Effect of a Combination of Torsional and Cyclic Fatigue Preloading on the Fracture Behavior of K3 and K3XF Instruments

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Abstract
Introduction: The purpose of this study was to evaluate the effect of various degrees of cyclic fatigue on torsional failure and torsional preloading on the cyclic fatigue life of heat-treated K3XF nickel–titanium (NiTi) instruments (SybronEndo, Orange, CA). Methods: The mean number of cycles until failure ($N_f$) of K3XF and K3 NiTi instruments was examined in a 3-point bending apparatus with a 7-mm radius and 45° curve. Torque and distortion angles at failure of new instruments and instruments stressed to 25%, 50%, and 75% of the $N_f$ were measured according to ISO 3630-1. Other new files were preloaded at 25%, 50%, and 75% of the mean distortion angles before the fatigue test. After torsional preloading, the $N_f$ was examined. The fracture surface of each fragment was examined with a scanning electron microscope. Results: The fatigue resistance of K3XF instruments was 2 times higher than that of K3 instruments ($P < .05$). The torque and angle of rotation at fracture of K3XF instruments were similar to those of K3 instruments. The 25%, 50%, and 75% torsional preloading significantly lowered the $N_f$ of both K3 and K3XF instruments ($P < .05$). In the fatigue prestressed groups, K3 instruments with 75% preloading had significantly lower torque and distortion angles than unused K3 instruments ($P < .05$). The fractographic patterns corresponded to the pattern defined by the last stage test. Conclusions: A low amount of torsional preloading reduced the fatigue resistance of K3 and K3XF instruments. A high amount of preloading significantly reduced the torsional resistance of K3 instruments. The torsional resistance of K3XF instruments was less affected by previous load cycling even after extensive preloading. (J Endod 2015;41:526–530)

Key Words
Endodontic, fatigue, fracture, K3, K3XF, nickel–titanium instrument, torsion

Unexpected instrument separation during use is a concern (1–4) and has a potential effect on the outcome of treatment (5). Fracture of a nickel–titanium (NiTi) instrument may occur in either 1 or a combination of 2 ways: torsional and flexural (fatigue) (6–8). Torsional fracture occurs when the torque resulting from the contact between the instrument and canal wall exceeds the torsional strength of the instrument or when the instrument tip is locked in a canal while the rest continues to rotate. This may also occur when instrument rotation is sufficiently slowed in relation to the cross-sectional diameter. Fracture caused by flexural fatigue occurs when a rotary endodontic instrument that has already been weakened by metal fatigue is placed under stress. Parashos et al (9) found cyclic fatigue to be the more common mechanism of instrument fracture in clinical practice; 70% of the fractures were attributable to “flexural fatigue.” Conversely, Sattapan et al (6) found that torsional stress was slightly more prevalent as the cause of fracture. Although fracture type classification in these studies was based on the longitudinal examination of the file only, which is subject to error (7), both fatigue and torsion are important mechanisms leading to instrument fracture.

Reducing the likelihood of instrument separation has been 1 of the main goals of manufacturers of NiTi rotary instruments, aiming at improved safety through innovative design and manufacturing processes (10–15). Recently, a new thermal process was introduced to the production of NiTi files subsequent to the grinding process. The manufacturer claims that K3XF (SybronEndo, Orange, CA) provides clinicians with the basic features of the original K3 (SybronEndo) plus an extraordinary new level of flexibility and resistance to cyclic fatigue with the proprietary R-Phase technology. Recent studies (16–19) have shown that K3XF instruments have fatigue resistance superior to K3 NiTi instruments. On the other hand, K3XF instruments maintain the same torsional properties as conventional superelastic NiTi instruments (K3) (18, 20). Clinically, NiTi rotary instruments are subjected to a combination of torsional load and cyclic fatigue, but little information is available on the subject. A recent study on files made of controlled memory wire showed much longer fatigue life in liquid conditions compared with dry conditions. However, there was no difference in the fatigue life of conventional NiTi instruments in various aqueous media (21). Therefore, the purpose of this study was to evaluate the effect of various degrees of cyclic...
fatigue on torsional failure and torsional preloading on the cyclic fatigue life of postmachining heat-treated K3 and K3XF instruments. The fatigue behavior of NiTi instruments was tested with the files immersed in aqueous media.

**Materials and Methods**

For the determination of resistance to cyclic fatigue, unused size 25/04 taper K3XF and K3 instruments (n = 15 in each group) were placed in a 3-point bending apparatus with a 7-mm radius and 45° curve in deionized water (21). The center of the curvature in the cyclic fatigue test was 3.2 mm away from the tip. To determine baseline scores, the instruments were then rotated at 500 rpm, as recommended by the manufacturer, until fracture occurred (Table 1). The fatigue life (ie, the total number of revolutions to failure [Nf]) was recorded.

To evaluate the effect that cyclic fatigue may have on torsion, cyclic preloading was done on the files under 4 conditions. Fifteen unused instruments in each group were exposed to 0%, 25%, 50%, or 75% of their respective mean Nf (Table 1). After cyclic preloading, torsional loading tests were performed in a torsion tester until rupture to establish the mean values of torque to failure and the maximum angular deflection of the instruments (22, 23). The torsion tests followed ISO 3650-1 standard (24) for the use of a torsion machine; 3 mm of the instrument tip was secured firmly in a specifically designed soft brass holder. The apparatus was composed of a torque sensor (Futek Model TFF 400; Futek, Irvine, CA) and a low-speed rotating motor. The instrument’s shank was then rotated at 2 rpm until fractures occurred. Before testing, each instrument handle was removed at the point where the handle is attached to the shaft. The end of the shaft was clamped into a chuck connected to a reversible geared motor. The torsional load and distortion angular were recorded until the instrument broke (22, 23). In the torsional preloading groups, 15 new instruments in each group were preloaded to 25% (199°), 50% (399°), or 75% (598°) of their respective mean angular deflection at torsional fracture. After torsional preloading, cyclic fatigue resistance was examined in a 3-point apparatus.

After preloading and after instrument fracture, all files were examined longitudinally under a scanning electron microscope (Stereoscan 260; Cambridge Instruments, Cambridge, UK). The length of the fractured file tip was measured using a light microscope (Leica MZ 6; Leica Microsystems Inc, Concord, ON, Canada) under an original magnification of 6.3×. The fracture surfaces of all fragments were examined with a scanning electron microscope.

The results were analyzed using 2-way analysis of variance and post hoc Tukey test (SPSS for Windows 11.0; SPSS, Chicago, IL) when necessary at a significance level of P < .05.

**Results**

In the cyclic fatigue test, the mean number of rotations until fracture of K3XF files with no torsional preloading was 2 times higher than the Nf of K3 instruments under corresponding conditions (Table 1) (P = 0). However, when the baseline values for torsional resistance of the 2 files were measured, the torque and angle of rotation at fracture of K3XF were similar to those of K3 instruments.

No instrument fractured during fatigue or torsional preloading. In torsional preloading groups, a low amount of preloading (25% of the mean the distortion angles) significantly reduced the mean Nf of both instruments (Fig. 1A–C) (P = .01) in cyclic fatigue testing. However, further torsional preloading of 50% and 75% did not cause additional reduction of the Nf in the following cyclic fatigue test of either file (P > .05). Similar to cyclic fatigue tests with no torsional preloading, K3XF instruments had a significantly higher mean Nf than the corresponding K3 instruments (P = .01) after torsional preloading.

There was little difference in the longitudinal or lateral view appearance between new and 25% torsionally preloaded K3 and K3XF files; the lateral aspect of the preloaded file did not show any specific topographic features. The K3XF instruments had unique surface characteristics with numerous irregular micropores. However, after 50% and 75% torsional preloading, all files had plastic deformation about 3 mm away from the tip (Fig. 2) in the lateral view. After 50% of torsional preloading, instruments showed numerous microcracks on the plastic deformation area (Fig. 2C and D). Of particular interest, the microcracks did not seem to follow the machining grooves on the instrument surface but rather ran irregularly. The length of the fractured piece ranged from 2.7–3.2 mm.

The K3 instruments after 75% fatigue prestress had significantly lower torque and distortion angles than the unused instruments (P = .01). However, in the K3XF instrument groups, there was no significant difference in torque value and distortion angle between the groups with and without precycling (P > .05). No plastic deformation was detected on any K3 and K3XF file after cyclic fatigue preloading. The length of the fractured piece ranged from 2.7–3.0 mm.

Fractographically, when the instruments failed by fatigue only (Fig. 2A and B) or by fatigue after torsional preloading (Fig. 2E and F), the crack origins and areas showing microscopic fatigue striations and dimple rupture could be identified on all fracture surfaces. Most of the K3XF and K3 instruments had a single crack origin, which was usually located at the cutting edge (Fig. 2B, E, and F). In the K3XF and K3 instruments in which the torsional test was applied without fatigue preloading (Fig. 2G and H) or after fatigue preloading (Fig. 2I and J), the fractography corresponded to the torsional fracture pattern with circular abrasion marks and skewed dimples near the center of rotation.

**Discussion**

There are only a few studies that have investigated either the effect of cyclic fatigue preloading on the torsional resistance (22, 25) or the effect of torsional preloads on the cyclic fatigue resistance of conventional NiTi superelastic instruments (26, 27). The aim of this study was to examine the impact of preloading of torsional angular deformation on the cyclic fatigue resistance as well as the impact of precycled fatigue on the torsional resistance of conventional superelastic K3 and heat-treated K3XF instruments. Identical design and cross-section of the 2 files makes them well suited for such comparison.

The mechanical behavior of the NiTi alloy is determined by the relative proportions and characteristics of the microstructural phases. Differential scanning calorimetric analyses has found that reverse transformation of the K3XF passes through the intermediate R-phase, thus reflecting the complex phase transformation behavior tracking back to the manufacturing process (20). Hence, it was perhaps not surprising that the K3XF instruments were more flexible and resistant to cyclic torsional preloads.
fatigue than the K3 instruments (16, 18–20). This was also confirmed by the present study. In the present study, the torque and angle of rotation at fracture of K3XF were similar to K3 instruments. Similar findings were reported in previous studies (18, 19).

Some studies (26, 27) showed that cyclic prestressing reduced the torsional resistance of conventional superelastic NiTi instruments. Ullmann and Peters (22) investigated the influence of previous flexural fatigue on the torsional resistance of ProTaper files (Dentsply Maillefer, Ballaigues, Switzerland). The instruments were previously submitted to flexural fatigue tests at 30%, 60%, and 90% of the number of cycles to fracture. The results showed that various instruments reacted differently to prestressing. Although torsional resistance for both S1 and S2 was unaltered, torques to failure decreased significantly for F1, F2, and F3. A similar study (25) evaluated the effect of cyclic fatigue on torsional failure on ProTaper F1 and Profile size 25/.06 tapers (Dentsply Maillefer). The instruments were cyclic precycled to 4 conditions (i.e., 0%, 25%, 50%, and 75% of the mean fatigue life) before the torsional resistance test was performed. The results indicated that 75% cyclic fatigue may reduce the torsional resistance of conventional NiTi instruments significantly irrespective of the instrument type. Recently, 1 study showed (23) that cyclic fatigue was not detrimental to the ability of Typhoon (conventional superelastic NiTi files) (Clinician’s Choice Dental Products, New Milford, CT) and Typhoon CM (heat-treated) (Clinician’s Choice Dental Products) files of size 25/.04 to withstand the torsional load. In the present study, 75% but not 25% or 50% fatigue preloading reduced the torsional strength and distortion angle of K3 instruments. Cyclic fatigue had no effect on the torsional fracture resistance of K3XF files. Even though the total number of rotations of K3XF instruments was higher than the K3 instruments in all precycling groups, the torsional resistance of K3XF instruments was higher than that of K3 instruments in all different precycling groups.

The influence of previous torsional angular deformation on the flexural fatigue life on conventional NiTi files has also been studied (26, 27). Unused K3 instruments were submitted to a predefined rotation (90°, 180°, or 420° angular deformation) before the flexural fatigue test. The results indicated that as the prior angular deformation increases, the number of cycles attained under flexural fatigue condition decreases (26). A reduction in the fatigue resistance was registered even with prior torsional loads below the elastic limit of the material (as low as 90° angular deformation). However, Cheung et al (28) found that the torsional preloads within the superelastic limit of the material may improve the cyclic fatigue resistance of conventional NiTi instruments. The 50% and 75% torsionally preloaded ProFile and all ProTaper preloading groups had a higher number of cycles to failure compared with the without preloading group(s). Comparisons between studies, however, cannot be made because different instruments, materials, sample sizes, and methodologies were used. In the present study, the slight torsional preloading reduced the flexural fatigue resistance of K3 and K3XF files. This behavior is probably associated with the generation of surface defects during torsional preloading, which can act as crack nucleation sites for flexural fatigue. Interestingly, the fatigue life was affected by even the 25% torsional preloading although there was no plastic deformation on the files in the present study. Any residual stress after the torsional preloads may interact with the propagating fatigue crack and manifest as branching of cracks from the fracture site. It seems that torsional overloads would act in tandem with flexural fatigue to reduce the resistance of NiTi files to failure in clinical situations. The file is likely exposed to greater torsional stresses from contacts with the canal, more than with cyclic fatigue during the early stage of canal enlargement. Therefore, the clinician should be careful when conventional superelastic and heat-treated NiTi files are used for instrumentation of curved canals with elevated friction between the file and root canal wall dentin. In the present study, the instruments were submitted to a standardized, predefined rotation before fatigue testing. However, in a clinical situation, the instrument may be subjected to repeat, reverse torsional loads inside the canal. The data obtained here cannot be
Figure 2. Fracture surface of (A) K3 and (B) K3XF instruments with crack origins (arrows) after fatigue testing. The lateral view of (C) 25% and (D) 50% torsional preloading of K3XF files before the fatigue test. Fracture surface after failure by fatigue of K3 XF instruments with (E) 25% and (F) 50% torsional preloading with crack origins (arrows). (G) K3 and (H) K3XF files after the torsional test as well as the torsional test after 75% fatigue prestressed (I) K3 and (J) K3XF.
directly extrapolated to clinical conditions, and any conclusions from the present study must be drawn with caution.

Within the limitations of this study, the fatigue resistance of K3XF instruments was twice as high as that of K3 instruments. The torque and angle of rotation at fracture of K3XF instruments were similar to those of K3 instruments. In fatigue prestressed groups, a high amount of pre-cycling (75%) significantly reduced the torsional resistance of K3 instruments. However, the torsional resistance of K3XF instruments was less affected by previous cyclic preloading. A low amount of torsional pre-loading significantly reduced the fatigue resistance of K3 and K3XF instruments. The fractographic patterns corresponded to the pattern defined by the last stage test.

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The authors deny any conflicts of interest related to this study.

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