Temperature- and Deflection- Dependences of Orthodontic Force with Ni-Ti Wires

Kotaro YANARU, Kazunori YAMAGUCHI, Hiroshi KAKIGAWA
and Yoshio KOZONO

Department of Orthodontics, Department of Materials Science, Kyushu Dental College, 2-6-1, Manazuru, Kokurakita, Kitakyushu 803-8580, Japan

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Orthodontic forces of Ni-Ti wires examined under the retrained condition on the dental arch model were evaluated with the changes in temperature and deflection. The tested specimens were a commercially available superelastic (W1) wire and two shape memory wires with their nominal Af points were 35°C (W2) and 40°C (W3), respectively. They showed typical superelastic hysteresis loops under the restraint condition at 40°C. The force levels were significantly larger than those generally obtained by simple three-bending test. The recovery forces in the plateau region at 1.0 mm deflection were much larger than desired in the clinical guidelines around oral temperatures. In the shape memory wire W3, the recovery force rapidly decreased to zero by a small reduction of the deflection from its maximum. However, the wire again exerted the force with the remaining permanent deflection by temperature rising. It was small compared to the guidelines of desirable orthodontic force and seemed to be useful especially for the hypersensitive patients.

Key words: Ni-Ti wire, Recovery force, Temperature dependence

INTRODUCTION

There have been various reports on the appropriate orthodontic force. In the clinical studies, for example, Storey et al. proposed the presence of the optimal force, in which the movement of the mandibular canine was the fastest at 150-200 gf. On the other hand, Hixon et al. reported that the movement of the mandibular canine increased with the larger forces among 64-1,515 gf and Andreasen et al. also demonstrated that the force of 400-500 gf was preferable to 100-200 gf. Another report suggested that only 20 gf was sufficient for the tooth movement and some others reported that no finite tendencies were found in the effective force. Thus, clinical studies showed large variance in the necessary force probably because of the different conditions of the cases.

On the physiological and histological points of view, it was suggested that the smaller orthodontic force might be desirable for minimizing the effects on the surrounding tissues. On the basis of these backgrounds, it is generally supported as a guideline that the force of 150 gf or less may be enough to move individual tooth without affecting the surrounding tissues.
In 1971, Ni-Ti wire was first introduced for orthodontic use, and in 1980's the new characteristic Ni-Ti wires having superelasticity were put on the market. It has been reported that they have clinical advantages over non-superelastic Ni-Ti wires or other wires. Since then, the superelastic Ni-Ti wires have been preferably used in orthodontics because they exert smaller, steady recovery force over a wide range of deflection when compared with the Co-Cr, Ni-Cr and stainless steel wires.

Another type of Ni-Ti, shape memory wires have also become available for orthodontic use. The shape memory phenomenon is based on the martensite-austenite transformation of the alloy. One of the advantages of the shape memory wire is the ability to be easily formed to the desired appliance at the atmospheric temperature and exert its recovery force at the oral temperature or higher. Some clinical trials have been made with this type of wire, involving the application to the treatment for closing the space between teeth utilizing the force of contraction of pre-stretched wire by Andreasen et al. and for alignment of teeth by Andreasen. Fischer et al. successfully performed the crossbite correction with shape memory archwires. Fukuizumi et al. suggested through the three-point bending test that the Ni-Ti shape memory wire with the Af point being 40°C might be especially useful for the orthodontic treatment in the hypersensitive patient.

Most of the mechanical characteristics of the Ni-Ti wires have been examined by the simple three-point bending test. The test is obviously easy to perform, in which both the ends of the wire specimen are maintained free. If the wire is mechanically restrained as in the clinical situation, however, the bending recovery force will be further larger. It is suspected that the three-point bending test may underestimate the recovery force of the wires for the practical orthodontic force in the mouth. Mohlin proposed that the mechanical properties of the archwire should be examined under restraint with brackets for clinical situation. A report demonstrated that the recovery forces of the superelastic wire examined with brackets and/or dental model were much larger than those obtained by the three-point bending test.

In order to evaluate the temperature- and deflection-dependences of the shape memory Ni-Ti wires for further useful clinical application, the present study performed the bending test on a dental arch model under the condition of the wire specimen being ligatured to brackets comparing with a superelastic Ni-Ti wire.

MATERIALS AND METHODS

The materials used are listed in Table 1. W1 is a commercially available Ni-Ti superelastic orthodontic archwire, and W2 and W3 are Ni-Ti shape memory orthodontic archwires with their nominal martensite-austenite transformation temperature (Af points) being 35 and 40°C, respectively. The actual Af points determined by DSC were 22.3°C for W1, 36.3°C for W2 and 39.0°C for W3. The size of the wire selected was 0.016×0.022 in for all the materials.
Table 1  Orthodontic Ni-Ti wires used

<table>
<thead>
<tr>
<th>Type</th>
<th>Material</th>
<th>Size</th>
<th>Manufacturer</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superelastic</td>
<td>SENTALLOY</td>
<td>0.016×0.022 in</td>
<td>Tommy International Inc., Tokyo, Japan</td>
<td>W1</td>
</tr>
<tr>
<td>(Medium)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shape memory</td>
<td>COPPER NI-TI</td>
<td>0.016×0.022 in</td>
<td>Ormco Subsidiary of Sybron Corporation, California, USA</td>
<td>W2</td>
</tr>
<tr>
<td>(35 C)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shape memory</td>
<td>COPPER NI-TI</td>
<td>0.016×0.022 in</td>
<td>Ormco Subsidiary of Sybron Corporation, California, USA</td>
<td>W3</td>
</tr>
<tr>
<td>(40 C)</td>
<td></td>
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</tbody>
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An upper dental arch resin model was prepared. Simulating the orthodontic treatment of the lingual malposed tooth, the left lateral incisor of the model was removed to form the testing space for deflection of the wire. The 0.018×0.025 in brackets (TWIN MINI DIAMOND, Ormco Co. Glendora, USA) were bonded to the teeth surfaces except for the first molars to which first molar tubes (ORTHOS ACCENT, Ormco Co. Glendora, USA) with preadjusted angulation and torque were attached. The wire was ligatured to the brackets on the teeth along the dental arch and a left lateral incisor bracket was directly ligatured to the wire at the center between the central incisor and canine brackets as in Fig. 1. The interbracket distance for the testing space was 14 mm.

Fig. 1 shows the block diagram of the testing apparatus. The deflection was applied to the wire with a rod connected to the load cell (TENSILON, load cell: 5 kg, ORIENTIC, Tokyo, Japan). The temperature was controlled with a water bath at 23, 32 or 40°C. The temperature 32°C was referred to as that of the anterior tooth surface. Since the tight bonding of the brackets to the artificial teeth was the prime requirement in the experiment, the arch model was made of acrylic resin. It was found in the preliminary experiment that these temperature ranges showed a slight effect of the temperature changes requiring a little correction of the load detection on account of the thermal expansion of the resin model. The blank test using 18-8 stainless steel wire detected the increase or decrease by approximately 10 gf when the temperature was changed between 23 and 32°C or 32 and 40°C. Therefore, the detected loads were corrected on the basis of the load at 23°C. As the effect of the thermal expansion of the resin model became measurably larger at 60°C, the present...
study limited the temperature change up to 40°C. The wire was loaded at a rate of 2.0 mm/min until the maximum deflection reached 1.0, 1.5 or 2.0 mm and successively unloaded with the same speed at each temperature.

After the wire was given a 1.0 mm maximum deflection at 32°C (point A in Fig. 2), the changes in the recovery force against the deflection were examined when the wire was subjected to the following temperature changes:

1. 32→40→32°C
2. 32→23→32°C

Furthermore, the changes in the recovery force were pursued during the deflection change from 1.0 to 0 mm at each temperature successively after the temperature was changed. Similar examinations were performed at the point B in Fig. 2 where the wire was once given a 2.0 mm maximum deflection and the deflection was reduced to 1.0 mm at 32°C.

All the examinations were repeated 3 times for each of 3 specimens and the results obtained were statistically analyzed by one-way ANOVA and Scheffe’s t-test.

RESULTS

Fig. 3 shows the load-deflection curves for three wires at 40, 32 and 23°C when the wire was loaded to give 2.0, 1.5 or 1.0 mm maximum deflection and then unloaded. In the superelastic wire W1, the hysteresis loop was observed at every temperature (Fig. 3-(1)). The force level was the highest at 40°C and the lowest at 23°C. As the deflection was reduced from the maximum 2.0 mm, the load was rapidly decreased during the first stage of about 0.5 mm. Then the curve showed a plateau where the deflection decreased as keeping the small and steady recovery force. Finally it went back to zero. When the maximum deflection was 1.5 or 1.0 mm, the load also rapidly decreased during the first 0.5 mm reduction of deflection and then gradually fell on the curve for the maximum deflection of 2.0 mm.

The shape memory wires W2 and W3 also showed superelastic behaviors with hysteresis loop at 40°C (Fig. 3-(2) and 3-(3)). The force level was the smallest in W3 and the largest in W1. At 32 and 23°C, the recovery forces of W2 and W3 reached
zero before the deflection was completely eliminated leaving apparently permanent deflection. The permanent deflections at 32 and 23°C were 0.1 and 0.3 mm, respectively, for W2, while they were 1.4 and 1.7 mm out of 2.0 mm, respectively, for W3. When the maximum deflection was 1.5 or 1.0 mm, the recovery force decreased leaving individually different permanent deflection.

Fig. 4 showed the changes in the recovery force of the wires with the temperature changes at the point A in Fig. 2. When the wire was given 1.0 mm maximum deflection at 32°C and the temperature was raised to 40°C as keeping the deflection constant, the recovery force increased in every wire. However, the resultant force level was significantly smaller than that on the loading at 40°C (p<0.01). As the deflection was reduced successively after the temperature reached 40°C, the force decreased in a manner of falling on the original recovery curve at 40°C. When the temperature was returned to 32°C from 40°C in the change of 32→40→32°C at the constant deflection, the force went down across the initial value to the level significantly smaller than it (p<0.01, Figs. 4 and 5-(1)). In the temperature changes of 32→23→32°C, the forces at 23°C and 32°C after changed were also significantly smaller than their originals on the curves of respective temperatures (p<0.01) as seen in Fig. 4 and 5-(2)).

Figs. 6 and 7 show the changes in the recovery force when the 2.0 mm maximum
Fig. 4 Load-deflection curves when the temperature was changed at 1.0 mm deflection on the loading curve (A in Fig. 2).

Fig. 5 Temperature dependence of the recovery force at the 1.0 mm deflection on the loading curve (A in Fig. 2).
Fig. 6 Load-deflection curves when the temperature was changed at 1.0 mm deflection on the descending curve from 2.0 mm deflection (B in Fig. 2).

Fig. 7 Temperature dependence of the recovery force at the 1.0 mm deflection on the descending curve from 2.0 mm deflection (B in Fig. 2).
deflection was once given and reduced to 1.0 mm at 32°C followed by the temperature changes there (point B in Fig. 2). Inversely to those at the point A, the recovery forces after the temperature changes of 32→40→32°C and 32→23→32°C changed to the values significantly larger than those of the original recovery curves at the respective temperatures in W1 and W2 (p<0.01). A distinctive behavior was recognized in W3. The recovery force of the wire already reached zero leaving 1.4 mm permanent deflection at 32°C and it was zero at 1.0 mm deflection. When the temperature was raised to 40°C there, the wire again exerted the recovery force. It was 200 gf, which was significantly larger than that of the original value at 40°C (p<0.01). As the deflection was then reduced at 40°C, the force decreased along the original curve at 40°C. By returning the temperature to 32°C from 40°C at the constant 1.0 mm deflection, the final recovery force was settled to 100 gf but not to zero.

DISCUSSION

Many of the load-deflection curves of Ni-Ti orthodontic wires have so far been derived from the free-end, simple three-point bending tests24-28,34-36,41-44). In the present study, the bending test was performed on a dental arch model under the wire being restrained the brackets simulating the orthodontic treatment of the lingual malposed, upper left lateral incisor. As seen in Fig.3-1, the load-deflection curves of the superelastic Ni-Ti wire, W1, also showed the hysteresis loop under the restraint condition. The load or the recovery force at a given deflection in the present study was significantly larger compared to those in the three-point bending test for Ni-Ti wires24-28,34-36,41-44). It was 3.5 times larger during loading and 1.6 times larger during unloading than those obtained from the three-point bending test by Chen48) for the same brand of wire and equivalent deflection and temperature. Chen roughly estimated from the test with the wire end being free or restricted by brackets that the recovery force in the mouth might be well correlated with the three-point bending load to give equivalent deflection at room temperature by a ratio of 1.548). Wilkinson et al. also reported that the force of a superelastic Ni-Ti wire was 2-3 times larger in the test on the dental arch model than in the simple three-point bending test46).

When a 2.0 mm maximum deflection was given at 32°C, W1 wire exerted as large as 1,200 gf of recovery force. The advantage of the lower recovery force in this wire is based on the plateau phase in the recovery process, and it should be noted that the wire exerts such a large level of force at the initial stage after set. Especially the accelerated increase in the superelastic load against the deflection beyond 1.5 mm might be due to the effect of the restraint of the wire. When the deflection was reduced from the maximum 2.0 mm to around 1.5 mm, the recovery force rapidly decreased to reach the plateau in the hysteresis loop. The plateau showed almost the steady force of 400 gf during the deflection range from 1.5 to 0.5 mm. It may still be much larger than the optimal orthodontic forces for individual tooth indicated in the guidelines22).

As the temperature was raised, the hysteresis loop of W1 shifted toward the
larger force level almost parallel in relation to the temperature changes, resulting in the plateau force being larger. These behaviors were demonstrated in the free-end, three-point bending tests of our previous reports and others. Although the present study employed the resin arch model, it was supported by the preliminary experiment and these references that the phenomena were not based on the thermal expansion of resin. As mentioned in the experimental method, the effects of the thermal expansion were well correctable within the temperature range of 23 to 40°C. The data have been corrected according to the preliminary experiment. The characteristic behaviors of Ni-Ti wires are based on the martensitic transformation followed by the inversed martensitic transformation. They involve the stress-inducing process and temperature-inducing process. The former is mainly associated with the superelastic behavior, and the latter the shape memory. However, both the processes may interact with each other even in the superelastic wire. In the load-deflection curve at a higher temperature, the applied load may induce the martensitic transformation to increase the deflection while the elevated temperature may induce the inversed martensitic transformation to reduce the deflection. This might be the reason why the force level of the hysteresis loop became higher at the higher temperature.

In the cases of the maximum deflection being 1.5 or 1.0 mm, the recovery force also rapidly decreased with the first 0.5 mm reduction of the deflection at any temperature (Fig. 3-(1)). Then it gradually fell on the curve for the maximum deflection of 2.0 mm. In this way, the rapid decrease in the recovery force before the plateau was commonly observed during the 0.5 mm reduction from any maximum deflection at any temperature. It means that the orthodontic force with this wire may markedly decrease even by the small movement of the tooth at the initial stage. Besides the plateau appeared for only a short or little range of deflection when the maximum deflection was set small. If a small, steady force is requested from the initial stage after the wire is set, it may be recommended to give the wire once excessive deflection before setting.

The shape memory Ni-Ti wires, W2 and W3, were different from W1 in the recovery curve with temperature changes (Figs. 3-(2) and 3-(3)) although the load to give a deflection became larger with the elevated temperature. As their Af points were 36.3°C and 39.0°C, respectively, they also exhibited superelastic behaviors in their load-deflection curves showing hysteresis loops at 40°C. The superelastic load or recovery force was the smallest in W3 and the largest in W1 at a given deflection, indicating that the wire having higher Af point showed smaller recovery force. When the maximum deflection was 1.5 or 1.0 mm, W2 and W3 showed almost the same behaviors of recovery with W1 at 40°C except for the force level.

At 32 and 23°C, W2 drew the load-deflection curve similar in most of the parts to the superelastic behavior although it left small amounts of permanent deflections. It showed the low level of plateau recovery force between around 0.5 and 1.5 mm, and its clinical utility might be rather analogous to the superelastic wire. The W3 wire, on the other hand, showed a typical load-deflection curve of the shape memory
wire. The load or recovery force at the 2.0 mm maximum deflection was 650 gf at 32°C. It was 5.1 times larger than that obtained in the three-point bending test by Fukuizumi et al.41) The ratio was much larger than that in W1. Wilkinson also recognized that the different materials showed different ratios among the testing methods46). When the deflection was reduced from its maximum, the recovery force of W3 was rapidly dropped to zero leaving 1.4 mm of permanent deflection at 32°C and 1.7 mm at 23°C. It means that the wire may apparently be useless after a short movement of the tooth if the temperature is unchanged.

The effects of the temperature changes on the recovery force appeared distinctively different by the time when the changes were given on the way of load-deflection curve. When the wire was given 1.0 mm maximum deflection at 32°C and the temperature was elevated to 40°C there (point A in Fig. 2), the force significantly increased (Figs. 4 and 5-(1)). It was found that this phenomenon appeared both in the superelastic and shape memory wires. The shape recovery of Ni-Ti wire from martensitic deformation is due to the inversed martensitic transformation by removing the stress that yields the deformation or by heating the wire. Thus, the elevation of the temperature from 32 to 40°C might induce the shape recovery from the deflection yielded at 32°C. As the shape change was restrained while the temperature was changed in this experiment, it might appear as the increase in the recovery force. However, the increased force was significantly smaller than that of the load-deflection curve at 40°C. It means that the larger force might be needed to give a deflection by the stress-induced martensitic transformation process when compared to the shape recovery force exerted by the temperature-induced inverse transformation process utilizing the deflection.

When the temperature was returned back to 32°C, the force decreased to the value significantly smaller than the initial. In the temperature changes of 32→23→32°C, the force also changed to the values significantly smaller than those on the load-deflection curves at the respective temperatures (Figs. 4 and 5-(2)). Finally the force at 32°C fell into the same level both after the temperature changes of 32→40→32°C and 32→23→32°C. These phenomena were observed in every wire regardless of the Af point. The results suggest that the wire once subjected to a temperature change, whether it is heated or cooled, may always show a smaller force than estimated from the load-deflection curve at any temperature. Such temperature changes ordinarily occur in the mouth by hot or cold foods and drinks, which may provide an advantage of Ni-Ti wire to lower the orthodontic force at the initial stage after setting.

The temperature-dependence at the point B in Fig. 2 appeared in quite different ways from the point A reflecting the history of the wire in spite of the same deflection. When the temperature was changed from 32 to 40°C at the point B on the load descending curve, the recovery force of W1 increased over that on the hysteresis curve of 40°C (Figs. 6-(1) and 7-(1)). By cooling it back to 32°C, the force never returned to the initial at 32°C but stopped at the level that was significantly larger than the initial. Otsubo demonstrated the analogous tendencies for superelastic Ni-Ti
wire in the three-point bending test except for the force level\cite{42,43}. It is the characteristic behavior in the stress-induced transformation of the Ni-Ti wire that the deflection rapidly decreased with a slight decrease in the load after the period of the first rapid decrease in the load. The results obtained in this experiment indicate that the reduction of deflection may be easier to occur in the stress-induced transformation process than in the temperature-induced process. The recovery force was also shifted to the values larger than those on the hysteresis curves at 23 and 32°C when the temperature was changed in a way of 32 → 23 → 32°C. Thus, the superelastic recovery forces after once subjected to the temperature changes were always shifted to the larger level than the original forces it showed at the respective temperatures. Therefore, it should be noted that the force may be much larger in the mouth than estimated by the simple laboratory test. Those values were thereafter unchanged even if the temperature changes were repeated as in the three-point bending tests by Otsubo\cite{42} and Fukuizumi et al.\cite{41}. When the deflection was reduced after temperature changes, the recovery force decreased in a manner gradually going close to the original curve at each temperature.

Although W2 is a shape memory wire and permanent deflections appeared at 23 and 32°C, it showed the same tendencies in the recovery force changes with W1 by the temperature changes at 1.0 mm deflection (point B).

Many of the practitioners may have experienced the tooth absorption after orthodontic treatment. It was suggested that the symptom might be induced by too larger orthodontic force\cite{49}. It was also reported that the occurrence of the root absorption became less frequently after Ni-Ti wires have been used\cite{7,8,50}. However, the risk of it seems to still remain considering the recovery force was significantly larger under the wire being restrained in the present study than estimated from the data through the simple three-point bending test as well as in the references\cite{24-28,34-36,41-44}.

The other shape memory wire W3 of which Af point is 39.0°C exhibited characteristic feature. In the load-deflection curve, the recovery force disappeared after the deflection was reduced by 0.6 mm from the maximum 2.0 mm at 32°C, leaving 1.4 mm permanent deflection as seen in Fig. 3. It may be suspected from this result that the wire will be no more useful if the tooth shortly moves as long as the temperature is kept unchanged. However, the permanent deflection was referred to the martensitic deformation and it might be the potential source of the recovery force for the shape memory mechanism. When the temperature was elevated to 40°C, the recovery force was again exerted by the shape recovery transformation from the remaining permanent deflection (Fig. 6-(3)). It reached as large as 200gf at 1.0 mm deflection, while no force was again exerted when the temperature was lowered to 23°C from 32°C because it was within the changes below the transformation temperature range. Even when the temperature dropped down to 32°C from 40°C, the recovery force maintained 100 gf but not zero. Although the force seemed to decrease to zero shortly with decrease in the deflection at 32°C in Fig. 6, the wire would continue to exert 100-200 gf because it would always be activated with existing martensitic deflection by the temperature changes between 32 and 40°C in oral circumstances.
The physiological and histological studies emphasized to apply smaller orthodontic force to protect the surrounding tissues\textsuperscript{10-21}. In the clinical studies, various levels of the forces ranging from 20 to 1,500 gf were proposed for a tooth movement although the tooth of interest was different with each other\textsuperscript{1-9}. It might be difficult to get clinically universal results because the situations as well as the treatments were inevitably different among the cases. At present, many orthodontists seem to affirm the guidelines that the force of 150 gf or less may be enough to move individual tooth without affecting the surrounding tissues\textsuperscript{22}, although they may actually use much larger forces. Providing the lighter force is desirable, W3 may be the best wire among the three examined. The recovery force of W3 seemed analogous to the physiologically desirable orthodontic force\textsuperscript{10-22} while W1 showed extremely larger force under the restrained condition.

There are various demands for orthodontic treatments, speedy achievement in some patient, less pain in some and so on. It was reported that the tooth surface temperature was 32°C during resting hours and raised to 52°C with hot foods or drinks\textsuperscript{41,42}. The recovery force of W3 is assumed to be the most susceptible to the effects of the changes in the oral temperature because its Af point is 39.0°C\textsuperscript{41} as seen in the present results. It may exert mild force comparative with the guideline for optimal orthodontic treatment\textsuperscript{22} at the resting oral temperature and intermittently larger force only when the patient takes hot foods or drinks. Thus, it may be useful especially for the hypersensitive or periodontal patients who need delicate force.

Various types of Ni-Ti orthodontic wires are commercially available. They involve superelastic and shape memory wires with many different martensite-austenite transformation temperatures as well as cross sectional shapes and sizes. Since they show different characteristics according to their martensitic transformation temperatures as mentioned above, they should be effectively utilized with deep knowledge of their particular temperature- and deflection-dependences.

REFERENCES


