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ORIGINAL ARTICLE

Comparison of the High Cycle Fatigue Behavior of the Orthodontic NiTi Wires: An *in Vitro* Study

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ABSTRACT

Objective: To compare the high-cycle fatigue behavior of four commercially available NiTi orthodontic wires. **Material and Methods:** Twelve NiTi orthodontic wires, round, 0.016-in, three per brand, were selected and divided into four groups: G1 - Heat-activated NiTi, G2 - Superelastic NiTi, G3 - Therma-Ti, and G4 - CopperNiTi. The atomic absorption spectrometry method was used to determine the chemical composition of investigated NiTi wires. We also performed a fatigue test at three-point bending using a universal testing machine for 1000 cycles in a 35 °C water bath. For the first and thousandth cycle, the average plateau load and the plateau length were determined in the unloading area of the force *versus* displacement diagram. In addition, we calculated the difference between the average plateau load of the first and thousandth cycle (ΔF), as well as the difference between the plateau length of both cases (ΔL). **Results:** According to our results, there were no significant differences between the average plateau load of the first and thousandth cycles of each group ($p>0.05$) and in the plateau length of the first and thousandth cycles of the groups ($p>0.05$). **Conclusion:** There were no significant differences between the groups changing the superelasticity property after high-cycle fatigue.

Keywords: Orthodontics; Orthodontic Wires; Stress, Mechanical; Fatigue; Elasticity.

Introduction

With the growing demand for orthodontic treatment, the need for orthodontic appliances has been increased [1]. Furthermore, it has been revealed that the quality of treatment by the fixed appliances (brackets [2], bands [3], and orthodontic wires [4]) is much better than with removable appliances [5].

In fixed orthodontic treatment, changes in the mechanical characteristics of the archwires may cause negative effects on the mechanical properties or working properties and, consequently, disturb the clinical progress and outcome [6]. When the archwires are placed in the brackets, cyclical forces during mastication can produce fatigue and limit the wire's lifespan [7].

In fixed orthodontic treatment, the functionality of archwires is quite essential for generating mechanical forces that are transmitted through brackets for causing movement in the teeth and correcting malocclusion, spacing, and/or crowding; they are also used for retentive purposes such as maintaining the teeth in their current position [8]. In addition, these wires are needed to remain in the mouth for a prolonged period of 18-24 months [9].

Various alloys have been used routinely in orthodontics, and these alloys are classified into four major types, namely stainless steel; cobalt-chromium nickel alloy (Elgiloy); titanium-molybdenum alloy (TMA); and nickel-titanium (NiTi) alloy [10,11]. In the early 1930s, the available orthodontic wires were made of gold. Later, austenitic stainless steel wires, with superior strength, high modulus of elasticity, and good corrosion resistance, were introduced as orthodontic wires in 1929 [12,13]. It was cheaper than gold; therefore, it became the most preferred material for orthodontic treatment [14]. Cobalt-chromium nickel alloy was first developed in the 1940s for the manufacture of watch springs. It was developed in 1950 and called (Elgiloy), initially manufactured by the Elgin Watch Company. Elgiloy for orthodontic use is supplied in four tempers (level of resilience) which are color-coded: Blue (soft), yellow (elastic), green (half elastic), and red (flexible). The blue type is the most commonly used orthodontics due to its formability and the possibility of increasing its durability by heat treatment [11].

A few years later, a beta-titanium alloy was introduced in orthodontic applications. Beta-titanium alloy is commercially available as “TMA” (titanium–molybdenum alloy). This wire has lower force magnitudes, lower elastic modulus, higher springback, lower yield strength, good ductility, weldability, high corrosion resistance, low potential for hypersensitivity, and high biocompatibility [15]. However, beta-titanium wire has disadvantages such as high surface roughness, which produces high friction between the archwire and bracket during the wire sliding process, and susceptibility to fracture under bending conditions; therefore, TMA is unsuitable for applications that require a flexible wire [16,17]. In 1962, Buehler and his co-workers in the Naval Ordnance Laboratory discovered that NiTi alloy could recover memory shape and superior mechanical properties [18].

Several brands of NiTi wires were introduced into the market in 1976. However, none of these wires demonstrated superelasticity properties [13]. In 1985 and 1986, new Ni-Ti alloys were developed in China and Japan, respectively; both Chinese and Japanese NiTi wires were active austenitic alloys that form stress-induced martensite [16]. In the early 1990s, Neo Sentalloy was introduced as a true active martensitic alloy that demonstrated the shape memory property by using the pseudoelastic effect during forming and the thermoelastic effect during unloading. In 1994, three Copper NiTi wires were manufactured that displayed the shape memory effect at 27 °C, 35 °C, or 40 °C. Among the most commonly applied orthodontic archwires, NiTi alloy wires are quite popular due to their favorable mechanical properties, especially superelasticity [19-21].

Considering this particular feature, this type of wire is usually used at the beginning of orthodontic treatment when more tooth movement is required [22]. In addition, in the case of superelastic NiTi wires, phase transformation between austenite and martensite can be induced by temperature alteration or stress application [19].

Throughout treatment with these wires, austenite is completely transformed into martensite after a certain stress and once the unloading stage begins, martensite transforms back into austenite and the transformation strain is fully recovered. In this way, NiTi orthodontic alloys are classified as nonsuperelastic or martensite-stabilized, which refers to a stable martensite without phase changes, superelastic, or austenite-active, in which deformation occurs by stress-induced martensite that returns to the austenitic phase after the unloading process; this procedure occurs in the course of activation, and martensite-active (heat-activated) in which thermal behaviors cause shape memory effects. Regarding to heat-activated wires, transition temperatures from martensite to austenite phase occur in the region of ambient oral temperature [23,24].

Nowadays, due to the large number of orthodontic wire trade brands available, some manufacturers invest in advertising the archwires by labeling them as superior products and emphasizing that they provide better performance and efficiency due to their good mechanical properties. However, these advertised mechanical features are not described on the product package. Moreover, the manifested qualities cannot usually be compared in exact measurements with similar products due to the different measuring tools, methods, and conditions [22]. Therefore, considering the lack of efficient information about the offered varying brands and the mechanical properties of their wires, it is quite difficult for clinicians to choose the appropriate and cost-benefit wires for their usage [25].

Changing the superelasticity of NiTi wires as a key property can negatively affect the archwires' performance and efficiency of orthodontic treatment. Although several studies have investigated NiTi wires' mechanical properties and transformation phase [20,25-28], few studies have evaluated the fatigue behavior of these materials in a high cycle fatigue regime or examined its effects on superelasticity properties. Due to the existing gaps in publications that are related to the comparison between fatigue behavior of NiTi wires, as well as gaining useful mechanical information about the different types of commercially available NiTi wires, the aim of the present study was set to investigate the high-cycle fatigue behavior of four commercially available NiTi orthodontic archwires. Our null hypothesis was to consider no significant differences between the wires in changing the superelasticity property through high-cycle fatigue.

Material and Methods

Study Design and Materials

This *in vitro* study contains the performed investigation on four commercially available NiTi orthodontic archwires from different manufacturers. NiTi orthodontic wires, round, 0.016-in, were selected and divided into four groups: Group 1: Heat-activated NiTi (3M Unitek Corp., Monrovia, CA, USA), Group 2: Superelastic NiTi (3M Unitek Corp., Monrovia, CA, USA), Group 3: Therma-Ti (American Orthodontics Corp., Sheboygan, WI, USA), and Group 4: CopperNiTi (TTR=27 °C) (Ormco Corp., Orange, CA, USA).

Data Collection

Initially, an atomic absorption spectrometry (GBC Scientific Equipment, Braeside, Victoria, Australia) was used to determine the chemical composition of investigated NiTi wires.

We also performed a fatigue test at three-point bending by the usage of a universal testing machine (STM20, Santam Eng. Design, Co. Ltd., Tehran, Iran) for 1000 cycles at a crosshead speed of 5mm/min and a span length of 10 mm according to the ADA specification no. 32. Samples of each archwire were obtained by cutting 30 mm of the straightest distal portion of an archwire (three per group). To simulate the conditions of oral cavity, the wire and supports were placed in a 35 °C water bath with a thermocouple (Figure 1). Moore et al. [29] found that usually, the temperature in the oral cavity is in the range of 33 °C to 37 °C for 79% of the time the archwire is in the mouth. Therefore the temperature of the water bath was kept at 35 ºC. Two supports were attached at the bottom of the water bath, while the distance between the supports was 10 mm. The bending force was exerted vertically on the midpoint of the wire at a crosshead speed of 5mm/min for 3 mm deflection.

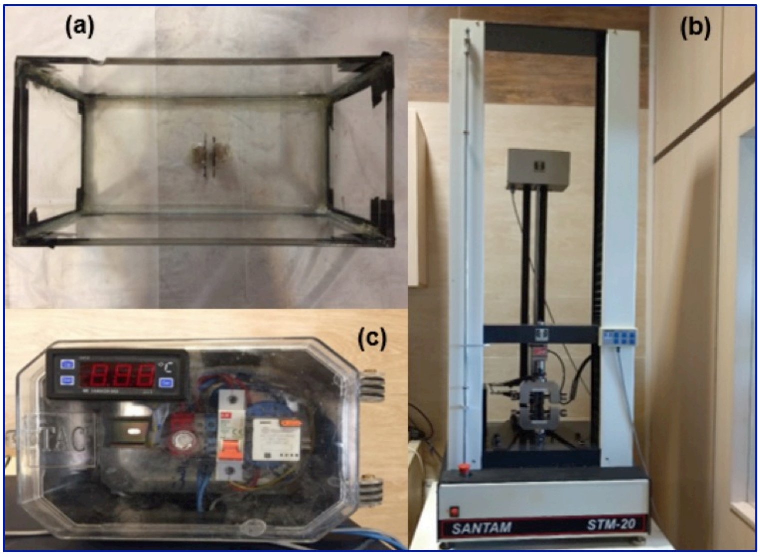

Figure 1. Experimental set up for high-cycle fatigue test: a) Water bath and supports, b) Universal testing machine, c) Thermocouple.

In the course of drawing the diagram of force versus displacement, the average plateau load for the first cycle and thousandth cycle in the unloading area of the diagram was determined. In the unloading area of the diagram of force versus displacement, the unloading plateau was divided into five equal sections, and the average plateau load was determined by the calculation of the average load at these points. The difference between the average plateau load of the first and thousandth cycle (ΔF) was calculated through the following formula: $\Delta F = F_1 - F_{1000}$, where F_1 and F_{1000} represented the average plateau load at first and thousandth cycles, respectively.

The difference between the plateau length of the first and thousandth cycles (ΔL) was determined by applying the following formula: $\Delta L = L_1 - L_{1000;}$ where L_1 and L_{1000} stand as the plateau length at first and thousandth cycles, respectively.

Data Analysis

Statistical analysis was performed by the exertion of SPSS software version 22 (SPSS Inc., Chicago, IL, USA). The normality of distribution was tested using the Shapiro-Wilk test ($p<0.05$). All of the gathered data were analyzed by One-Way Analysis of Variance (ANOVA) at a significance level of 0.05. The sample size (n=3) was determined with respect to other studies [30,31].

Results

The chemical composition of the NiTi wires is demonstrated in Table 1.

Table 1. Chemical composition of the investigated NiTi wires.

Element	Weight Percentage (%)			
	Therma-Ti	Superelastic-NiTi	ORMCO	Heat-activated NiTi
Ni	55.5	55	43.7	57.1
Cr	0.0326	0.0351	0.92	0.0688
Fe	2.5	2.6	7	2.3
Cu	0.0453	0.0559	3.87	0.0657
Co	0.03	0.0511	0.0454	0.0297
Ti	42	43	44.5	41

The diagram of force displacement for each wire is exhibited in Figure 2. Accordingly, the superelasticity feature of all the studied wires was confirmed by observing a hysteresis loop.

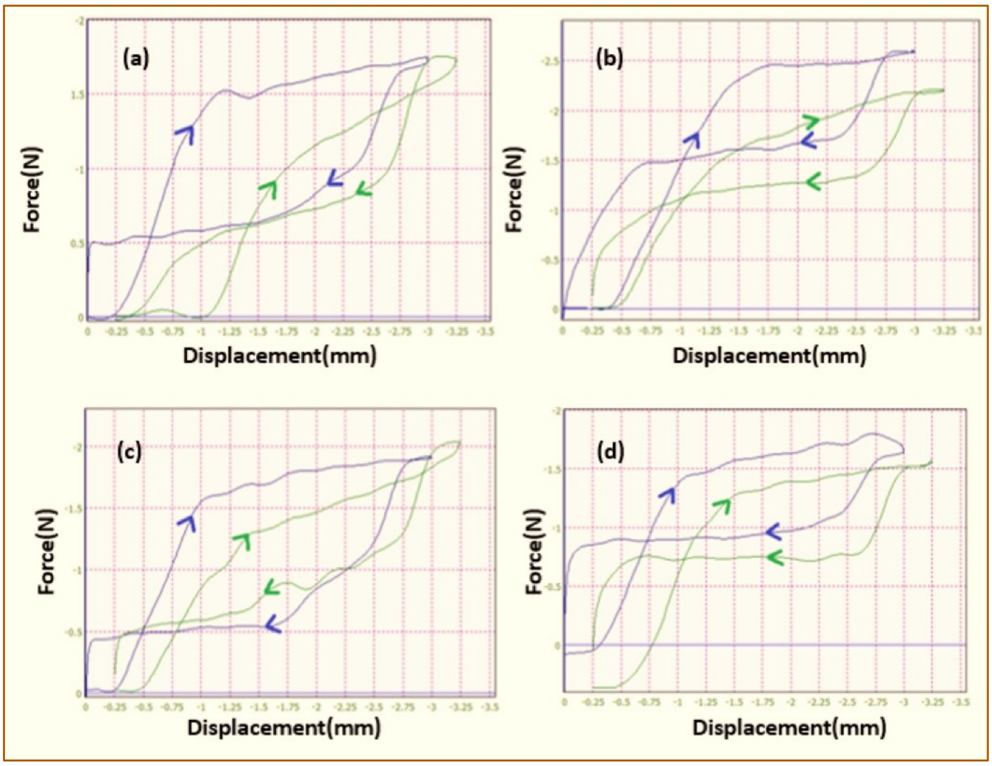

Figure 2. Force-displacement diagrams of four NiTi wires (at first cycle: blue curve; at thousandth cycle: green curve): a) Heat-activated NiTi, b) Superelastic-NiTi, c) Therma-Ti, d) ORMCO.

The difference between the average plateau load of the first and thousandth cycle (ΔF) of each group is displayed in Table 2. No significant differences in terms of ΔF between the groups were indicated by the results of ANOVA test ($p>0.05$).

Table 2. The difference between the average plateau load of the first and thousandth cycle (ΔF).

Groups	Mean (N)	Standard Deviation (N)	p-value
Heat-activated NiTi	0.1479	0.3421	0.315
Superelastic-NiTi	0.1893	0.1853	
Therma-Ti	0.2813	0.2105	
ORMCO	0.0828	0.4524	

The difference between the plateau length of the first and thousandth cycle (ΔL) is demonstrated in Table 3. According to the results of ANOVA test, the ΔL was not significantly different between the four groups ($p>0.05$).

Table 3. The difference between plateau length of the first and thousandth cycle (ΔL).

Groups	ΔL (mm)	Standard Deviation (mm)	p-value
Heat-activated NiTi	0.6741	0.2432	0.165
Superelastic-NiTi	0.3997	0.3558	
Therma-Ti	0.3068	0.6076	
ORMCO	0.3514	0.6224	

Discussion

One of the important factors in orthodontic treatments is to provide a light and continuous force to achieve a controlled tooth movement. For this purpose, superelastic NiTi wires were introduced to supply the required constant light forces for a longer period [32]. In materials science, fatigue is the progressive and localized structural damage that occurs when a material is subjected to cyclic loading. When the archwires are placed in the bracket's slot during orthodontic treatment, they suffer fatigue phenomenon. This stress caused by cyclical forces that occur during mastication and that limit the wire's lifespan [7].

There is a lack of sufficient information about the high-cycle fatigue behavior of NiTi orthodontic wires and its effect on changing the superelasticity property of NiTi wires. Our observations showed no significant differences between the groups in terms of average plateau load and plateau length of the first and thousandth cycle. In other words, there were no significant differences in the reduction value of superelasticity property between the four NiTi wires after undergoing high-cycle fatigue. It should be mentioned that the lack of significance observed in our study might be due to the small sample size.

Bartzela et al. [19] studied the mechanical properties of varying types of NiTi wires produced by five different manufacturers, which included an evaluation of superelastic properties of NiTi wires that was conducted through a three-point bending test. Their results revealed that a significant fraction of the tested wires either lacked any superelasticity or displayed weak signs. Their study contained the loading of each sample until reaching a deflection of 3 mm, which were then unloaded until the force became zero; however, they did not investigate the high-cycle fatigue behavior of the wires.

In another study, Prymak et al. [33] reported the fatigue resistance of nickel-titanium (NiTi) and CuNiTi orthodontic wires that were subjected to forces and fluids. According to their results, the fracture occurred within a short number of loading cycles, while prior to this occurrence, the mechanical properties remained mostly constant. Racek et al. [34] demonstrated that the wires, which were covered by the carefully engineered 70 nm thick TiO_2 oxide, displayed poorer fatigue performance upon tensile cycling under specific critical loading conditions.

Other authors, like Silva et al. [35], investigated the effects of aging treatments on the fatigue resistance of superelastic NiTi wires. The heat treatments were effective in improving the fatigue resistance, especially upon the formation of R-phase. Atik et al. [36] studied the clinical efficiency between premium heat-activated Ni-Ti and superelastic nickel-titanium archwires during the initial orthodontic alignment in adolescents. In conformity to their outcomes, there were no significant between-group differences in terms of alignment efficiency, arch width, and incisor inclination change.

Bellini et al. [22] evaluated the effects of thermal treatments on mechanical behavior and microstructure of Ni-Ti archwires that contained different compositions. According to their report, the heat treatment at 600 °C produces particular precipitation in the matrix, which is rich in titanium, and this fact leads to an alteration in the chemical composition of matrix and disables its superelasticity. However, these precipitates are not produced at 400 °C and the forces delivered by the wires are very similar to that of the untreated wires.

Aydin et al. [37] investigated the alignment efficiency of nickel-titanium (NiTi) and copper-nickel-titanium (CuNiTi) round archwires. It was indicative by their results that the NiTi and CuNiTi round archwires exhibited similar effects in terms of alignment efficiency.

Silva et al. [35] performed heat treatments in a wide range of temperatures in an initially superelastic NiTi wire and investigated the fatigue resistance of the resultant microstructure when subjected to an aggressive strain-controlled condition. Their results showed that the heat treatments were effective in improving fatigue resistance, especially when the R-phase was formed. Furthermore, the highest number of cycles to failure was obtained in the samples heat-treated at 400 ºC and 450 ºC.

This study has limitations, among which is the fact that it is an *in vitro* evaluation and lacks a full report on oral conditions. Therefore, further examination of more clinically relevant conditions is required for better comprehension in the future.

Conclusion

There were no significant differences between the studied NiTi wires in changing the superelasticity property after high-cycle fatigue. However, it should be mentioned that the lack of significance observed in our study might be due to the small sample size.

Authors' Contributions

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HS	https://orcid.org/0000-0001-7924-4654	Methodology, Investigation, Writing - Original Draft and Writing - Review and Editing.
HN	https://orcid.org/0000-0002-6639-1361	Methodology, Formal Analysis, Investigation and Writing - Review and Editing.
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AR	https://orcid.org/0000-0002-6323-6112	Conceptualization, Formal Analysis, Investigation, Writing - Original Draft and Writing - Review and Editing.

All authors declare that they contributed to critical review of intellectual content and approval of the final version to be published.

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None.

Conflict of Interest

The authors declare no conflicts of interest.

Data Availability

The data used to support the findings of this study can be made available upon request to the corresponding author.

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