs. 5 and 6, most of the creep deformation for TMA occurred in the first day. Another factor which may have influenced the results is the amount of play in the testing apparatus. The system in this study using 0.406 x 0.558 mm (0.016 x 0.022") rectangular wires and 0.457 mm (0.018") slots has less play when compared with the design by Hudgins *et al*[8] which used 0.406 mm (0.016") round wires and 0.457 mm (0.018") slots. The lack of play in this system may have resulted in greater permanent deformation which in turn led to increased creep deformation.

In contrast, time-dependent deformation in Nitinol (13.06 per cent after 28 days) is less than that reported by Lopez *et al*[5] (18 per cent after 48 hours). The larger value in Lopez *et al*'s study may be due to testing Nitinol at room temperature; Hazel *et al*[4] showed

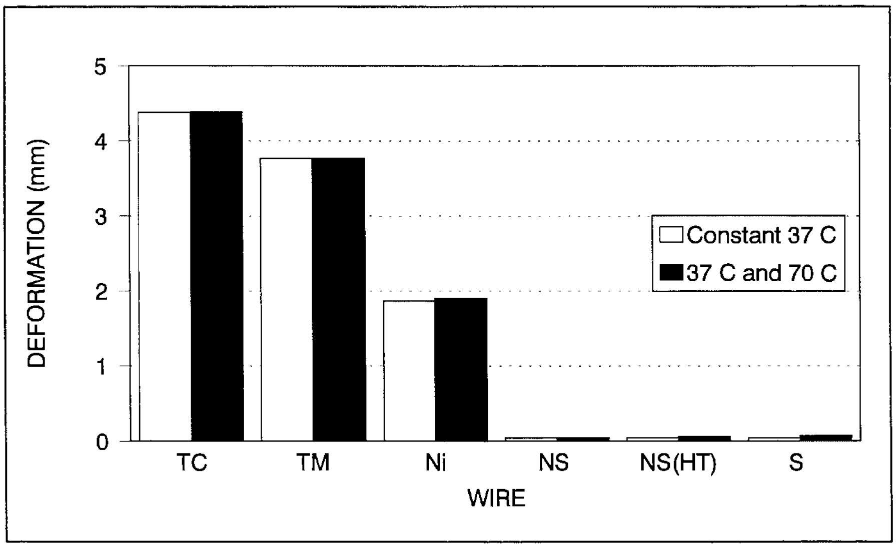

Fig. 7. Effect of repeated temperature increase. TC = Tru-Chrome, TM = TMA. Ni = Nitinol, NS = Neo Sentalloy, NS (HT) = Neo Sentalloy (DERHT), S = Sentalloy.

that Nitinol stress relaxed at 21°C but not at 37°C.

The relatively small increase in permanent deformation for stainless steel wires recorded in this study is similar to that reported by Barrowes[6] and Burstone *et al*[7].

The findings in Table 4 (except for the percentage values for TMA) suggest that subjecting wires to increase in deflection (strain and stress) may lead to an increase in the absolute magnitude and percentage of time-dependent deformation. This is partially in accordance with the theory of stress relaxation which suggests that the initial stress level has little effect on the percentage of stress relaxation, although it affects the magnitude.[1] It is uncertain why TMA showed a higher percentage of creep deformation with a lower initial deflection. This may be a result of error during testing. It is conceivable that only a very small error is required to affect the calculation of the percentage value. Furthermore, there may have been some inconsistencies in the properties of the batch of TMA tested.

Direct electric resistance heat treatment of Neo Sentalloy wire according to the manufacturer's instructions did not appear to result in deterioration of its working range and time-dependent properties.

In the second part of this study, wires were exposed to 70°C for 10 minutes a day for 7 days. If the results showed that exposure to repeated temperature increase had a significant effect on time-dependent deformation, further testing was carried out with different temperatures and duration of exposure. Temperature increase is not synonymous with thermal cycling (i.e. repeated heating and cooling). The effect of thermal cycling has not been investigated. According to the theory of stress relaxation, subjecting metals to extreme hot and cold temperatures may accelerate the process of creep and stress relaxation.[1] However, it is doubtful if temperature fluctuations in the mouth are large enough to affect stress relaxation behaviour.

The clinical significance of time-dependent deformation is not clear. One of the main reasons is the uncertainty about what constitutes optimum force or stress for tooth movement. According to the theory of stress relaxation, elastic strain is converted into plastic strain (creep strain). This phenomenon was demonstrated in this study. Although not measured here, stress relaxation results in a decrease in the force exerted by the wire. There is no certainty that a decrease in force will result in a decrease in the amount of tooth movement. However, a decrease in the amount of stored elastic energy may lead to a decrease in tooth movement. In the clinical situation, if the wire used for tooth movement has undergone considerable creep deformation, more frequent activation and arch wire changes may be required.

Laboratory testing provides further information on the mechanical properties of orthodontic wires; it does not simulate the force delivery system in the clinical situation. The apparatus in this study represented a malaligned tooth with a wire deflected between two abutment teeth. It is different to a continuous wire in a dental arch. The apparatus also did not simulate the movement of teeth. Furthermore, the wires were tested in a controlled environment devoid of saliva and mechanical insults; therefore, the possible effects of corrosion, mastication and oral hygiene measures were avoided.

Conclusions

1. All the materials tested demonstrated time-dependent deformation of varying amounts (from 0 to 17.66 per cent).
2. The material that experienced the most creep deformation was beta titanium followed by non-superelastic nickel titanium, stainless steel and superelastic nickel titanium (in order of decreasing creep).
3. An increase in the initial deflection of the wire resulted in an increase in creep deformation.
4. Exposure to periods of temperature increase (70°C) did not influence time-dependent deformation.
5. Direct electric resistance heat treatment of superelastic nickel titanium did not affect time-dependent deformation.

Acknowledgements

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Footnotes

§ Rocky Mountain Orthodontics. Denver, Colorado.

|| Ormco. Glendora, California.

¶ Unitek. Monrovia, California.

** Japanese NiTi is marketed as Sentalloy and Neo Sentalloy. GAC. Central Islip, New York.

†† Arch-mate. Wire Bender. Tomy. Includes heat treating instructions.

‡‡ Ligature Director. ETM 2104.

§§ Mitutoyo Micrometer. Japan 0-25 mm. 0.001 mm.

|| || Qualtex Oven. Andrew Thom Ltd. Sydney, Australia.

¶¶ Elektro Helios Oven. Atherton & Sons Pty Ltd. Melbourne.