Structural Analysis of Cyclic-loaded Nickel-Titanium Rotary Instruments by Using Resonance Frequency as a Parameter

Haw-Ming Huang, PhD,[*†] *Wei-Jen Chang, DDS, PhD,*[*] *Nai-Chia Teng, DDS, PhD,*[*] *Hung-Lung Lin, DDS, MS,*[*] *and Sung-Chih Hsieh, DDS, CAGS, DScD*[*‡]

Abstract

Introduction: The aim of this study was to investigate the relationship between fatigue life and resonance frequency (RF) of various types of nickel-titanium (NiTi) rotary instruments. In addition, the influence of NiTi instruments with different manufacturing methods on cyclic loading was evaluated by using RF as a parameter. **Methods:** Twenty-eight ProFile instruments and 10 Twisted File instruments were subjected to cyclic fatigue-loading until fracture by repeated preparation with simulated root canals made of clear resin. The RF of each sample was recorded immediately after the simulated canal block was prepared. For each sample, the microscopic images on the fracture surface, change in lengthening deformation, number of canal blocks prepared, and corresponding RF changes were recorded. **Results:** For all the tested instruments, RF values decreased gradually before breakdown when the fatigue failure of the instruments was associated with plastic deformation. In addition, there was a linear relationship between the RF change and the corresponding deformation of the failed instruments. **Conclusions:** These results demonstrate that the RF analysis has potential as a tool for structural analysis in NiTi instruments. *(J Endod 2011;37:993–996)*

Key Words

Cyclic fatigue, fracture, natural frequency, rotary NiTi instrument

From the *School of Dentistry, College of Oral Medicine; †Graduate Institute of Biomedical Materials and Tissue Engineering, College of Oral Medicine; and ‡Department of Dentistry, Wan Fang Hospital, Taipei Medical University, Taipei, Taiwan.

Address requests for reprints to Dr Sung-Chih Hsieh, School of Dentistry, College of Oral Medicine, Taipei Medical University, 250 Wu-Hsing Street, Taipei, Taiwan. E-mail address: endo@tmu.edu.tw

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Root canal therapy is a treatment for preventing periodontal ligament inflammation. During root canal treatment, rotary instruments are used to provide faster and more consistent preparation with fewer procedural mishaps (1). To increase the flexibility and resistance to fracture of the rotary instrument, nickel-titanium (NiTi) alloy was introduced to manufacture rotary instruments. Nonetheless, unexpected damage due to torsional overloading and cyclic fatigue still occurred with NiTi rotary instruments (2).

To increase the flexibility and resistance to fracture of rotary NiTi instruments, several new designs, such as Twisted Files (TF) (SybronEndo, Orange, CA), that use modified shape design and manufacturing processes have been applied in clinical treatments. The instrument was subjected to a series of manufacturing processes such as R-phase heat treatment, twisting of the metal, and special surface conditioning (3). These instruments had greater flexibility and resistance to cyclic fatigue (4). However, as with the traditional NiTi instruments, these newly designed instruments showed no visible signs of permanent deformation after clinical use. Thus, TFs are still prone to unexpected fracture during preparation for root canals. Few studies in the literature have focused on developing a method for predicting the remaining life of used rotary NiTi instruments.

In engineering, resonance frequency (RF) is used for nondestructive detection of structural microscopic damage. Potential applications of RF analysis in detecting stiffness of metal structures have been investigated by several research groups (5, 6). RF analysis has been used for measuring the structural status of small threaded structures such as orthopedic fixation pins (7) and has become the standard for detecting dental implant stability (8, 9). In 2010, Hsieh et al (10) found that RF effectively detected the microstructural status of conventional NiTi rotary instruments before they broke down. Their data demonstrated that when ProFile (PF) instruments (Dentsply Maillefer, Ballaigues, Switzerland) are close to the end of their life spans, RF values were 5% lower than their initial values.

Because an appropriate method for determining the remaining life of a used TF instrument is still unavailable, we investigated whether RF can be used for monitoring the structural status of fatigue-loaded TF instruments.

Materials and Methods

To perform the experiments on rotary instruments, 28 PFs (Dentsply Maillefer) measuring 21 mm in length and 10 TFs (SybronEndo) measuring 23 mm in length were chosen as test samples. All the tested samples, ISO size 25 with 0.06 taper NiTi instruments, were subjected to cyclic loads with a simulated canal curve as described previously (11). Briefly, simulated root canals made of clear resin (Plastic Practice Block; SybronEndo) were tightly fixed on a metal clamping stand in a stable vertical position. The simulated root canals were prepared by using the test instruments, which were mounted on a contra-angle handpiece and powered by an electric motor. The rotational speeds of the instruments were set at 300 rpm. During preparation, each test file was inserted with slight pressure and withdrawn from the simulated canal. All preparations were performed by an endodontist at a 17-mm working length. During preparation, ethylenediaminetetraacetic acid gel and distilled water were used for lubrication and irrigation. The simulated canal was enlarged to an apical size of 25, and the RF values of the rotary NiTi instruments were determined as described in our previous report (10). Then the simulated canal was replaced with a new one, and the above procedure was repeated. Each NiTi rotary instrument was continuously operated to enlarge simulated canals until fracture.

In this study, the RF value of each sample was recorded immediately after the simulated canal block was prepared. The life parameter of each rotary NiTi instrument was represented as the number of simulated canal blocks prepared. Student *t* tests were used to compare differences in mean RF values between unused and loaded instruments. *P* values less than .05 were considered as statistically significant.

The fatigue-fractured surfaces of the tested instruments were gold-sputtered and then examined by using a scanning electron microscope (SEM) (S-2400; Hitachi, Tokyo, Japan) at an acceleration potential of 18 kV. SEM photomicrographs were taken with 150× and 200× magnifications for PF and TF instrument analysis.

Results

The average times needed to prepare a simulated canal block by using PF and TF instruments were 169.4 ± 18.1 and 71.8 ± 10.5 seconds, respectively. Typical SEM images of the fractured surfaces of TF instruments are shown in Figure 1*A* (defined as group A). The fractured surfaces showed 2 different textures. A significant boundary between the peripheral smooth and central dimpled areas is shown on the fracture surface. This image demonstrates that the TF instruments fractured as a result of torsional overloading at the last cycle of fatigue. SEM images of the fractured surfaces of the PF instruments were classified into 2 types. Eight of the 28 PF samples (defined as group B), similar to the TF samples, had two-phase fractured surfaces (Fig. 1*B*). Figure 1*C* shows a typical fractured surface of the other 20 PF samples, which shows a different fracture pattern (defined as group C). In Figure 1*C*, a typical brittle fracture, characterized by multiple striations and microcracks, and a surface pattern with a ductile rupture, characterized by dimples and cones, were observed in the same fracture plane.

In group A, 21.4 ± 5.3 simulated canal blocks were prepared by TF instruments before fracture. All 10 laboratory-tested instruments demonstrated similar frequency response spectra when they received repeated rotational loading (Fig. 2*A*). The mean RF value of the 10 instruments was 5213 ± 33 Hz, and it decreased markedly to 5043 ± 55 Hz ($P < .05$) after 1 simulated canal block was prepared. Then the RF values of the instruments remained stable until they were about to fracture. The average RF value of these 10 TF instruments at their last measurement was 4825 ± 76 Hz, which was 7.5% lower than the initial RF value. Before fracture, all the tested TF instruments demonstrated an invisible straightening deformation and lengthened by 0.17 ± 0.04 mm.

For group B samples, although the 8 NiTi instruments in this group differed in the number of simulated canals prepared, all the samples showed similar decreases in RF values when subjected to repeated loading. The mean RF value of unused instruments was 5282 ± 102 Hz (Fig. 2*B*), and it significantly reduced ($P < .05$) to 4763 ± 125 Hz (with a decreasing ratio of 9.8%) before they fractured. A similarly decreasing RF pattern was also found for group C samples (Fig. 2*C*). The mean RF value of the samples detected before fracture (5080 ± 185 Hz) was significantly lower than the RF value before use (5373 ± 78 Hz). The average number of simulated canal blocks prepared by PF instruments before fracture was 5.6 ± 1.6 for group B and 5.7 ± 2.1 for group C. Statistical analysis showed no difference between the 2 groups. However, the lengthening deformation of the group B samples before fracture was 0.32 ± 0.07 mm, which was almost 8-fold larger than that for the group C samples (0.04 ± 0.02 mm).

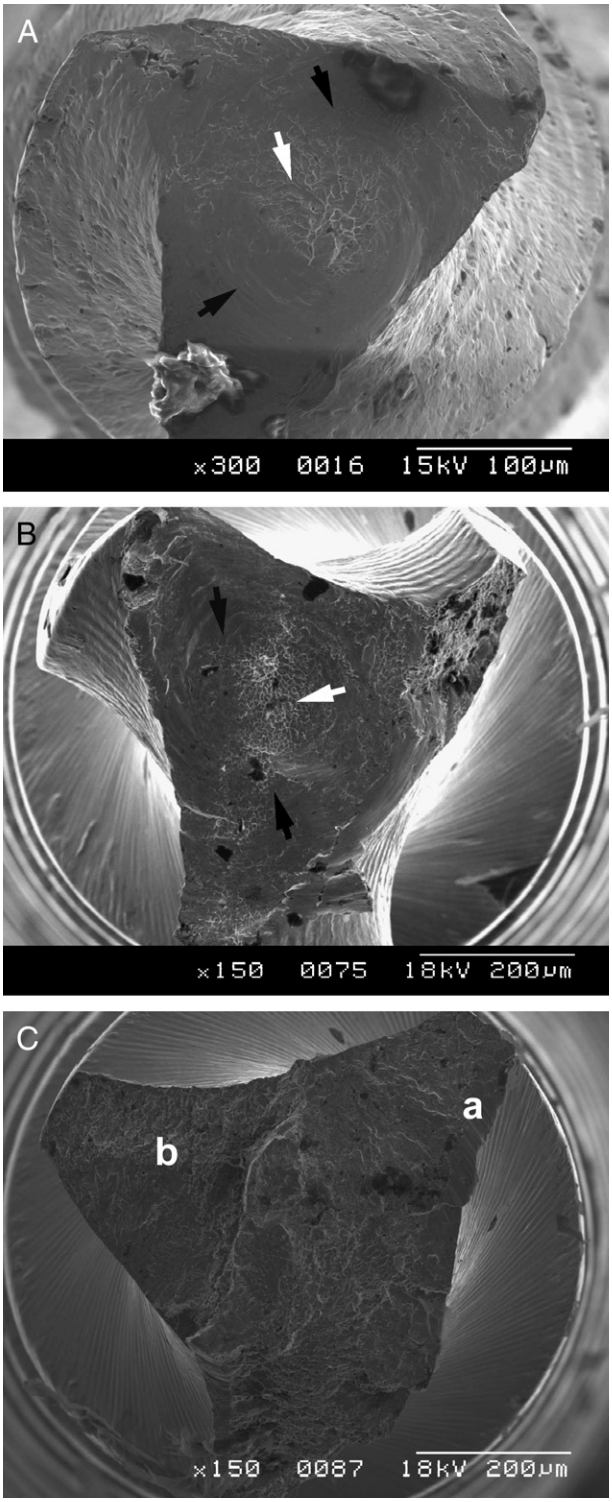

Figure 1. Fractographic analysis of rotary NiTi instruments. For overloading fractures of TF (*A*) and PF (*B*) samples, peripheral smooth (*black arrows*) and central dimpled (*white arrow*) areas are visible. For fatigue failures of PF samples (*C*), multiple striations (a) and surface pattern with dimples and cones (b) are observed in the same fracture plane.

Discussion

Unexpected breakage of NiTi instruments is always a serious concern for endodontic treatment. To evaluate the life span of NiTi rotary instruments, both numbers of cycles to failure (12, 13) and

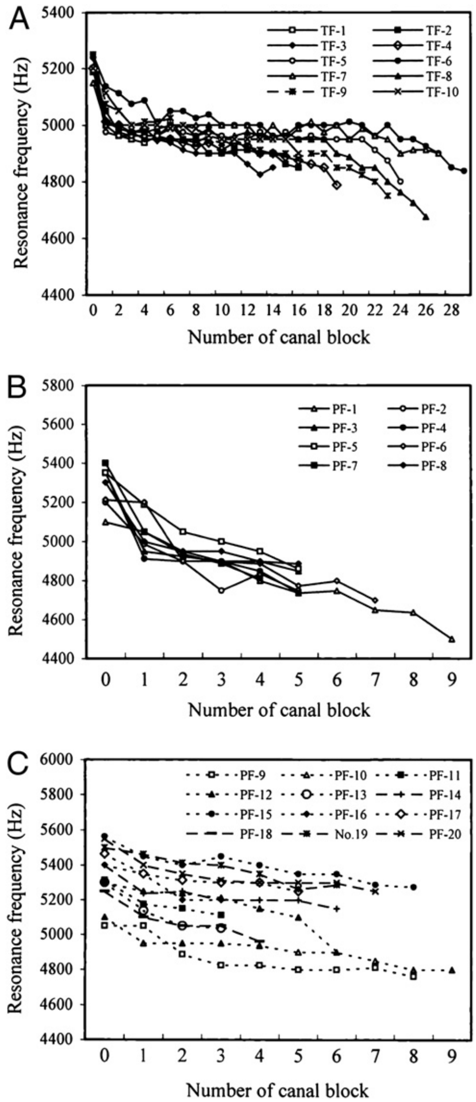

Figure 2. (*A*) Changes in RF during fatigue testing of TF instruments, (*B*) group B PF instruments, and (*C*) group C PF instruments.

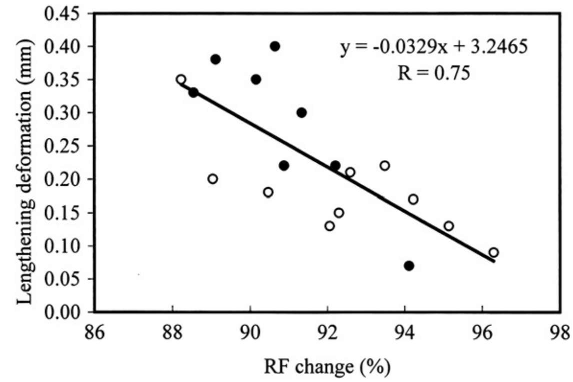

Figure 3. A linear relationship was found between RF change and its corresponding length deformation of group A (*open circles*) and group B (*closed circles*) samples.

numbers of treated teeth (14) were used as evaluation parameters. Oh et al (12) reported that the number of cycles to failure of TF instruments was about 1.2-fold larger than that of PF instruments. Our data showed that the average number of prepared canal blocks before fracture for TF instruments was almost 4-fold larger than that for groups B and C for PF samples. This could be due to the fact that Oh et al used metallic material, whereas canals in our study were made from plastic material. In this study, we found that the tested PF instruments sustained preparation of 5 simulated canal blocks before fracture. This result is similar to the results of a clinical study that suggested that PF instruments might be used to prepare 4 molar teeth, with no increase in the incidence of instrument fracture (15).

The fracture modes of a rotary NiTi instrument can be divided into 2 categories (16, 17). During the process of plastic deformation, stress concentrates at the tips of the cracks, thus accelerating the speed of microcrack propagation. Finally, the material fractures as the concentrated stress surpasses its limitation. As the microcracks start, initially the velocity of crack propagation is slow, and a smoother surface can be identified. While the repeated load continues, the stable fracture process is followed by an unstable fracture stage, resulting in the final breakdown of the instrument. When the final breakdown occurs, a dimpled area becomes visible on the central surface (12, 18, 19). Thus, the peripheral smooth and central dimpled areas on the fracture surfaces shown in Figure 1*A* and *B* confirm that both group A TF instruments and group B PF instruments used in this study were fractured because of torsional overloading at the last cycle of fatigue. On the contrary, striations on the fracture surfaces of group C PF instruments (Fig. 1*C*) are markers of fatigue crack growth (12, 20). These results can be confirmed by the brittle failure of the tested samples. Clinical findings indicate that fatigued NiTi instruments might show no plastic deformation or demonstrate significant deformation (21). Our results showed that group A TF and group B PF instruments demonstrated significantly greater lengthening deformation when compared with group C PF samples. Although all the tested instruments failed because of fatigue, group A TF instruments and group B PF instruments were fractured associated with plastic deformation, whereas in contrast, the major cause of breakdown of group C samples was brittle failure.

For stainless steel instruments, visible distortion before fracture is a warning sign of impending breakage. However, unlike stainless steel instruments, NiTi rotary instruments fracture without warning (22–24). The limitation of RF technique for predicating life span of NiTi rotary instruments can be found in Figure 2*C*. The reduction in RF of instrument without plastic deformation is often less than 5%, but the variation in RF of these samples at the beginning of loading is almost 10%. However, from Figure 2*A* and *B*, structural damage in all the samples with invisible plastic deformation can be detected by monitoring changes in RF.

Interestingly, when the RF change (final RF divided by initial RF) of each tested NiTi rotary instrument with plastic deformation (Fig. 2*A* and *B*) was plotted against their corresponding length deformation (instrument length before fracture divided by its initial value), a linear relationship ($R = 0.75$, $P < .05$) was observed (Fig. 3). Mechanically, both a decrease in elastic modulus and an increase in structural length caused by a lengthening deformation can result in decreased RF (25). Thus, when the instrument is continuously used for preparation, regardless of invisible microdamage inside the instrument or plastic deformation, RF is reduced. This result indicates that the RF analysis has potential as a useful tool for structural analysis of NiTi rotary instruments, especially for instrument failure associated with plastic deformation.

Acknowledgments

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

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