Deflecting load of nickel titanium rotary instruments during cyclic fatigue

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The dispersion of the lifetime of NiTi instruments, and their deflecting load (DL) changes during cyclic fatigue were investigated. A total of 120 ProFile NiTi rotary instruments were tested using a specially designed cyclic fatigue testing apparatus with three pins. Using these pins, the instrument was bent and rotated at 300 rpm to fracture. DL was recorded using a load cell attached to the central pin. For each sample, the working time was converted to number of cycles to fracture (NCF) and the mean DL (DLm) was calculated. The averages of NCF and DLm of 120 samples were 584.3±180.5 cycles and 6.44±0.91 N, respectively. All samples showed a sequential decrease in DL during rotation. Based on the present study, it is impossible to estimate the lifetime of a NiTi instrument from NCF. Thus, the change in DL could be an alternative criterion to determine the remaining lifetime.

Keywords: Deflecting load, NiTi rotary file, Number of cycles to fracture

INTRODUCTION

Nickel titanium (NiTi) instruments are widely attractive among dentists because they enable more predictable preparation for root canals and significantly better treatment outcomes compared with stainless steel instruments3). However, the potential for fracture of these instruments is still a main concern associated with their use2,5). Root canal curvature6,7), instrument geometry6,8), working speed7), the use of irrigant8), torque and sterilization procedures9,10), metal surface treatments11,12), heat treatment13), metallurgical characterization of the NiTi alloys14,15), and repeated clinical use14,15) are factors that might enhance instrument fatigue. Moreover, these factors show different effects on the lifespans of different NiTi instrument systems.

Instrument fracture reportedly occurs as a result of two types: torsion and flexural fatigue16). Torsional fracture occurs when the torque resulted 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 whilst the rest continues to rotate. Flexural fatigue occurs by metal fatigue where the instrument rotates freely in a curvature, producing alternating tension-compression cycles at the greatest curvature until fracture. In the engineering field, mechanical fatigue of NiTi alloy mainly occurs as the result of repetitive stress much lower than that required for fracture on a single load application and without any obvious warning17).

The manufacturing of NiTi instruments often results in internal residual stresses, work hardening and surface defects that limit the overall strength of the instrument18). In unused NiTi instruments, work hardening19) and surface defects20) have been reported. Although many studies have been conducted to compare the magnitude of cyclic fatigue in different NiTi instrument systems16), there has been a lack of evaluation of the dispersion of the number of cycles to fracture (NCF) under the same experimental conditions using a large number of identically shaped instruments. We aimed to determine the stochastic dispersion of the lifetime of NiTi instruments and evaluate the DL change during the cyclic fatigue test.

MATERIALS AND METHODS

ProFile instruments (PF; Dentsply Maillefer, Ballaigues, Switzerland) were chosen since they are one of the earliest NiTi systems and have been a commonly used system for more than 15 years.

A total of 120 PF NiTi rotary instruments, size 30 taper 0.06, from four lot numbers (4058380, 4429300, 5353660 and 6292090) were used with 30 instruments of each.

Cyclic fatigue testing was performed using a three-pin device attached to a load cell, which has been described in a previous study21). This device has 3 highly polished, stainless steel pins with an internal diameter of 2 mm. The positions of the pins are set vertically with 5-mm distance between pins #1 and #2, and #2 and #3. Horizontally, they can be adjusted to define an instrument curvature with precise reproducibility (Fig. 1).

The PF instrument was connected to a micromotor (Dentaport ZX, J Morita, Kyoto, Japan) and moved 3 mm beyond the level of pin #3. Then, the pins were adjusted to fix the instrument in a straight position.

The load cell (LUR-A-50NSA1, Kyowa Electronic Instruments Co., Tokyo, Japan) was attached to the #2 pin to measure the magnitude of the deflecting load (DL) imposed by the instrument. 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., Tsuchiura, Japan), and the output of the A/D converter was conducted to a personal computer (PC). Data were...
recorded and analyzed using the attached software of the A/D converter.

Once the instrument was fixed straight by the 3 pins, the load cell was zeroed. Afterwards, the fixed instrument was deflected 2 mm horizontally by the #3 pin and the maximum tensile strain was generated about 7 mm from the instrument tip showing about 4% amplitude strain.

The bent instrument was rotated at 300 rotations per minute (rpm) with the micromotor until fracture occurred. The fracture was identified by a sudden change in DL. The change in the DL was monitored on the PC display and saved as excel file. Sampling time was set at 100 milliseconds.

In each sample, DL data were converted into sequential DL change percentages (DL change%) as follows:

\[ \text{DL change\%} = \frac{(\text{DL} - \text{initial DL})}{\text{initial DL}} \times 100\% \]

where DL represents the mean data for each 5-s interval, and initial DL is the DL measured in the beginning of instrument rotation.

Then, the DL change\% versus NCF was drawn for each sample to show its behavior during the cyclic fatigue test. Afterwards, at 5, 6, 7 and 8% DL decreasing levels shown in the graphs of all PF samples, the mean remaining lifetime (whole lifetime of each sample was defined as 100%) and the risk for instrument breakage (number of the remaining instruments/120) were calculated.

All measurements were performed at room temperature. Silicone oil (KF-96-100CS, Shin-Etsu Chemical Co., Tokyo, Japan) was used as a lubricant to minimize friction and heat generation. For each sample, the time to fracture (in min) was multiplied by 300 rpm to obtain the NCF, and the mean DL (DL_m) was calculated.

### RESULTS

Four groups with different lot numbers were used in order to observe any difference among them in the frequency of file breakage. Nonetheless, comparably each group showed wide range of NCF and DL readings.

Minimum, maximum, mean, and median of NCF and DL_m are shown in Table 1. The distribution of NCF was abnormal by the Shapiro-Wilk test (p=0.002, Fig. 2). The distribution of DL_m, however, shown in Fig. 3, was normal by the same test (p=0.295). Analysis revealed a poor correlation between NCF and DL_m (Fig. 4, R²=0.067).

From the sequential change in DL (Figs. 5, 6), the influence of cyclic fatigue on lifetime was analyzed. The overall pattern of DL over the period of fatigue test appeared to change gradually with working time.

At 4 DL decreasing levels (Fig. 6), it was shown that if the rotation stopped when DL had 5%-decrease, the average remaining lifetime was estimated as 55.9% and the risk for instrument breakage during preparation to be 2.5%. While the average remaining lifetimes of 6, 7 and 8%-decrease were 49.7, 42.8 and 36.7%, respectively showing the risk for breakage to be greater as 4.2, 9.2 and 11.7%, respectively.

### DISCUSSION

The most striking disadvantage of NiTi instruments is the risk of sudden fracture. The study showed the
Theoretically, identically shaped NiTi instruments should have the same lifetime; however, the machine-based manufacturing process is complex and may produce NiTi instruments with different amounts of internal residual stresses, work hardening and defects along the NiTi instrument\textsuperscript{18,19,22,23}, which makes the prospect of lifetime by NCF difficult to attain.

Considering the distribution of NCF data, our results from 120 samples showed that the manufacturing process has a direct influence on endodontic NiTi instrument fracture where it had a wide range (i.e., 270–1,148 cycles) of discrepancy. This is very troublesome, especially in clinical use where the mean lifetime (mean NCF) has shown no clinical relevance. In addition, using scanning electron microscopy\textsuperscript{24,25}, unused NiTi instruments were found to contain at least one defect. After clinical single use, Arens et al.\textsuperscript{26} found that 14% of NiTi instruments showed various defects and
0.9% fractured. Moreover, Lask et al. found variations in the tip diameter of PF instruments, with large percentage differences from the nominal 0.30-mm diameter. Collectively, all of these factors might contribute to the wide distribution of NCF results. To decrease these discrepancies in the mechanical character of NiTi instruments, a more refined machining process should be developed.

Theoretically, once deflected, a NiTi instrument with a large DL suggests stiff instrument having a short lifetime (i.e. NCF). However, in our experiment, only a weak relationship between NCF and DL of the same shaped NiTi instrument was shown (Fig. 4).

Cheung and Darvell constrained the NiTi instrument into a curvature using three stainless steel pins so that curvature geometry could be adjusted as a function of deflection by moving the pins horizontally. Yahata et al. modified Cheung’s device to be able to measure the magnitude of the DL on the area with the greatest curvature that was close to the point of fracture.

One limitation of this study is that the setting does not reflect clinical conditions; the instrument rotated by point contact with three pins and without an up-down motion. This generated a rather small torque on the instrument.

Superelasticity of NiTi alloys occurs in association with the stress-induced martensitic transformation from austenite to a more flexible structure, martensite. The present study showed that PF instruments became less stiff and more susceptible to fracture under cyclic fatigue, which has two explanations. First, cyclic loadings tend to lower the critical stress. Critical stress is defined as the amount of stress needed to induce austenite-martensite transformation; as cyclic fatigue proceeds, stress-induced martensite reconfiguration and stabilization will occur and residual strain accumulation will result from dislocations and internal stresses which in turn lead to a decrease in the critical stress. Nonetheless, martensite stabilization will locally reduce the microstructure potential for stress relaxation and this may unfavorably affect fatigue life. The increased flexibility of the tested instruments is consistent with results of a nanoindentation study where it showed that the elastic modulus of the fatigued instruments decreased significantly after cyclic fatigue process.

Second, crack propagation by tension-compression cycles might reduce NiTi instrument stiffness. Thus, more cyclic loadings mean higher flexibility, but an increased chance of crack propagation.

All of the tested PF instruments had changes in DL during rotation, characterized by a gradual decrease with working time (Figs. 5, 6). Consistent with our results, Li et al. suggested the fracture failure criterion to be a decrease in stiffness. On the contrary, Kuhn and Jordan found that stiffness of PF instruments was increased after clinical use.

Defects weaken the instrument, allowing cracks to nucleate and spread until sudden fracture, even at stresses below the yield point stress. Furthermore, fatigue-crack growth rates in NiTi alloys have been reported to be significantly greater than in other metals of similar strength. Bahia et al. showed that nucleation of fatigue cracks occurs early in PF instruments, probably due to their machining-induced irregular surface characteristics, which act as stress concentrators. The fatigue mechanism of NiTi endodontic instruments is a type of deformation-controlled, low-cycle fatigue in which slow crack propagation has a major effect on the instrument’s fatigue life. Although martensitic transformation hinders crack formation, work hardening resulted during the manufacturing of NiTi instruments will prevent martensite to reorient and reform easily that will influence crack formation. Moreover, NiTi volume will minimally decrease in stressed situation, presenting an insignificant martensitic effect near growing cracks.

Clinically, the change in its DL monitored before and during use utilizing a similar device as used in this experiment might estimate the remaining lifetime. A calculated DL decrease would show the conditions under which the used NiTi instrument should be discarded. The effect of clinical use on instrument stiffness must be investigated.

Yet, no evidence-based guidelines for the number of uses has been available, although some authors have suggested that up to 10 clinical uses might be safe. From the endodontic literature, to prevent intracanal instrument separation, inspection of the NiTi instrument before each use under high magnification is recommended which might reveal defects necessitating instrument disposal. In addition, change in the resonance frequency of vibration of the NiTi instrument was shown to be a useful parameter to predict the lifespan of NiTi instruments.

This study focused on one brand of one size and taper of NiTi instruments where differences in thermomechanical history and geometry of other instruments will show different DL measurements. Thus, further investigations should be performed using other NiTi instrument systems, with different manufacturing processes, treatment techniques and dimensions to inspect the dispersion of their lifetimes, to map the relationship between the instrument lifetime and DL change and to develop a reliable method for predicting the lifespan of NiTi instruments.

According to the present study, since it is impossible to estimate the lifetime of a NiTi instrument only from NCF, measuring the change in DL could be an alternative criterion to determine the remaining lifetime.

REFERENCES

3) Glossen CR, Haller RH, Dove SB, del Rio CE. A comparison of