Prediction of Cyclic Fatigue Life of Nickel-Titanium Rotary Files by Virtual Modeling and Finite Elements Analysis

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Abstract

Introduction: The finite element method (FEM) has been proposed as a method to analyze stress distribution in nickel-titanium (NiTi) rotary instruments but has not been assessed as a method of predicting the number of cycles to failure (NCF). The objective of this study was to predict NCF and failure location of NiTi rotary instruments by FEM virtual simulation of an experimental nonstatic fatigue test. **Methods:** ProTaper Next (PTN) X1, X2, and X3 files (Dentsply Maillefer, Baillagues, Switzerland) (n = 20 each) were tested to failure using a customized fatigue testing device. The device and file geometries were replicated with computer-aided design software. Computer-aided design geometries (geometric model) were imported and discretized (numeric model). The typical material model of an M-Wire alloy was applied. The numeric model of the device and file geometries were exported for finite element analysis (FEA). Multiaxial random fatigue methodology was used to analyze stress history and predict instrument life. Experimental data from PTN X2 and X3 were used for virtual model tuning through a reverse engineering approach to optimize material mechanical properties. Tuned material parameters were used to predict the average NCF and failure locations of PTN X1 by FEA; *t* tests were used to compare FEA and experimental findings (*P* < .05). **Results:** Experimental NCF and failure locations did not differ from those predicted with FEA (*P* = .098). **Conclusions:** File NCF and failure location may be predicted by FEA. Virtual design, testing, and analysis of file geometries could save considerable time and resources during instrument development. (*J Endod 2015;41:1867–1870*)

Key Words

C-S criterion, finite element analysis, multiaxial random fatigue, nickel-titanium rotary instrument, virtual modeling

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Since their introduction, nickel-titanium (NiTi) rotary instruments have considerably simplified endodontic practice by improving speed, accuracy, and safety during root canal shaping (1, 2). Continuous enhancements in the design and manufacture of NiTi rotary instruments have significantly reduced but not completely eliminated the occurrence of failure during canal shaping (3, 4). Although rare, breakage of NiTi rotary instruments may lead to incomplete chemomechanical treatment of the root canal system and hinder healing, particularly in the presence of preexisting apical radiolucency (5, 6). Furthermore, excessive removal of the tooth structure can occur during fragment elimination procedures (5, 6). Although many variables can contribute to instrument failure, the primary causes are cyclic bending fatigue and torsional overload. Torsional overload is related to the risk of taper lock, and its incidence might be reduced by performing a glide path and preliminary enlargement (7–9). However, NiTi instrument failures are mainly caused by cyclic bending fatigue, which occurs when a NiTi instrument rotates in a curved root canal (10–14). During rotation, the instrument material is alternatively subjected to compressive and tensile stresses (11). Such stresses may initiate crack formation and propagation, leading to eventual failure (4, 15). Instruments that fail because of bending fatigue usually exhibit no specific macroscopic patterns, and failure may occur without any visible warning (1, 5, 16, 17). Canal shape, instrument geometry, rotational speed, torque, instrument surface treatments, and the chemical composition of NiTi alloys are the main factors affecting the number of cycles to failure (NCF) of NiTi rotary instruments (2, 4, 18–21). Standardized experimental conditions are not possible for extracted teeth (22), but several self-designed devices and methods have been used to assess the NCF of NiTi rotary instruments *in vitro* (22). However, there is no international standard for testing the cyclic fatigue behavior of endodontic rotary instruments *in vitro* (22). A 3-dimensional computerized approach based on the finite element method (FEM) (23–27) has been recently proposed to analyze stress distribution in bending fatigue. This approach takes cyclic loading conditions into consideration (25, 27) but makes no attempt to predict NCF.

The objective of this study was to assess the possibility of predicting the NCF and failure location of NiTi rotary instruments by the virtual simulation of an experimental fatigue test (nonstatic loading condition) using the FEM.

Materials and Methods

ProTaper Next (PTN) X1, X2, and X3 files (n = 20 each), 25 mm in length, were tested to failure using a tempered steel fatigue testing device developed by Dentsply Maillefer (Baillagues, Switzerland), which produced a reproducible simulation of rotary instrumentation within a curved canal. Testing configurations adopted for every file type are reported in Figure 1 and Table 1. Testing configurations for file X1 and files X2 and X3 differ with respect to canal depth and the position of the curvature center of the component simulating the inner canal wall. The testing device is covered with a glass or steel element to prevent the file leaving the canal during rotation. Each file was inserted, leaving the noncutting tip outside the canal, and rotation initiated with an electric motor (X-Smart, Dentsply Maillefer) at the suggested settings (300 rpm, 5 Ncm). Time to failure was recorded and converted to NCF. Experimental tests were performed by Dentsply Maillefer; tested files were photographed with a digital camera
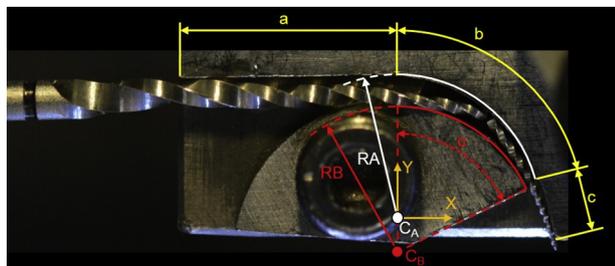
Figure 1. A scheme of the device used for cyclic bending fatigue testing of investigated files; the testing device with its main dimensions as reported in Table 1. α, contact angle; a, initial straight portion of the canal; b, curved portion of the canal; c, final straight portion of the canal; CA, center of the osculating circle for the outer canal wall; CB, center of the osculating circle for the inner canal wall; p, canal depth; RA, radius of the osculating circle for the outer canal wall; RB, radius of the osculating circle for the inner canal wall; X,Y, reference system.

after failure (Canon EOS 350D, 8 Mpx resolution, ISO 100, f 18, 1/60 seconds; Canon, Tokyo, Japan), and failure locations were measured in millimeters from the tip of the instrument (image analysis, caliper).

The customized fatigue testing device and file geometries were computer replicated (Supplemental Video S1) with computer-aided design software (SolidWorks 2013; Dassault Systems, Waltham, MA). Computer-aided design geometries (geometric model) were imported in a prepost processor (Hypermesh 12.0; Altair, Troy, MI) and discretized (numeric model). The main body of each file was modeled with 18,000 brick elements, with an average size of 0.1 mm (Fig. 2). The tip and neck of the file were modeled with tetrahedral elements with the same average dimensions. The typical material model of an M-Wire alloy (NiTi alloy), taken from the literature (28), was applied. The testing device was modeled with 2000 shell element and was considered a rigid material. Contact between the file and the testing device was introduced with a penalty contact formulation implemented in LS-Dyna (LS-Dyna R7.1; Livermore, Livermore, CA). The penalty method introduces a force at the contact detection points that penetrates across the target surface with the purpose of eliminating penetration (29). The numeric model of the customized fatigue testing device and the file geometries were exported into the finite element solver (LS-Dyna R7.1) for finite element analyses (FEA). The FEA aimed to mimic the experimental test performed with the Maillefer customized fatigue testing device. The file, in rest configuration (straight file), was inserted into the testing device and then bent by the simulated canal walls (rigid shell elements). It was finally put into rotation at 300 rpm. The stress state in the brick elements of each file model was recorded every 0.2 seconds for 2 seconds (Supplemental Videos S2–S4).

TABLE 1. Testing Configurations Adopted for Each Investigated File

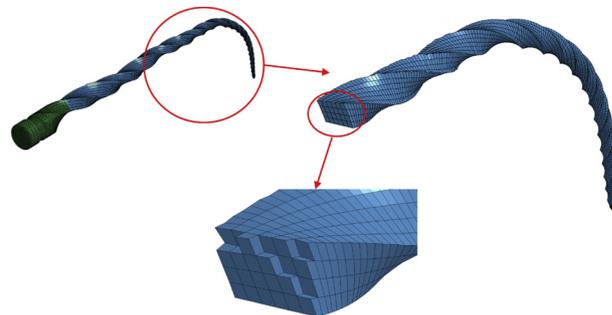| Dimensions	X1	X2, X3
R_A [mm]	5	5
R_B [mm]	4.6	4.6
Alpha [°]	78	78
a [mm]	6	6
b [mm]	7	7
c [mm]	1	1
p [mm]	0.6	0.8
X_{CB} [mm]	+0.18	+0.04
Y_{CB} [mm]	−0.04	−0.45

Figure 2. Finite element model of the PTN X1 file.

Traditional life prediction methods developed for uniaxial variable amplitude loading could not be used in this study because of the complexity of the stress-strain state and the loading history over time (multiaxial random loading). Element stress history must be analyzed by applying an appropriate multiaxial random fatigue (MRF) criterion. Few methodologies concerning MRF have been proposed, and research on the topic is still in progress. A recent MRF methodology, proposed by Carpinteri et al (30) and named the C-S criterion, was adopted in this study to analyze the stress history of each file element. The C-S criterion was implemented in Matlab 2014 (The MathWorks Inc, Natick, MA) with the assumption that the stress history recorded in the first 2 seconds was identically repeated until failure. The C-S criterion was used to calculate the time to failure for each brick element and, as a consequence, to predict the file NCF (the minimum NCF in the file).

The mechanical properties of a material are not provided, and the influence of manufacturing surface defects cannot be evaluated a priori. As a consequence, a reverse engineering approach for model tuning was adopted to obtain the required information. Several material properties were taken into account through the Matlab model and were tuned to match the experimental NCF of PTN X2 and X3 files. Material parameters were altered through an optimization algorithm implemented in Matlab 2014 to reduce the difference between the file NCF obtained with FEM and the experimental NCF. The tuned material parameters were then used to predict the average NCF of PTN X1 file with FEA. Failure locations for each file type were recorded and compared with the failure locations of the files photographed after failure in the Maillefer customized fatigue testing device; t tests were performed to compare FEA and experimental results ($P = .05$).

Results

The main results of the analyses are presented in Table 2. The NCF of PTN X2 and X3 files was used for the tuning of material parameters involved in the C-S criterion. Their P values for the NCF were subsequently extremely large ($P = .896$ and $.787$, respectively). There was also no significance in the NCF of the PTN X1 file ($P = .098$). Therefore, no significant statistical difference was found between the experimental NCF and the NCF predicted by FEA.

In addition, no significant statistical difference was found between the experimental failure locations and the failure locations predicted by FEA ($P = .148$ for PTN X1 file, $P = .995$ for PTN X2 file, and $P = .481$ for PTN X3 file).

Possible failure locations predicted with FEA, together with the experimental failure locations obtained from the photographed files, are shown in Figure 3. For every file type, vertical lines indicate 95% confidence intervals of the experimental failure locations, whereas

TABLE 2. Main Results of the Analyses

Instrument	Cyclic fatigue test		FEA		P value	
	NCF	Fracture length*	NCF	Fracture length	NCF	Fracture length
X1	671 ± 170 [592; 751]	5.59 ± 0.38 [5.41; 5.79]	605	5.77	.10	.15
X2	522 ± 67.2 [491; 553]	5.46 ± 0.50 [5.23; 5.69]	518	5.46	.89	.99
X3	334 ± 61.1 [305; 362]	5.44 ± 0.16 [5.37; 5.51]	329	5.40	.78	.48

FEA, finite element analysis; NCF, number of cycles to failure.

Mean ± standard deviation; in square brackets, 95% confidence interval for the mean.

*Length and location from the file tip in mm (mean ± SD).

the highlighted point denotes the location of the element with the smallest NCF where the predicted failure occurred.

Discussion

Multiaxial loading usually acts on NiTi rotary instruments during shaping (31, 32) as a result of the simultaneous presence of bending and torsion. Given a file type (geometry and material), the torsional overload largely depends on the preexisting root canal size and the apical force exerted during instrumentation, whereas the cyclic bending fatigue depends on unmodifiable anatomic factors such as the root canal radius and degree of curvature (22). File rotation around a curved axis (the axis of the file inserted into a curved canal root) leads to a continuously varying complex stress state including normal and shear components (15) and, therefore, to a fatigue phenomenon, which accounts for up to 90% of endodontic instrument mechanical failures (2, 33).

In the present study, FEA analysis was introduced as a virtual testing approach to predict mechanical behavior of the NiTi file. FEA is a numeric method that calculates the stress field in any file geometry according to the file material properties and the boundary loading conditions (27). Virtual testing results obtained by simulating the rotation of ProTaper Next X1, X2, and X3 instruments were compared with the experimental results obtained with a customized fatigue testing device. A reverse engineering approach was used to overcome the lack of information regarding the material behavior and the local stress concentration effects caused by manufacturing surface defects (5, 34, 35).

The instrument stress state obtained by FEA was elaborated according to the C-S criterion proposed by Carpinteri et al (30) to calculate the NCF and failure location caused by cyclic bending fatigue. The C-S criterion is applicable when stresses are below the yield strength of the material (ie, no plasticity phenomena occur during load application). The applicability of the C-S criterion is not influenced by file rotation speed or, more generally, by the applied load frequency. The authors verified the applicability of the C-S criterion; for the analyzed cases, the stress state was far below the yield strength of the material, and, therefore, no plasticity occurred during load application.

Unknown material properties (eg, the normal stress fatigue limit and the shear stress fatigue limit) were required for the application of the C-S criterion, and a reverse engineering approach was performed to estimate them. Material properties were modified and optimized to reduce the difference between the file NCF obtained with FEA and the NCF obtained with the fatigue testing device for ProTaper Next X2 and X3. The tuned parameters are specific for the material used to manufacture the analyzed files. The same parameters can be used for any FEA in which the file material is kept the same. If the file material changes, the material properties change and must be found through a further tuning process. The optimized material properties and the fatigue prediction model based on the C-S criterion were used to predict the NCF of the ProTaper Next X1.

The results presented here show that virtual simulation through FEA can be usefully adopted to predict the file NCF and the failure location. As a consequence, given the material properties obtained through
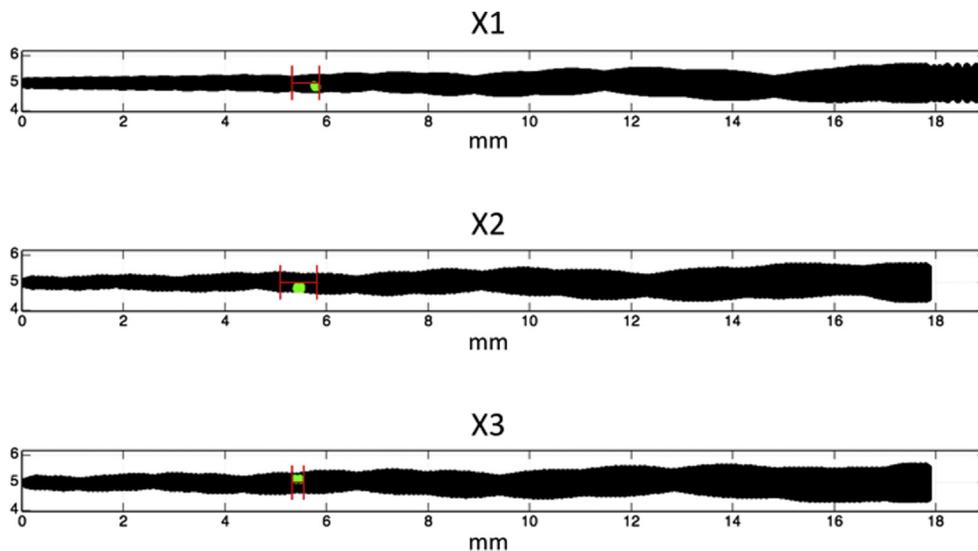

Figure 3. Comparison between FEA and experimental failure locations; vertical red lines denote 95% confidence intervals for the experimental failure locations, and highlighted green points denote the location of the element with the smallest NCF.

the reverse engineering approach, FEA can be effectively used to virtually design new file geometries. Therefore, the FEA approach would potentially overcome the usual expensive trial and error approach based on repetitive prototype manufacturing and testing. This study shows the feasibility of numerically analyzing instrument geometries to predict the file NCF and location of failure. The evaluation of material mechanical properties through a reverse engineering approach based on a multiaxial random fatigue criterion allows the virtual verification of new file geometries toward cyclic bending fatigue failure. The virtual analysis of file behavior may lead to a considerable saving of time and resources during instrument development.

The evaluation of the material properties through a reverse engineering approach could be avoided if the material properties and the manufacturing defects are properly characterized and taken into account.

Acknowledgments

Supplementary Material

Supplementary material related to this article can be found at http://dx.doi.org/10.1016/j.joen.2015.07.010.

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