Effect of the Addition of 3% Co in NiTi Alloy on Loading/Unloading Force

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Abstract. The study evaluated the loading-unloading force in the load-deflection curve of the fabricated NiTiCo and NiTi wires. Wire alloys with Nickel, Titanium, and Cobalt (purity-99.95%) with atomic weight ratio 47Ni:50Ti:3Co and 50.6Ni:49.4Ti were prepared, sliced, and cold-rolled at 30% reduction, followed by heat treatment in a furnace at 400°C for 1 hour. The specimens of wire size of 0.016 x 0.022 inch² were cut and subjected to three-point bending test to investigate the load-deflection curve at deflection point 0.25, 0.5, 0.75, 1.0, 1.25, and 1.5 mm. Descriptive statistic was used to evaluate each variables and independent t-test was used to compare between the groups. The results presented a load-deflection curve that resembled a typical superelastic wire. However, significant differences were seen in the loading-unloading forces between the two with an average loading force of 412.53g and 304.98g and unloading force of 292.40g and 208.08g for NiTiCo and NiTi wire, respectively. The force at each deflection point of NiTiCo in loading-unloading force was higher than NiTi wire. This study concluded that the addition of 3%Co in NiTi alloy can increase the loading-unloading force of NiTi wire but were within the range for orthodontic tooth movement.

1. Introduction

In fixed orthodontic treatment, archwires play a crucial role for the delivery of force required for tooth movement. They are able to deliver vertical (intrusion and extrusion), horizontal (buccal and lingual), and torque forces (bucco-lingual and linguo-buccal). The efficiency of these forces is dependent on the quality, type, and size of wire. Nowadays, there are many types of wires used in orthodontic treatment and are generally imported or exported to other countries with different quality and price. NiTi (nickel-titanium) wires have found wide applications in orthodontics due to their exceptional mechanical properties but may vary based on composition, transformation temperature range, and loading and unloading forces [1-2]. The so-fabricated NiTi alloys used in this study, 50.6%Ni:49.4%Ti (NiTi), 46%Ni:49%Ti:5%Cu (NiTiCu), and 47%Ni:50%Ti:3%Co (NiTiCo) have suitable mechanical properties and superelastic behavior as commercial orthodontic wires. Studies have also considered compositional changes in the NiTi wires to control or develop potentially better wire properties. For eg. Cu has been added to decrease the hysteresis temperature [3], and Co to...
increase the corrosion resistance [4-5]. These wires, Ni:Ti; Ni:Ti:Cu, and Ni:Ti:Co, had an austenite finish (Af) temperature close to 37°C which gave superior superelastic behavior without residual permanent strain after unloading [6]. NiTiCo wire is reported to have adequate mechanical properties and improved corrosion resistance [7-8]; however, the current literature rarely present data on the loading and unloading force, which is important if these wires are to be clinically used for the orthodontic tooth movement. The mechanical property of wire used in orthodontics should be optimized before clinical utilization. The possible differences in the components of alloys can change their mechanical properties and, consequently, their clinical performance. Therefore, the aim of this study was to investigate the loading and unloading force of the so-fabricated wires using load-deflection curve with a three-point bending test for their possible application in orthodontic tooth movement.

2. Materials and Methods

Ingots of Nickel (purity 99.9%), Titanium (purity 99.8%), and Cobalt (purity 99.95%) were first cleaned in acid (HF:HNO₃:H₂O=1:4:5), following which 47.0% Nickel, 50.0%Titanium and 3.0%Cobalt (Ni:Ti:Co) and 50.6%Ni:49.4%Ti (Ni:Ti) atomic weight elements were melted and mixed to form alloy ingots by vacuum arc melting method in argon gas. After homogenization at 800°C for 60 min, the cast ingots were sliced into thin bars with 1.5 mm thickness using an EDM wire cutting machine, cold-rolled at reduction 30%, and annealed at 400°C for 60 min. Then, the polished thin bars were cut and finely polished with sand paper for the fabrication of NiTiCo and NiTi wire specimens with dimensions - 0.016 x 0.022 inch² (0.4064 x 0.5588 mm²).

Three-point bending test was performed by a universal testing machine (UTM-Instron) for each of the three so-fabricated NiTiCo and NiTi wire specimens to obtain a load-deflection curve for assessing the loading and unloading forces. For the bending test, a wire span wire of 10 mm between supports was used. The specimen wires were loaded to a maximum deflection of 1.5 mm with 1 KN load cell with the deflection rate 5 mm/min at 36±1°C in a water bath. The loading and unloading forces were reported at the deflection points of 0.25, 0.5, 0.75, 1.0, 1.25, and 1.5 mm from the load-deflection curve (Fig 1-2). Descriptive statistics were used to evaluate each variables and independence t-test was used to analyze the differences between each deflection point.

![Fig 1: Load-deflection curve of the three fabricated NiTi wire specimens](image1)

![Fig 2. Load-deflection curve of the three fabricated NiTiCo wire specimens](image2)
3. Results

The results showed that the mean forces were 426.10 g (range 186.15-545.70 g) for loading and 304.80 g (range 508.47-106.59 g) for unloading of NiTiCo wire and 304.98 g (range 157.08-435.54 g) for loading and 208.08 g (range 412.08-100.98 g) for unloading of NiTi wire (Table 1-3). There were significant (p<0.05) differences in the loading and unloading forces between NiTiCo and NiTi wire. The NiTiCo wire had a higher force at each deflection point and the differences between each deflection point was more than NiTi wire (Table 2-5). Figure 1 and 2 showed the load-deflection curves of the fabricated NiTi and NiTiCo wires respectively (3 specimens each), and were notably different in the ‘plateau region’ of loading and unloading curves.

Table 1: Mean and standard deviation of the fabricated NiTi and NiTiCo wires in loading and unloading forces

|          | NiTi          | NiTiCo        | NiTi          | NiTiCo        |
|----------|---------------|---------------|---------------|---------------|
| N        | Loading       | Unloading     | Loading       | Unloading     |
|          | Mean          | SD            | Mean          | SD            | Mean          | SD            | Mean          | SD            | Mean          | SD            |
| 1        | 286.62        | 1.08          | 464.51        | 0.19          | 191.76        | 0.92          | 335.38        | 0.15          |
| 2        | 314.16        | 1.25          | 410.04        | 0.14          | 210.12        | 1.04          | 289.34        | 0.06          |
| 3        | 312.12        | 1.24          | 403.75        | 0.12          | 222.36        | 1.07          | 289.68        | 0.17          |
| Total    | 304.98*       | 1.19          | 426.10*       | 0.15          | 208.08*       | 1.01          | 304.80*       | 0.13          |

* significant difference at p<0.05

Table 2: Mean and standard deviation of loading and unloading forces of the fabricated NiTi wire at each deflection point

| NiTi | Deflection | 0.25 | 0.5  | 0.75 | 1.00 | 1.25 | 1.50 |
|------|------------|------|------|------|------|------|------|
|      | Loading    | Mean | SD   | Mean | SD   | Mean | SD   |
|      | Unloading  | Mean | SD   | Mean | SD   | Mean | SD   |
|      |            | Mean | SD   | Mean | SD   | Mean | SD   | Mean | SD   |
|      |            | Mean | SD   | Mean | SD   | Mean | SD   |
|      | Loading    | 157.08 | 0.02 | 278.46 | 0.09 | 347.82 | 0.21 | 388.62 | 0.22 | 415.14 | 0.23 | 435.54 | 0.23 |
|      | Unloading  | 100.98 | 0.02 | 170.34 | 0.18 | 207.06 | 0.19 | 250.92 | 0.22 | 319.26 | 0.22 | 412.08 | 0.23 |

Table 3: Mean and standard deviation of loading and unloading forces of the fabricated NiTiCo archwire at each deflection point

| NiTiCo | Deflection | 0.25 | 0.5  | 0.75 | 1.00 | 1.25 | 1.50 |
|--------|------------|------|------|------|------|------|------|
|        | Loading    | Mean | SD   | Mean | SD   | Mean | SD   | Mean | SD   | Mean | SD   | Mean | SD   |
|        | Unloading  | Mean | SD   | Mean | SD   | Mean | SD   | Mean | SD   | Mean | SD   | Mean | SD   |
|        |            | Mean | SD   | Mean | SD   | Mean | SD   |
|        | Loading    | 186.15 | 9.38 | 331.5 | 7.21 | 408.00 | 4.33 | 463.59 | 3.61 | 508.47 | 2.16 | 545.70 | 2.88 |
|        | Unloading  | 106.59 | 2.16 | 184.11 | 0.72 | 243.27 | 2.61 | 306.0 | 0.0 | 390.15 | 2.16 | 508.47 | 2.16 |

Table 4: Mean and standard deviation of loading and unloading forces between each deflection point of the fabricated NiTi wire

| Force | Diff. between each deflection point |
|-------|-----------------------------------|
|       | 0.5-0.25 | 0.75-0.5 | 1.0-0.75 | 1.25-1.0 | 1.5-1.25 |
| Loading Force | 121.38 | 69.36 | 40.80 | 26.52 | 20.40 |
| Unloading Force | 69.36 | 36.72 | 43.86 | 68.34 | 92.82 |

Table 5: Mean and standard deviation of loading and unloading forces between each deflection point of the fabricated NiTiCo wire

| Force | Diff. between each deflection point |
|-------|-----------------------------------|
|       | 0.5-0.25 | 0.75-0.5 | 1.0-0.75 | 1.25-1.0 | 1.5-1.25 |
| Loading Force | 142.46 | 73.78 | 52.7 | 45.9 | 32.64 |
| Unloading Force | 76.84 | 57.46 | 63.24 | 84.32 | 131.24 |
4. Discussion

This study used three-point bending test to evaluate the loading and unloading forces of fabricated wires according to the recommendations made by the American Dental Association and Standard No.32 from the American Nation Standards Institute. Three-point bending test is an appropriate mechanical testing method for beams, like orthodontic wires, to evaluale inactivation (loading) and deactivation (unloading) forces [9]. During this test, the induced stresses may increase the transformation temperature range, as described by the Clausius-Clapayron relationship [10]. Supereelastic behavior application of the stress led to a linear increase in strain up to the point where the martensitic transformation started to occur during loading. This plateau-phase was due to formation of stress-induced martensitic transformation (SIM). In unloading, a relationship exists between stress and strain down to the point where the austenitic transformation starts to occur. The unloading plateau increases until the restoration of austenitic structure is complete.

Evans and Durning classified orthodontic alloys into five categories: 1) stainless steel, gold; 2) first stabilized NiTi; 3) superelastic wires – active austenites with TTR below intraoral temperature (pseudoelastic): 4) thermodynamic wire- active martensite with TTR close to intraoral temperature; 5) a group of thermodynamic wires featuring diverse TTR (e.g. NiTiCu35oC, 37oC, 40oC) [11]. According to the TTR of the wires used in this study (the TTR AF37oC-Ms 36oC of the fabrication Ni:Ti and AF39oC-Ms 37oC of the fabrication Ni:Ti:Co) [12], the Ni:Ti wire may be classified under Category 4- active martensite and Ni:Ti:Co may be classified under Category 5. Moreover, both wires would be classified as thermodynamic wires. The scientific basis enabling the use of thermoelastic arch wires are various and accounts the argument that bone remodels itself more effectively if subjected to a dynamic load rather than a static one [13-14]. The thermoelastic properties feature is the so-called “shape memory effect”, which has remarkable clinical applications. Through deflection and repeated temperature cycles, the wire in the austenitic phase is able to memorize a preformed shape, including specific orthodontic archforms. By lowering the temperature, the alloy is transformed into martensite and becomes pliable and easily deformed. However, every time the temperature rises above Af the austenitic phase, the wire will remember and recover the ideal archform. The forces of orthodontic wire, which are applied to the crowns of the teeth, are distributed over the entire supporting structure and so are the stresses and strains. From a cellular point of view, distribution of stress (force per unit area), distortion of the periodontal ligament (shear stress, strain), and bone deformation (strain) are critical factors, and the remodeling response is directly related to stress and strain levels within the periodontium [15]. The orthodontic force as an extrinsic mechanical stimulus, thus, evokes a biologic cellular response that aims to restore equilibrium by remodeling of the periodontal supporting tissue [16-17]. Because it is very difficult to measure stresses and strains within the periodontal ligament of loaded teeth directly, measurement of only the forces that are applied directly to teeth with known root surface areas can provide an estimate of these parameters.

Load-deflection properties of archwires, which are considered the most important parameters determining the biological nature of tooth movement, are obtained by classic three-point bending tests. For rectangular wires, these tests are conducted such that the force is applied perpendicular to the ribbon side of archwire. The unloading curve is the curve of interest for orthodontic tooth movement. In superelastic archwires, this curve is characterized by an almost horizontal unloading plateau, which shows that these NiTi archwires are able to exert constant forces in certain range of deflection [18-22]. For this study (Fig. 1 & 2), the unloading plateaus were not parallel to the horizontal plane, which showed that these two fabricated NiTi wires did not exert the constant force in the range of deflection.

In orthodontics, an optimal approach should result in the highest possible rate of tooth movement without irreversible damage to the periodontal ligament, the alveolar bone, or the root. Nikolai [23] defined optimum force as the force that yielded the maximum desirable biologic response with minimum tissue injury producing rapid tooth movement with small or no clinical discomfort. In order to move teeth, it is necessary to apply an orthodontic force, which produce a pressure above a dental root film capillary blood pressure of about 15g/cm2 and below 20 g/cm2, onto the dental root film (US Patent 5759029). Thus, the magnitude of the optimal orthodontic force required is normally with the range of 0.5 to 3 N. This relatively low force should be applied continuously in order to achieve correction of teeth. Such force may reduce the potential for patient discomfort, tissue hyalinization,
and undermining resorption. Hence, the ideal wire should behave elastically and be able to produce light and continuous forces over the period of use.

In this study presented much higher force of NiTiCo and NiTi (Table 1-5); however, the forces of orthodontic tooth movement should depend on which tooth to move, type of tooth movement, and length of the root. A previous study reported the numerical force for optimal tooth movement in different root length and found 110-130 g. of force for mandibular canine movement, 130-170g for maxillary canine movement, 270-320g for mandibular first molar movement, and 320-360g for maxillary first molar movement in the long root length group [24]. Each deflection point of this study (Table 2-3) showed that the fabricated wire had unloading at deflection point range 0 - 1.25 mm for NiTi and range 0 - 1.0 mm for NiTiCo in the range of tooth movement. Therefore, these fabricated NiTi wires could be used in adjusting teeth irregularity of not more than 1.00 mm.

For achieving optimal forces, it is essential to select an appropriate diameter and to eliminate rectangular archwires from the leveling phase. Trials evaluating superelastic and conventional NiTi archwires with regard to the movement speed of a tooth as well as the pain sensation have not validated the differences in their properties [25]. The superelastic austenitic NiTi significantly reduces the need for replacing thin archwires with the thicker for leveling and alignment [26].

Clinically, there is no single archwire that possesses all of the desired qualities necessary for all stages of orthodontic treatment. A straight superelastic leveling archwire is a highly complex, statically in determinate system, and it is impossible to predict exactly the force system acting on each tooth. The excessive forces exerted by NiTi archwire may lie far beyond biologically safe limits [27-29]. In orthodontic treatment, there are many phase of treatment and many levels of teeth irregularity. In early leveling phase of the treatment, if the malocclusion has severe teeth irregularity, the treatment should be started with the small diameter wires which have more flexibility for loading force into the bracket to move the teeth to correct the teeth in proper position by unloading force.

5. Conclusion
The study presented the load-deflection curve of two fabricated orthodontic rectangular wires (in size diameter 0.016 x 0.022 inch2), namely NiTi and NiTiCo. Significant differences in the loading-unloading forces were noted with the addition of 3% Co in NiTi composition. Both wires had high loading and unloading force in each deflection point, thus, they should be used in later leveling phase or in teeth with mild irregularity.

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