Original Article

The effect of short-term temperature changes on the mechanical properties of rectangular nickel titanium archwires tested in torsion

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Like many metal alloys, nickel titanium (NiTi) alloys can exist in more than one crystal structure, depending on the temperature and mechanical stress the alloy is subjected to.[1] The ability to easily transform between a high-temperature austenite and a low-temperature martensite phase by either lowering the temperature or applying stress[2,3] gives NiTi archwires two remarkable properties, namely shape memory and superelasticity.[4]

Shape memory alloys can be plastically deformed in their martensite phase, but will return to an austenite phase and thereby recover their original shapes if heated above a certain temperature range.[3] The original arch form is set ("memorized") while the alloy is in an austenite or parent phase during high-temperature treatment.[5] If the transition temperature is somewhat below or around mouth temperature, bends can be placed in a thermodynamic archwire in its highly ductile martensite 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.

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

Abstract

Due to their exceptional temperature sensitivity, superelastic nickel titanium wires may be affected by temperature changes associated with ingestion of cold or hot food. It has been assumed that the alterations in archwire stiffness associated with short-term cooling or heating are transient. This investigation studied the effect of these temperature changes on the torsional stiffness of nickel titanium alloys. Eight rectangular superelastic wires were activated to 20 degrees, in longitudinal torsion at body temperature and subjected to cold (10°C) or hot (80°C) water with the strain held constant. The torsional stiffness of some wires was strongly affected. The effect of hot water disappeared quickly, but the wires remained at a level of reduced torsional stiffness (up to 85% less than baseline) after short applications of cold water. The most thermodynamic archwires showed incremental reductions in torsional stiffness when cold water was repeatedly applied. Furthermore, the torsional stiffness remained low (up to 50% less than baseline) and showed no tendency to increase even after 2 hours of post-exposure restitution. It is conceivable that some wires may provide inadequate forces for tooth movement after ingestion of cold liquids.

Key Words

Orthodontic archwires • Materials testing • Torsional stiffness • Nickel titanium alloys • Copper nickel titanium • alloys • Superelasticity

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Table 1
Wires used in this 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

called *stress-induced martensite* (SIM), and the driving force for the transformation is mechanical, not thermal.[4] Within the temperature range, martensite can be made stable with the application of stress, but it becomes unstable again when the stress is removed. Furthermore, 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.[4]

Due to the exceptional temperature sensitivity,[6] transient mouth temperature changes associated with ingestion of cold or hot food may lead to changes in the load. The slope of the stress versus temperature plot of superelastic wires is of particular interest in this respect. A steep slope implies that high forces can occur in response to even slight increases in the deformation temperature. The stresses exerted on the periodontal structures may exceed the pain threshold and cause patient discomfort.[7] Conversely, transient reductions in wire stiffness as a response to a lower deformation temperature may decrease the load on the periodontal structures and temporarily increase blood flow.[8] It has been hypothesized that these changes may allow replenishment of cells and nutrients to the cellular elements involved in the repair process in areas where blood stasis has occurred due to capillary strangulation.[7,8] As this will maintain vitality and normal function, tooth movement may be accelerated.[7] However, these phenomena are neither easily measured nor controlled in the oral environment, and their clinical importance is debatable. On the other hand, the changes are thought to be transient and unlikely to adversely affect tooth movement.[9]

The effect of temperature on the torsional stiffness of superelastic wires has not been investigated in depth. The purpose of this investigation was to evaluate the effect of transient alterations in 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 (NiTi) and copper nickel titanium (CuNiTi) wires commonly used in the 0.018 inch edgewise technique were tested in as-received condition. Six manufacturers supplied a total of eight different sizes and types of wire, all claimed to exhibit superelastic properties (Table 1). The wires were supplied in arch forms. One manufacturer supplied wires of the same dimension but of varying quality. Four major suppliers from the United States and two from Germany were selected.

From each batch, three 25-mm pieces were cut from the nearly straight, posterior section of individual archwire blanks. The pieces were tested in a torque-measuring instrument with an interbracket distance of 4 mm. This instrument has been described before[10] and is a further development of a previously reported apparatus[11,12] 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 pulley radius, i.e., the moment arm.

The torque experiments were carried out in an electrically heated room measuring 5 x 8 feet. The temperature was regulated by a thermostat accurate 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. A pilot study demonstrated that the preset temperature could be maintained within ± 0.5°C (unpublished results).

To study the effect of short-term temperature alterations, three test specimens from each wire type were tested at 37°C ambient temperature and subjected to a sequence of short-term exposure to cold (10°C) or hot (80°C) water. The water temperatures were chosen after multiple temperature measurements of cold soda and hot coffee, using a calibrated thermometer accurate to ±1°C (unpublished results).

The test pieces were ligated into the three holding brackets using Alastik A-Modules (3M Unitek, Monrovia, Calif) and subsequently activated to 20 degrees of longitudinal torsion, as this was at the end of the plateau-like phase of the torque-twist diagrams (unpublished results). The magnitude of twist was read off the scale. The load cell was coupled to a PC employing an A/D converter card (Strawberry Tree, Sunnyvale, Calif) and programmed to make one recording of torque per second, with each recording a mean of 10 subrecordings. The program was developed by Mr. Robert Sandvik. As we found a slight tendency for wire creep during the initial phase of activation, the wire was kept at 20 degrees of twist for 2 minutes before further testing. After this initial period, the wire was subjected to 5 ml of cold water for 10 seconds and kept activated for 5 minutes. The wire was then deactivated for 30 seconds prior to subsequent testing in order to examine whether permanent changes in wire properties had occurred during cold exposure. The wire was reactivated to 20 degrees of twist and, after a restitution phase of 1 minute, subjected to 5 ml of hot water for 10 seconds and kept activated for 5 minutes. The wire was then deactivated for 30 seconds prior to subsequent testing to examine whether permanent changes in wire properties had occurred during heat exposure. Subsequently, the wire was reactivated to 20 degrees of twist. After a restitution phase of 1 minute, the wire was subjected to 5 ml of cold water for 10 seconds, kept activated for 5 minutes, then subjected to 5 ml of hot water for 10 seconds and kept activated for another 5 minutes. Finally, to control for any permanent wire damage or creep, the wire was deactivated for 30 seconds, reactivated to 20 degrees of twist, and kept constant for a final 1-minute period.

To study the effect of repeated cold temperature provocations, the four most temperature-sensitive wire types were selected for further study. Each wire was activated to 20 degrees of twist at body temperature. The wire was kept activated for 2 minutes and subsequently subjected to 10 cycles of 5 ml of cold water for 10 seconds. Thereafter, the wire was kept activated undisturbed for 2 hours to study the speed and extent of recovery.

Results

Effect of short-term temperature changes

The effect of short-term temperature changes on torsional stiffness is shown in torque-time diagrams for 20 degrees of constant twist (Figure 1A-H). The wires were generally more affected by exposure to cold water than hot. The effect of heating disappeared quickly, and the baseline torque level was completely restored. The wires demonstrating the greatest changes due to variation in ambient temperature (unpublished results) also showed the greatest sensitivity to application of hot and cold water. In general, deactivation followed by reactivation restored the initial torque level regardless of prior exposure to heat or cold, indicating that no permanent damage was inflicted on the test specimens during exposure to heat or cold. There was no difference in torque level whether or not the wire was deactivated prior to application of hot water.

Of the 0.017 x 0.025 inch wires, the Dentaurum wire showed the least change in torque level when subjected to cold or hot water (Figure 1A). The Ormco CuNiTi wires demonstrated a marked drop in torque when subjected to cold water. These wires tended to stabilize at a lower torque level than the original. Deactivation restored the torque level for the 27°C wire (Figure 1B), nearly restored it for the 35°C wire (Figure 1C), but failed to do so for the 40°C wire (Figure 1D). Application of hot water led to an increase in torque, most markedly for the 40°C wire. Application of cold water to these wires after heating led to a reduction in torque to a level close to that observed after the first application of cold water.

With respect to the 0.018 x 0.025 inch wires, the Forestadent and Unitek wires were more sensitive to hot water than to cold (Figure 1E-H). The

Figure 1A-H
The effect of short-term temperature changes on the torsional stiffness of superelastic NiTi wires. Ambient temperature constant at 37°C. Temperature stimulus: cold water (10°C) or hot water (80°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.
E: Forestadent Titanol 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.

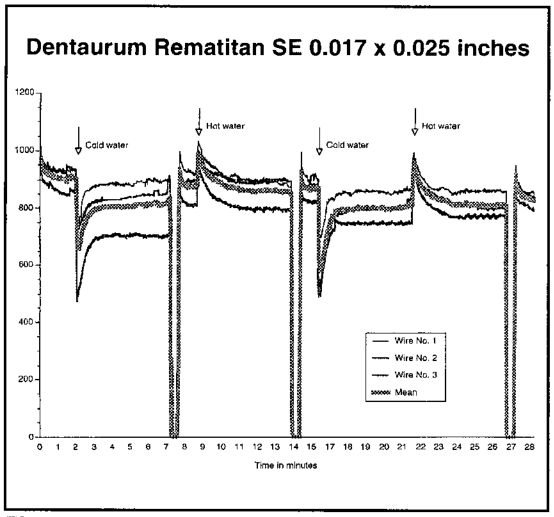

Figure 1A

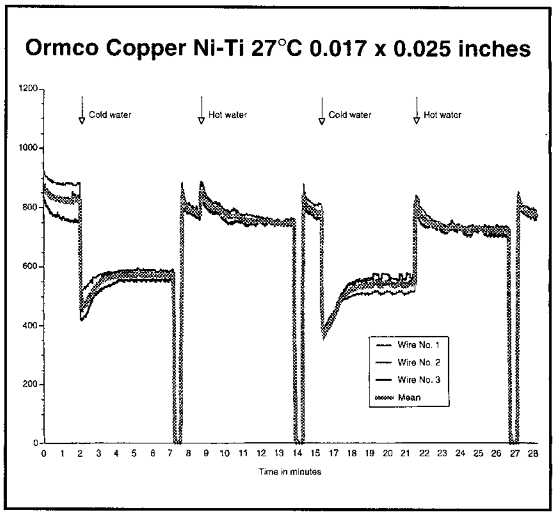

Figure 1B

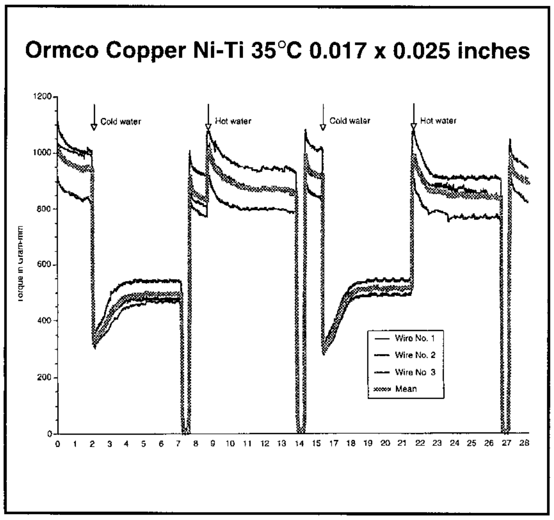

Figure 1C

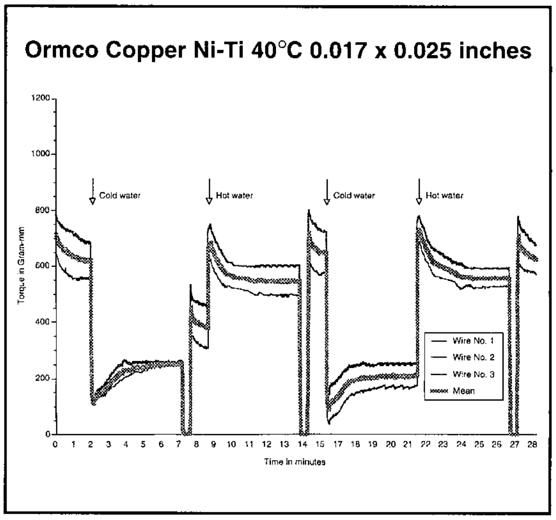

Figure 1D

Masel wire (Figure 1G), on the other hand, showed more sensitivity to cold water. In general, these three wires tended to return to their original torque level relatively quickly, regardless of temperature stimulus. The GAC wire (Figure 1F) showed a marked drop after application of cold, similar to that observed with the CuNiTi wires, but had a greater ability to return to its initial torque level. The effect of heat on the GAC wire was also more pronounced compared with any of the other wires.

Effect of repeated exposure to cold

The effects of repeated exposure to cold on the most temperature-sensitive archwires (Ormco and GAC) are shown in Figure 2A-D. In general, all the wires were strongly influenced by cooling and showed a tendency to stabilize at a very low torque level. It should be noted that the markedly reduced torque level remained low even after 2 hours.

With respect to the CuNiTi wires, the wire most affected by cold water exposure was the 35°C wire (Figure 2B). The torque level at 20 degrees of twist fell from 950 to 150 g-mm, or almost 85%. The 40°C wire fell from 650 to 80 g-mm, or 81% (Figure 2C), whereas the 27°C wire fell from 800 to 300 g-mm, or 63% (Figure 2A). The wires regained some of their torsional stiffness after 30 minutes and even more after 60 minutes. However, all the wires exerted significantly less torque after exposure to cold water. After two hours, the 27°C wire exerted about 70% of its original torque, the 35°C wire about 60%, and the 40°C wire about 50%. Torque levels after stabilization were similar to the stable levels after a single cold exposure.

The GAC wire moved back toward its baseline level quicker and to a greater extent than the CuNiTi wires (Figure 2D). The torque level fell from approximately 1000 to 280 g-mm, or 72%, during cold exposure. However, it remained at a sub-baseline torque level of about 70% even

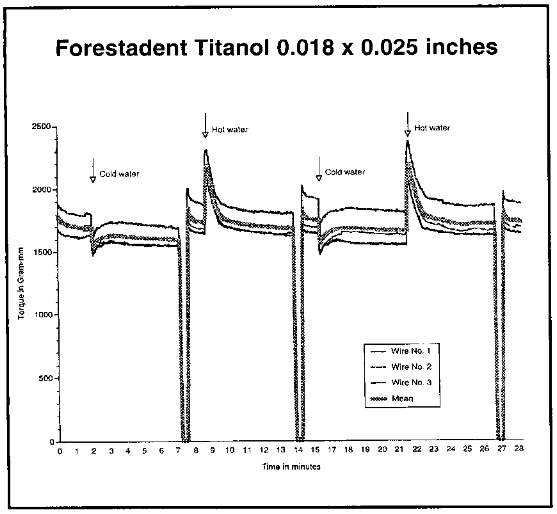

Figure 1E

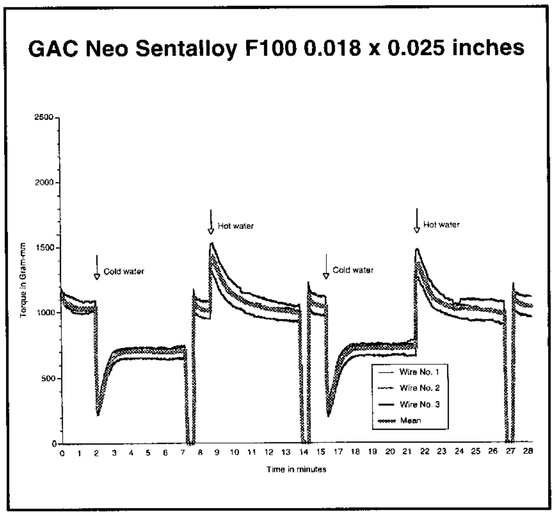

Figure 1F

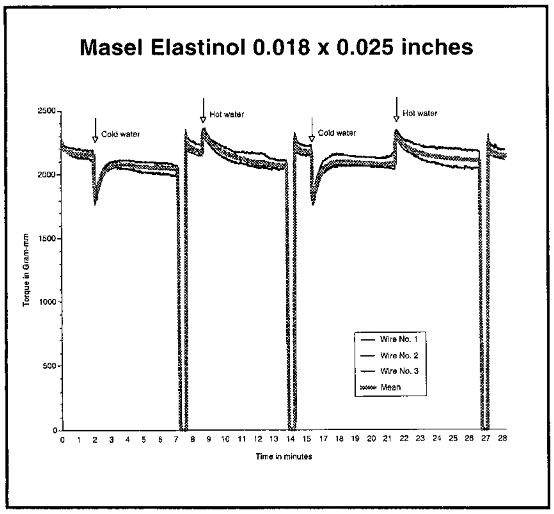

Figure 1G

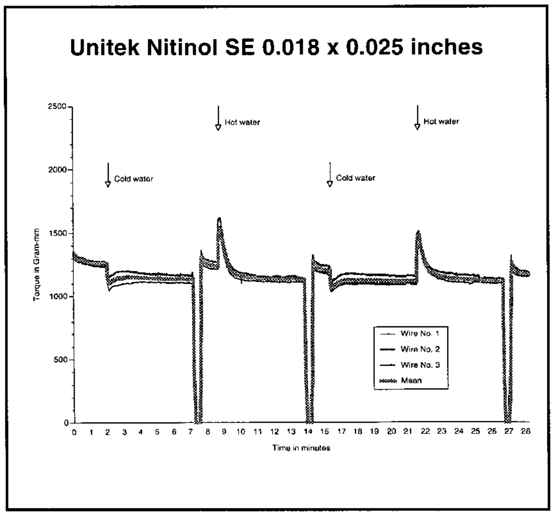

Figure 1H

after 2 hours of post-exposure restitution.

Discussion

Thermodynamic superelastic nickel titanium wires exert lower forces for a given deflection at low temperatures. It has been suggested that transient archwire cooling, such as during ingestion of cold food or drinks, may temporarily reduce the load imparted on the dental structures from the deflected wire.[7,9] We have studied the effect of short-term temperature changes on the torsional stiffnesses of thermodynamic wires under clinically relevant test conditions. Samples of rectangular superelastic nickel titanium alloy archwires were subjected to controlled bench-testing in a torque-measuring instrument at body temperature. The test specimens were subjected to longitudinal torsion and kept at constant activation while subjected to a sequence of transient archwire cooling or heating, simulating temperature exposures that would occur during ingestion of cold or hot drinks.

The torque apparatus simulates application of torque (actio) to a single tooth with standard edgewise brackets with 0.018 inch slots and no "pretorque" or angulation, using an interbracket distance of 4 mm. The reactio-torque will be transferred to a neighboring "anchor" tooth on either side. This is valid for the study of torsional stiffnesses, but the results may not have direct relevance for simultaneous application of torque to multiple teeth. In vivo, 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.[13] However, the anterior segment can be perceived as a wide bracket if the central and lateral incisors are aligned. Consequently, our experimental data may be extrapolated, with certain reservations as to the effects of force interactions and archwire curvatures, to the even more clinically relevant situation where torque

Figure 2A-D
The effect of repeated short-term exposure to cold water (10°C) on the torsional stiffness of temperature sensitive superelastic Ni-Ti wires. Ambient temperature constant at 37°C. Note the prolonged effect.
A: Ormco Copper Ni-Ti 27°C 0.017 x 0.025 inch wire.
B: Ormco Copper Ni-Ti 35°C 0.017 x 0.025 inch wire.
C: Ormco Copper Ni-Ti 40°C 0.017 x 0.025 inch wire.
D: GAC Neo Sentalloy F100 0.018 x 0.025 inch wire.

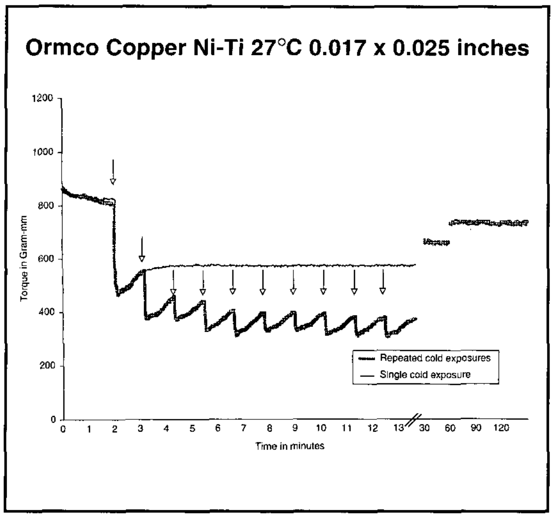

Figure 2A

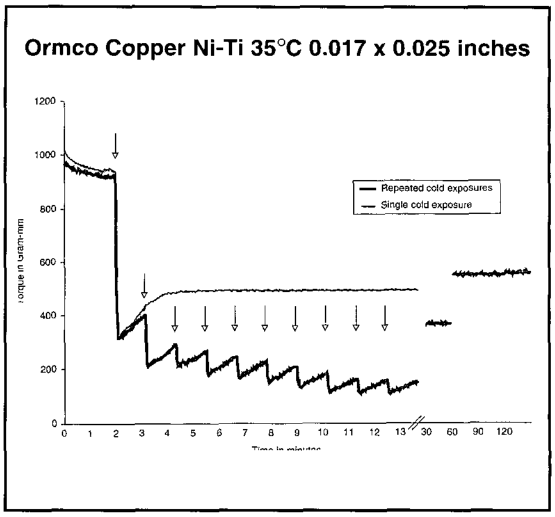

Figure 2B

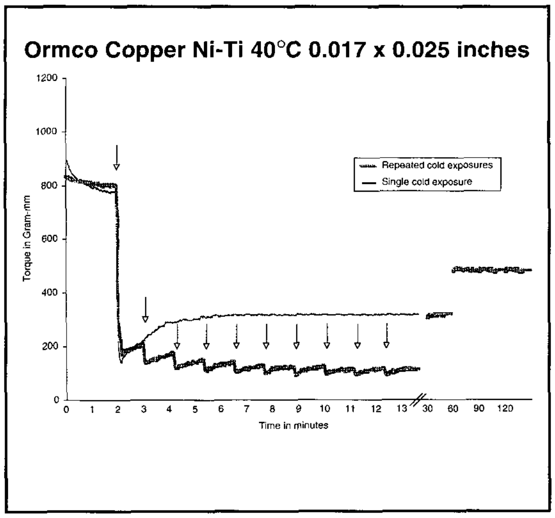

Figure 2C

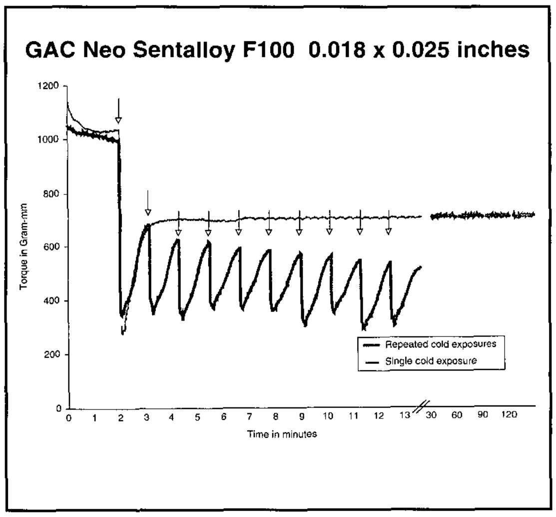

Figure 2D

is applied to the whole anterior segment.

This study shows that short-term increases in wire temperature increase the torque exerted for a given deflection (i.e., wire stiffness), but that the baseline torque level is quickly restored. This phenomenon may be exploited to apply intermittent forces to teeth with compromised periodontal conditions. An archwire that is very flexible and exerts low forces at body temperature will temporarily become stiffer and may exert orthodontically active forces only when heated during ingestion of hot meals or drinks.

Short-term archwire cooling markedly reduced the torque exerted (up to 85%). The baseline torque level was not completely restored for the majority of the wires, and most of them exerted significantly less torque (up to 70%less) even after a 5-minute post-exposure restitution phase.

When the wire was subjected to hot water (80°C) after being cooled, the baseline torque level was restored. Thus, the increase in torsional stiffness due to heating was sufficient to overcome the internal friction in the apparatus, indicating that the friction was minimal and that lack of "rebound" after short-term archwire cooling was not an artifact of frictional forces. Furthermore, when the wire was deactivated and then reactivated, torque was also restored at the baseline level. This indicates that the observed reduction in exerted torque was not due to permanent damages inflicted on the test specimens by transient cooling.

Repeated cold exposures to the most temperature-sensitive wires led to a 60% to 85% reduction in exerted torque immediately after the last cold exposure. The wires regained some of their torsional stiffness after 30 minutes and even more after 60 minutes, but they exerted from 30% to 50% less torque than the baseline amount even after 2 hours of post-exposure restitution. Furthermore, the torque level after 2 hours of restitution was similar to the torque level after a single cold exposure. The wires were kept at 37°C ambient temperature, and although the partial restitution of the wires after exposure to cold may occur faster intraorally, it is not likely to occur to a greater extent since the wires were kept for two hours at 37°C after the last cold exposure.

The superelastic wires that show little or moderate temperature sensitivity and demonstrate rebound after cooling may positively affect tooth movement due to intermittent reductions in force level.[7] However, the clinical effect of the most temperature-sensitive wires is more unpredictable. It has been assumed that temperature variation brought about by food or drink is of little consequence due to its transient nature.[9] We have shown that short-term application of cold water led to a marked and sustained reduction in the torque levels with respect to the most temperature-sensitive wires. On the other hand, these wires will rebound to the baseline torque levels after ingestion of hot drinks or food. Whether these two opposing effects cancel each other out during a meal remains unknown.

One may speculate that adults will be more frequently subjected to elevations as they tend to ingest more hot food and drinks than children. Since the torque level was restored through deactivation (Figure 1A-H), the end result is even more unpredictable, as mastication and the accompanying movement of the wire may have a similar effect and serve to modify the effect of temperature-related changes in torsional stiffness. However, this study demonstrates that some superelastic nickel titanium archwires may exert very low torque for long periods after ingestion of cold drinks (Figure 2A-D). Assuming that minimal levels of torque are necessary to cause biologic tissue response compatible with tooth movement, it is conceivable that several wires may provide inadequate forces for tooth movement after ingestion of cold liquids.

Conclusions

From the foregoing, the following conclusions seem valid:

1. The torsional stiffnesses of the superelastic nickel-titanium wires tested were markedly influenced by a single short-term application of cold (10°C) or hot (80°C) water. The effect of hot water was transient (Figure 1A-H). However, after cooling, the torque exerted remained subbaseline during the 5 minute post-exposure restitution phase for the majority of the wires tested (Figure 1A-H).

2. The most thermodynamic wires also showed a tendency toward incremental reductions in torsional stiffness when cold water was repeatedly applied. Furthermore, torsional stiffness remained low for a prolonged period and showed no sign of increasing after 60 minutes of post-exposure restitution (Figure 2A-D). Assuming that minimal levels of torque are necessary to cause biologic tissue response compatible with tooth movement, it is conceivable that these wires provide inadequate forces for tooth movement after ingestion of cold liquids.

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