The effect of temperature on the elastic responses to longitudinal torsion of rectangular nickel titanium archwires

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Nickel titanium (NiTi) alloys have received considerable attention since their introduction to orthodontics. Like many metal alloys, NiTi can exist in more than one crystal structure, depending on the temperature and mechanical stress the alloy is subjected to.[1] The first NiTi wires had no applicable phase transition effect, but gained popularity because of their low stiffness and excellent springback properties.[2,3] Later, NiTi archwires that easily transform between a high-temperature austenite phase and a low-temperature martensite phase were introduced.[4,5] Transformation can occur either by lowering the temperature or, within a defined temperature range, by applying stress, giving these archwires two remarkable properties, namely, shape memory and superelasticity.[6]

Shape memory

Shape memory alloys can be plastically deformed in their martensite phase, but will return to an austenite phase, thereby recovering their original shapes, if heated above a temperature range.[5] The original arch form is set ("memorized") while the alloy is in an austenitic or parent phase during high temperature treatment.[7]

Abstract

To investigate responses to longitudinal torsion and the effect of temperature on the torsional stiffness of superelastic nickel titanium archwires, eight batches of rectangular wires were tested at 18, 27, 37, and 40°C ambient temperature. The wires were twisted 25 degrees and studied in deactivation. The resulting torque-twist diagrams show that only half the wires had discernible deactivation plateaus at body temperature. The plateaus were generally narrow (1 to 3 degrees) and started at 20 to 23 degrees of torsional twist. The clinical significance of these deactivation plateaus is debatable. Only one wire had a well-defined plateau that was fairly wide (6 degrees) and started at a lower level of twist (17 degrees). The wires without plateaus when deactivated from 25 degrees of twist were retested at body temperature. All exhibited deactivation plateaus subsequent to activating twists of 45 and 60 degrees, and the plateaus became more distinct as the degree of prior activation increased. This indicates that the stress imparted on the alloys by 25 degrees of activating twist is insufficient to induce martensitic transformation at body temperature. As prescriptions advocate bracket pretorque of less than 25 degrees for a maxillary central incisor, the clinical relevance of alloys requiring large activations before they demonstrate deactivation plateaus is questionable. Half the wires tested were markedly influenced by ambient temperature changes; the other half were relatively insensitive to temperature. Responsiveness to thermal stimuli seemed closely related to superelastic tendency.

Key Words

Archwires • Materials testing • Torsional stiffness • Nickel titanium alloys • Copper nickel titanium alloys • Superelasticity

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In a thermodynamic archwire, bends can be placed in its highly ductile martensitic state at room temperature to allow complete engagement in brackets of severely malpositioned teeth. Upon heating subsequent to intraoral insertion, the archwire will attempt to return to its original shape and consequently exert force on the teeth. Thus, to be clinically relevant, the transition temperature should be somewhat below or around mouth temperature.[8]

In an original study, Bishara et al.[9] determined the transition temperatures of three thermodynamic archwires. The transition temperatures showed little variation, with means ranging from 24.7 to 25.3°C. Furthermore, the transition temperature ranges (TTR) were similar for all three wires (from 6.2 to 6.7°C), but the standard deviations differed. The authors suggested that this may be a function of manufacturing during alloying or heat treatment of the archwire.

The TTR is extremely sensitive to the slightest departures in the manufacturing process.[10] As the compositional accuracy required for NiTi alloys is often more precise than the errors in chemical analysis, the TTR itself is often used for quality control purposes.[11] The TTR can be adjusted by increasing the nickel content in the alloy.[11] The shape memory properties of NiTi are modified by adding a third element chemically similar to nickel or titanium, copper, for example.[12] Apart from depressing the TTR, the addition of a third element to NiTi is used to increase the stability of the transformation start temperature, control hysteresis width, and improve corrosive resistance.[11]

Superelasticity

In a shape memory alloy, transformation from an austenite to a martensite phase can also occur by application of stress within a defined temperature range. The martensite so-formed is called stress-induced martensite (SIM), and the driving force for the transformation is mechanical, as opposed to thermal.[6] Within a temperature range, martensite can be made stable with the application of stress, but it becomes unstable again when the stress is removed. There is a linear relationship between stress and temperature with respect to induction of martensite; a decrease in temperature is equivalent to an increase in stress.[6]

The terms *pseudo-elasticity* and *superelasticity* have often been used interchangeably. The former is a more general term, denoting any nonlinearity in the stress-strain curve during unloading.[13] Pseudo-elasticity can be caused by either twinning, i.e., reversible motion of twin boundaries in the crystal structure,[6] or by transformation, i.e., a stress-induced martensitic transformation from an austenitic phase.[13] Transformational pseudo-elasticity is called *superelasticity* in its fully evolved form,[13] and manifests itself by a flat or nearly flat plateau in the stress-strain curve during which the transformation takes place.[10,13] At the plateau, a superelastic alloy does not follow Hooke´s law, since there is little change in stress with increasing strain. Thus, superelastic archwires may exert the same amount of force independent of the degree of activation within a wide range.[4,5,10,14,15] Since low and continuous forces are believed to be most efficient for tooth movement,[5,16-18] such archwires have been proposed as nearly ideal for orthodontic treatment.[4,5]

Superelastic behavior of NiTi alloys in bending has been demonstrated in numerous reports, where clearly defined plateaus are depicted.[4,5,19,20] However, the distinctiveness of the deactivation plateau is dependent upon the degree of activation,[4] and recent reports have shown that superelastic NiTi archwires do not always exhibit clearly discernible deactivation plateaus when tested in bending with clinically relevant interbracket and deflection distances.[19,20] Schumacher et al.[21] claimed that there is little advantage in using superelastic NiTi wires as levelling arches compared with conventional NiTi or multistranded stainless steel. Recently, Segner and Ibe[20] tested 16 different NiTi archwire materials in bending and found that many either did not show superelastic behavior or the wire parameters were such that the wires did not constitute an advantage over conventional work-hardened NiTi materials.[20] Consequently, the clinical significance of the current superelastic wires has been questioned apart from cases with severely malpositioned teeth.[19-21]

Effect of temperature

Apart from the degree of activating stress, the temperature at which the archwires are tested may be of critical importance.[4,22] To study the effect of temperature on the load-deflection behavior of superelastic NiTi alloys, Tonner and Waters[19] examined 17 archwires in a heat chamber over a temperature range of 5 to 50°C, using a three-point bending test. Their investigation demonstrated a close relationship between temperature and loading and unloading curves. Furthermore, the bending stiffness decreased dramatically over a narrow temperature range of 10°C (from 30 to 20°C).

Yoneyama et al.[23] studied the thermal behavior of 20 commercial NiTi wires using differen-

Table 1
Wires used in investigation

Producer	Address	Type	Dimensions 17x25	Dimensions 18x25
Dentaurum	Pforzheim, Ger.	Rematitan Super Elastic	X	
Forestadent	Pforzheim, Ger.	Titanol Super Elastic		X
GAC	Central Islip, NY	Neo Sentalloy F100		X
Masel	Bristol, Penn.	Elastinol		X
Ormco	Glendora, Calif.	Copper Ni-Ti 27° C	X	
Ormco	Glendora, Calif.	Copper Ni-Ti 35° C	X	
Ormco	Glendora, Calif.	Copper Ni-Ti 40° C	X	
Unitek	Monrovia, Calif.	NiTinol SE		X

Values for dimensions are given in 1/1000 in.
For metric values, 0.017 in = 0.4318 mm, 0.018 in = 0.4572 mm, and 0.025 in = 0.6350 mm.

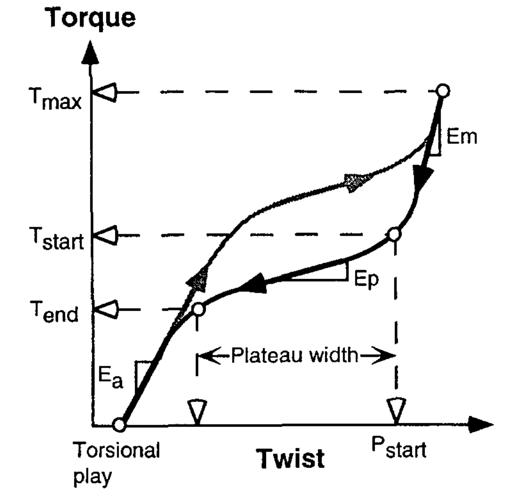

Figure 1

Figure 1
Idealized activation and deactivation torque-twist curve. The deactivation curve has three distinct phases, each with certain characteristic parameters that were determined in this investigation. The wires were activated to a set, predetermined amount of twist (25 degrees) and the torque exerted at this level was recorded (T_{max}). The E_m gives the slope (stiffness) of the initial deactivation phase, when the alloy is in a stress-induced martensitic crystal state. The transformation or plateau phase starts at a certain amount of twist (S_p) and torque (T_{start}), and has a characteristic slope (E_p) and width. T_{end} gives the torque level at the end of the plateau. E_a gives the slope of the final phase, when the alloy is in an austenitic state. The torsional play or third-order clearance was determined as the intercept between the abscissa and a linear regression line fitted to the final part of the deactivation curve.

tial scanning calorimetry and found that most of the wires had transition temperatures between 17 and 32°C. However, some of the wires did not have the correct transition temperature to exhibit superelastic behavior at body temperature.

Aims

As accurate prediction of orthodontic forces from superelastic NiTi wires is difficult because of nonlinearity during deactivation and activation-dependent stiffnesses,[4] there is a need for experimental data from clinically relevant investigations. Furthermore, as torsional or bending curves may look substantially different from tensile stress-strain curves due to nonlinear strain distribution across the wire cross-section,[13] it is important that the wires be tested in all modes of bending. Finally, since the load-deflection behavior of so-called superelastic wires may be critically temperature-dependent[19,23] and show wide intrabatch variations,[24] characteristics of these archwires should be determined at different temperatures. The purpose of this investigation was to evaluate the effect of temperature on the elastic responses of superelastic nickel-titanium-based archwires to longitudinal torsion when tested in a situation simulating application of torque to a single tooth.

Materials and methods

Rectangular nickel titanium and copper nickel titanium (CuNiTi) wires commonly used in the 0.018 edgewise technique were tested in as-received condition. Six manufacturers supplied a total of eight different sizes or types of wires all claimed to exhibit superelastic properties (Table 1). The wires were supplied in arch forms, 10 pieces of each. One manufacturer supplied wires of the same dimensions but with varying features. Four major suppliers from the United States and two from Germany were selected.

From each batch, 25-mm lengths were cut from the nearly straight, posterior sections of the 10 archwire blanks. These cut lengths were tested in a torque-measuring instrument with an interbracket distance of 4 mm. This instrument has been described before[25] and is a further development of a previously reported apparatus.[26,27] The principle of the instrument design is that the test-piece is held in position by three 0.018-inch standard medium twin edgewise brackets with zero degrees torque and angulation (Ormco, Glendora, Calif). The center bracket is stationary while the two supporting brackets are fixed to a crossbar that can rotate around its long axis. When mounted, the brackets are oriented such that an orthodontic wire passing through the bracket slots will have its central axis coinciding with the central axis of the crossbar. Thus, torque input occurs through the two side-brackets as carried by the crossbar. The test-specimen is partitioned into two mirror-imaged cantilevers, as is the case when torque is applied to a single tooth.

The angle of twist can be recorded to the nearest 1/50 degree on a measuring scale. Torque is measured by a Minibeam load cell type MB-10 (Interface Inc, Scottsdale, Ariz) indirectly coupled to the crossbar. The load cell is attached to a moveable stage and connected via a wire to a pulley at the end of the crossbar. The stage can be moved in both directions through a spindle. By moving the stage away from the crossbar, the load cell will pull on the connecting wire and hence the pulley, thereby rotating the crossbar. The linear pulling force is recorded by the load cell and the torque calculated by multiplying the torsional force by the radius of the pulley (35 mm), i.e., the moment arm. As the linear force is

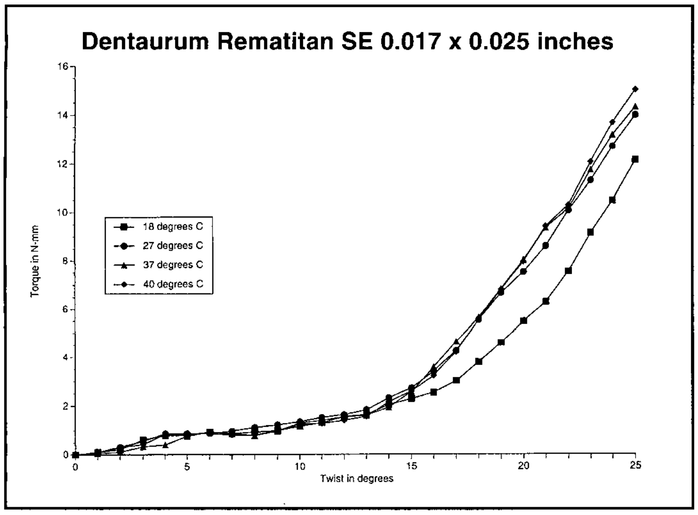

Figure 2A

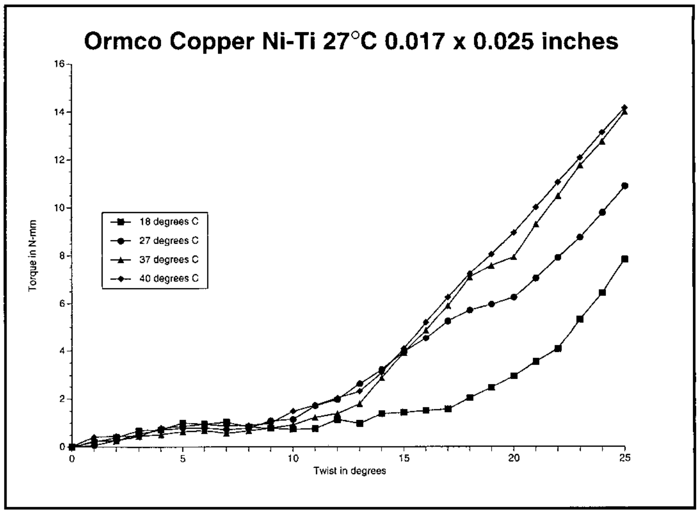

Figure 2B

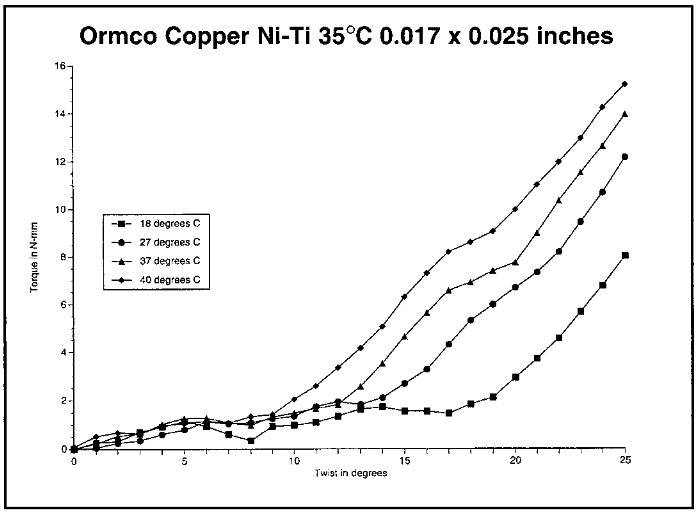

Figure 2C

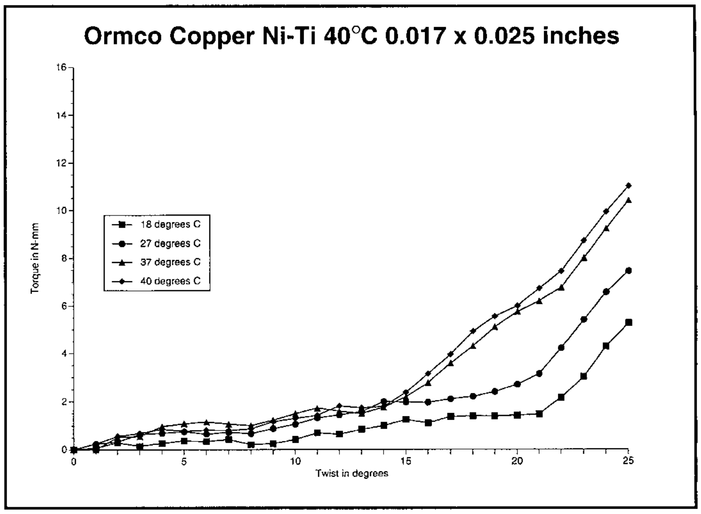

Figure 2D

Figure 2A-D
The effect of ambient temperature on the torsional stiffness of superelastic NiTi wires tested at 18, 27, 37, and 40°C.
A: Dentaurum Rematitan SE 0.017 x 0.025 inch wires
B: Ormco Copper Ni-Ti 27°C 0.017 x 0.025 inch wires.
C: Ormco Copper Ni-Ti 35°C 0.017 x 0.025 inch wires.
D: Ormco Copper Ni-Ti 40°C 0.017 x 0.025 inch wires.

recorded accurate to 1 gram, the torque can be estimated accurate to 0.35 N-mm.

The wire test-piece was ligated into the three holding brackets using Alastik A-Modules (3M Unitek, Monrovia, Calif) and subsequently activated 25 degrees of longitudinal torsion. The wire was then deactivated and allowed to return to zero degrees of twist. The magnitude of twist was read off the scale, and for each degree of return, the force exerted on the load cell was recorded 10 times and the arithmetic mean used in the subsequent calculations. The load cell was coupled to a PC employing an A/D converter card (Strawberry Tree, Sunnyvale, Calif). The program used to record the forces was developed by Dr. Dietmar Segner. For each test-piece a torsional moment-versus-angle-of-twist curve was made. Subsequently, a mean torque-twist curve was calculated for each archwire batch.

An "ideal" superelastic curve is characterized by three distinct phases, each reflective of the predominant crystalline structure in the material at a given loading circumstance. In order to compare the deactivation torque-twist curves of the wires tested, certain descriptive parameters were determined (Figure 1).

In the initial deactivation phase, the wire material is in a stress-induced martensitic structure, and the initial slope of the deactivation curve expresses the torsional stiffness of martensitic NiTi.

The subsequent deactivation plateau phase (martensitic transformation phase) has several important characteristics. Not merely the existence, but also the position, slope, width, and distinctiveness of the deactivation plateau are of major clinical interest. If angle of twist and amount of torque (i.e., the x- and y-coordinates) at the plateau's initial and final points are determined, the plateau can be described in detail.

In the final deactivation phase, the wire material is in an austenitic structure, and the final

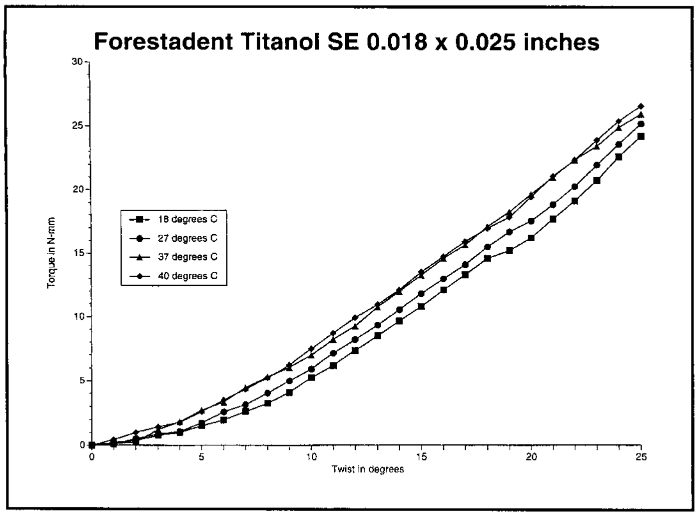

Figure 2E

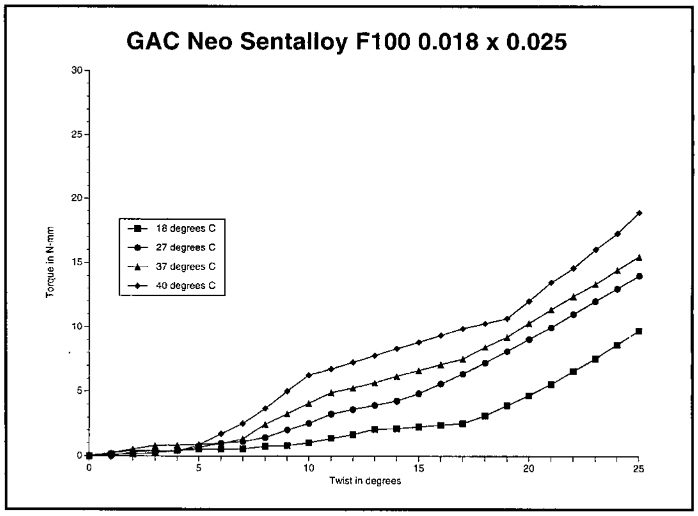

Figure 2F

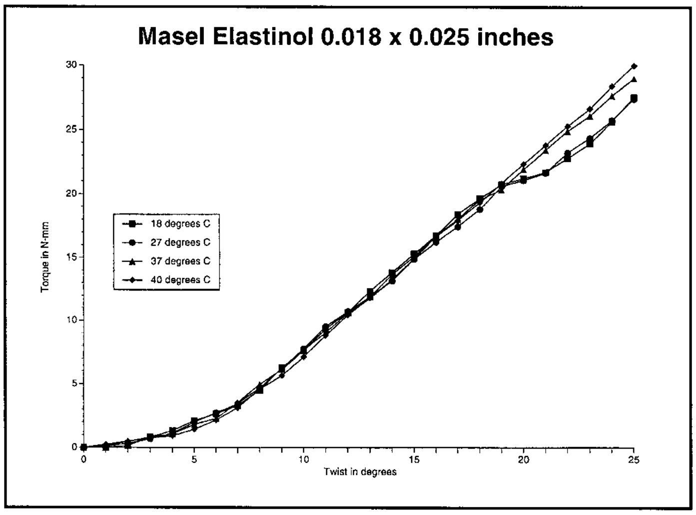

Figure 2G

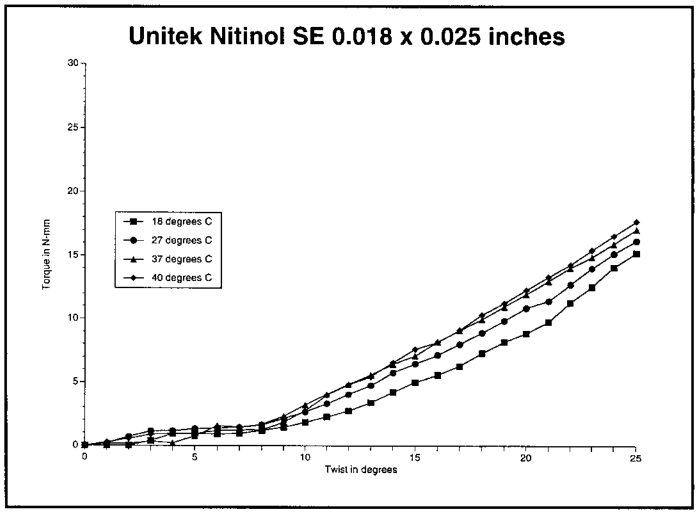

Figure 2H

Figure 2E-H
The effect of ambient temperature on the torsional stiffness of superelastic NiTi wires tested at 18, 27, 37, and 40°C.
E: Forestadent Titanol SE 0.018 x 0.025 inch wires.
F: GAC Neo Sentalloy F100 0.018 x 0.025 inch wires.
G: Masel Elastinol 0.018 x 0.025 inch wires.
H: Unitek Nitinol SE 0.018 x 0.025 inch wires.

slope of the deactivation curve expresses the torsional stiffness of austenitic NiTi.

Finally, the torque at 25 degrees of twist and the torsional play (third-order clearance) were determined. The torsional play that has to be negated when torque is applied to a single tooth is the torsional play from a center position to one extreme in two brackets (i.e., two third-order clearances). In order to estimate torsional play, a regression line was fitted to the linear portion of the torsional moment-versus-angle-of-twist diagram at 37°C using the least squares method. The line's intercept with the abscissa represents the amount of torsional play between wire and bracket.[28] For wires demonstrating pseudo-elasticity, the intercept between the abscissa and a regression line fitted to the linear part of the curve down from the last discernible portion of the hysteresis loop that follows the plateau was used.

Wires that did not exhibit superelastic behavior or tendencies during deactivation from 25 degrees of twist were retested at body temperature up to 15, 30, 45, and 60 degrees of activation.

Torque experiments were carried out in an electrically heated room that measured 5 x 8 feet. The temperature was regulated by a thermostat capable of controlling the temperature with to ±0.5°C (Micromatic, Vejle, Denmark). The temperature was monitored continually using an electronic thermometer accurate to 0.1°C and capable of recording minimum, maximum, and actual temperature. The preset temperature could be maintained within ±0.5°C. To study the effect of ambient temperature, the superelastic archwires were tested according to the method described above at 18, 27, 37, and 40°C (Figure 2A-H, Table 3).

In order to get an impression of the thermal responsiveness of the test wires, the increase in torque exerted at 20 degrees of twist when the ambient temperature was raised from room (18°C) to body (37°C) temperature was calculated (Table 3).

Results

The elastic responses to longitudinal torsion at different temperatures are presented in torque-twist diagrams (Figure 2A-H). Experimentally determined mean values of torque at 25 degrees of twist, torsional stiffness at various temperatures, and torsional play (third-order clearance) are given in Tables 2 and 3.

Superelasticity

The amount of torque exerted at 25 degrees of twist varied considerably and is a result of variations in torsional play and stiffness (Table 2). Within the 0.017 x 0.025 group, the range was from 10.4 to 14.3 N-mm at body temperature. The Dentaurum wire was the stiffest, whereas the Ormco Copper Ni-Ti 40°C wire was the most flexible. The range was from 15.5 to 28.9 N-mm for the 0.018 x 0.025 inch wires, with Masel as the stiffest and GAC as the most flexible wire in this size group.

The Dentaurum Rematitan SE wire had no discernible deactivation plateau at 18°C, and only ill-defined plateaus at the other temperatures (Figure 2A). At body temperature the plateau was very short (1 degree) and started at a high level of twist (22 degrees).

The Ormco Copper Ni-Ti 27°C wire had no detectable plateau at the lowest temperature, but the deactivation curve seemed to have two phases (Figure 2B). When tested at 27°C ambient temperature, it exhibited a distinct deactivation plateau. The wire became stiffer as ambient temperature increased and had no discernible plateau at 40°C. The deactivation plateau at body temperature was short (2 degrees) and occurred at a rather high level of torsional twist (20 to 18 degrees).

The Ormco Copper Ni-Ti 35°C wire had a torsional stiffness intermediate to the two other Ormco wires (Table 2). It had no discernible deactivation plateau at 18°C and only an ill-defined plateau at 27°C (Figure 2C). However, at body temperature it exhibited a distinct deactivation plateau, indicating that the transition temperature is above 27°C and close to 37°C, in accordance with the vendor's claim. At 37°C, the wire had the best defined deactivation plateau of the wires tested (Table 2). On the other hand, the plateau was rather short (3 degrees) and occurred between 20 and 17 degrees of twist.

The Ormco Copper Ni-Ti 40°C alloy had no discernible deactivation plateaus at 18 or 27°C (Figure 2D). At body temperature this wire had a well-defined defined plateau, but it was rather narrow (3 degrees) and at a high level of torsional twist (22 to 19 degrees, (Table 2). Only minor differences were found in elastic response to longitudinal torsion at 37 and 40°C. The wire was very flexible at body temperature, a feature believed to be advantageous in patients sensitive to pain and with compromised periodontal conditions.

The Forestadent Titanol SE wire exerted 25.8 N-mm of torque at 25 degrees of twist, making it one of the stiffest wires tested (Table 2). It had deactivation plateaus at the two lower temperatures, whereas no plateaus could be detected when the wire was tested at 37 and 40°C (Figure 1E).

The GAC Neo Sentalloy F100 wire was very flexible and had well-defined deactivation plateaus at all test temperatures (Figure 1F), indicating a rather wide TTR for this alloy. The ratio between final slope and plateau slope was 2.4 at body temperature, the plateau was quite wide (6 degrees), occurred between 17 and 11 degrees of twist, and the torque level at the plateau was low (5.0 to 7.5 N-mm). Thus, under the present test conditions, this wire delivered low, continuous torquing forces for an appreciable range of twist.

The Masel Elastinol wire was the stiffest wire tested and exerted a torque of 28.9 N-mm at 25 degrees of twist. It had well-defined deactivation plateaus at 18 and 27°C ambient temperature. When activated at body temperature and 40°C, it had no discernible deactivation plateau.

The Unitek Nitinol SE wire was very flexible in torsion and exerted a torque at 25 degrees of twist similar to the GAC wire. Its deactivation curve had two phases at room temperature and a short deactivation plateau at 27°C. At body temperature this wire had no deactivation plateau.

The four wires with minor or no superelastic tendencies during deactivation after 25 degrees of activation, were retested at body temperature after prior activation up to 15, 30, 45, and 60 degrees of twist (Figure 3). The results show that all the wires then started to show significant deactivation plateaus when activated to 45 degrees or more. Furthermore, plateau slope decreased as activation increased.

Thermosensitivity

All the wires were affected by temperature changes to varying extents and exerted more torque for a given amount of twist at the highest temperature (Figure 2A-H and Table 3). Fur-

Table 2
Results from archwire testing in longitudinal torsion at body temperature

Vendor and wire type	Wire size	Torque at 25 deg of twist	Torsional stiffness at 37°C			Superelasticity ratio		Plateau characteristics				Torsional play
			Initial phase	Plateau phase	Final phase	Initial slope to plateau slope	Final slope to plateau slope	Twist at start (deg)	Width of plateau (deg)	Torque at start (Nmm)	Torque at end (Nmm)	
	(inches)	(Nmm)	(Nmm/deg)									(deg)
Dentaurum Rematitan SE	0.017 x 0.025	14.29	1.51	0.79	1.15	1.41	1.26	22	1	10.12	9.33	12.8
Ormco Copper Ni-Ti 27°C	0.017 x 0.025	13.97	1.21	0.42	1.02	2.88	2.43	20	2	7.92	7.92	11.3
Ormco Copper Ni-Ti 35°C	0.017 x 0.025	13.93	1.24	0.39	1.03	3.18	2.64	20	3	7.74	7.74	10.4
Ormco Copper Ni-Ti 40°C	0.017 x 0.025	10.40	1.21	0.50	0.78	2.42	1.56	22	2	6.76	6.76	12.1
Forestadent Titanol SE	0.018 x 0.025	25.84	1.29*	-	-	-	-	-	-	-	-	4.8
GAC Neo Sentalloy F100	0.018 x 0.025	15.48	1.04	0.44	0.81	2.36	1.84	17	6	7.48	7.48	5.2
Masel Elastinol	0.018 x 0.025	28.93	1.45*	-	-	-	-	-	-	-	-	5.1
Unitek Nitinol SE	0.018 x 0.025	17.08	0.99*	-	-		-	-	-	-	-	7.2

* No discernible plateau

Table 3
Results from archwire testing in longitudinal torsion at different ambient temperatures

Vendor and wire type	Torsional stiffness: Initial phase				Plateau phase				Final phase				Temperature sensitivity	Torque at 25 degrees of twist			
Wire size (inches)	18°C	27°C	37°C	40°C	18°C	27°C	37°C	40°C	18°C	27°C	37°C	40°C		18°C	27°C	37°C	40°C
Dentaurum Rematitan SE 0.017 x 0.025	1.52*	1.35	1.51	1.70	-	0.96	0.79	1.16	0.82	1.21	1.15	1.25	46%	12.10	13.96	14.29	14.99
Ormco Copper Ni-Ti 27°C 0.017 x 0.025	1.25*	1.06	1.21	1.04	-	0.27	0.42	0.86	0.50	0.65	1.02	1.08	168%	7.82	10.86	13.97	14.13
Ormco Copper Ni-Ti 35°C 0.017 x 0.025	1.17*	1.32	1.24	1.02	-	0.67	0.39	0.42	-	1.03	1.03	1.05	164%	8.01	12.14	13.93	15.17
Ormco Copper Ni-Ti 40°C 0.017 x 0.025	0.95*	1.08*	1.21	1.19	-	-	0.50	0.63	-	-	0.78	0.90	303%	5.27	7.44	10.40	11.00
Forestadent Titanol SE 0.018 x 0.025	1.62	1.64	1.29*	1.32*	0.81	1.07	-	-	1.20	1.21	-	-	21%	24.12	25.10	25.84	26.48
GAC Neo Sentalloy F100 0.018 x 0.025	0.97	0.99	1.04	1.37	0.12	0.39	0.44	0.57	0.35	0.61	0.81	1.24	121%	9.73	14.03	15.48	18.90
Masel Elastinol 0.018 x 0.025	1.81	1.52	1.45*	1.52*	0.48	0.52	-	-	1.50	1.38	-	-	5%	27.48	27.36	28.93	29.93
Unitek Nitinol SE 0.018 x 0.025	1.32*	1.19	0.99*	1.06*	-	0.57	-	-	0.95	0.92	-	-	35%	15.24	16.19	17.08	17.72

*No discernible plateau

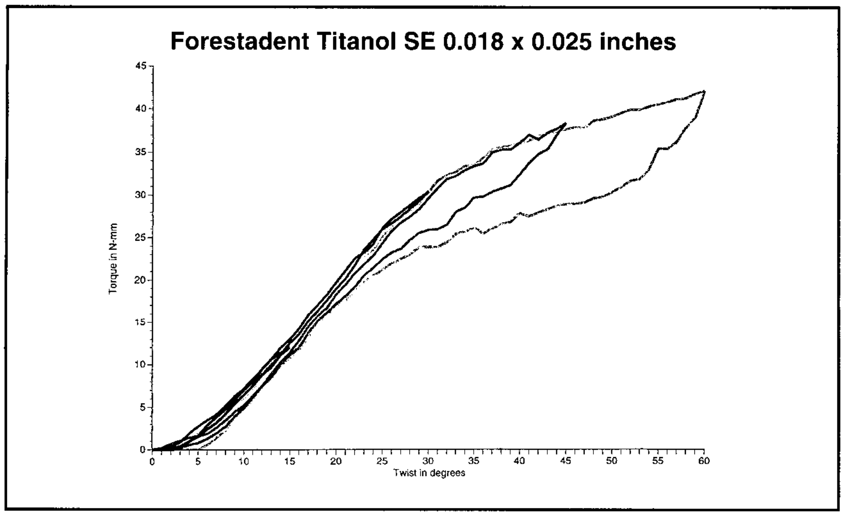

Figure 3

Figure 3
Typical activation-deactivation curve for archwires with slight or no superelastic tendencies when deactivated from 25 degrees of twist (Forestadent Titanol SE 0.018 x 0.025 inches). The wires were tested at body temperature and activated to 15, 30, 45, and 60 degrees of twist prior to deactivation. All the wires exhibited deactivation plateaus when activated to 45 degrees or more.

thermore, the wires exerted the least amount of torque for 18°C ambient temperature. The torque-twist diagrams at 37 and 40°C ambient temperature were relatively similar for the majority of the wires tested.

With respect to the 0.017 x 0.022 inch wires, the Dentaurum wire was only moderately temperature-sensitive, with an increase in torque level at 20 degrees of twist of approximately 46% when the temperature was raised from room to body temperature (Table 3). The three Ormco Copper Ni-Ti wires were far more thermodynamic than the other wires tested, with the exception of the GAC wire. Of the three Ormco Copper Ni-Ti wires, the 40°C wire demonstrated the greatest thermal response (303%), followed by the 27°C wire (168%), and the 35°C wire (164%, Table 3).

The 0.018 x 0.025 inch wires were also a heterogeneous group. The Forestadent wire was slightly temperature-sensitive, with an increase in torque of only 21% between 18 and 37°C at 20 degrees of twist (Figure 2E). The GAC Neo Sentalloy was very flexible at room temperature and showed an intermediate temperature-sensitivity, with an increase of 121% between 18 and 37°C (Figure 2F). The Masel wire was temperature-insensitive (5% from 18 to 37°C), whereas the Unitek wire had only a minor temperature-sensitivity (35% from 18 to 37°C, Table 3).

Discussion

In this investigation, rectangular superelastic nickel titanium alloy archwires were subjected to controlled bench-testing in a torque-measuring instrument. The test specimens were subjected to longitudinal torsion and studied in deactivation, as only the deactivation curve is of clinical interest. The objective was to study archwires under clinically relevant test conditions, and the torque apparatus simulates application of torque to a single tooth with standard edgewise brackets with 0.018 inch slots and no "pretorque" or angulation. The interbracket distance was set at 4 mm.

The test design simulates application of torque (actio) to a single tooth. The reactio-torque will be transferred to the neighboring "anchor" teeth. This is valid for the study of torsional stiffnesses, but the results may not have direct relevance for application of torque to multiple teeth simultaneously because the archwire is curved as viewed from an occlusal perspective and both first- and second-order bends or deviations may influence torque delivery via effects on torsional play.[29] However, the anterior segment can be perceived as a wide bracket if the central and lateral incisors are perfectly aligned. Consequently, our experimental data may be extrapolated, with certain reservations as to the effects of force interactions and archwire curvatures, to a more clinically relevant situation where torque is applied to the anterior segment.

Superelasticity

As metallurgic and orthodontic interpretations of the term superelasticity may differ, a working definition must be established in order to compare superelastic archwires. Segner and Ibe[20] studied superelastic wires in bending and developed certain parameters to better describe the deactivation curve. They expressed the distinctiveness of the deactivation plateau by the ratio of the slope of the final part of the deactivation curve to the slope of the plateau (SE ratio). According to this model, an ideal superelastic archwire should yield an SE ratio of infinity, and stainless steel wires a ratio of approximately 1. The investigators suggested a definition of superelasticity as a ratio above 8 and superelastic tendency as a ratio between 2 and 8.

Whether or not one should define superelastic behavior using an arbitrary limit of the SE ratio as a criterion remains debatable. However, even if one accepts the rationale of defining superelastic behavior in this way for comparative reasons, where the limit should be set is not obvious. If the criteria for load-deflection behavior proposed by Segner and Ibe[20] are used, none of the wires tested in this investigation exhibited superelastic behavior and only one exhibited superelastic tendency in longitudinal torsion when deactivated from 25 degrees of twist at body temperature (Table 2). However, many orthodontists would describe the torque-twist curve of the GAC Neo Sentalloy wire, and possibly also the three Ormco Copper Ni-Ti wires, as superelastic (Figure 2B-D, F). Thus, the sensitivity of the SE ratio as an indicator of superelastic behavior of archwires in longitudinal torsion can be questioned. Furthermore, the specificity of this parameter is also unsatisfactory. On the other hand, if the distinctiveness of the deactivation plateau is expressed as the ratio of the initial slope to the plateau slope, somewhat different results are obtained (Table 2). The four previously mentioned wires have ratios above 2 at body temperature. Thus, there is better general agreement between the visual impression of the torque-twist curves and this ratio, indicating improved sensitivity and specificity.

Superelastic materials display clinical advantages over a flexible work-hardened NiTi wire only if the working point is on the plateau.[20] Although some prescriptions advocate up to 22 degrees of pretorque for a maxillary central incisor, the majority suggest 10 to 14 degrees.[30] Consequently, the mere existence of a deactivation plateau may not provide clinically detectable advantages if it is narrow or starts at a high level of twist. With the exception of GAC Neo Sentalloy F100, the wires with pseudo-elastic torque-twist curves had deactivation plateaus that generally started at 20 to 23 degrees of torsional twist and were narrow (1 to 3 degrees). Thus, the clinical importance of these deactivation plateaus is debatable. The GAC wire had a well-defined deactivation plateau that was fairly wide (6 degrees) and started at a lower level of twist (17 degrees). Furthermore, as the torque level at the plateau was low (7.5 to 5.0 N-mm), this wire delivered low, continuous forces over a considerable range.

The general lack of distinct superelastic behavior under clinically relevant test conditions is in accordance with previous observations.[25] Two factors may help explain these findings; one is related to the archwire materials and the other to the test conditions.

Minute differences in the manufacturing process seem to have significant impacts on the archwires.[10] Among these are nickel content, oxygen content, processing heat treatment, and work-hardening history. The observed scarcity of superelastic behavior among the test specimens may in part be due to the difficulty of making an alloy with an exact transition temperature.[23]

The amount of activating twist is of critical importance. As demonstrated by Burstone et al.,[4] the stiffness of superelastic archwires is dependent upon the degree of activation. The load-deformation rate at small activations is considerably higher than at higher activations.[4,19] Consequently, the distinctiveness of the deactivation plateau becomes more pronounced as prior activation increases.[10,19,25] Since none of the commonly used pretorque prescriptions have incorporated more than 22 degrees of twist into the maxillary central incisor bracket,[30] this may be considered the upper limit of clinically relevant third-order activation. However, when inserted into the bracket, the wire is often twisted somewhat more than the exact prescribed torque. Allowing for some extra twist, we were of the opinion that an activation to 25 degrees of twist would be reasonable from a clinical point of view.

To examine whether lack of superelastic behavior could be due to too low archwire activations, the four wires with little or no superelastic tendencies were activated to 15, 30, 45, and 60 degrees of twist and studied in deactivation at body temperature. Figure 3 demonstrates a typical torque-twist diagram with four activation-deactivation loops. All the wires tested exhibited deactivation plateaus after being activated 45 and 60 degrees and the plateaus became more well-defined as the degree of activation increased. This finding lends support to the post-hoc hypothesis that an activating twist of 25 degrees was insufficient to "unveil" the superelasticity in these wires and induce martensitic transformation. However, when subjected to more stress, the wires exhibited deactivation plateaus, indicating that martensitic transformation did occur. Consequently, the superelasticity of these wires seems to be of questionable clinical importance for torque application. However, the wires were clearly more flexible than stainless steel,[26] chrome cobalt,[31] or beta-titanium wires,[25] and as such can be of great clinical value.

Thermosensitivity

Stress-induced martensite is responsible for the superelastic characteristics of NiTi alloys. However, martensitic transformation is also temperature dependent. There is a linear relationship between temperature and stress.[6] Furthermore, martensite can be induced by stress only within a definite temperature range, that is between the transition temperature (Af) and the maximum temperature at which martensite can exist (Md). It follows that the working temperature of the orthodontic appliance should be greater than Af to exploit its superelasticity to its fullest potential. The Ormco Copper Ni-Ti wires have different transition temperatures (Table 1). The rationale is that the force generated by NiTi alloys is determined by the differential between the Af and the working temperature. Thus, a wire with a transition temperature of 27°C will generate higher forces than wires with higher Af points after intraoral insertion. This investigation confirms that the Ormco Copper Ni-Ti 35°C wire had a torsional stiffness intermediate to the Ormco wires with Af points at 27°C and 40°C, in accordance with the vendor's claim (Table 2).

The wires showed varying degrees of temperature sensitivity. Overall, raising the temperature from 37 to 40°C had only minor effect on the torque-twist diagrams for the majority of the wires, but each wire exerted more torque for a given amount of twist at the highest test temperature (Figure 2A-H, Table 3). Furthermore, the wires exerted the least amount of torque at 18°C ambient temperature.

For the wires with superelastic tendencies, the gradient of the initial slope decreased markedly as the temperature was reduced. Furthermore, the values of the torque in the deactivation plateau regions decreased as ambient temperature was reduced (Table 3). These findings are in agreement with those previously reported by Tonner and Waters.[19]

The temperature-sensitive wires were flexible at room temperature and became stiffer as the temperature increased toward body temperature. This may be of benefit, since it makes wire insertion easier.[9] However, it may be a disadvantage since the orthodontist cannot feel how much force the activated appliance will exert. Wires without temperature sensitivity will not show this effect and the orthodontist will immediately appreciate the stiffness of the wire being inserted.

The Ormco Copper Ni-Ti wire with Af point at 35°C was far more thermodynamic than the other wires tested. The torque exerted at 20 degrees of twist increased by more than 300% when the ambient temperature was raised from room to body temperature. The other two CuNiTi wires and the GAC Neo Sentalloy wire had intermediate temperature sensitivities, with an increase in torque from 121% to 168%. The other wires were only moderately temperature sensitive, with an increase in torque level at 20 degrees of twist of 5% to 46% (Table 3).

The responsiveness of a wire to thermal stimuli seemed closely related to its superelastic tendency, in accordance with data reported by Yoneyama et al.[23] The most temperature-sensitive wires had the most distinct deactivation plateaus, whereas the wires without discernible plateaus at body temperature exhibited only moderate temperature-sensitivity.

Conclusions

From the foregoing, the following conclusions seem valid:

1. Only four of the eight nickel titanium alloy wires tested in longitudinal torsion exhibited superelastic behavior when deactivated from 25 degrees of torsional twist at body temperature under the present conditions (Figure 2A-H). The majority of these wires had narrow deactivation plateaus at high levels of twist, and only one wire had a wide plateau at twist angles below the pretorque recommended in commonly used prescriptions.

2. The wires with slight or no pseudo-elasticity demonstrated distinct deactivation plateaus when deactivated from 45 or 60 degrees of twist. This finding lends support to the post-hoc hypothesis that these alloys have superelastic properties, but that an activating twist of 25 degrees was insufficient to induce martensitic transformation. As the recommended pretorque for an upper central incisor is between 7 and 22 degrees in various prescriptions, the clinical value of these wires in torque applications seems debatable.

3. The wires were flexible at room temperature and became stiffer as the temperature increased. Half of the wires were markedly influenced by the ambient temperature changes, whereas the other half were relatively temperature insensitive (Figure 2A-H). The thermal responsiveness of a wire seemed closely related to its superelastic tendency.

4. Expressing the degree of superelastic behavior of an orthodontic archwire as the distinctiveness of the deactivation plateau relative to the final part of the deactivation curve may be valid. However, the best cutoff value for optimal sensitivity and specificity of the parameter remains debatable.

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