Correlation between cyclic fatigue and the bending properties of nickel titanium endodontic instruments

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INTRODUCTION

The effects of cyclic fatigue on bending properties of NiTi endodontic instruments were investigated. Sixteen Profiles⁸ were divided into two groups (A, and B). The sequence of cantilever bending test and cyclic fatigue test was alternated repeatedly until file separation occurred. In the cyclic fatigue test, the instrument curvature was 19° in group A and 38° in group B. Fractographic examination was performed to determine fracture patterns. In group A, there were significant differences between the bending load values measured before the cyclic fatigue test and the last cantilever bending test before instrument fracture at each deflection (P<0.05). Fractographic examination showed the specific patterns of cyclic fatigue fracture. The stress required to induce martensitic transformation might be reduced due to the softening behavior caused by the cyclic fatigue under the relaxation condition of the superelasticity range (group A). The SEM images were able to display specific patterns indicating cyclic fatigue fracture.

Keywords: Bending properties, Bending test, Cyclic fatigue fracture, Fractographic examination, Nickel-titanium rotary file

At present, each type of NiTi file has a different cross-sectional shape and manufacturing procedure and, therefore, the mechanism of NiTi file separation is still unclear. Many studies have been conducted to compare the separation resistance and/or analyze the cause of separation of various NiTi instrument systems⁵⁻¹⁰. Some of the procedures used include the cyclic fatigue test¹⁰, the bending test¹⁸⁻¹⁹, differential scanning calorimetry²⁰, and the nano-indentation test²¹. Most studies using the cyclic fatigue test have used the method of continuously rotating the NiTi files until failure. However, there have been no cyclic fatigue studies wherein the rotation of the NiTi file is stopped before separation, rotation is resumed, and these steps are repeated until separation occurs. Considering that the duration of each file use in the clinical environment is short, it is ideal to evaluate the NiTi file characteristics during application by using a cyclic fatigue test that stops and restarts the rotation prior to file separation, and repeats the same procedure until failure. This method procedure is different from previous, traditional cyclic fatigue tests.

In the present study, we used a cyclic fatigue test with these new procedures to investigate the effect of cyclic fatigue on the bending properties of ProFile® NiTi endodontic instruments (DENTSPLY Maillefer, Ballaigues, Switzerland).

MATERIALS AND METHODS

Specimens

Sixteen ProFile® NiTi rotary instruments (DENTSPLY
Maillefer, Ballaigues, Switzerland) with a tip size 30, and a 0.06 taper were selected. The instruments were randomly divided into two groups, groups A and B (n=8, each).

Methods
The study procedure was as follows: all files in both groups A and B first underwent the cantilever bending test, and subsequently the cyclic fatigue test for 20 s. This sequence of the cantilever bending test and cyclic fatigue test was alternated repeatedly until file separation occurred.

The concrete procedure of the cantilever bending test and the cyclic fatigue test is described below.

Cantilever bending test
An original cantilever bending test apparatus, introduced in the previous studies, was used in this study. The cantilever bending test was performed to both instrument groups under the same conditions. The instrument was first mounted on a movable stage and clamped at a distance of 7.0 mm from the tip, and the loading point was set at 2.0 mm from the tip (Fig. 1). The instrument was loaded (1.0 mm/min) until it achieved a 3-mm maximum deflection, and it was then unloaded. The bending loads were measured at deflection values of 0.5, 1.0, 1.5, 2.0, and 2.5 mm during the loading process, and the load values thereby obtained before the cyclic fatigue test and the last cantilever bending test before instrument fracture were evaluated.

During the test, the temperature of the instrument and apparatus was maintained at 37°C.

Cyclic fatigue test
An original stainless steel three-pin device was used in this study, with a 2-mm internal diameter of the stainless steel pin. Instrument curvature was accurately reproduced by horizontally adjusting the No. 3 pin to the left (Fig. 2). Silicone oil (KF-96-100CS; Shin-Etsu Chemical Co, Tokyo, Japan) was used to reduce friction and heat generation, and the temperature of the instrument and apparatus was maintained at 37°C during the test.

The instrument was fixed using the No. 1 and No. 2 pins, and protruded 2 mm beyond the No. 3 pin. The instrument curvature was 19° in group A and 38° in group B, with a curvature radius of 5 mm. The experiment was performed for 20 s at 300 rpm using an X-smart Plus® (Dentsply Maillefer, Ballaigues, Switzerland).

A load cell (LUR-A-50NSA1; Kyowa Electronic Instruments Co., Tokyo, Japan) was fixed to the No. 2 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 Co., Tsujiura, 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.

The fracture surface for each instrument was examined under a scanning electron microscope (SEM) (Hitachi High-Tech S-3400, Tokyo, Japan) at an accelerating voltage of 15 kV. Fractographic examination was used to determine fracture patterns.

The data obtained were statistically analyzed by the Wilcoxon signed-rank test and the t-test. The statistical significance was set at p=0.05.

RESULTS
Cantilever bending test
In group A, there are significant differences between the bending load values measured before the cyclic fatigue test and the last cantilever bending test before instrument fracture at the deflection values of 0.5, 1.0, 1.5, and 2.0 mm (p<0.05), though no significant difference appears at the 2.5 mm deflection (p>0.05) (Fig. 3).

In group B, there are no significant differences between the bending load values at any deflection measured before the cyclic fatigue test and the last cantilever bending test before instrument fracture (p>0.05) (Fig. 3).

The number of repetitions of the cantilever bending
Fig. 3  Bending load values of groups A and B at each deflection (0.5, 1.0, 1.5, 2.0, and 2.5 mm) before cyclic fatigue test and the last cantilever bending test before instrument fracture.

* Statistically significant: \( p < 0.05 \)

Table 1  The number of repetitions of the cantilever bending test before instrument fracture.

| Group | Specimen | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|-------|----------|---|---|---|---|---|---|---|---|
| A     | 33       | 33 | 27 | 4 | 5 | 28 | 31 | 21 | 25 |
| B     | 5        | 5  | 5  | 4 | 4 | 3  | 4  | 4  | 4  |

test prior to instrument fracture for all specimens are shown in Table 1.

Cyclic fatigue test
During the cyclic fatigue test, the NCF are 2857±401.98 for group A and 382±57.11 for group B. It was demonstrated that instruments in group B were fractured significantly earlier than those in group A \( (p < 0.05) \).

SEM
Macroscopically, the crack initiation area is identified by noting the chevron pattern, also called 'herringbone marks'\(^{22}\), on the fracture surface. Also, striations and dimples are observed microscopically. Fig. 4(a) shows the crack initiation and propagation at the periphery of the fractured surface, and Fig. 4(b) shows the final fracture area of the fractured surface of a file from groups A and B, respectively (original magnification \( \times 180 \)). In the crack propagation area, striations are observed, as shown in Fig. 4(c) (original magnification \( \times 2000 \)). At the final fracture area, dimples are observed, as shown in Fig. 4(d) (original magnification \( \times 2000 \)).

As found by fractographic examination, all of the fractured instruments show specific patterns of cyclic fatigue fracture, including a crack initiation area, a crack propagation region, and a final rupture of a ductile nature that is characterized by dimples.

DISCUSSION
Bending properties
Tests for endodontic treatment instruments have been established by the International Standards Organization, Publication 3630/1, and by the American National Standards Institute/American Dental Association, specification No. 28. However, these tests are established for stainless steel files, such as K files and reamers, and are therefore not suitable to evaluate the characteristics of rotary NiTi files. For this reason, we used the cantilever bending test in this experiment.

Sudden fracture of rotary NiTi instruments occurs when the files are stacked in narrow canals. This may be caused by the concentration of torsional stress and/or repeated bending stress at the same location\(^{1,10,23-26}\).

The superelastic behavior of the NiTi alloy is different from the plastic deformation of metals, allowing the alloy to return to its original shape after unloading of the external force. Plastic deformation is due to a slip deformation, which is irreversible. The superelastic deformation of this material is achieved by a change of the crystal structure via a stress-induced martensitic transformation upon exposure to an external force, with a reverse transformation occurring after unloading of the external force. Thus, the files can return to their original shape after removal of the external force.

The stress that occurs during root canal shaping...
Fig. 4 SEM images of a fracture surface in groups A and B. 
(a) Crack initiation and propagation area (original magnification×180), (b) final fracture area (original magnification×180), (c) striations (arrows) (original magnification×2000), and (d) dimples were observed (original magnification×2000).

may cause transformation of areas in the files from the austenite phase to the martensite phase. A permanent deformation for most metals may be induced in the lattice by dislocation slip when the external force is large enough. However, stress-induced martensitic transformation is more commonly induced in the Ni-Ti alloy compared with the dislocation slip, which may be the reason the NiTi alloy files are able to return to their original shape.

The work softening phenomenon found for group A (Fig. 3) is similar to the results in a previous study\textsuperscript{21}, which indicates that work softening occurred in the fractured files.

The work softening phenomenon is thought to be reflected by the following mechanism: During cyclic loading test, stress-induced martensite reconfiguration occurs and residual strain accumulation results from dislocations and internal stresses. These phenomena lead to a decrease in the critical stress required for martensitic transformation\textsuperscript{27-29}. Therefore, the stress needed for austenite-martensite transformation is reduced as the number of cycles increases\textsuperscript{30}. In the present study, the same phenomenon was found in group A. The bending load values (Fig. 3) at deflection from 0.5 to 2.0 mm before cyclic fatigue test were significantly higher than the values the last cantilever bending test before instrument fracture. This means that the stress-induced martensite of the ProFile\textsuperscript{®} is easily produced because of the nature of the cyclic fatigue. We speculate that the softening occurs during the bending load test after the external force unloading, and that the files may be resistant to fracture under the conditions.
experienced by group A, compared with group B.

We consider that the cantilever bending test can be a useful method to determine the lifespan of a ProFile® used in a clinical setting if the use is restricted in the superelasticity range.

In group B (Fig. 3) no significant difference was found between the bending load values before and after cyclic fatigue test. This means that the crack propagations in the files took place before the softening phenomenon appeared. The deflection angle for the fatigue tests may affect the bending behavior. Therefore, the future study will be necessary to confirm the range of softening from the point of deflection angle.

**Cyclic fatigue properties**

Various cyclic fatigue studies have used 30°, 45°, 60°, and 90° angles of curvature, with a 0.25-mm file size and a 0.06 taper. In the present study, the 0.30-mm, 0.06 taper ProFile® was used to facilitate comparison with our previous results. The experimental method in the present study using conditions selected from our preliminary experiments was different from previous fatigue tests. These experimental conditions include 19° (group A) and 38° (group B) angles of curvature, which simulate the relaxation and tension conditions of the superelasticity range, respectively.

According to previous studies, the fatigue life of NiTi rotary instruments is significantly influenced by the angle and the radius of curvature. Increasing the angle and the radius of the curves around which the instrument rotates decreases the instrument lifespan. This study confirms those results.

The finding that cyclic fatigue can be induced by repeated tension-compression stress was obtained through research investigating the change of the resistance of file fractures. Both tension and compression stress exist in the curvature part of the files when they rotate in canals. When the instrument is held in a static position and continues to rotate, half of the instrument shaft on the outside of the curve is in tension, whereas the half of the shaft on the inside of the curve is in compression. The rotation within curved canals resulted in repeated tension-compression cycle in a specific condition such as group A, which increased cyclic fatigue of the instrument over time. This kind of repeated cycle may be an important factor in instrument fracture. File fracture occurs because of the concentration of metal fatigue caused by tension/compression cycles at the point of maximum flexure.

In this study, statistical analysis is performed only for the bending load values measured before the cyclic fatigue test and the last cantilever bending test before instrument fracture, though the bending load values during the repeated measurement are easily collected. This is because we want to confirm that it is possible to determine the useful lifespan of files using the bending load value obtained via the bending test before the files separate due to cyclic fatigue. The tests in this study were done in static mode so the instrument was able to work in an accurate trajectory. However, future studies will be done in dynamic mode, because this more accurately reflects the conditions that files will experience in clinical use.

**SEM**

From the fractographic examination, the specific patterns of cyclic fatigue fracture, including crack initiation area, crack propagation area and final failure area, are shown for all instruments in the two groups. These indicate that instrument fatigue failure occurs because of the cyclic loads.

**CONCLUSIONS**

In the present study, the stress required to induce martensitic transformation of the ProFile® may be reduced due to the softening behavior caused by the cyclic fatigue under the simulate relaxation condition of the superelasticity range (group A). However, the effect of cyclic fatigue on the stress required to induce martensitic transformation of the ProFile® was not found under the simulate tension condition of the superelasticity range (group B).

The SEM images for both groups display specific patterns indicating cyclic fatigue fracture.

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