Comparative analysis of mechanical properties of differently tapered nickel-titanium endodontic rotary instruments

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INTRODUCTION

Endodontic rotary instruments made of nickel-titanium alloy (Ni-Ti rotary instruments) have a number of advantages over conventional stainless steel instruments, such as greater flexibility, more rapid and centered root canal preparation, and working length control consistency. Thus, a variety of products that differ in their design features (taper, cross-sectional shape, pitch, shape of cutting edges, helicoidal angles) and manufacturing processes (application of thermomechanical processing) have been developed, aimed at improving the accuracy and efficacy of root canal preparation.

Flexibility, i.e. the ability to be bent with a smaller load, is an important property of Ni-Ti rotary instruments, because it is a decisive factor for the mechanical behavior and performance of endodontic instruments while shaping curved canals. Moreover, the flexibility of endodontic instruments influences the outcome of torsional and cyclic fatigue properties. Due to its superelastic effect, Ni-Ti alloy recovers its original shape from deformations when stress is removed, unlike stainless steel. Plastic deformation is due to slip deformation, which is irreversible. However, superelastic deformation of Ni-Ti alloy is achieved by crystalline change via stress-induced martensitic transformation upon exposure to an external force, with reverse transformation occurring after unloading of the external force.

One of the main goals during root canal preparation is maintaining the original canal shape. Transportation occurs due to a tendency for endodontic instruments to straighten the root canal during canal shaping. Moreover, the transportation of the canal is determined by the flexibility of the preparation instruments, the movement of the instruments in the canal, as well as the length of time the instrument is in contact with the canal wall during preparation.

The major concern for the clinical use of Ni-Ti rotary instruments is unexpected intracanal fracture due to torsion or cyclic fatigue. Torsional fracture occurs when an instrument tip or another part of the instrument is locked in a canal whilst the shank continues to rotate. When the elastic limit of Ni-Ti alloy of the instrument is exceeded by the torque exerted by the motor, fracture of the tip becomes inevitable. Fracture due to cyclic fatigue is induced by alternating tension-compression cycles which occur when instruments are flexed in the maximum curvature region of the canal and rotated. Therefore, continuous modifications have been made to increase the fracture resistance of rotary instruments.

EndoWave Ni-Ti rotary instruments (FKG Dentaire, La Chaux-de-Fonds, Switzerland) have a triangular cross-section along its length, and helical and undulated edges. According to the manufacturer, EndoWave is characterized by its “alternate contact point” design, which aims to increase flexibility and reduce transportation while maintaining its centering in the root canal. Another important feature of this instrument is the electrochemical polishing that produces smooth surfaces. Electropolishing may have beneficial effects in prolonging the fatigue life of Ni-Ti rotary instruments.

Stainless steel hand files typically have 0.02 tapers. However, irrigant replacement provided by a 0.02-tapered canal space is small, and a greater canal taper is advantageous for more efficient irrigant replacement. Another advantage of a greater taper is the accuracy of obturation, as demonstrated in a previous study showing...
that a final taper of 0.08 showed less voids and gaps than final tapers of 0.04 and 0.06\textsuperscript{20}. Nowadays, most Ni-Ti rotary instruments have a greater taper than stainless steel files. Either a constant or a multiple taper design is applied to the greater taper instruments. However, a larger preparation may increase the risk of vertical root fracture\textsuperscript{21}, and thus there is no consensus regarding the optimal taper that should be given during root canal preparation.

Mechanical properties of Ni-Ti rotary instruments are known to be influenced by various factors, such as different configuration and metallurgical properties\textsuperscript{22,23}. However, limited knowledge is available regarding the influence of taper on the properties of these instruments\textsuperscript{24-26}. Additionally, few studies have been conducted on the mechanical properties of EndoWave Ni-Ti rotary instruments\textsuperscript{18,27,28}. Thus, the purpose of this study was to compare the mechanical properties of differently tapered EndoWave instruments. The null hypothesis was that 0.04- and 0.06-tapered EndoWave instruments do not differ in terms of their mechanical properties.

**MATERIALS AND METHODS**

New EndoWave instruments with a tip size 30 and a 0.04 taper (Group 0.04), and a tip size 30 and a 0.06 taper (Group 0.06), were used in this study.

**Cyclic fatigue test**

An original stainless steel three-pin device that has previously been described in detail\textsuperscript{9,29} was used in this study. The instrument (n = 7 in each group) was fixed using three pins at an instrument curvature of 38° with a curvature radius of 5 mm, and the tip was protruded 2 mm beyond the most apical pin (Fig. 1). The experiment was performed at 300 rpm using a motor (Dentaport ZX OTR Module, J. MORITA MFG, Kyoto, Japan) until fracture occurred. Silicone oil (KF-96-100CS, ShinEtsu Chemical, Tokyo, Japan) was used to reduce friction and to minimize the release of heat during the test. A load cell (LUR-A-50NSA1, Kyowa Electronic Instruments, Tokyo, Japan) was fixed to the middle pin to determine the magnitude of the deflection load imposed by the instrument during rotation. The output of the load cell was connected to an analog-to-digital (A/D) converter with a bridge box (TUSB-S01LC, Turtle Industry, Ibaraki, Japan), and the output of the A/D converter was connected to a personal computer. The number of cycles to fracture (NCF) was recorded by measuring the time to fracture.

**Cantilever bending test**

An original cantilever bending test apparatus described in previous studies\textsuperscript{9,22,29} was used. The test was performed for both instrument groups under the same conditions. The instrument was mounted on a movable stage and clamped at distance of 7.0 mm from the tip, and the loading point was set at 2.0 mm from the tip (Fig. 2). The instrument was loaded (1.0 mm/min) until it achieved a 3.0 mm maximum deflection, and then unloaded. The bending loads were measured at deflection values of 0.5 and 2.0 mm.
**Root canal transportation**

Fourteen J-shaped simulated resin canals (Endo Training Bloc, Dentsply Sirona, Ballaigues, Switzerland) were randomly divided into two groups \((n=7\) in each group). All instrumentation was performed at a working length of 17 mm by one trained operator (YF). Each canal was sequentially prepared with size #10 to #25 stainless steel K-files (Zipperer, Munich, Germany), followed by 0.04- or 0.06-tapered EndoWave instruments rotated at 300 rpm with a motor (Dentaport ZX OTR Module). After each instrumentation, the canal was flushed with distilled water. RC-Prep (Premier, Plymouth Meeting, PA, USA) was used as a lubricant. The time taken to prepare each canal, including instrumentation, irrigation, and file change, was recorded in seconds. The instruments were examined visually after each use, and instrument deformations and fractures were recorded.

Digital images of the canals were taken using a stereomicroscope (Keyence VH8000, Osaka, Japan) fixed on a customized stand on which the blocks were repositioned to obtain the pre-and postoperative images. The images were superimposed using image processing software (Adobe Photoshop CC 2015, Adobe Systems, San Jose, CA, USA) by precisely overlapping the reference points of each image. The canal width was measured at 200% magnification in 3-mm increments along the canal on both the inner and outer boundaries of the canal wall. The measurements were made perpendicular to the surface of the canal wall (long axis of the preoperative canal). The inner/outer preparation volume was determined as the length from the center of the preoperative canal to the surface of the postoperative canal (inner and outer curvature sides). The difference between the inner/outer preparation volume and the radius of the file at the measuring point was defined as the transportation value (Figs. 3, 4). A value equal to 0 means that the instrument maintained its original canal shape. In the present study, final apical preparation was set at size 30. This was because several studies have reported that the minimum instrumentation size necessary for the penetration of irrigants to the apical third of the root canal is size 30\(^{30,31}\).

**Torque and apical force**

Fourteen simulated resin canal models with a straight canal (END3L001, Nissin Dental Products, Kyoto, Japan) were randomly divided into two groups \((n=7\). All instrumentation was performed using a custom-made device described below, at a working length of 14 mm. Before the use of EndoWave instruments, all canals were sequentially prepared with size #10 to #25 stainless steel K-files. RC-Prep was used as a lubricant. After each instrumentation, the canal was flushed with distilled water.

Measurement of the torque and apical force is considered as a reasonable method for evaluating the cutting efficiency of files in artificial root canals\(^{32}\). Therefore, a custom-made automated root canal instrumentation and torque/force analyzing device, described elsewhere\(^{33}\), was used to conduct this study (Fig. 5). This device made it possible to exclude the influence of the operator’s experience and habitual motion. The resin canal models, mounted on a metal stage through an acrylic tube with three screws, were prepared with EndoWave instruments rotated at 300 rpm with a motor (Dentaport ZX OTR Module) that
Fig. 5  Schematic diagram of the custom-made automated root canal instrumentation and torque/force analyzing device.
(a) movable stage; (b) endodontic motor (Dentaport ZX OTR Module); (c) plastic model; (d) metal stage; (e) metal cylinder; (f) strain gauge; (g) torque sensor.

was attached to a movable stage (MX2-500N, IMADA, Aichi, Japan) using a custom-made holder. The movable stage provided a pecking movement consisting of 2 mm downward and 1 mm upward movements at 10 mm/min. To measure apical force values, the metal stage on which the plastic block was fixed was connected to a torque sensor (LUX-B-ID, Kyowa Dengyo, Tokyo, Japan) with a metal cylinder.

To measure torque values, a strain gauge (KFG-2-120-D31-11, Kyowa Dengyo) was attached to the flat part of the metal cylinder. A correlation coefficient of 2.609 for the conversion of distortion values (measured by the strain gauges) to torque values was determined by applying known torques (in the clockwise and counterclockwise directions) to the metal cylinder by hanging weights with a string of a known length. Assessment was conducted to evaluate the medians of the torque and apical forces generated when shaping plastic blocks with the rotary instruments. Torque values of the clockwise and counterclockwise rotations were defined as positive and negative domains, respectively. Apical force values in the apical and opposite direction were defined as positive and negative domains, respectively.

Fig. 6  Typical load-deflection curves for each group.

Statistical analysis
The data obtained were analyzed using the Statistical Package for Social Sciences (SPSS) software (Version 17, SPSS, Chicago, IL, USA). NCF, the transportation and instrumentation time, and the torque and apical force values were compared using the Mann-Whitney U-test. Bending loads at deflection values of 0.5 and 2.0 mm were compared using the Welch t-test. p-Values < 0.05 were considered statistically significant.

RESULTS
Cyclic fatigue test
The median (minimum, maximum) NCF values were 115.5 (57.5, 220.0) and 46.5 (22.0, 68.5) in the Groups 0.04 and 0.06, respectively. Group 0.04 showed significantly higher values compared with Group 0.06 (p < 0.05).

Bending test
Typical load-deflection curves for both groups, indicating super-elastic behavior, are shown in Fig. 6. Curves for both groups were initially linear, signifying elastic deformation. Above this range, the load level was almost constant, because of stress-induced martensitic transformation. During the unloading process, the load decreased rapidly and became constant, because of reverse transformation.

The mean bending load values at deflection of 0.5 and 2.0 mm are shown in Table 1. The values of Group
Table 1  Bending load values (N) at a deflection of 0.5 and 2.0 mm

<table>
<thead>
<tr>
<th>Group</th>
<th>0.5 mm</th>
<th>2.0 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.04</td>
<td>0.60 (0.07)*</td>
<td>1.51 (0.12)*</td>
</tr>
<tr>
<td>0.06</td>
<td>1.07 (0.19)</td>
<td>3.15 (0.25)</td>
</tr>
</tbody>
</table>

Values indicate the mean (standard deviations). n=7 (per group).
*p<0.05 versus corresponding Group 0.06.

Table 2  Canal transportation (mm) at three levels

<table>
<thead>
<tr>
<th>Group</th>
<th>0 mm</th>
<th>Inner</th>
<th>3 mm</th>
<th>Inner</th>
<th>6 mm</th>
<th>Outer</th>
<th>Inner</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.04</td>
<td>0.03*</td>
<td>-0.09</td>
<td>0.09*</td>
<td>-0.02</td>
<td>-0.17</td>
<td>0.00*</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.02, 0.20)</td>
<td>(-0.15, -0.04)</td>
<td>(-0.02, 0.15)</td>
<td>(-0.10, 0.12)</td>
<td>(-0.23, -0.07)</td>
<td>(-0.04, 0.10)</td>
<td></td>
</tr>
<tr>
<td>0.06</td>
<td>0.22</td>
<td>-0.09</td>
<td>0.20</td>
<td>-0.05</td>
<td>-0.19</td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(-0.08, 0.42)</td>
<td>(-0.11, -0.03)</td>
<td>(0.11, 0.34)</td>
<td>(-0.15, 0.00)</td>
<td>(-0.24, -0.03)</td>
<td>(0.00, 0.13)</td>
<td></td>
</tr>
</tbody>
</table>

Values indicate the median (minimum, maximum). n=7 (per group).
*p<0.05 versus corresponding Group 0.06.

Table 3  Torque (N•mm) generated during preparation

<table>
<thead>
<tr>
<th>Group</th>
<th>Positive domain</th>
<th>Negative domain</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.04</td>
<td>0.44 (0.16, 0.71)*</td>
<td>-0.11 (-0.34, -0.03)</td>
</tr>
<tr>
<td>0.06</td>
<td>2.25 (1.68, 3.49)</td>
<td>-0.10 (-0.21, -0.04)</td>
</tr>
</tbody>
</table>

Values indicate the median (minimum, maximum). n=7 (per group).
*p<0.05 versus corresponding Group 0.06.

Table 4  Apical force (N) generated during preparation

<table>
<thead>
<tr>
<th>Group</th>
<th>Positive domain</th>
<th>Negative domain</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.04</td>
<td>0.13 (0.06, 0.26)</td>
<td>-0.10 (-0.21, -0.04)</td>
</tr>
<tr>
<td>0.06</td>
<td>0.21 (0.12, 0.55)</td>
<td>-0.09 (-0.16, -0.05)</td>
</tr>
</tbody>
</table>

Values indicate the median (minimum, maximum). n=7 (per group).
There was no significant difference between both groups.

0.04 were significantly smaller than those of Group 0.06 (p<0.05).

**Transportation**

As shown in Table 2, Group 0.06 showed transportation values significantly greater than those of Group 0.04 (p<0.05) at the 0- and 3-mm level of the outer side and at the 6-mm level of the inner side. The median preparation time (minimum, maximum) was 195 (146, 207) and 230 (150, 468) seconds in Groups 0.04 and 0.06, respectively, and there was no significant difference between the two groups (p>0.05). None of the instruments showed visible deformation or fracture.

**Torque and apical force**

As shown in Table 3, Group 0.06 showed significantly larger torque values in the positive domain compared with Group 0.04 (p<0.05). There was no significant difference in the apical force values between both groups (Table 4; p>0.05).

**DISCUSSION**

This study compared 0.04- and 0.06-tapered EndoWave instruments in terms of torsional and bending properties, shaping ability (degree of canal transportation), and torque/force values. The findings clearly demonstrated that the differently-tapered instruments differed...
significantly in terms of NCF, bending loads, transportation values, and median clockwise torque values. Therefore, the null hypothesis was rejected.

Cyclic fatigue properties
The cyclic fatigue life of Ni-Ti rotary instruments is reported to be affected by the angle and radius of curvature\(^{34,35}\). However, one study has shown that the radius of curvature is not a factor that influenced instrument fracture, although rotational speed and the angle of curvature of the canal are relevant to instrument fracture\(^{36}\). In several studies, a curvature radius of 3, 5 or 8 mm and curvature angles of 45°, 51°, 60°, or 90° have been used to test the cyclic fatigue resistance of instruments\(^{37}\). Although there are no standardized specifications for Ni-Ti rotary instruments, a 5 mm radius and a curvature angle of 38° were chosen in the present study to facilitate comparison with our previous results\(^{38}\).

Several studies have reported that increasing the diameter of Ni-Ti rotary instruments decreases the resistance to fracture\(^{39,40}\), which is in consistent with our present findings. Other factors, such as material properties, cross-section shape, fluting, and speed, may also influence the NCF\(^{40}\). Moreover, the stress applied to the files is dependent on the radius of curvature and the diameter of the file\(^{40}\). Therefore, when used clinically, root canal morphology may determine the fatigue life of the file.

Rigid instruments are known to generate lower NCF values because of a buildup of tension at the point of maximum flexure\(^{41}\). In the cantilever bending test, Group 0.04 showed smaller bending loads in both elastic and superelastic ranges compared to Group 0.06. It has previously been reported that flexible instruments are not highly resistant to torsional load but are resistant to cyclic fatigue\(^{42}\). Such flexibility is also considered to be a factor related to the significantly smaller NCF values of Group 0.04 compared with those of Group 0.06.

Bending properties
Several mechanical requirements for root canal instruments are listed in International Standards Organization (ISO) publication 3630-1, or in the American National Standards Institute/American Dental Association Specification No. 28. However, these tests are established not for rotary Ni-Ti instruments, but for stainless-steel instruments. The test conforming to the ISO standard is a 45-degree bending test method and aims at the evaluation of the bending characteristic in the elastic region before exceeding the yield point. Therefore, the test is not suitable for evaluating characteristics under severe usage conditions, like for the Ni-Ti rotary files. Thus, a cantilever bending test was used in the present study to evaluate the characteristics of Ni-Ti rotary instruments, as already reported by other authors\(^{25,29}\).

In the cantilever bending test, bending loads at 0.5 and 2.0 mm correspond to elastic and superelastic ranges, respectively. A typical stress-strain curve of a Ni-Ti super-elastic alloy forms a hysteresis loop. Our results showed that the bending load value of Group 0.04 was lower than that of Group 0.06 in both elastic range and superelastic range. Therefore, it is clear that Group 0.04 is more flexible than Group 0.06.

The flexibility of Ni-Ti rotary instruments is influenced by the composition and thermomechanical treatment of the metallic as well as the instrument geometry, including its size and cross-sectional design, the number of flutes, and the taper\(^{23,43-45}\). In particular, the moment of inertia of the area, determined by the cross-section, is considered as a main factor defining the value of the bending load\(^{46}\). In this study, it was confirmed that the difference in the taper led to a difference in the cross-sectional area and to a difference in the moment of inertia of the area, and therefore Group 0.04 showed a lower bending value than Group 0.06.

Transportation
In this study, the central axis of the artificial root canal was considered to be the central axis of the Ni-Ti rotary preparation, and the amount of deviation from the position where the file actually passed was defined as the transportation value. In the inner curvature side, canal transportation values of both groups at 0 mm, 3 mm from the apical foramen position showed negative values. This means that the canals shifted to the outer curvature side. In the outer curvature side, canal transportation values of both groups at 6 mm from the apical foramen position showed negative values. The measuring point of 6 mm was near the beginning part of the curvature (Fig. 3), and thus the canals shifted to the inner curvature side. Therefore, rotary files tended to straighten the root canal without completely following the curvature in both groups, which is in accordance with previous reports\(^{47,48}\). However, Group 0.04 showed superior results at three levels. Consequently, Group 0.04 better maintained the original canal shape in comparison to Group 0.06, most probably because of its flexibility, as shown in this study. This finding is consistent with several studies showing that an instrument with a larger taper generates larger values of transportation\(^{49,50}\).

In this study, J-shaped simulated resin canals were used instead of extracted teeth. There are limitations with the use of resin canals as the surface texture, hardness, and cross-sections differ from those of natural teeth\(^{51}\). However, resin blocks are widely used to evaluate the shaping ability of endodontic instruments\(^{49,52,53}\), because of their uniform root canal diameter, length, and curvature in terms of angle and radius\(^{54}\).

Torque and apical force
Torque generated by a rotating instrument during root canal instrumentation depends on the preoperative canal volume, applied apical force, diameter and cross-sectional design of the instrument, repeated use of the instrument, manufacturing process, and contact area between the instrument and the root canal walls\(^{55}\). In this study, the difference in the instrument’s diameter may have affected the torque values of the positive
domain, and it was verified that torque values of the positive domain of Group 0.04 were significantly lower than those of Group 0.06.

Apical force values of the negative domain were not significantly different between the two groups. This result was consistent with a previous study showing that 0.04- and 0.06-tapered instruments generate comparable screw-in forces\(^{26}\). Thus, the screw-in effect might not be related to the torque directly\(^{26}\). Apical force values of the positive domain were not significantly different between the two groups in this study, although it has been reported that higher apical force values are required to allow instruments with larger cross-sectional areas to move axially inside the canal\(^{22}\).

CONCLUSION

Under the present experimental conditions, 0.04-tapered EndoWave instruments exhibited significantly larger NCF values and smaller bending load values, transportation values, and clockwise torque values compared with 0.06-tapered instruments. Thus, differences in the taper showed significant influences on the mechanical properties of EndoWave instruments.

REFERENCES


