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Effect of Short-term Temperature Changes on Force Exerted by Super-Elastic Ni-Ti Alloy Orthodontic Closed Coil Spring

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Recently, Nickel Titanium (NiTi) coil springs have been used extensively in orthodontic treatment. Closed coil springs are generally used for distalization of canines, mesial movement of molar and anterior space closure. The springs are believed to exert a light constant, continuous force, which is suitable for physiologic orthodontic tooth movement, over a long range of activation[1]. However, the temperature fluctuation in the oral environment may affect force delivery of the springs. In this study, the effect of short-term temperature change on the force delivery of NiTi close coil springs in their superelastic range was investigated. Commercially available NiTi closed coil springs were subjected to a tensile test. At the mid-point of the unloading plateau, the springs were held in a constant extension and subjected to heating cycle (from 37°C to 60°C to 37°C) and cooling cycle (from 37°C to 10°C to37° C). During both procedures, the force was continually recorded. For the heating cycle, load values of all the springs examined were found to increase with rising temperatures and did not return to their original values. For the cooling cycle, load values of the springs decreased with dropping temperature and increased to the original value when temperature return back to 37°C. These findings demonstrate that the superelastic NiTi coil springs do not provide a predictable light continuous force in the fluctuating oral temperature environment.

Introduction

In orthodontic treatment, space opening and closing procedures utilize several force delivery system such as elastomeric material, magnet, and coil spring. For coil spring, they can be classified into 2 types: open and close. Open coil springs are commonly employed in opening space, whereas closed coil spring are generally used for space closure (Fig1a,b). Coil springs have been manufactured from several types of alloy, precious metal, stainless steel, cobalt chromium and recently Nickel Titanium[2].

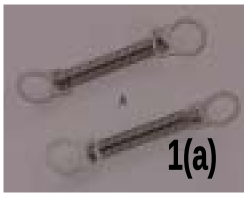


Fig 1(a) The NiTi closed coiled spring

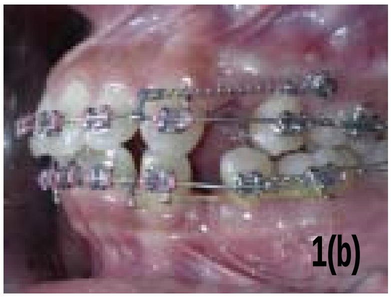


Fig 1(b) Illustrate the clinical use of NiTi closed coil spring with mini-implant anchorage (MIA) for anterior space closure to move all anterior teeth back to close extraction space.

The special desirable property of Nickel Titanium alloy, such as shape memory effect (SME) and superelasticity, lead to further investigations in this alloy for the coil spring. NiTi alloy has shape memory effect that can exist in 2 crystallographic structures: austenitic phase (high temperature, B2 cubic structure) and martensitic phase (low temperature, B19' monoclinic structure) which can change back and forth through variation of temperature. Each alloy phase has a different physical property. Martensitic phase is highly ductile so that it can be physically deformed. Austenitic phase has a superior springback property. The transition between these two phases is induced over a transitional temperature range (TTR). Due to its extraordinary crystallographic structure, NiTi alloy exhibits unusual mechanical characteristics. First, very low Young's modulus allows the alloy to deform to a great extent without permanent plastic deformation and exert relatively constant force. Second, they encompass shape memory effect. At low temperature, martensitic phase are highly ductile and may be plastically deformed. Martensitic phase can be transformed into austenitic phase with increasing temperature. When the temperature reaches TTR, deformed martensitic phase then return back to its original shape. Third, the most interesting property for orthodontic application is superelasticity. Superelasticity is a stress-induced phenomenon. Bending a superelastic wire in austenitic phase can create martensitic transformation that can reverse when strain is reduced. Superelastic behavior can occur at temperature above the TTR. Both superelastic and shape memory effect have their common basis in the thermo - elastic phase transformation from austenitic to martensitic. This phase transformation depends on temperature as well as mechanical stress

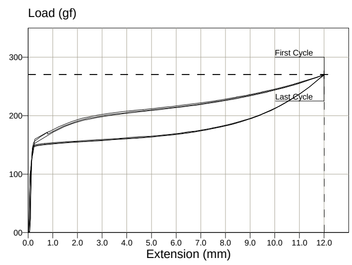


Fig 2 Load-Deflection curve of NiTi closed coil spring that exert relative constant light continuous force (graph tested at normal oral temperature, 37 °C)

The application of superelastic orthodontic appliance has many advantages over conventional devices. Nearly constant forces over a broad range of activation prevent the appliance to exert heavy force due to over activation. Other advantages include reducing number of activation, minimizing risk of trauma to teeth or supporting structures as well as unwanted effect and reliably predicted tooth movement.

At present, varieties of orthodontic NiTi coil springs are commercial available. Most manufactures claim that their products comprise superelasticity property (Fig.2) without mechanical property data of these springs in simulated oral temperature that can change during eating or drinking. Most data always supply only at normal oral temperature, 37 °C. Previous research data show relative light constant different force level at different constant temperature[3]. Short-term temperature changing during day will change forces exerted by these springs beyond or less than the manufacture description. The investigation of force delivery by these coil spring during various temperature conditions will remind orthodontists that force delivery can be altered from the initial loading due to increased or decreased temperature. A precaution should be used to avoid excessive forces throughout treatment.

The purpose of the study is to characterize the effect of short-term temperature change (heat and cool) on force exerted by NiTi closed coil spring. These mechanical properties will support data to orthodontist in able to choose proper devices for treatment.

Material and method

Three types of NiTi closed coil spring (Sentalloy, GAC) were used in this study (light, medium, heavy). Types of coil springs were classified according to the level of force delivery which is set by spring lumen, wire diameter and length of spring[4].

The specimens were tested by tensile test machine with a self–calibrating system, *Nexygen from Lloyd Instrument Ltd.*, (Fig3)

Fig 3 *Nexygen from Lloyd Instrument Ltd* with water bath for thermal control and thermocoupling to monitor temperature change.

All three types of springs (5 specimens each) were tested in temperature-controlled water-bath setting the baseline temperature at 37ºC. Thermal variations in water-bath were monitored by thermocoupling. First, springs were placed in the water-bath and activated to 400% extension (claimed by manufacturer that there is no permanent deformation) and then unloaded to mid-point of unloading plateau (Fig 4). The springs activation was performed by moving the stroke of tensile test machine up and down vertically with the speed 0.25 mm./sec. During deactivation, NiTi coil springs were maintained at 7-mm. extension. This was chosen from the average data from specimens. After deactivation to 7-mm. extension, the water-bath's temperature was increased (60°C) or decreased (12°C) to simulate oral cavity temperature during the day. The data, force/compression, were continuously obtained (Fig 4). For heating cycle, the water temperature was increased to 60°C for 60 seconds and return to normal oral temperature (37°C). After resting period,90 second, the water temperature was increased to 60°C again. This hot cycle was repeated 3 times. Similar procedures were performed for cooling cycle, the temperature was decrease to 12°C and then returned to oral temperature and also repeated 3 cycles.

Fig 3 The thermocoupling that can monitor and record temperature in 1 decimal.

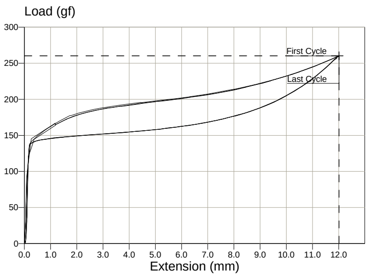


Fig 4 A Load-deflection curve from NiTi closed coil spring (medium type).

Result

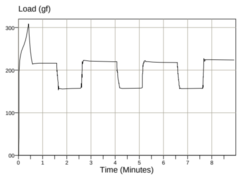
Cool treatment

In cooling cycle, the forces of NiTi coil spring from all types (light, medium, heavy) was reduced as temperature decreasing but able to recover to relative original level after temperature returned back to 37°C. (Table 1)

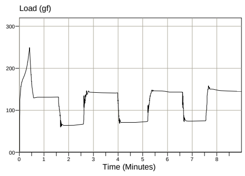
Type	Temperature			%
	before	after	*P* value	change
Heavy	216.1±0.7	215.6±0.8	0.088	-0.2
Medium	158.6±0.5	157.8±0.9	0.106	-0.5
Light	106.7±0.9	106.3±1.0	0.219	-0.3

Table 1 Average force that delivered from NiTi closed coil spring before and after cooling cycle and percentage change of force after return to 37°C. There is no statistical significant different in any of spring types (paired *t*-test).

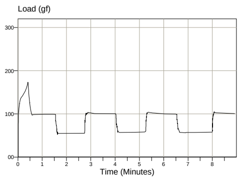
For heavy type, the force reduced from 216.1 gm. to 155.1 gm. then increased to 216.3 gm., in medium type, the force reduced from 158.5 gm. to 71.5 gm. then increased to 158.9 gm. And in light type the force reduced from 107.9 gm. to 62.1 gm. then increased to 108.57 gm. (Fig 6).



Heavy



Medium



Light

Fig 5 Graphs demonstrate the change of force during cooling cycle.

It is seen that no statistical significant difference in loading force changes (pretreatment VS post-treatment) of light, medium or heavy types (One-way Analysis of Variance, p = 0.778).

Heat treatment

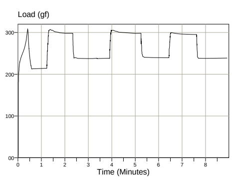
On the other hand, for heating cycle, the force increased as temperature rise; however, when temperature was returned to original level, the force did not go back to the same original level (table2).

Type	Temperature			%
	pre	post	*p*-value	change
Heavy	210.4±0.4	243.7±0.4	< 0.001	11.40
Medium	158.5±1.2	182.3±0.7	< 0.001	14.98
Light	107.1±0.4	133.2±0.7	< 0.001	24.36

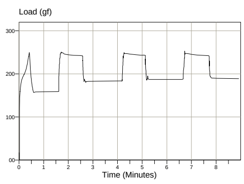
Table2 Average force that delivered from NiTi closed coil spring pre and post heating cycle and percent change of force after returning to 37°C. All post-heating forces are significantly differed from pre-heating value. (paired *t*-test)

For heavy type, the force increased from 210.4 gm. to 296.9 gm. then decreased to 243.47 gm., in medium type, the force increased from 158.5 gm. to 246.6 gm. then decreased to 182.3 gm. and in light type the force increased from 107.1 gm. to 190.9 gm. then decreased to 133.2 gm. (Fig 6).

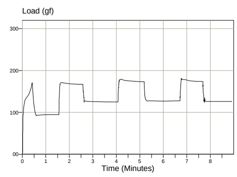
Amount of force that did not reduced to original level was different in each type, 11.4 % for heavy type, 14.89 % for medium type and 24.36 % for light type.



Heavy



Medium



Light

<u>Fig 6</u> Graphs demonstrate the change of force during heating cycle.

In the repeat heating cycles, the recovery forces were equal level to the first cycle.

For the differences in changes of forces before and after heat treatment, data indicated that there are significant differences among types of the spring (One-way ANOVA, p < 0.001). Post-hoc comparisons (Turkey test) revealed that each type of the spring was significantly different from other two types (p < 0.001).l

Discussion

The present study clearly indicated that the mechanical properties of superelastic NiTi closed coil springs were affected by temperature change even with short time exposure. The effects on springs were similar to NiTi superelastic archwires that had been tested previously[5]. When a superelastic wire is subjected to cold water during the deactivation phase, the effect of brief cooling is transient. Furthermore, the effect of brief heating is prolonged. This effect was permanent as long as the strain remains constant when the wire is heated in the deactivation phase[5-6].

To explain this phenomenon, Differential Scanning Caloriemetry (DSC) was used to determine the transition temperature range (TTR) of superelastic orthodontic NiTi coil spring[7]. The TTR provide the information on temperature at which NiTi spring can assume superelastic properties and when this quality disappears. The NiTi closed coil spring's DSC data was shown in table 3.

	Spring type		
	heavy	**medium**	**light**
DSC (cooling)			
Ms (onset, °C)	32.6	28.4	29.8
Mf (offset, °C)	12.7	6.5	11.6
DSC (heating)			
As (onset, °C)	16	9.7	15.2
Af (offset, °C)	37	33	34.4

<u>Table 3</u> The result from DSC evaluation of 3 types of coil spring from GAC that were tested[7].(Modified from Barwart O, Rollinger JM, Burger A. An evaluation of transition temperature range of super-elastic orthodontic NiTi springs using differential scanning calorimetry. Eur J Orthod 1999;21:497-502.)

From the DSC data, in our study can explain the effect of short term temperature change on NiTi closed coil spring in metallurgic terms[8]. The alloy is mainly austenitic at body temperature when no load is applied. When activated in stretching, the alloy is transformed from austenite to martensite, and the martensite-austenite ratio increases. At low deflections, the degree of transformation is low, while at large deflections the transformation is presumably more complete. The alloy is subsequently deactivated and the martensite-austenite ratio decreases.

When the alloy is subjected to cold water, it is cooled below the Ms temperature and is transformed into the low-temperature martensitic phase. Because martensite is more flexible than austenite, the force exerted by the deflected specimens is reduced during cold-water exposure. After temperature was returned to normal oral temperature, the specimen's stiffness increases because the alloy gains energy from the environment. The baseline force level is completely restored, which indicates that the original martensite-austenite ratio is also restored.

Because the specimens are subjected to stress, the Af points are no longer as manufacturer prescribed before, but are somewhat higher (above 33 - 37°C). Consequently, under these test conditions, the alloys will not become completely austenitic at body temperature after the brief cooling.

During brief heating, the specimen's stiffness increases because the alloy is completely transformed into the high temperature austenite phase (martensite-austenite ratio=0). After the water temperature was reduce, the alloy loses energy to the environment and the stiffness decreases and remains unaltered. The specimens now exert suprabaseline forces for a prolonged period of time, which indicates less transformation of austenite back to martensite during heat liberation. A possible explanation for this finding is that the ambient (body) temperature is not insufficient to restore the original martensite-austenite composition[5].

Since the springs were used in oral cavity all time, high temperature food would change force dramatically. Increasing the magnitude of force raises the possibility of causing irreversible tissue damage, including extensive hyalinization of the periodontal membrane and root resorption. In contrast, decreasing sub-optimal force would cause the retardation of tooth movement.

Summary

From this study, we found that

1. NiTi springs, when subjected to temperature variation, were not be able to provide a predictable constant continuous force.

2. In cooling cycle, after increasing temperature to normal oral temperature, the force can recover to original level.

3. In heating cycle, after temperature decreased to normal oral temperature, the force did not recover to original level.

4. In heating cycle,The changes of force during temperature cycle compared to original (%change) are different for each types of springs.

From these results, orthodontist should keep in mind that they should carefully use NiTi coil spring with caution to avoid excessive force produced during day during hot food or beverage consuming.This study also provide the information regarding how to select coil spring for special purpose.

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