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Force Degradation Properties of Two Nickel-Titanium Closed Coil Springs

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Abstract

Background and Aim: The aim of this study was to compare two nickel-titanium (NiTi) closed coil springs (CCSs) from two different manufacturers regarding their force degradation over 4- and 8-week periods.

Materials and Methods: In this in vitro experimental study, 20 NiTi CCSs from 3M® and GAC® were compared. The springs were extended until a tensile strength of 250 g was achieved, and the length of springs was recorded. They were then mounted on customized jigs according to the registered length, so as to keep them extended constantly. Springs from each manufacturer (n=10) were randomly divided into two subgroups (n=5): one subgroup was stored in artificial saliva and the other was stored in a dry environment. The forces were assessed 4 and 8 weeks later. Data were analyzed by repeated measures ANOVA and the Tukey post-hoc test (alpha=0.05).

Results: The mean force of 3M® CCSs significantly decreased by 56% after 4 weeks and 14% after 8 weeks in dry condition, and by 46% after 4 weeks in wet environment; however, after 8 weeks in wet environment, the force decay was insignificant. The changes in force of GAC® CCSs in dry environment after 4 weeks and 8 weeks were not significant, indicating a constant force property. However, in artificial saliva, a statistically significant yet mild increase in force level was recorded.

Conclusion: The results showed a force decay for the 3M® CCSs after 4 weeks while for the GAC® CCSs, an almost constant force level was observed even after 8 weeks.

Key Words: Orthodontics; Dental Alloys; Orthodontic Appliance Design; Artificial Saliva

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Introduction

Research shows that light, continuous, and constant force provides an optimal force system to achieve orthodontic tooth movement in a biologically compatible manner with fewer adverse side effects [1-4]. Nickel-titanium (NiTi) was introduced in the mid-1980s as a promising material which could overcome the force decay while providing force for a long duration of time [5, 6]. The superiority of NiTi closed coil springs (CCSs) over other devices, such as elastomeric chains or other coil springs, has already been shown in the literature [4, 7, 8]. This unique property of NiTi alloy is due to its capacity to alter the crystalline bonding patterns between the martensitic and austenitic phases as a function of temperature and applied stress without permanent dislocation of atoms [4, 6-9]. Each of these two phases has a different modulus of elasticity, and due to this special property of NiTi alloy, the behavior of NiTi CCSs is sometimes perplexing [4-7, 9, 10]. On the other hand, with numerous variables and limitations of in vitro studies, even with sophisticated research methods, the results regarding force degradation of NiTi CCSs have always been a subtle confusion for clinicians [4-10].

Previous in vitro studies on force degradation properties of NiTi CCSs provided contradictory reports from no significant force change after 45 days [4, 11] to an increase in force level [12, 13]; however, many others reported a decrease in NiTi CCS force [9, 14-17]. Interestingly, a previous study showed an increase in unloading forces following incubation and a reduction in force when the CCSs were kept at room temperature [13]. As far as the force decay is concerned, however, studies have reported force decay from 7% to 12% based on the environment [18], 8% to 20% according to their metal alloy [19], and 22.6% to 45.8% based on the manufacturing company [15].

In order to simulate the clinical situation, it appears that repeated stretching and relaxing of springs should be avoided [12]. Therefore, we designed a study to compare the level of unloading force of NiTi CCSs from two different manufacturers available in Iran, when extended to an average force of 2.45 N (approximately 250 g) and kept extended during all stages of the tests in different conditions (wet and dry) for 4- and 8-week periods. The null hypothesis was that there would be no significant difference in force degradation properties of the two brands of NiTi CCSs.

Materials and Methods

This in vitro experimental study included 20 NiTi CCSs from two different manufacturers namely 3M (3M® International Inc., Minnesota, USA) and GAC (GAC® International Inc., Bohemia, NY, USA). The length of the samples from both companies was 12 mm from the eyelet to eyelet [5, 15]. Initially, the springs were extended until a tensile strength of 2.45 N was achieved in a universal testing machine (Instron Corp., Canton, Massachusetts, USA). Then, the length of each spring was recorded [15, 20]. A customized jig as per the extended recorded length was made for each spring (20 plexiglass jigs) so as to keep the force level constant during the tests [12]. Each jig had two rigid stainless-steel posts with 1.2 mm diameter on either end, which was covered by a rigid metal tube [20]. The spring was extended as per the initial readings and was attached to the metal tubes (Figure 1a). In the universal testing machine, two customized arms were designed, and each arm had a stainless-steel post which could receive the metal tubes from the jigs (Figure 1b). The jigs with tubes were designed for constant extension of coils during the test, even when transferring them to the universal testing machine [12]. All coils underwent a preliminary test; therefore, they were transferred from jigs back to the universal testing machine and if the force was not 2.45 N, the coil was extended or relaxed until it reached 2.45 N; then, a new custom-made jig was made and the coil was re-engaged [16]. The minimum measured length of 20 mm and 11 mm was recorded for the 3M® and GAC® CCSs, respectively.

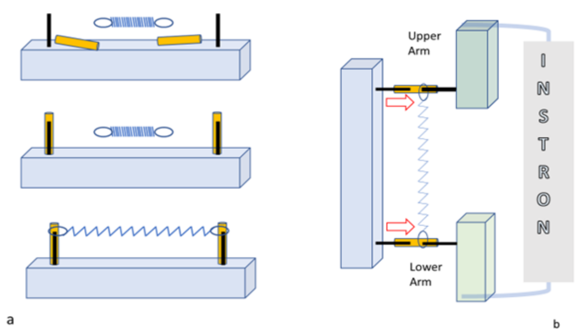

Figure 1. (a) Customized jig with spring attached to the tubes, (b) transfer of the springs to a universal testing machine

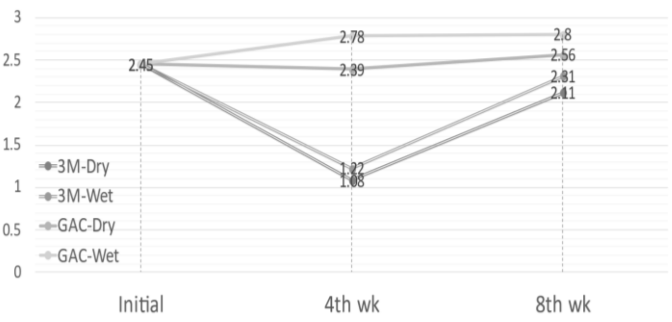

Figure 2. Force properties of NiTi CCSs (Newtons)

Ten springs from each manufacturer were randomly divided into 2 subgroups; half of the samples in each group were stored in a dry environment and the other half were immersed in artificial saliva (Hypozalix, Biocodex, France) for 4 and 8 weeks [16].

For comparability of dry and wet conditions and standardization of factors during the study, the temperature was fixed at body temperature (37°C) [15, 20]. For the dry environment, the temperature was adjusted by a 150 W lamp in an appropriate distance from the samples and was checked by a digital thermometer [21]. In the artificial saliva, the temperature was adjusted with a heater [7]. The examiner was blinded to the manufacturing company of CCSs [16].

After the first 4 weeks, the samples were transferred again to the universal testing machine and their force was recorded while maintaining the length of each spring constant. Then, the test was repeated for another 4 weeks. Finally, the mean force for each subgroup was calculated after each time interval [16]. Data were analyzed by SPSS version 24. Repeated measures ANOVA and Tukey post-hoc test were used to analyze whether the means were significantly different between the groups. A P-value of less than 0.05 was considered statistically significant.

Results

Due to the fact that the study was based on the unloading force of 2.45 N, initially the amount of coil extension was compared between the two groups. Table 1 shows the mean values of the eyelet-eyelet length of NiTi CCSs from the two manufacturers in wet and dry conditions. The highest mean of eyelet-eyelet length was recorded for 3M® springs in the dry environment while the GAC® samples in the same environment had the lowest mean. Although the mean value for the 3M® springs was almost double that of GAC® springs, yet the differences were not significant (P=0.15).

Table 1. Length of NiTi CCSs recorded in millimeters and the percentage of elongation during stretching to a force of 2.45 N

	Dry environment (%)	Wet environment (%)
3M®	24.4 ± 7.4 (103.5%)	22.2 ±1.6 (85%)
GAC®	17.7 ± 5.6 (47.5%)	23.4 ±6.9 (95%)

The percentage of force changes for all springs is shown in Table 2. The mean force of 3M® springs in dry condition significantly decreased by 56% after 4 weeks (P<.001). At 8 weeks, the mean force of 3M® springs increased by 95% in comparison with 4 weeks, and this change was statistically significant (P<.001). However, comparison of the initial mean force and the 8th week force revealed a reduction by 14%, and this reduction was statistically significant (P=.048). For the 3M® samples in artificial saliva, there was also a statistically significant force decay of 46% after 4 weeks (P<.001). At 8 weeks, the mean force improved by 75% and this difference was statistically significant (P=.001). Meanwhile, comparison of the mean force between baseline and 8 weeks showed only 5.7% force decay, which was not statistically significant (P=.08).

The mean force of GAC® springs in dry environment decreased by 2.4% after 4 weeks, which was not statistically significant (P=.06).

Table 2. Mean force at baseline, 4 weeks, and 8 weeks in the two brands of CCSs in dry and wet environments

Brand	Environment	Baseline Mean (Newtons)(%)	4th week Mean (Newtons)(%)	8th week Mean (Newtons)(%)
3M®	Dry	2.45 (100%)	1.08 ± 0.16 (-56%)	2.11 ± 0.21 (-14%)
	Wet	2.45 (100%)	1.22 ± 0.16 (-46%)	2.31 ± 0.27 (-5.7%)
GAC®	Dry	2.45 (100%)	2.39 ± 0.16 (-2.4%)	2.56 ± 0.53 (+4.5%)
	Wet	2.45 (100%)	2.78 ± 0.16 (+13.5%)	2.8 ± 0.39 (+14.3%)

At 8 weeks, the mean force of GAC® springs increased by 7.0% which was not statistically significant either (P=.50). The overall change in force levels from baseline to 8 weeks was only 4.5% increase which was insignificant (P=.08). When tested in artificial saliva, there was 13.5% increase in force level after 4 weeks and this change was statistically significant (P=.04). At 8 weeks, the mean force increased by another 1.0% and this difference was not statistically significant (P=.06). Meanwhile, comparison of the mean force between baseline and 8 weeks showed an increase in force level (14.3%), which was statistically significant (P=.009).

ANOVA showed that the amount of force in the four subgroups was significantly different (P=.009). The Tukey's test demonstrated that the mean change of force level in 3M® springs was higher than that in GAC® springs (P=.006), but the difference according to the storage environment was not significant (P=.18). In addition, at 8 weeks, ANOVA showed that the difference among the four groups was statistically significant (P =.034).

Discussion

In the present study, the force property of 20 NiTi CCSs (as received from the company) was compared. The tests were performed under dry and wet (artificial saliva) conditions for a period of 8 weeks. The results showed that the mean unloading force of 3M® CCSs in both dry and wet environments and the GAC® CCSs in dry environment had a descending trend (force decay) during the first 4 weeks. However, for GAC® CCSs in wet environment, the results showed an increase although insignificant in the first 4 weeks. However, after 8 weeks, the force recorded for 3M® CCSs had decreased compared with the baseline value (-14.5% and -5.7% force decay in dry and wet environments, respectively) but it was higher than the values recorded at 4 weeks. Insignificantly increased force levels were also recorded for GAC® CCSs in both wet and dry environments at 8 weeks. Thus, the mean force levels of CCSs from the two manufacturers were not the same, especially in the first 4 weeks (Figure 2). A surprising finding of this study was that the force levels for both brands of CCSs were quite similar at the end of 8 weeks (Table 2).

Lack of standardization of force values of NiTi CCSs as reported by their manufacturers is a problem repeatedly investigated [9,11,15,17,18,22]. In a study by Cox et al, a constant force level of 300 g was considered. Their justification was that, testing coils at higher force levels than that reported by the manufacturer will allow to capture the entire range of loading and unloading force curves of NiTi CCSs, and if they are extended beyond the guidelines, then many coils can experience distortion [16]. In order to simulate the use of coils in the oral environment, we considered 2.45 N (250 g) unloading force level. In order to achieve this force level in the present study, we observed a varied extended length of 94.2% and 71.3% for 3M® and GAC® respectively, but the difference was not statistically significant (P=.15). The mean extended lengths in this study were very close to other studies where the extensions varied from 30% to 100% [9, 11, 13, 17] or were considered as twice the length of the original length [15, 17].

Similar to many studies [3, 5, 8, 9, 15-17, 19], we recorded a force degradation, especially with 3M® product in the first 4 weeks, but the increase in force levels after that, under similar in vitro conditions, was a surprising finding.

The results on CCSs are contradictory and need further investigations. Regarding the change in forces produced by NiTi CCSs, many studies have observed basically a force decay [3, 5, 9, 15-17]; however, few studies reported some increase in force levels [12, 13]. Alavi and Haerian reported an increase in force level at 22 days (T1) in a 45-day study, which was related to differences in the environment [13]. They reported that the incubated coils, either preactivated or non-preactivated, showed a reduction in force over time; however, the coils kept at room temperature showed an increase in force overtime [13].

Nattrass et al. reported that in their study, as temperature raised, the measured force of coil springs increased. They showed that the NiTi CCSs stored in distilled water at 37°C actually showed an increase in residual forces [12]. Momeni Danaei et al, in a study on reuse of NiTi open coils also showed that autoclaving increased the coils' strength; however, the authors concluded that the increase was not clinically significant [23].

The increased force levels observed in this study should be interpreted with caution. In order to generalize the results, two different brands of NiTi CCSs were examined, and since both types experienced similar conditions, then the effect of environmental factors was eliminated. Therefore, other variables such as composition of material (Young's module of elasticity, transition temperature, and hysteresis), manufacturing method, and geometry (length, gauge, lumen size, winding configuration of coil) might have affected the force properties of the coils [14, 15]. On the other hand, the force properties of NiTi CCSs highly depend on initial activation [7, 24]. The NiTi CCSs in this study were extended to a length to achieve 250 g, simulating routine clinical use of coils. Therefore, it is possible that some coils never reached the transforming stage between the austenitic and martensitic crystalline phases and therefore, showed abnormal behaviors. However, if the initial and final pseudo-elastic force-deflection curves for each spring would be recorded, then it would be easy to confirm for each coil that whether the coil had experienced the stress-induced martensitic transformation during loading and unloading phases. For this study, we wanted to evaluate the coils as received from the company, so any undue activation of coils was avoided, which is one of the factors to be considered in future studies.

It should be noted that as far as NiTi CCSs are concerned, in vitro studies are preferred to in vivo studies in terms of simplicity, understanding of different test results, and control over various interfering factors. One of the variables that is often overlooked by many, is the handling of NiTi springs during the tests [12]. Many studies allow the stretched springs to relax during laboratory steps, which can alter the stress/strain curve of NiTi springs and therefore will affect their force properties. This limitation is unavoidable in clinical trials since the coils need to be removed from the patient's mouth and stored, before evaluation in the testing machine in the laboratory.

Magno et al. investigated the force decay of NiTi CCSs in a clinical trial [17]. According to the nature of clinical trials, it is obvious that presence of oral flora, accumulation of plaque on testing materials, and influences of oral function play important roles in the results and affect the recorded force decay [17, 25]. Also, in an in vivo study, Cox et al. evaluated force decay in intraoral and laboratorial conditions following 4 and 8 weeks and showed that the force reduction of NiTi springs was 12% of their initial force after 4 weeks of clinical application [16]. However, the length of the springs used in their study was 9 mm (unlike ours: 12 mm). They also reported that between 4 and 8 weeks, the force decay was almost 7%. After the 8th week, the force level appeared to be more stabilized [16]; whereas, in our study, the mean force decay for the 3M CCSs was much more (56% and 46%, respectively). In contrast, the GAC CCSs experienced an increase in force which was more stabilized.

In a study by Santos et al., the force decayed from 37.4% to 71.6%. Difference in force decay in their study compared with our results is due to the fact that Santos et al. used different brands of springs (Morelli®, Abzil®, TP Orthodontics®, and American Orthodontics®) [15]. Kishorekumar studied the force decay characteristics of NiTi closed coil spring at different time intervals after placing them in artificial saliva [26]. At the end of 4 weeks, the force decay for GAC® spring was greater than other brands. GAC® showed significant force degradation during the intervals in accordance with the study by Angolkar et al. which was in contrast to our findings [5]. In these studies, the springs were extended to deliver a force of 150 g; whereas, in our study, it was 250 g based on the manufacturer's guidelines [26].

Different ranges of force decay have been reported for various coil springs [16]. Alloy, wire size, lumen size, pitch angle, length, and manufacturing conditions play a major role in force properties of these springs [5, 16]. The force decay mechanism of NiTi CCSs can also be related to hysteresis phenomenon [16, 17, 27).

Conclusion

The present results revealed that NiTi CCSs from two different manufacturers did not deliver constant force. The mean of force degradation in 3M® springs was higher than that of GAC® springs regardless of their environments after 4 weeks. At the end of 8 weeks, interestingly, the net forces for both products were quite similar.

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