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ORIGINAL STUDY

Influence of Intraoral Temperature Changes on the Mechanical Properties of Different Nickel Titanium Orthodontic Arch-wires

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Abstract

Purpose: To evaluate and compare the effect of intraoral temperature changes on the mechanical properties of three different Nickel-titanium orthodontic arch-wires. **Patients and methods:** A total of 45 specimens of three different 0.014-inch upper round Nickel-titanium orthodontic arch-wires, namely, 3M Nitinol classic, 3M Nitinol super-elastic, and 3M Nitinol heat-activated were used in this study. Fifteen specimens from each wire type were subjected to a modified three-point bending test under three different temperatures (5, 37, and 55 °C). Loads were plotted for 4, 3, 2, and 1 mm deflections during unloading. **Results:** It was found that Nitinol heat-activated shows the lowest mean load value followed by Nitinol super-elastic and Nitinol classic, respectively, at 5, 37, and 55 °C, for all deflections with the exception at 1 mm deflection. At 37 °C, Nitinol super-elastic shows the highest mean value, while at 55 °C, Nitinol heat-activated shows the highest mean load value at 1 mm deflection. Nitinol heat-activated acquires the longest plateau of the working force and the least plateau slope of the three wires. At 5 °C, Nitinol heat-activated exhibits a diminished working force. The working force increases as the temperature increases from 5 to 55 °C and the working force plateau becomes more obvious as the temperature increases to 37 °C then tends to decrease again at 55 °C. **Conclusion:** The low, constant working force offered by Nitinol heat-activated makes this wire favorable to periodontal ligaments and improves the patient's discomfort during orthodontic treatment. The working force of all of the three wires increases as the temperature rises.

Keywords: Load deflection, Mechanical properties, Nickel-titanium arch-wire, Temperature changes, Three-point bending

1. Introduction

Orthodontic tooth movement is achieved by applying forces to teeth. Forces are produced by the deformation of an orthodontic arch-wire elastically allowing the release of its stored energy to the teeth over a specific period. Light continuous forces are physiologically desirable and produce optimum tooth movement. Typical forces are in the range of 100–150 g, ~1 N [1–3].

Understanding the properties of arch-wires is a must before making the decision to use which one so that the decision could be justified and optimum predictable treatment results can be accomplished. Some of the important parameters in the selection of a wire are the modulus of elasticity (stiffness, load deflection rate); range (maximum elastic strain), which is the distance the wire will bend or deflect elastically before permanent deformation occurs; spring-back (the amount, in length units, a wire will return beyond its yield point), which is the difference between a given deflection (activation) and the residual deformation after unloading to 0 g-mm [1,2,4].

Various alloys are used for the fabrication of orthodontic arch-wires. Nickel-titanium (NiTi), since its introduction into the dental market, has been

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marketed for its potential clinical advantage in the first stage of orthodontic treatment, the alignment and leveling stage, which is attributed to the material's low stiffness, excellent spring-back, and constant forces while unloading [1,2,5]. NiTi arch-wires provide considerably constant light force to the dentition over a large range of activation, resulting in the desirable biological response. Therefore, full leveling can be achieved without frequent arch-wire changes. It is claimed that optimum force levels provided by NiTi wires during orthodontic treatment lower the risk of patient discomfort, damage to the supporting tissues, root resorption, or loss of pulp vitality [1,6].

The distinctive mechanical behavior of NiTi alloys is attributed to NiTi alloy's unique, 'shape memory effect' and 'super-elastic' properties. These unique properties of NiTi are due to the fact that such alloys are polymorphic, meaning that they can exist in two different equilibrium crystal structures. Each structure has a different crystal lattice and exhibits different properties. One of the phases is the high temperature phase under low stress typically called austenite (A) (generally cubic) and the other is the low temperature higher stress phase called martensite (M) which has a different crystal structure (tetragonal, orthorhombic, or monoclinic). The transformation from one structure to the other is instantaneous and occurs by shear lattice distortion instead of atomic diffusion [1,2,5–7].

The term shape memory effect refers to the alloy ability to regain its original shape after being plastically deformed. This ability is due to temperature-induced phase transformation from the low-temperature martensite to the high-temperature austenitic phase. Phase transformation to parent austenite causes the alloy to fully restore its initial form, after being previously mechanically deformed by detwinning of the twinned martensite. This deformation that has occurred previously in the low-temperature martensitic phase was the result of engaging the bracket/brackets of the malposed tooth/teeth. This property provides the clinician with the distinct advantage of being able to activate NiTi arch-wires over a long period of time without the risk of deforming the appliance permanently [1,2,6,7].

Super-elasticity is a different attribute of the NiTi alloys, and the term typically refers to the ability of the alloy to accommodate high, yet reversible strains in the orthodontic arch-wire without failure as a result of the stress-induced martensite transformation. At high temperature at which austenite phase is stable, if the mechanical stress experienced by the wire exceeds a certain threshold during loading, the transformation from the austenitic to the detwinned martensitic phase occurs without any temperature change. This procedure is commonly referred to as stress-induced martensite. Upon unloading to zero stress state, transformation occurs back to austenite with strain recovery. This property is demonstrated more clearly in the almost flat horizontal section of the load-deflection curve during unloading, referred to as the plateau [1,2,6–8].

There are mainly three types of NiTi orthodontic arch-wires:

(a) Conventional Martensite stabilized alloys that have no shape memory or super-elasticity effects and can be permanently deformed if certain stress is exceeded [2,5,8].
(b) Martensite active alloys (thermally activated NiTi) demonstrate super-elasticity and shape memory effects at oral temperatures [2,5,8].
(c) Austenite active alloys that display super-elastic behavior but no thermo-elastic behavior at oral temperatures [2,5,8].

Each NiTi alloy has a unique composition-dependent temperature range over which the phase transition starts and proceeds, called the transition temperature range [7]. On cooling, the martensitic transition usually commences, as the alloy passes through a specific temperature known as martensite start (M_s) and becomes completed at martensite finish (M_f). On heating, the transition of martensite in austenite begins at a temperature A_s (austenite start) and finalizes at A_f (austenite finish) [9].

The NiTi phase transition is associated with changes in the mechanical properties of the alloy since the austenitic and martensitic phases have different elastic moduli and yield strengths. Oral temperature is not constant, but it varies with every intake of air, hot or cold food, or beverage; these temperature changes can greatly affect both the thermal and mechanical properties of NiTi arch-wires and, thus, the resulting orthodontic forces as well [6]. Therefore, in this study we investigated and compared the influence of intraoral temperature changes on the mechanical properties of the three different types of NiTi orthodontic arch-wires.

2. Patients and methods

A total of 45 wire specimens of three different commercially available upper round 0.014-inch NiTi orthodontic arch-wires were used in this study, namely, 3M Nitinol classic, Nitinol super-elastic, and Nitinol heat-activated orthodontic arch-wires. Fifteen specimens of 5.5 cm length were cut from the straightest distal end of each wire type and subjected to a modified three-point bending test using an Instron 2519-104 Universal Testing Machine. To evaluate the samples under conditions similar to the final operating one, they were mounted in four Roth stainless steel brackets (slot, 0.022 inch; Damon 3 Mx, Ormco). These brackets were glued to an acrylic resin base in such a way as to create a 14-mm span between the internal sides of the two middle brackets, which is considered to be the actual interbracket distance between the upper central incisor and upper canine (Fig. 1) [1,2,10].

To simulate the oral conditions and investigate the effect of temperature changes within the oral cavity on the load–deflection properties of the NiTi orthodontic arch-wires, the resin base was, in turn, placed in a water bath filled with water of temperatures 5, 37, and 55 °C (Fig. 2) [1,6,11]. The water was cooled to 5 °C and heated to 37 and 55 °C with a digitally controlled thermocycler (Julabo, THE-1100 SD Mechatroniks, Germany). Each sample was immersed in the water for at least 60 s before being subjected to the testing procedure to reach thermal equilibrium [1,6]. Water temperature was controlled using a thermometer submerged in the water bath and was monitored continuously by the operator.

Each sample was deflected at its midpoint by the aid of the metal blade of the Instron machine to 1, 2, 3, and 4 mm maximum deflection at a crosshead speed of 1 mm/min as specified by the ISO 15841 standard. Then the samples were unloaded at the same crosshead speed until the released force became zero. This degree of deflection was chosen because of its possible occurrence under clinical conditions [1,6,11].

Force versus deflection during loading and unloading was monitored and recorded for each test specimen by Bluehill computer software version 3.3.

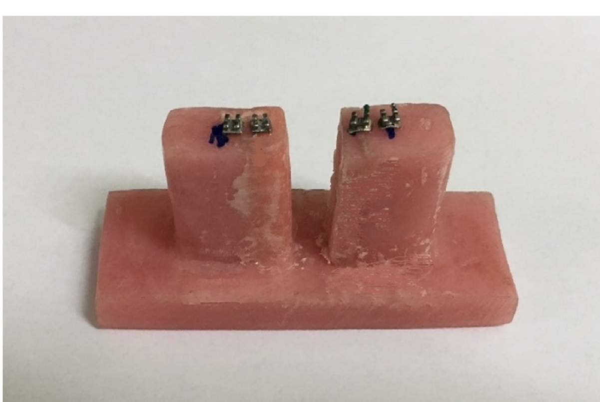

Fig. 1. Acrylic resin base with four Roth stainless steel brackets glued to it, creating a 14-mm span between the internal sides of the two middle brackets.

Fig. 2. Three-point bending test for orthodontic arch-wire carried out at 37 °C by placing the resin base into a water bath with controlled water temperature at 37 °C.

The same software then used the collected data to plot a graph for each test, showing the deflection of the test specimen on the x-axis and the force exerted on the y-axis. Loads were plotted for 0.5, 1.5, 2.5, and 3.5 mm deflections during loading and 4, 3, 2, and 1 mm deflections during unloading. Each curve obtained thereby represents the initial loading phase (upper curve) and the discharge or unloading phase (lower curve), which indicates the entity of the force exerted on the teeth during orthodontic treatment [1,6].

ETHICS CODE REC Code: REC-CL-23-06.

3. Results

Figure 3 shows the present load-deflection curves obtained experimentally for the three tested wires, Nitinol Classic, Nitinol Super-elastic, and Nitinol Heat-activated, respectively, at 5 °C. Each load-deflection curve consists of an upper loading curve and a lower unloading curve, where loads were plotted for deflections of 0.5, 1.5, 2.5, and 3.5 mm on loading each wire specimen, while during unloading loads were plotted at 4, 3, 2, and 1 mm deflections. Hysteresis can be noticed between upper

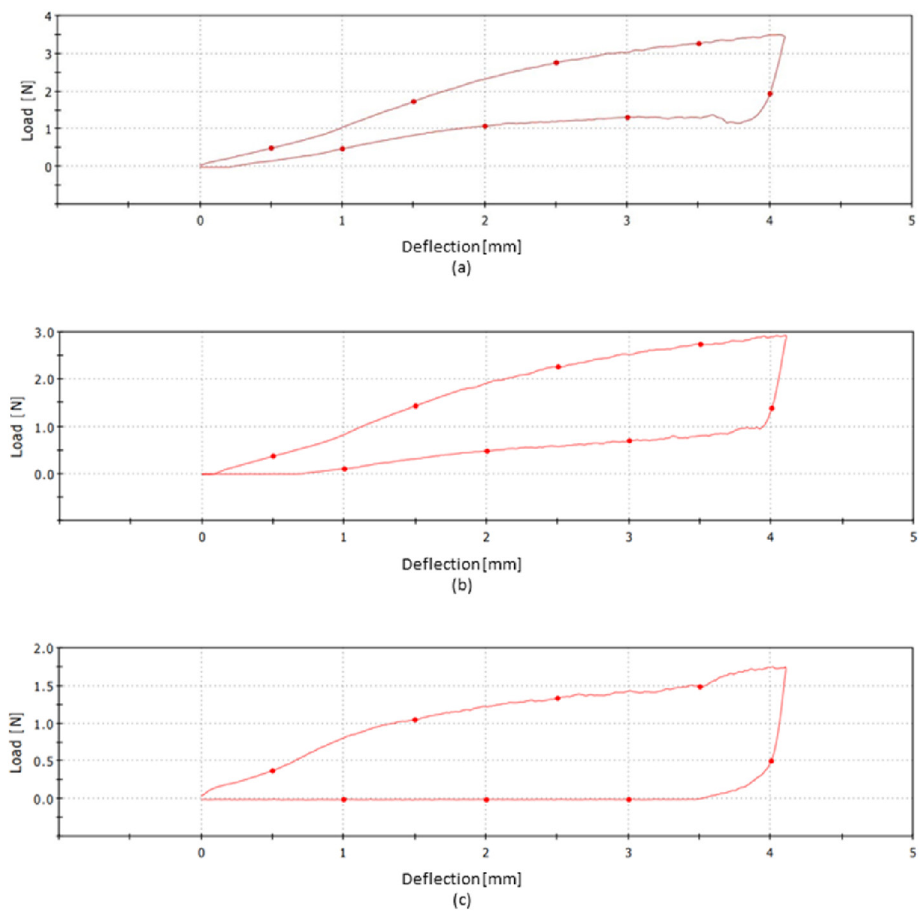

Fig. 3. Load deflection curves for a) Nitinol classic, b) Nitinol super-elastic, and c) Nitinol heat-activated arch-wires at 5 °C.

and lower curves, as the loads detected for every deflection during loading were much higher than those detected during unloading Table 1.

It is clear that at 5 °C, the mean values for both the loading force and the working force were highest for Nitinol classic, followed by Nitinol super-elastic, and Nitinol heat-activated, respectively. Diminished working forces were observed for nitinol heat-activated at 5 °C for all deflections.

The residual strain was observed in Nitinol heat-activated when tested at 5 °C after load removal which was recoverable as the temperature increased; see Fig. 4.

Figure 5 shows the load-deflection curves for the three wires, Nitinol classic, Nitinol super-elastic, and Nitinol heat-activated, respectively, at 37 °C. The Nitinol heat-activated arch-wire shows the longest plateau of the working force of the three wires with a marked reduction in the plateau slope..

It is obvious that at 37 °C Nitinol heat-activated arch-wire shows the lowest mean values for both loading and working force, followed by Nitinol super-elastic and Nitinol classic, respectively, for all deflections except for the loading force at deflections of 0.5 and 1.5 mm, Nitinol heat-activated shows slightly higher mean load values than Nitinol super-

Table 1. Shows the mean values and standard deviations for the three nickel-titanium wires when tested at 5 °C.

	Loading at 0.5 mm deflection		Loading at 1.5 mm deflection		Loading at 2.5 mm deflection		Loading at 3.5 mm deflection		Unloading at 4 mm deflection		Unloading at 3 mm deflection		Unloading at 2 mm deflection		Unloading at 1 mm deflection	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Nitinol classic	0.48	0.02	1.72	0.02	2.8	0.2	3.45	0.33	1.92	0.06	1.31	0.04	1.07	0.01	0.5	0.02
Nitinol super-elastic	0.43	0.12	1.56	0.22	2.36	0.13	2.76	0.03	1.44	0.05	0.67	0.04	0.48	0.01	0.16	0.12
Nitinol heat-activated	0.47	0.15	1.07	0.11	1.39	0.05	1.6	0.11	0.53	0.03	0	0	0	0	0	0

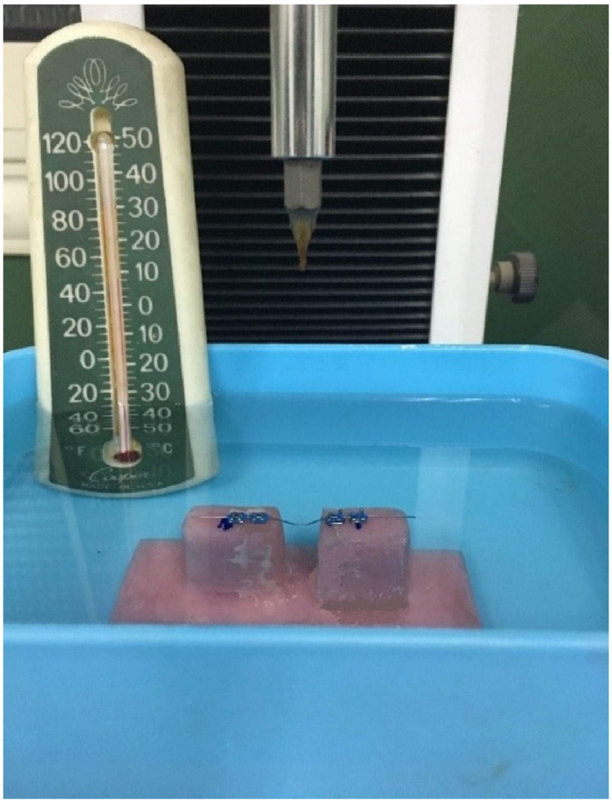

Fig. 4. Residual strain within the wire specimen observed after load removal at 5 °C.

elastic and Nitinol super-elastic shows slightly higher mean load values than Nitinol classic. During unloading at 1 mm deflection Nitinol super-elastic shows slightly higher mean load values than Nitinol classic.

Figure 6 shows the load-deflection curves for the three wires, Nitinol classic, Nitinol super-elastic, and Nitinol heat-activated, respectively, at 55 °C.

The above load-deflection curves revealed that at 55 °C there is a sharp drop in the working force during unloading from 4 mm deflection experienced by all three wires, followed by a plateau. Nitinol heat-activated shows the longest plateau of working force and the least plateau slope of the three wires. As, for Nitinol heat-activated, the force plateau ends nearly at 1 mm deflection while it ends nearly at 2 mm deflection for both Nitinol super-elastic and Nitinol classic Table 3.

It was noticed that at 55 °C Nitinol heat-activated arch-wire shows the lowest mean values for both loading and working force, followed by Nitinol super-elastic and Nitinol classic, respectively, for all deflections except for the loading force at deflections 0.5 and 1.5 mm, Nitinol heat-activated shows slightly higher mean load values than Nitinol super-elastic, and Nitinol super-elastic shows slightly higher mean load values than Nitinol classic at the same temperature. During unloading at 1 mm deflection, Nitinol heat-activated shows the highest mean load values than Nitinol super-elastic followed by Nitinol classic.

Generally, the working force mean values increase as the temperature rises from 5 °C to 37 °C–55 °C, and the working force plateau becomes more obvious as the temperature increases to 37 °C, then tends to decrease again at 55 °C.

4. Discussion

NiTi arch-wires, since their introduction into the dental market, have been marketed as the wire of choice for the initial stage of orthodontic treatment, which is the alignment and initial leveling phase, because of their capability of exerting small and continuous forces over a wide interval of deflection [12–14]. In this study, special emphasis was given to NiTi wires of round cross-section and 0.014-inch diameter, which are so-called light wires, to investigate their efficiency in aligning and leveling the dentition during the first stage of orthodontic treatment. Keeping in mind that round light wire is the wire of choice during the first stage of orthodontic treatment to allow easy engagement of the wire to the crowded malposed teeth with minimum patient discomfort [15].

There are mainly three different types of NiTi arch-wires as discussed previously in the introduction [14]. To select the most suitable wire type that should provide optimal and predictable treatment results, a thorough understanding of the mechanical behavior of an orthodontic arch-wire is needed. The most important of which are the load–deflection properties. A low load deflection rate (low elastic modulus, low stiffness, light forces) helps in maintaining desirable stress levels in the periodontal ligament. To simulate the conditions encountered clinically, a modified three-point bending test was implemented to quantify the load-deflection behavior of the three types of NiTi wires at deflections of 1, 2, 3, and 4 mm due to their possible occurrence during orthodontic treatment [1,14].

Oral temperature is not constant but varies with every intake of air, hot or cold food or beverage. To simulate the oral conditions and investigate the effect of temperature changes within the oral cavity on the load–deflection properties of the NiTi orthodontic arch-wires, the test was performed in a water bath under three different temperatures: 5, 37, and 55 °C. These temperatures were chosen in agreement with those revealed in the study of Moore et al. who reported during a period of 24 h a

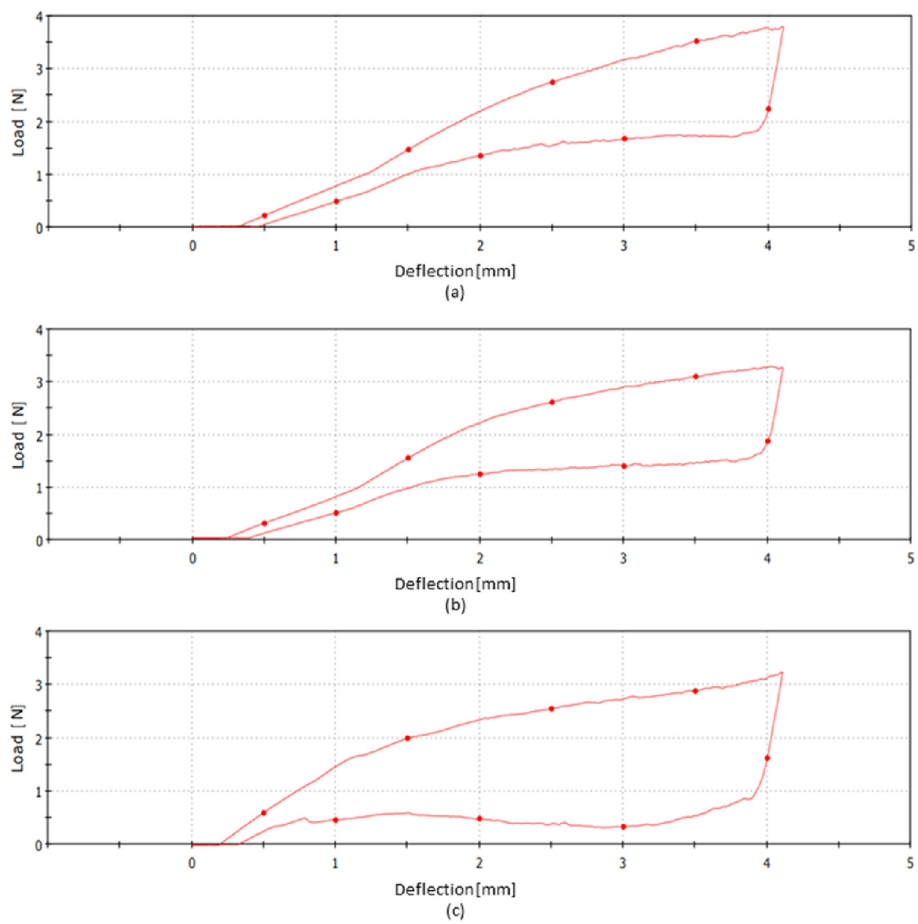

Fig. 5. Load deflection curves for a) Nitinol classic, b) Nitinol super-elastic, and c) Nitinol heat-activated arch-wires at 37 °C Table 2.

Table 2. Shows the mean values and standard deviations for the three nickel-titanium wires tested at 37 °C.

	Loading at 0.5 mm deflection		Loading at 1.5 mm deflection		Loading at 2.5 mm deflection		Loading at 3.5 mm deflection		Unloading at 4 mm deflection		Unloading at 3 mm deflection		Unloading at 2 mm deflection		Unloading at 1 mm deflection	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Nitinol classic	0.25	0.04	1.48	0.02	2.74	0.06	3.55	0.03	2.24	0.01	1.76	0.06	1.44	0.07	0.54	0.04
Nitinol super-elastic	0.37	0.04	1.71	0.17	2.61	0	3.02	0.07	1.87	0.09	1.38	0.16	1.21	0.07	0.61	0.09
Nitinol heat-activated	0.49	0.27	1.85	0.15	2.41	0.12	2.72	0.15	1.50	0.11	0.50	0.27	0.60	0.24	0.48	0.18

temperature range from 5.6 °C to 58.5 °C at the incisor site and from 7.9 °C to 54 °C at the premolar site [6]. It is also in agreement with two studies performed by Lombardo et al. who investigated the mechanical behavior of NiTi wires from seven different manufacturers at 5 and 55 °C [6] and compared the results with those of one of his previous studies that was performed at 37 °C [11].

Force versus deflection during loading and unloading was monitored and recorded for each test specimen and used to plot a graph of the load-deflection curve. Each curve obtained consists of an upper curve representing the initial loading phase and a lower curve illustrating the discharge or unloading phase [14]. The upper loading curve indicates the force felt by the clinician while handling the wire to engage brackets on malposed teeth, which is called the loading force, and it is of no clinical significance. The lower unloading curve represents the force exerted on the teeth during orthodontic treatment, known as the working force, and it is of particular clinical importance. The hysteresis noticed between the upper and lower curves is due to the energy dissipated in the transformation cycle, where the loads detected for every deflection during loading were much higher than those detected during unloading. Therefore, the force delivered to the periodontium is low compared with

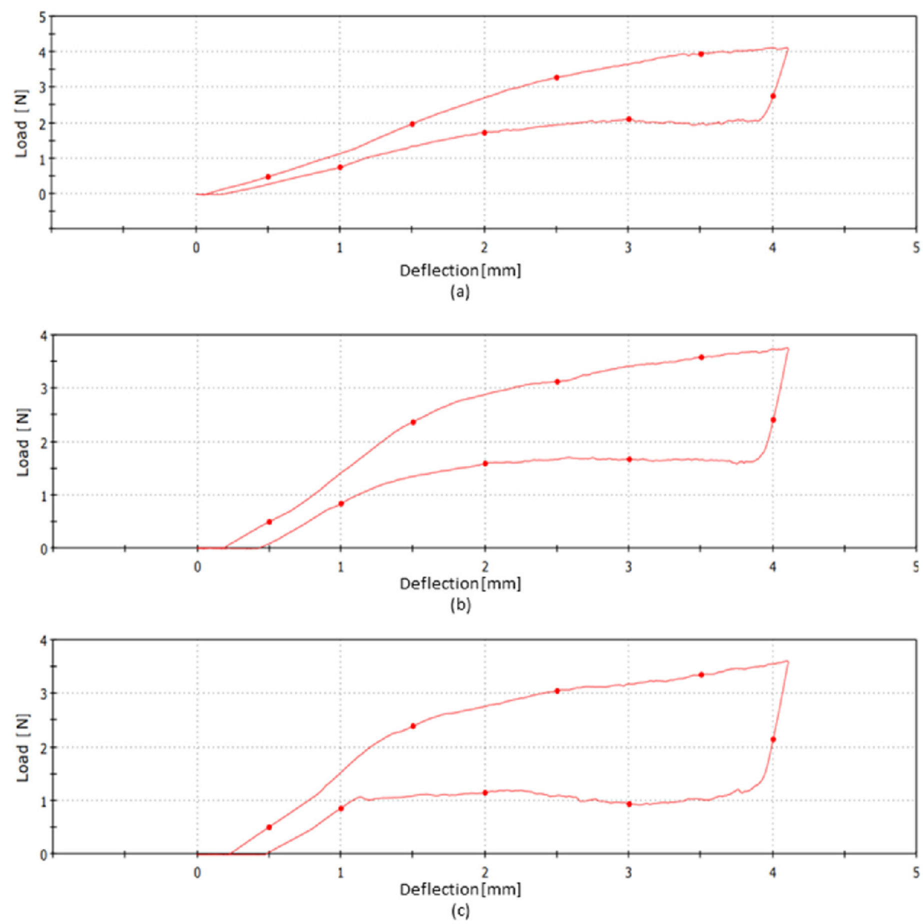

Fig. 6. Load deflection curves for a) Nitinol classic, b) Nitinol super-elastic, and c) Nitinol heat-activated arch-wires at 55 °C.

Table 3. Shows the mean values and standard deviations for the three nickel titanium wires when tested at 55 °C.

	Loading at 0.5 mm deflection		Loading at 1.5 mm deflection		Loading at 2.5 mm deflection		Loading at 3.5 mm deflection		Unloading at 4 mm deflection		Unloading at 3 mm deflection		Unloading at 2 mm deflection		Unloading at 1 mm deflection	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Nitinol classic	0.56	0.08	2.09	0.12	3.42	0.14	4.07	0.17	2.89	0.12	2.05	0.06	1.80	0.10	0.79	0.03
Nitinol super-elastic	0.52	0.02	2.37	0.04	3.22	0.08	3.73	0.14	2.48	0.06	1.55	0.16	1.53	0.09	0.87	0.02
Nitinol heat-activated	0.57	0.05	2.39	0	3.03	0.02	3.39	0.05	2.14	0.03	0.91	0.05	1.10	0.06	0.89	0.04

the force applied for arch-wire activation, which is one of the advantages of NiTi arch-wires [5].

Results revealed that the working force increase as the temperature increases from 5 °C to 37 °C–55 °C. This may be due to the existence of the NiTi alloy in the austenite phase at high temperatures, which is known for its high stiffness; therefore, a greater force is required to produce strain than when the martensite phase exists as in case of low temperatures. Our results confirm the behavior described by Lombardo et al., who found that the force expressed by NiTi wires increases with the increase in temperature from 5 to 55 °C and drops as the temperature decreases. They explained that at high temperatures, at which the NiTi wires exist solely in the austenitic phase, a higher stress is needed to produce a given strain [6].

The diminished working force observed for the Nitinol Heat-activated arch-wire at 5 °C may be due to the residual strain that was noticed after load removal when the wire specimen was tested at 5 °C. This residual strain was recoverable as the temperature increased, this may be attributed to the presence of Nitinol Heat-activated in the martensitic phase at 5 °C, which is known for its low elastic modulus. On loading, the twinned martensite will be plastically deformed to detwinned martensite at much lower forces than those needed to cause plastic deformation. Unloading the specimen at 5 °C caused the wire to retain its detwinned martensite state, and it would not be able to transform back to austenite and regain its original shape by what is known shape memory effect unless the temperature rose. As the increase in temperature reaches the austenite start temperature, austenite phase transformation begins and is accompanied by shape recovery. This recoverable residual strain was also noticed by Lombardo et al. at 5 °C [6].

Nitinol heat-activated arch-wire showed the lowest mean values for working force, followed by Nitinol super-elastic and Nitinol classic, respectively, at 5, 37, and 55 °C at nearly all deflections recorded in this study. This observation was similar to that of Tikku and colleagues who compared the force-deflection values of 3M Nitinol super-elastic and 3M Nitinol heat -activated but at 37 °C and deflections of 1, 1.5, 2, and 2.5 mm, and he found that Nitinol heat-activated showed lower mean load values when compared with Nitinol super-elastic at all of the four levels of deflection [16]. In our study at 37 °C, Nitinol heat-activated provided a light continuous working force of less than 1N at all deflections less than 4 mm at 37 °C and provided around 1N of constant light force at 55 °C, which is in accordance with the desirable physiological orthodontic force range [1–3].

Light working force offered by Nitinol heat-activated in all situations even at high deflections make it the most favorable for periodontally compromised patients and in sever crowded cases as well. This finding is in consistence with the conclusion of a study made by Choudary D et al., who evaluated and compared the load deflection rate of four arch-wires used in the alignment phase of fixed orthodontic treatment at 37 °C [4]. Similar findings were provided by a study made by Tikku and colleagues who compared the force-deflection values of different types of NiTi (pseudo-elastic NiTi, heat-activated NiTi, and esthetic coated NiTi) wires during the unloading phase at varying deflections, 1, 1.5, 2, and 2.5 mm, using modified bending test under controlled temperature conditions [16].

The increase in the working force plateau length experienced by the Nitinol heat-activated arch-wire also suggests constant working force exerted by the wire on the teeth during unloading which is favorable to the periodontal ligaments and hence produces optimum treatment results with minimal patient discomfort and a low risk of undesirable biologic responses such as damage to the supporting tissues, root resorption, or loss of pulp vitality. This plateau of the working force is due to the crystallographic transformation of the NiTi wire from high-stress phase martensite to low-stress phase austenite. Therefore, the load remains nearly constant, forming a plateau while the deflection declines until the transformation process is completed. The beginning of the plateau represents the start of the transformation to austenite, and its end represents the end of the transformation [17].

The longest working force plateau was presented by Nitinol heat-activated at 37 °C as it represents martensite-austenite phase transformation. At higher temperatures, the transformation from martensite to austenite might occur earlier, resulting in a shorter plateau. While at low temperatures, transformation to austenite might not start until the temperature rises and austenite start temperature is reached. This is consistent with the results of the two studies made by Lombardo and colleagues who reported a reduction in plateau length and an increase in force manifested by both Heat-activated and traditional NiTi wires at 55 °C when compared with test results at 37 °C. Decreased force and plateau length were also observed at 5 °C when compared with test results at 37 °C [6,11].

4.1. Conclusion

Both mechanical behavior and working force values of all of the three types of NiTi arch-wires showed detectable changes in respect to intra-oral temperature changes. Residual strain observed in Nitinol heat-activated at low temperatures can be recovered as the temperature rises. The light constant working force provided by Nitinol heat-activated at all deflections when compared with Nitinol super-elastic and Nitinol classic, made Nitinol heat-activated the wire of choice for periodontally compromised patients and in cases with severe crowding.

4.2. Recommendations

It is recommended to use Nitinol heat-activated orthodontic arch-wire in cases with sever crowding and with periodontally compromised cases.

Ethics information

Ethics code REC Code: REC-CL-23-06.

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Conflict of interest

There are no conflicts of interest.

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