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Cyclic fatigue resistance tests of Nickel-Titanium rotary files using simulated canal and weight loading conditions

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Objectives: This study compared the cyclic fatigue resistance of nickel–titanium (NiTi) files obtained in a conventional test using a simulated canal with a newly developed method that allows the application of constant fatigue load conditions. ***Materials and Methods:*** ProFile and K3 files of #25/.06, #30/.06, and #40/.04 were selected. Two types of testing devices were built to test their fatigue performance. The first (conventional) device prescribed curvature inside a simulated canal (C-test), the second new device exerted a constant load (L-test) whilst allowing any resulting curvature. Ten new instruments of each size and brand were tested with each device. The files were rotated until fracture and the number of cycles to failure (NCF) was determined. The NCF were subjected to one-way ANOVA and Duncan's *post-hoc* test for each method. Spearman's rank correlation coefficient was computed to examine any association between methods. ***Results:*** Spearman's rank correlation coefficient (ρ = -0.905) showed a significant negative correlation between methods. Groups with significant difference after the L-test divided into 4 clusters, whilst the C-test gave just 2 clusters. From the L-test, considering the negative correlation of NCF, K3 gave a significantly lower fatigue resistance than ProFile as in the C-test. K3 #30/.06 showed a lower fatigue resistance than K3 #25/.06, which was not found by the C-test. Variation in fatigue test methodology resulted in different cyclic fatigue resistance rankings for various NiTi files. ***Conclusions:*** The new methodology standardized the load during fatigue testing, allowing determination fatigue behavior under constant load conditions. (*Restor Dent Endod* 2013;38(1):31-35)

Key words: Constant angle; Constant load; Cyclic fatigue fracture; Nickel-titanium rotary file; Simulated canal

Introduction

Rotary nickel–titanium (NiTi) instruments are well-known for their efficiency in preparation of the root canal.[1] The super-elastic behavior of NiTi material lends an exceptionally good flexibility to the instrument allowing it to effectively follow the original path of the root canal.[2] However, fracture of instruments in root canals continues to be a serious, albeit infrequent, hazard during root canal treatment.

Flexural fatigue and torsional overload have been identified as the main reasons for rotary NiTi instrument failure, both of which might contribute to fracture depending on canal curvature, instrument geometry, and manufacturing method.[3-7] Continuous rotation of rotary instruments in curved root canals results in cyclic compression and tension, which in turn produces material fatigue.[4,8] Fractographically, the instruments' fracture surfaces show a combination of fatigue striations and ductile failure, implicating cyclic fatigue as an important cause of failure.[3,9] Cyclic flexural fatigue of NiTi rotary instruments has been studied extensively under simulated conditions.[3] Often, a metal tube or cylindrical canal with constant curvature and radius, an artificial slope, or a 3-point bending method are used to impose the effect of a constant canal curvature and to standardize the test geometry, and hence the stress state in an instrument.[10-12]

The actual stress state is affected by many factors, including the size, taper, cross-sectional profile, alloy composition, manufacturing methods, flexibility and rigidity, instrument shape and direction of rotation, but also by the artificial loading condition.[2,13-15] Plotino *et al.* reported that differences in the methodology affected the fatigue behavior of rotary instruments and therefore the outcome.[12] They suggested that an international standard for cyclic fatigue testing of NiTi rotary instruments is required to ensure uniformity of methodology and comparable results.

The purpose of this study was to introduce a new cyclic fatigue test method using a controlled constant load condition instead of the conventional cyclic fatigue test with simulated canal of constant canal curvature and to compare the results from both test methods. It is hypothesized that instruments tested under a controlled constant load will have a reversed correlation with the fatigue resistance found using a conventional cyclic fatigue test.

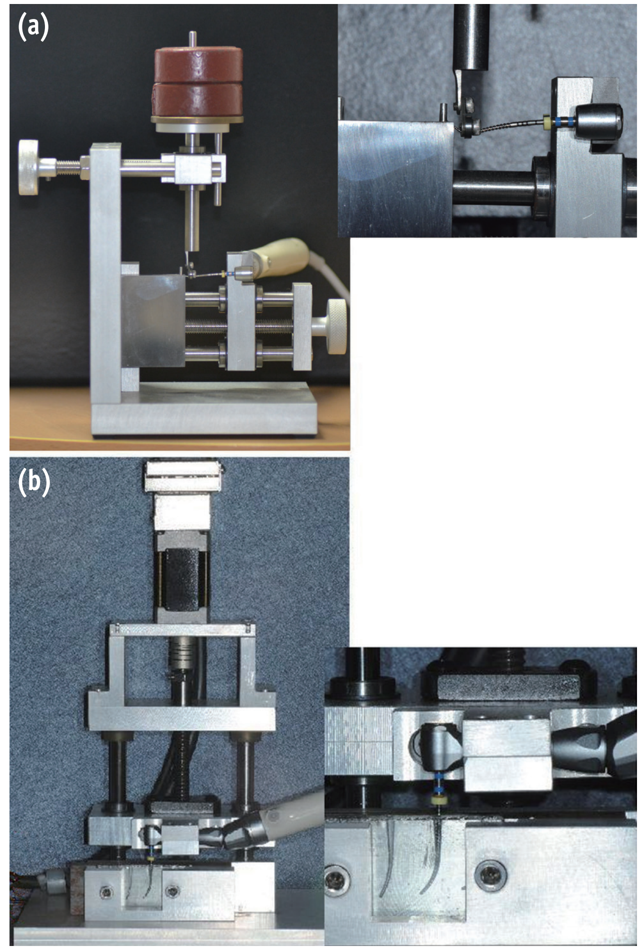

Figure 1. (a) Customized cyclic fatigue test device for applying a controlled constant load condition for the L-test; (b) An artificial curved root canal with constant curvature in the C-test.

Materials and Methods

Two customized devices were built for the fatigue tests in this study. The first device (a 'loaded tester') is a novel technique to test cyclic fatigue under a controlled constant load by putting weights on the rotating file (Figure 1a). A constant load of 500 g (based on unpublished data from a preliminary study) was applied at D6 (6 mm short from the tip), with 3 mm of the file tip resting or supported on a guiding plate. This test was denoted as the controlled-load test (L-test). The second device (fixed-curvature tester) is a commonly used fatigue test method that uses a simulated canal made of tempered steel (Figure 1b). The artificial canal had a curvature of 7.8 mm radius and 35-degree angle and was 17 mm long measured from the canal entrance. The apical diameter was 600 micrometer, lubricated with a synthetic oil (WD-40, WD-40 Company, San Diego, CA, USA) for free rotation of the files without mechanical binding in this fixed-curvature test (C-test).

Two brands of NiTi instruments with different cross-sectional geometries were tested: ProFile (Dentsply Maillefer, Ballaigues, Switzerland) and K3 (SybronEndo, Orange County, CA, USA). The sizes #25/.06, #30/.06, and #40/.04 were selected in this study. Ten new instruments of each size were tested in each device. The files were rotated at 300 rpm using an electric motor (X-smart, Dentsply Maillefer) at maximum torque (5.2 Ncm). The file was set to rotate, synchronized with a chronometer. The instruments were allowed to rotate until fracture. The timer was stopped when fracture was detected visually and audibly. The time to fracture was then converted into number of cycles to failure (NCF).

The broken fragments were ultrasonically cleaned in absolute alcohol for approximately 120 seconds prior to examination in a scanning electron microscope (SEM) (Hitachi S-4800 II, Hitachi High Technologies, Pleasanton, CA, USA). Randomly selected fragments (n = 5) for each group were mounted on the microscope stage with the fracture end facing upward and they were also examined in lateral view at various magnifications. The fractographic examination was conducted to check for differences in the fracture surface appearance between the two experimental methods.

The NCF data obtained from each method were subjected to the one-way ANOVA and Duncan's *post hoc* test to identify the group(s) significantly different from others. Spearman's rank correlation coefficient was computed to measure the association between the two tests' results. Statistical significance was determined at a 95% confidence level.

Results

The mean and standard error (SE) of the NCF value for instruments in the L-test and C-test, are presented in the legend of Figure 2. The Spearman's rank correlation coefficient (ρ = -0.905) showed that the results from the two methods had a significant negative correlation (p = 0.013).

Groups with significant difference after the L-test divided into 4 clusters, whilst the C-test gave just 2 clusters (Figure 2). Results of the C-test indicated that all three sizes of ProFile were more resistant to fatigue fracture than K3 files ($p < 0.05$), but there were no significant differences between files of the same brand ($p > 0.05$). For the L-test, considering the negative correlation of NCF with the fatigue resistance, K3 files gave a significantly lower fatigue resistance than ProFile ($p < 0.05$) as in the C-test. K3 size #30/.06 showed a lower fatigue resistance than size #25/.06 of the same brand ($p < 0.05$), which difference was not found by the C-test.

The topographic appearances of the fractured cross-sections demonstrated similar fractographic features from the two methods, with the presence of crack initiation origins, crack propagation region, and an overload (fast fracture) zone. The crack origins were found at the cutting edge or radial land region in most instruments (Figure 3).

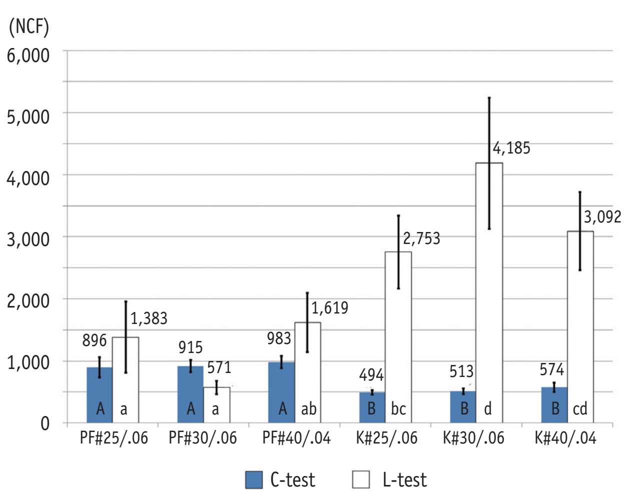

Figure 2. Mean number of cycles to failure (NCF) values under the constant load (L-test) and fixed-curvature condition (C-test). Groups with different superscript letters, for each test method, were significantly different from each other ($p < 0.05$). Note that the higher bar in L-test means the lower fatigue resistance whilst the higher bar means higher resistance in C-test. The numbers with the bar means the mean NCF and error bar indicates standard error.
PF, ProFile; K, K3.

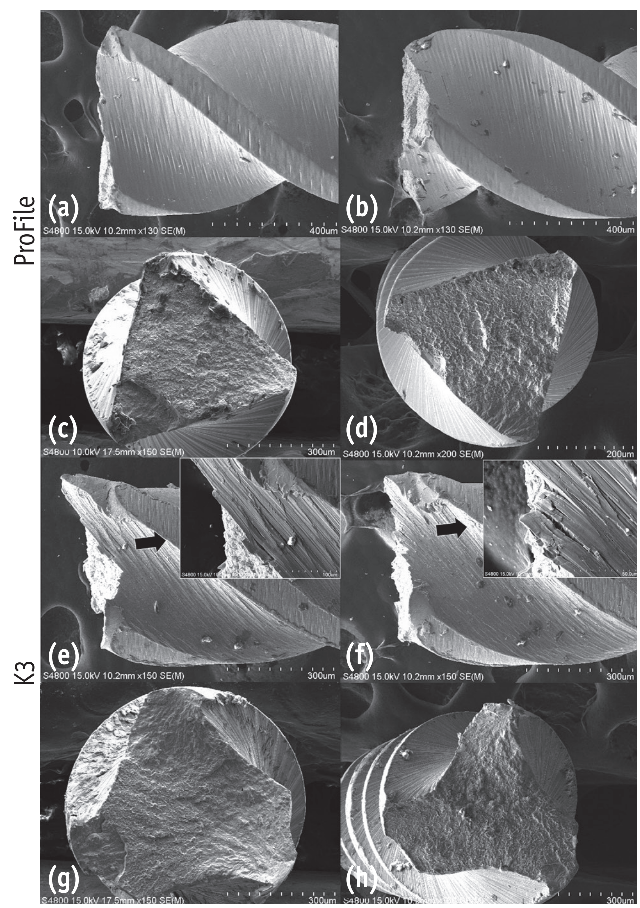

Figure 3. Scanning electron micrographs of the fracture surface of specimens after the fatigue test (a to d, ProFile; e to h, K3): L-test (Left column) and C-test (Right column). Both experimental methods showed similar fractographic features of cyclic fatigue failure for all instruments.

Discussion

Cyclic fatigue resistance has been tested extensively for various NiTi rotary systems.[3] An ideal fatigue model should involve instrumentation of curved root canals in natural teeth. However, such tests would be destructive for the sample (the tooth) and the curvature of the root canal can hardly be standardized. As a result, the various devices and methods that have been used to investigate the fatigue resistance of NiTi rotary instruments *in vitro* typically involve rotating the instruments freely (without resistance) at a prescribed curvature.[4,7,9-12] Whilst these tests may provide information as to the durability of the files when rotated within a curved canal of certain curvature angle and radius, the instruments may be subjected to different loads (stresses) in the clinical situation. Files with different designs or sizes have different mechanical responses to different conditions, even in the simulated canal with a same curvature.[5,6,16] There appears to be no report on the fatigue resistance of rotary files that under constant loading.

Plotino *et al*. suggested that the artificial canal does not provide a constant condition for every file being tested, because various instruments may have different trajectories in an artificial canal.[12] Depending on tip size, taper, design, pitch length, and other geometric features, an instrument will assure its own curvature in the simulated canals or tubes that failed to sufficiently constrain its shafts, especially for the smaller files. Thus, the effective curvature of the instruments will differ from that of the artificial canal.[5,6,12] Another possible problem with a loose-fitting canal is that the file may vibrate or tremble in that space, leading to a change in the magnitude of stress and potential variation in the results. To limit these problems, Cheung and Darvell constrained the rotating instrument into a curvature using three hard cylindrical, stainless steel pins.[11] The pins were adjustable in the horizontal direction and determined the curvature for each instrument. It seems that this method of three-point bending can produce a static curvature with minimal tremor. Ideally, an instrument should be measured in a stable condition in terms of radius and angle of curvature and point of maximum curve in a fatigue test, to allow comparison of various instrument designs. However, torsional or lateral loading of the instrument as may be experienced in the clinical situation is not reproduced in such test method.

In the present study, a new test apparatus was developed that includes a device to apply a constant load whilst maintaining a stable curvature condition to minimize discrepancies in the result. Three instrument sizes (#25/.06, #30/.06, and #40/.04) were selected for both ProFile and K3, because they are commonly used in root canal shaping. The applied load was determined in a preliminary study as the value that produced file fracture and NCF within in a reasonable time rather than being based on a clinical value, which would have varied by file design and canal curvature. Prior to the experiment, it was anticipated that a negative correlation between the two test methods would be present, because the loading in the L-test would generate higher stresses and more abrupt curvature for the smaller files close to the load application site, compared to those in the C-test. Constant load tests also tend to be more progressive during fatigue failure than constant curvature tests because when fatigue failure develops, stress concentrations tend to increase under constant load application whilst applied loads decrease under constant curvature conditions. The present study found that a significant negative correlation indeed existed.

From the C-test, all of the three sizes of ProFile systems had a better fatigue resistance than K3, regardless of the files sizes. On the other hand, from the L-test, the three ProFile sizes showed lower NCF values than sizes of #30/.06 and #40/.04 K3, whereas the #25/.06 K3 had a similar NCF value as size #40/.04 ProFile. Therefore, when subjected to a constant load in the L-test, the fatigue resistance generally showed the expected negative correlation between the two file designs (i.e., ProFile had higher fatigue resistance than K3 designs in the C-test but lower in the L-test). However, where the C-test did not detect differences within the two file designs, the L-test identified differences in fatigue sensitivity between the different sizes. In this case, owing to the negative correlation, our results suggest that for a specific canal curvature, #25/.06 is likely to be more fatigue resistance than the other two sizes K3 instruments (Figure 2). Although a negative correlation between the NCF values from both tests was evident, no direct correlation should be made because these two test designs measure different fatigue aspects. Therefore, the new L-test should be considered complementary rather than (reversely) comparable with the conventional C-test.

From the fractographic examination, the general features of cyclic fatigue fracture, including crack initiation area, crack propagation region, and overload fast-fracture zone, were shown for all instruments regardless of the test method. It indicated that both experimental methods indeed subjected the instrument fatigue failure due to the cyclic loads.

It has been more than 20 years since the introduction of NiTi rotary instruments. Yet, no specification or standard for testing their dynamic property (such as fatigue resistance) has been established. Recently, Park *et al*. proposed an alternative test method for torsional resistance. Similarly, there is a need for a scientific and clinically relevant test methodology to evaluate the resistance to cyclic fatigue fracture.[17] It is evident that an international standard is needed to validate NiTi rotary instruments.

In summary, a novel controlled-load test (L-test) was introduced to apply a standardized load during fatigue testing of rotary instruments. The results by such L-test were rather different from those of a conventional fixed-curvature test. The L-test method is clinically relevant as it reproduces fatigue resistance of the instrument under controlled loading conditions. Such loading may occur when the operator pushes on the handpiece, such as during the down-stroke of the pecking motion. This novel method may provide a more dependable test for the durability of rotary instruments against cyclic fatigue under constant load, and should be considered in addition to the 'basic' cyclic fatigue test of NiTi instruments for the clinical safety of rotary instruments. It is recognized that the complex loading condition in the clinical situation is not fully reproduced, but this new test method may be one step closer to a more comprehensive representation of generalized conditions.

Conclusions

This study proposes a new fatigue testing method for NiTi rotary instruments in which the number of fatigue cycles to failure is determined under controlled loading conditions. Unlike common fatigue tests that impose the flexure in artificial canal shapes, this test allows a precise control over how a file is loaded during the test. This precise control can help standardize fatigue performance testing, and help to better predict the fatigue life-time of NiTi rotary instruments.

Conflict of Interest: No potential conflict of interest relevant to this article was reported.

References

1. Glosson CR, Haller RH, Dove SB, del Rio CE. A comparison of root canal preparations using Ni-Ti hand, Ni-Ti engine-driven, and K-Flex endodontic instruments. *J Endod* 1995;21:146-151.
2. Sattapan B, Nervo GJ, Palamara JE, Messer HH. Defects in rotary nickel-titanium files after clinical use. *J Endod* 2000;26:161-165.
3. Cheung GSP. Instrument fracture: mechanisms, removal of fragments, and clinical outcomes. *Endod Topics* 2009;16:1-26.
4. Pruett JP, Clement DJ, Carnes DL Jr. Cyclic fatigue testing of nickel-titanium endodontic instruments. *J Endod* 1997;23:77-85.
5. Kim HC, Kim HJ, Lee CJ, Kim BM, Park JK, Versluis A. Mechanical response of nickel-titanium instruments with different cross-sectional designs during shaping of simulated curved canals. *Int Endod J* 2009;42:593-602.
6. Kim TO, Cheung GS, Lee JM, Kim BM, Hur B, Kim HC. Stress distribution of three NiTi rotary files under bending and torsional conditions using a mathematic analysis. *Int Endod J* 2009;42:14-21.
7. Kim HC, Yum J, Hur B, Cheung GS. Cyclic fatigue and fracture characteristics of ground and twisted nickel-titanium rotary files. *J Endod* 2010;36:147-152.
8. Bahia MG, Buono VT. Decrease in the fatigue resistance of nickel-titanium rotary instruments after clinical use in curved root canals. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 2005;100:249-255.
9. Haïkel Y, Serfaty R, Bateman G, Senger B, Allemann C. Dynamic and cyclic fatigue of engine-driven rotary nickel-titanium endodontic instruments. *J Endod* 1999;25:434-440.
10. Gambarini G. Cyclic fatigue of nickel-titanium rotary instruments after clinical use with low- and high-torque endodontic motors. *J Endod* 2001;27:772-774.
11. Cheung GS, Darvell BW. Fatigue testing of a NiTi rotary instrument. Part 1: strain-life relationship. *Int Endod J* 2007;40:612-618.
12. Plotino G, Grande NM, Cordaro M, Testarelli L, Gambarini G. A review of cyclic fatigue testing of nickel-titanium rotary instruments. *J Endod* 2009;35:1469-1476.
13. Hilt BR, Cunningham CJ, Shen C, Richards N. Torsional properties of stainless steel and nickel-titanium files after multiple autoclave sterilizations. *J Endod* 2000;26:76-80.
14. You SY, Bae KS, Baek SH, Kum KY, Shon WJ, Lee W. Lifespan of one nickel-titanium rotary file with reciprocating motion in curved root canals. *J Endod* 2010;36:1991-1994.
15. Kim HC. Mechanical and geometric features of endodontic instruments and its clinical effect. *J Korean Acad Conserv Dent* 2011;36:1-11.
16. Xu X, Eng M, Zheng Y, Eng D. Comparative study of torsional and bending properties for six models of nickel-titanium root canal instruments with different cross-sections. *J Endod* 2006;32:372-375.
17. Park SY, Cheung GS, Yum J, Hur B, Park JK, Kim HC. Dynamic torsional resistance of nickel-titanium rotary instruments. *J Endod* 2010;36:1200-1204.