The effects of different bending techniques on corrosion resistance and nickel release of superelastic orthodontic NiTi archwires

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Abstract. Bending superelastic NiTi archwire is indicated in some stages of orthodontic treatment. The difference in bending techniques may affect corrosion resistance and nickel release. The purpose of this study was to investigate the corrosion resistance and nickel release after different bending techniques of NiTi archwires. Preform-curved NiTi archwires were used as a template for bending and used as a control group. 0.016×0.022 inches superelastic NiTi archwires were bent to curve-shape by cold bending, DERHT bending and cold bending then DERHT technique. Potentiodynamic polarization technique was used to measure corrosion behavior of the wires. Corrosion potential (ECORR), corrosion density (ICORR), and breakdown potential of each wire were determined. In addition, the amount of nickel release in the solution after the test was inductively coupled plasma mass spectrometry (ICP-MS). Although, the results showed that ECORR and ICORR were not statistically significantly different among all groups, the difference in breakdown potential and nickel release were observed. Similar corrosion resistance and nickel release were presented in the preform-curved NiTi archwires, cold bending, and cold bending then DERHT group. The DERHT bending group showed the lowest breakdown potential and highest nickel release.

1. Introduction

Superelastic nickel titanium (NiTi) archwires are widely used in clinical orthodontics because of their superelasticity properties, giving continuous and light force transmitted to the dentition over a long period of activation. The constant stress allows the design of orthodontic archwires to communicate through the brackets for leveling and alignment in the stages of tooth movement [1].

The best technique of bending NiTi archwires has not been clarified. There are two ways to alter the shape of the archwires. Heat treatment, for example direct electrical resistance heat treatment (DERHT), allows shape setting of superelastic wires. Without DERHT, NiTi archwires can be shaped by mechanical force (cold bending) until it reaches to permanent deformation. Both techniques have been recommended for using in orthodontic practice [2, 3].

Heat treatment at 500 °C ranged from minutes to an hour can alter the surface structure of NiTi archwires. Therefore, after heat treatment, the oxide layer in the form of TiO₂ will increase. These titanium oxides are important for protection of wire surface and increase the corrosion resistance. This
indicates that heat treatment may produce protective surface and favor of good biocompatibility of NiTi archwires [4, 5].

On the other hands, mechanical bending can affect the surface of NiTi archwires. The influence of surface roughness might be a reason for varying corrosion tendency. The corrosion resistance is higher in the smooth surface of the NiTi archwires [6, 7].

During orthodontic treatment, orthodontic metallic appliances are prone to corrosion or degradation in the oral environment. This degradation of metal has been demonstrated to adversely affect biocompatibility, which considered a concern for clinicians due to the long period of orthodontic treatment. The Corrosion of NiTi archwires raises a major concern because of their high nickel content (47% to 50% nickel) [8, 9]. These individualized reports have indicated that insertion of NiTi alloys may occasionally lead to formation of rashes, swelling, and painful erythematous lesions in oral and labial mucosa [10].

Unfortunately, there is not much study about different modes of wire bending on corrosion resistance and nickel release. Thus the purpose of this study was to investigate the corrosion resistance and nickel release after different bending techniques of superelastic orthodontic NiTi archwires.

2. Material and methods

2.1. Sample preparation

0.016×0.022 inch superelastic NiTi archwires (Highland, USA) were used in this study and divided into 4 groups with different bending techniques as illustrated in Table 1.

| Group | Condition | Performing methods |
|-------|-----------|---------------------|
| 1     | As-received | Preform-curved NiTi archwires |
| 2     | Retrieve   | Cold bending by mechanical force |
| 3     | Retrieve   | DERHT bending using Bender soarer-X at heat level 4 |
| 4     | Retrieve   | Cold bending then DERHT using Bender soarer-X at heat level 4 for 3 seconds |

2.1.1. Group 1. 0.016×0.022 inch NiTi preform-curved NiTi archwire (Highland, USA) was used as a control. The template was made from preform-curved NiTi archwire with acrylic resin.

2.1.2. Group 2. 0.016×0.022 inch NiTi plain archwire was bent by mechanical force from thumb and index finger. The archwire was curved until the shape was similar to preform-curved NiTi archwires (group 1) by using the template as a guide. Permanent deformation occurred after bending.

2.1.3. Group 3. 0.016×0.022 inch NiTi plain archwire was bent by using DERHT (Bender soarer-X equipment) at level 4 (Figure 1). The pliers from DERHT were used to sweep the archwires. The archwire was permanently curved until the shape was similar to preform-curved NiTi archwires (group 1) by using the template as a guide.

2.1.4. Group 4. 0.016×0.022 inch NiTi plain archwire was bent by mechanical force from thumb and index finger. The archwire was curved until the shape was similar to preform-curved NiTi archwires
(group 1) by using the template as a guide. Once the permanent deformation achieved, the wire was DERHT (Bender soarer-X equipment) at level 4 for 3 seconds.

Figure 1. DERHT bending using Bender soarer-X equipment, Tomy Incor, Japan

2.2. Surface morphology examination
All groups were examined surface morphology with scanning electron microscope & energy-dispersive X-ray microanalysis type (SEM-EDS, JSM5410LV, JEOL LTD) at 400x and 800x magnification and operating voltage at 20 kV.

2.3. Potentiodynamic polarization testing
The curved ends of the archwires were cut to a length of 30 mm. All samples were cleaned with ethanol in an ultrasonic bath for 5 minutes and dried for 20 seconds. The corrosion behaviors were examined by measuring potentiodynamic polarization measurements (Autolab PGSTAT302N - High Performance, The Netherlands). Modified Fusayama artificial saliva with pH 5.3 was used as the electrolyte. The compositions of saliva were listed in Table 2. Reference and counter electrodes were Ag/AgCl and Pt, respectively.

Table 2. Composition of Modified Fusayama artificial saliva

| Compound           | Concentration (g/L) |
|--------------------|---------------------|
| KCL                | 0.4                 |
| NaCl               | 0.4                 |
| CaCl₂·2H₂O         | 0.906               |
| Na₃H₂PO₄·2H₂O      | 0.690               |
| Na₂S.9H₂O          | 0.005               |
| Urea               | 1                   |

The wire samples were immersed in the electrolyte and were maintained at 37°C. Open circuit potentials (OCP) were run for 30 minutes. After that, anodic polarizations were run at a scan rate of 10 mV/min. Corrosion potential (E₉₀₀₀₀), corrosion density (I₉₀₀₀₀) and breakdown potentials of each group were determined. The experiments were performed 4 times for each group.

2.4. Nickel release testing
The amount of nickel release in solution after potentiodynamic polarization test was determined by inductively coupled plasma mass spectrometry (ICP-MS, ELAN-6000) at Faculty of Science, Mahidol University.

2.5. Statistical analysis
E₉₀₀₀₀, I₉₀₀₀₀ and breakdown potentials were analyzed by Kruskal-Wallis Test and a Mann-Whitney U
Test for the post hoc test at 95 % confidence interval ( \( \alpha = 0.05 \)). All statistical analyses were performed with IBM SPSS statistics 20 software.

3. Results

3.1. Surface morphology examination
Scanning electron micrographs of each group at 400x and 800x magnification were presented in Figure 2 and 3, respectively.

![Figure 2](image)

**Figure 2.** Scanning electron micrographs at 400x magnification: (a) group 1, (b) group 2, (c) group 3, and (d) group 4.

![Figure 3](image)

**Figure 3.** Scanning electron micrographs at 800x magnification: (a) group 1, (b) group 2, (c) group 3, and (d) group 4.

3.2. Potentiodynamic polarization testing
Polarization curves were shown in Figure 4. The passive current density of group 4 was lower than that of others. (It should be noted that the experiment was assumed surface area as 1 cm\(^2\), however actual exposed area was smaller approximately of 0.11 cm\(^2\).)

The means and standard deviations for \( E_{\text{CORR}} \), \( I_{\text{CORR}} \), and breakdown potentials for each group were shown in Table 3. \( E_{\text{CORR}} \) and \( I_{\text{CORR}} \) were similar for all groups. Breakdown potential of group 3 was statistically significantly less than that of the others (0.76±0.10 V, (Ag/AgCl)) (P<0.005, \( \alpha = 0.05 \)). There were no statistically significantly different between group 1 and group 2 as shown in Table 4.
Table 3. $E_{\text{CORR}}$, $I_{\text{CORR}}$, and breakdown potentials for each group

| Group | $E_{\text{CORR}}$ (V, Ag/AgCl) | $I_{\text{CORR}}$ (A/cm$^2$) | Breakdown potential (V, Ag/AgCl) |
|-------|-------------------------------|-------------------------------|----------------------------------|
| 1     | -0.09±0.02                    | 1.59x10$^{-7}$±8.5 x10$^{-10}$ | 1.33±0.00                        |
| 2     | -0.15±0.02                    | 1.30 x10$^{-7}$±5.4 x10$^{-9}$ | 1.35±0.01                        |
| 3     | -0.16±0.01                    | 1.38 x10$^{-7}$±3.05 x10$^{-9}$ | 0.76±0.10                        |
| 4     | -0.09±0.01                    | 1.18 x10$^{-7}$±4.3 x10$^{-9}$ | 1.28±0.00                        |

Table 4. Significantly different among four groups of breakdown potentials

| Group | 1 | 2 | 3 | 4 |
|-------|---|---|---|---|
| 1     | - | NS| * | * |
| 2     | NS| - | * | * |
| 3     | * | * | - | * |
| 4     | * | * | * | - |

*Significantly different at P<0.005 and $\alpha = 0.05$.

3.3 Nickel release testing

In Figure 5, the amount of nickel release in each group was shown. The amount of nickel release of group 3 was higher than that of others (269±11.0 $\mu$g/L). There were similarities in the amount of nickel in group 1, groups 2 and group 4. The mean nickel release was presented in Table 5.
Figure 5. The amount of nickel release in all groups

Table 5. The amount of nickel release

| Group | Mean amount of Nickel (μg/L) | SD  |
|-------|-----------------------------|-----|
| 1     | 2.65                        | 0.65|
| 2     | 4.35                        | 2.25|
| 3     | 269.00                      | 11.0|
| 4     | 3.45                        | 0.35|

4. Discussion
As a chair-side procedure, the manipulation of NiTi archwires can be achieved mechanically through cold bending and forming from the heat sources [2, 3].

In orthodontics, DERHT is one of the methods to alter NiTi mechanical properties. DERHT transformed electric current to high temperature and induced restructuring of the lattice. However, the temperature received on the archwire was not as high as heat treatment by furnace in air or salt bath in the laboratory [11]. In our study, the temperature received on the archwire in DERHT bending and cold bending then DERHT group was 42.83±1.96°C and 210.33±6.96°C respectively.

The temperature used as a chair side heat treatment in orthodontics treatment should not reach 500°C. Considering the mechanical properties, heat treatment will increase hardness and unloading force of the wire. Moreover, transitional temperature range (TTR) will decrease. Thus, NiTi archwire will increase its superelasticity. However, at a very high temperature, heat treatment will deteriorate these mechanical properties [5].

From SEM, the surface of DERHT bending group was rougher than that others. In Figure 3, DERHT bending group showed deep and wide spread area of corrosion as a result of the process of wire bending. The DERHT-pliers (Figure 1) were used to sweep the archwire until the shape was set. During sweeping, the beak of the pliers could scratch the wire surface. On the other hands, thumb and index fingers were used to sweep the archwire in cold bending and cold bending then DERHT group. This resulted in smoother surface than DERHT bending group and was similar to preform-curved NiTi archwire.

The breakdown potential in our study ranged from 0.76-1.35 V (Ag/AgCl). The breakdown potential of preform-curved NiTi archwire was 1.33 V (Ag/AgCl). This was not significantly different.
in cold bending group (1.35 V (Ag/AgCl)). Iijima previously studied the corrosion resistance of NiTi archwire. The breakdown potential of as-received wire was similar to our study [12].

Heat treatment was applied in 2 groups: DERHT bending group and cold bending then DERHT group. The heat treatment had an effect on corrosion behavior by affecting on surface structure. The oxidization on NiTi surface depended on the temperature of the heat treatment. The increase in temperature would increase in protective oxide layer [13, 14].

The passive current density was a measure of a protective oxide film. The more negative passive current density, the more oxide film was presented. However, once the passive current density was more positive, this oxide layer was breakdown. Thus corrosion occurred [15]. In our study, cold bending then DERHT group received highest temperature in heat treatment. From polarization curve (Figure 4), cold bending then DERHT group had lowest passive current density. This implied that this group had greater protective oxide layer.

Recent studies from Shabalovskaya and Firstov found that the temperature that suitable for the formation of titanium oxide layer (TiO₂) was 500°C [4, 9]. At this temperature, it would produce a smooth protective oxide surface, nickel-free and favor of good biocompatibility of NiTi [4, 5]. The increase in temperature would increase oxide layer leading to greater corrosion resistance. This oxide layer serves two purposes. Firstly, it increases the surface layer stability and protects the surface from corrosion. Secondly, it creates a physical and chemical barrier against nickel oxidation by modifying the oxidation pathways of the nickel [13].

The amounts of nickel release of preform-curved NiTi archwire, cold bending, and cold bending then DERHT group were similar (2.65, 4.35, and 3.45 μg/L respectively). Hwang studied Ni release from simulated fixed orthodontic appliance and found nickel release of 17.03 μg/L, which was greater than our study. The amount of nickel release increased in the first 3 months after that nickel release decreased or stopped after the certain time [16]. However, the result of nickel release in this study cannot be compared with that of Hwang because of different methodology.

In our study, DERHT bending group presented the lowest breakdown potential (0.76±0.10 V (Ag/AgCl)) and highest amount of nickel release (269±11.0 μg/L). This may be because of the process of bending the archwire by using DERHT-pliers, which could damage the surface of archwire, resulting in surface roughness. The increase in surface roughness will decrease in corrosion resistance [6, 7]. Moreover, the temperature received on wire during DERHT bending was relatively low. Once the heat treatment is below 300°C, the surface of NiTi will be modified in a different way. Titanium and nickel-enriched will be formed at the surface. The coexisting NiTi archwire will invite galvanic corrosion. The enriched matrix will serve as a reservoir for potential nickel release, especially when the surface is damaged, for example by mechanical bend of the archwire [9].

Orthodontic appliances unlike to medical uses of nickel alloys because they are not implanted; rather, they are placed in the oral environment and exposed to oral fluid. Many researches have recognized the potential biological implications of nickel release, focusing on the rate of corrosive products of alloys used in orthodontic treatment. The increase in corrosion rate might be at risk for patient especially patient with nickel hypersensitivity [10, 17].

5. Conclusion
The results showed that similar corrosion resistance and nickel release were presented in the preform-curved, cold bending, and cold bending then DERHT NiTi archwires. The DERHT bending archwires showed the lowest breakdown potential and the highest nickel release. The cold bending then DERHT archwires showed the lowest passive current density and the greatest protective oxide layer. Therefore, it is recommended that the cold bending then DERHT technique be used to bend a superelastic orthodontic NiTi archwire.

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