Fracture Resistance of Electropolished Rotary Nickel–Titanium Endodontic Instruments

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Abstract
The purpose of this study was to investigate the effect of electropolishing on cyclic flexural fatigue and torsional strength of rotary nickel-titanium endodontic instruments. Electropolished and nonelectropolished ISO size 30 (0.04 taper) EndoWave (J Morita Corporation, Osaka, Japan), ProFile (Dentsply Maillefer, Ballaigues, Switzerland), and RaCe (FKG, La-Chaux De Fonds, Switzerland) instruments from the same manufacturing batches were investigated. The number of rotations to fracture and torque at fracture were determined and compared among the instruments tested. Instruments were viewed under a scanning electron microscope (SEM) to assess the degree and quality of electropolishing. Overall, electropolished instruments performed significantly better than nonelectropolished instruments in cyclic fatigue testing and, to a lesser extent, in static torsional loading. When viewing electropolished instruments with the SEM, milling grooves, cracks, pits, and areas of metal rollover were observed, although they were more evident in the nonelectropolished instruments. Electropolishing may have beneficial effects in prolonging the fatigue life of rotary NiTi endodontic instruments. The benefits of electropolishing are likely to be caused by a reduction in surface irregularities that serve as points for stress concentration and crack initiation. (J Endod 2007;33:1212–1216)

Key Words
Cyclic fatigue, electropolishing, endodontics, fracture strength, rotary nickel titanium

Despite the advantages of rotary nickel-titanium (NiTi) instruments (1), concern has been expressed by many authors and clinicians about the potential for rotary NiTi instruments to fracture within the root canal system during endodontic treatment (2–4). Although instrument fracture may not adversely affect the prognosis when endodontic treatment can be performed to a high technical standard, it may present a problem if microbial control is compromised (3) or should excessive removal of tooth structure be required to eliminate the fragment (4).

The fracture of an endodontic instrument within a root canal is a complex event. Two modes of fracture of rotary NiTi endodontic instruments have been identified in the clinical situation: (1) torsional fracture and (2) flexural fracture (5). Of clinical concern is the fact that flexural fatigue occurs with no visible signs of deformation of the instrument, and, as such, there are no signs to alert the clinician that the instrument is fatigued. An understanding of factors that contribute to instrument fracture is important in preventing its occurrence. These include the following: anatomy of the root canal system, both in terms of radius and degree of curvature (6, 7); operator proficiency (8, 9); operating speed and torque (7, 10); previous use (11–14), sterilization procedures (15–17), and cross-sectional area and design of the instrument (18–20). The consequences of rotary NiTi instrument fracture have recently been reviewed (21).

Manufacturing NiTi rotary instruments involves the machining of a wire blank, leaving a surface that is irregular, stressed, plastically deformed, or contaminated (22). Electropolishing may enhance the fatigue life of instruments by removing surface irregularities, cracks, and residual stresses (18, 23).

Therefore, the aims of this study were to investigate the effect of electropolishing on the cyclic flexural and torsional strength of three brands of rotary NiTi endodontic instruments and to compare the fatigue life of these instruments.

Materials and Methods
The instruments evaluated were ProFile (Dentsply Maillefer, Ballaigues, Switzerland), EndoWave (J Morita Corporation, Osaka, Japan), and RaCe (FKG, La-Chaux De Fonds, Switzerland); all files were of ISO size 30, 0.04 taper, and 25 mm in length. In the United States, EndoWaves are marketed as EndoSequence (Brassler USA, Savannah, GA). Two groups of each instrument type were evaluated: electropolished and nonelectropolished, giving a total of six experimental groups. Samples were obtained from the manufacturer from the same batch, with nonelectropolished instruments being removed from the production line before the electropolishing process. Because the study was a direct comparison between electropolished and nonelectropolished instruments of the same brand, a separate control group was not required.

Cyclic fatigue testing was conducted in a manner similar to that of Pruett et al (6), with the instrument rotating freely within an artificial canal defined by both the angle and radius of curvature. A glass tube of internal diameter 1.2 mm was curved by heating over a flame and curving over a metal cylinder, which gave a radius of curvature of 5 mm. Two different angles of curvature were used: 45° and 90°. The maximum curvature was 18 mm into the tube, such that when each instrument was inserted to a length of 23 mm, the maximum curvature was 5 mm from the tip. The instruments were rotated at 280 rpm using the ATR motor (Dentsply Maillefer) set at maximum torque. Graphite powder was used as a lubricant and refreshed after each instrument was used. The instrument was allowed to rotate freely in the glass tube until fracture occurred. The time until fracture was recorded in seconds by using a stopwatch, and the number of rotations to
fracture was then calculated. Ten instruments were tested in each of the six experimental groups and for both angles of curvature to give a total of 120 instruments tested.

The maximum torque at failure of the instruments was determined by using a specially developed torque measuring device. Torsional loading of the instruments was achieved by mounting the file into the drill chuck of a bench-top drill that had been modified to rotate at 280 rpm, which was verified with the use of a stroboscope. Before rotation commenced, 3 mm of the tip of the file was first clasped between two aluminum plates that were connected via a shaft to a horizontal lever arm. This lever arm was in contact with a load cell of 100-N capacity (MTS Corporation, Eden Prairie, MN). The load cell was precalibrated and checked with standard weights before testing. The torque at failure was calculated in newton millimeters (Nmm) from the peak load recorded on the load cell. Ten instruments of each experimental group were tested to give a total of 60 instruments tested.

Samples of new instruments (five from each group) were first cleaned by ultrasonication in distilled water for 15 minutes and examined under the scanning electron microscope (SEM) (Phillips XL30 FEG; FEI Company, Hillsboro, OR).

Results of the cyclic fatigue tests were analyzed by using a two-way analysis of variance (Minitab version 14.1; Minitab Inc, State College, PA). Because data for torsional testing showed strong evidence of non-normality, analyses of the medians was considered to be more appropriate for the data. Accordingly, nonparametric Kruskal-Wallis and Mann-Whitney tests were performed. The significance level was set at p < 0.05.

**Results**

**Cyclic Fatigue Testing**

The mean number of rotations to fracture, when the instruments were rotated around a 45° and 90° angle of curvature, are presented in Table 1. The number of rotations to failure for electropolished instruments was significantly greater across all brands of endodontic instruments tested, with the exception of ProFile instruments rotated around a 45° curvature, where no significant difference was noted.

**Torsional Fatigue Testing**

The mean torques at failure for the test groups are presented in Table 2. The difference between electropolished and nonelectropolished instruments was significant only for the RaCe instruments. When data for all brands of instruments were pooled, a significantly greater torque at failure was noted for electropolished instruments (p = 0.001).

**SEM Observations**

In general, nonelectropolished instruments showed rougher and more irregular surfaces than electropolished instruments (Fig. 1). Before electropolishing, ProFile instruments showed the roughest surface, with deep milling grooves, metal rollover, and notching of the cutting blades being a frequent observation. Although the surface of RaCe instruments after machining showed a smoother surface than ProFiles because the milling marks were not as deep, longitudinal scratches were frequently noted along the length of the instrument (Fig. 1). Even before electropolishing, EndoWave instruments had relatively shallow milling marks and few areas of metal rollover (Fig. 1).

After electropolishing, all instruments showed an obvious reduction in surface irregularities relative to their nonelectropolished counterparts. Electropolishing appeared to eliminate surface defects to a similar extent for all instruments; thus, ProFiles, which had the roughest “native” surface, showed the roughest surface after electropolishing (Fig. 1). Although milling marks were still evident, the marks appeared more rounded, and the electropolishing process eliminated metal rollover at the cutting edges. Electropolishing appeared to remove the majority of the longitudinal scratches noted on the unpolished RaCe instruments, but small surface irregularities were still noted, often with an “orange peel”-type appearance (Fig. 1). The surfaces of electropolished EndoWave instruments were largely featureless, showing the smoothest surface (Fig. 1).

**Discussion**

Three popular brands of electropolished rotary NiTi instruments were assessed: ProFile, EndoWave, and RaCe. ProTaper instruments are also electropolished and commonly used but were not included in the study because of their variable taper, which did not allow for direct comparison with the other brands.

Electropolishing is a method of surface finishing used by manufacturers of rotary NiTi instruments to remove surface defects that may remain after machining. It is a controlled chemical process that involves submerging the instrument, acting as an anode, into an electrolytic solution that contains a cathode. When a low current is passed though the solution, a balance is achieved between the formation of a passive layer and dissolving of the surface into the electrolyte, leading to selective removal of protruding surface defects; therefore, a leveling and smoothing of a rough surface will occur at a rate of approximately 3.5 μm per minute (24). Electropolished instruments appear shinier to the naked eye than those that have not been polished. When viewing all the instruments under the SEM, milling grooves, cracks, pits, and metal rollover at the cutting edges were readily identified, in agreement with SEM observations of other investigators (23, 25-27). These defects were more obvious in instruments that had not undergone electropolishing and less occasionally observed in instruments that had been polished.

An interesting observation was the relative resistance of ProFile instruments to cyclic fatigue when rotated around a gentle (45°) curvature. This may be attributed to the U-flute cross-sectional design of the instrument; mathematical modelling suggests that instruments with this cross-sectional profile are more flexible than those with a triple helix.

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**TABLE 1.** Mean ± SD and p Value of Rotations to Fracture for Electropolished (EP) and Nonelectropolished (NEP) Instruments

<table>
<thead>
<tr>
<th>Instruments</th>
<th>45°</th>
<th>90°</th>
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<th>90°</th>
</tr>
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<tr>
<td>EP</td>
<td>1242.7 ± 225.6</td>
<td>410 ± 70.8</td>
<td>5430.3 ± 741.4</td>
<td>295.8 ± 40.9</td>
<td>1304.4 ± 289.6</td>
<td>282.5 ± 63.9</td>
</tr>
<tr>
<td>NEP</td>
<td>610.9 ± 149.9</td>
<td>244.9 ± 49.3</td>
<td>6624.8 ± 2107</td>
<td>184.4 ± 27.6</td>
<td>1171.7 ± 288.1</td>
<td>160.3 ± 32.7</td>
</tr>
<tr>
<td>p</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>0.124</td>
<td>&lt;0.001</td>
<td>0.007</td>
<td>&lt;0.001</td>
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</table>

**TABLE 2.** Mean ± SD, and p Value of Torque at Fracture (Nmm) at Fracture for Electropolished (EP) and Nonelectropolished (NEP) Instruments

<table>
<thead>
<tr>
<th>Instruments</th>
<th>EP</th>
<th>NEP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque</td>
<td>14.7 ± 3.2</td>
<td>12.4 ± 2.6</td>
</tr>
<tr>
<td>p</td>
<td>0.117</td>
<td>0.017</td>
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**FIGURE 1.** SEM observations of other investigators (23, 25-27). These defects were more obvious in instruments that had not undergone electropolishing and less occasionally observed in instruments that had been polished.
EndoWave and RaCe showed similar resistance to cyclic fatigue in the 45° curvature, which may have been caused by the similar triangular cross-sectional profile of the two instruments.

When considering the performance of the files around a sharper (90°) curvature, it was somewhat surprising that EndoWave performed better than RaCe instruments (which have a very similar cross-sectional profile) and ProFile instruments. This may well be related to the quality of the surface finish because EndoWave instruments showed a very smooth surface in the SEM analysis. It is uncertain why ProFile instruments performed so well in cyclic fatigue testing at a degree of curvature of 45° yet behaved similarly to the other brands at an angle of 90°, and why electropolishing did not seem to have any effect in this group. However, this finding indicates that electropolishing per se is not the only factor influencing resistance to cyclic fatigue. The cross-sectional shape may be of greater importance, with “stiffer” file designs benefiting more from electropolishing.

Figure 1. SEM images of electropolished and nonelectropolished instruments.
Furthermore, surface topography has a significant influence on metal fracture, in particular, fatigue failure (29). Fracture of metals will begin with the formation of microcracks at the surface of the metal and is then followed by crack propagation and finally rupture of the metal as the cracks coalesce. Cracks will initiate in small surface defects, and, as such, the initiation stage of metal fracture is greatly facilitated by pre-existing surface irregularities. Failure is then largely a process of crack propagation. In contrast, when cracks are not present on the surface of the material, failure will be a function of first crack initiation, then propagation, and finally rupture. Considering that crack initiation may comprise a major proportion of fatigue life, resistance to fatigue can be enhanced by a smooth, defect-free surface (25).

Another possible explanation for the enhanced performance of the electropolished instruments is the elimination of residual stresses. When an instrument is machined, plastic deformation (smearing) occurs at the surface of the metal, resulting in residual stresses that remain at the surface (30). The effect of residual stresses on material fracture will depend largely on the type of residual stress (compressive or tensile) and the type of loading the material is under (static load or fatigue). Compressive residual stresses will have a beneficial effect on the fatigue life because they delay crack initiation and propagation. Conversely, tensile residual stresses may significantly reduce the fatigue life of materials because they accelerate crack initiation and growth (29, 31). Under repeated cycles of loading, residual stresses (whether beneficial compressive stresses or detrimental tensile stresses) play a significant role in determining the fatigue life of the material. Residual stresses play less of a role when failure occurs by a single overload event (31). By removing the surface layer of the instrument, electropolishing may potentially eliminate residual stresses. The exact nature and extent of residual stress remaining at the surface of rotary NiTi instruments after manufacture is unknown, as is the ability of electropolishing to remove such stresses. Synchrotron analysis, which uses neutron diffraction to quantify and characterize residual stresses (31), may be useful to elucidate the contribution of these stresses in determining the fatigue life of rotary NiTi endodontic instruments.

In addition to improving resistance to cyclic fatigue, electropolishing also increased the resistance of rotary NiTi instruments to fracture under static torsional load, albeit to a lesser extent. The fracture mechanisms for the two failure modes are quite different. In cyclic fatigue, the instrument is subjected to repeated cycles of compressive and tensile loading, producing cumulative changes and leading to fracture at a load well below the ultimate tensile strength of the material (32). On the other hand, in the torsional model, the instrument is subjected to a single overload event; a large plastic deformation occurs and fracture occurs as a result of shear forces exceeding the yield strength of the metal. In such an event, surface topography and residual stresses play a lesser role (31).

The results of this study indicate that surface finish is among the factors determining the resistance of rotary NiTi instruments to fracture. This is contrary to a recent article by Herold et al (33) whose findings may not be valid because electropolished ProFiles were not assessed, and the ex vivo model does not allow predictable standardization. Furthermore, the results obtained using extracted teeth may differ from those obtained from the glass walls of simulated canals; therefore, the findings should be interpreted accordingly. Nevertheless, although surface finish may be a consideration when selecting an instrumentation system, other factors, such as instrument design, quality of the resulting root canal preparation, efficiency, and safety, will prevail.

Acknowledgments

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References