International Endodontic Journal

doi:10.1111/j.1365-2591.2010.01838.x

A numerical method for predicting the bending fatigue life of NiTi and stainless steel root canal instruments

G. S. P. Cheung[1], E. W. Zhang[2] & Y. F. Zheng[2]

[1]Area of Endodontics, Comprehensive Dental Care, Faculty of Dentistry, the University of Hong Kong, Hong Kong Special Administrative Region; and [2]State Key Laboratory for Turbulence and Complex Systems and Department of Advanced Materials and Nanotechnology, College of Engineering, Peking University, Beijing, China

Abstract

Cheung GSP, Zhang EW, Zheng YF. A numerical method for predicting the bending fatigue life of NiTi and stainless steel root canal instruments. *International Endodontic Journal*, **44**, 357–361, 2011.

Aim To evaluate the bending fatigue lifetime of nickel–titanium alloy (NiTi) and stainless steel (SS) endodontic files using finite element analysis.

Methodology The strain-life approach was adopted and two theoretical geometry profiles, the triangular (TR) and the square cross-sections, were considered. Both low-cycle fatigue (LCF) lifetime and high-cycle fatigue (HCF) lifetime were evaluated.

Results The bending fatigue behaviour was affected by the material property and the cross-sectional configuration of the instrument. Both the cross-section factor and material property had a substantial impact on fatigue lifetime. The NiTi material and TR geometry profiles were associated with better fatigue resistance than that of SS and square cross-sections.

Conclusions Within the limitations of this study, finite element models were established for endodontic files to prejudge their fatigue lifetime, a tool that would be useful for dentist to prevent premature fatigue fracture of endodontic files.

Keywords: bending fatigue, finite element analysis, nickel–titanium, root canal instruments, stainless steel.

Received 14 September 2010; accepted 14 November 2010

Introduction

Fatigue is the progressive, localized and permanent structural change that occurs in a material subjected to repeated or fluctuating strains at nominal stresses below (and often much less than) the yield strength of the material (Bannantine *et al.* 1989, ASM International 1996). The material will succumb to propagating fatigue–cracks and fail after a sufficient number of load fluctuations. Nickel–titanium (NiTi) rotary files are susceptible to fatigue fracture, especially when they are used in curved root canals in continuous rotation. These instruments are 'sensitive', because they are small (in relation to most structures in engineering) and are subjected to harsh working (corrosive) conditions under a combination of torsional and bending moments of force. Fatigue has been implicated to be the main reason for the fracture of endodontic files used clinically (Sattapan *et al.* 2000, Shen *et al.* 2006, Spanaki-Voreadi *et al.* 2006, Cheung 2009). Both torsional (Best *et al.* 2004) and bending (flexural) fatigue (Pruett *et al.* 1997, Sattapan *et al.* 2000, Lopes *et al.* 2007) can lead to fracture of NiTi instruments. There have been many reports of various factors that can affect the fatigue fracture of NiTi rotary files, including the geometric configuration (Yao *et al.* 2006), surface finish (Anderson *et al.* 2007, Cheung *et al.* 2007a, Bui *et al.* 2008), working environment (Cheung *et al.* 2007a,b), applied torque (Gambarini

Correspondence: Yu-Feng Zheng, Department of Advanced Materials and Nanotechnology, College of Engineering, Peking University, Beijing 100871, China (Tel.: 0086 10 6276 7411; fax: 0086 10 6276 7411; e-mail: yfzheng@pku.edu.cn).

2001), rotation rate and angle of root canal curvature (Martín *et al.* 2003).

A major drawback of most laboratory tests of the fatigue behaviour of NiTi rotary instrument is that one cannot eliminate the confounding of different factors, such as material properties, design and dimensions of the instrument, which are specific to the brand(s) being tested. This makes it difficult to quantify the effect of a single variable on fatigue behaviour. The beauty of numerical simulation (in a finite element analysis) is that any variable may be fixed and shielded from interference by others for the effect being studied. There is a scarcity of reports on the fatigue behaviour of rotary endodontic files using a numerical method that incorporates the nonlinear, superelastic property of NiTi material. In contrary, the numerical approach has been applied widely to fatigue analysis in structural and mechanical engineering (Bannantine *et al.* 1989, ASM International 1996, Browell & Hancq 2006). The fatigue lifetime analysis is a basic method to examine both the low-cycle (LCF) and high-cycle fatigue (HCF) of a structural part (ASM International 1996), the method of analysis which is available in software of some finite element analysis packages (Browell & Hancq 2006). Numerical prediction of the fatigue lifetime of a component under cyclic loading is possible with acceptable precision (Bannantine *et al.* 1989). The purpose of this study was to estimate the fatigue behaviour of stainless steel (SS) versus NiTi rotary files of two hypothetical cross-sections using a numerical method.

Materials and methods

Generally, there are three main fatigue analysis methods: stress-life, strain-life and fatigue-crack propagation (or fatigue tolerance) analysis, with the first two analyses being available in the 'fatigue module' (a plug-in component) of a finite element analysis software, ANSYS (ANSYS Inc., Canonsburg, PA, USA) (Browell & Hancq 2006). The strain-life approach was adopted for estimating the fatigue life of NiTi instrument, because (i) the magnitude of the alternating strain can be measured, which has been shown to be an excellent parameter for characterizing both LCF and HCF (Bannantine *et al.* 1989, Browell & Hancq 2006) and (ii) the strain-life is typically concerned with crack initiation, whereas the stress-life is concerned with total life and does not distinguish between initiation and propagation (Stephens *et al.* 1980, Bannantine *et al.* 1989, ASM International 1996). Various constants for the strain-life behaviour may be obtained by fitting a curve to the data from a stain-controlled fatigue test. For instance, the cyclic strength coefficient (K') and the cyclic strain hardening exponent (n') can be obtained by fitting the stable stress amplitude versus plastic strain amplitude data into the Coffin-Manson equation for strain-life relationship (Bannantine *et al.* 1989):

$$\sigma_a = K'(\varepsilon_{\mathrm{ap}})^{n'} \tag{1}$$

where σ_a and $\varepsilon_{\mathrm{ap}}$ are the stress amplitude and the plastic strain amplitude, respectively. The variation in fatigue life (total lifetime before fracture), in terms of the number of cycles to failure (N_f) and the total strain amplitude (ε_a), is analysed using the strain-life relationship in the following form:

$$\varepsilon_a = \frac{\sigma'_f}{E}(2N_f)^b + \varepsilon'_f(2N_f)^c \tag{2}$$

where σ_f', b, ε_f' *and* c are the fatigue strength coefficient, the fatigue strength exponent, the fatigue ductility coefficient and the fatigue ductility exponent, respectively.

In this study, the fatigue parameters for SS were taken directly from a standard textbook (Stephens *et al.* 1980), and those for NiTi alloy were derived from the results of a published study (Cheung & Darvell 2007a). These values (Table 1) were entered into the numerical model to simulate the stress- and strain-controlled fatigue behaviours for instruments made of these two materials in software.

Two hypothetical cross-sections, triangular (TR) and square (SQ), were used to produced a 3-D finite element model (Fig. 1). The diameter of the circum-circle for both cross-sections (i.e. outermost diameter, which is usually referred as the 'size' of the instrument in hundredths of a millimetre) increased from 0.3 to 0.4 mm over a length of 5 mm (i.e. ISO taper of 0.02). A fully reversed displacement was applied to the tip of geometrical model, and another tip was fixed in ANSYS, known as a cantilever beam model for this analysis. The applied displacement ranged from 0 to 2.0 mm. There are 3216 elements with 17344 nodes for the triangle FE model, and 3624 elements with 18983 nodes for the square FE model. As the load was completely reversed in every cycle, the mean stress equalled to zero in both the fatigue tests. Infinite fatigue life (also known as 'endurance limit') was defined as 10^7 cycles or above. A total of four numerical models were set up to examine the various combinations of cross-sectional configuration (TR vs. SQ), material (SS

Table 1 Representative parameters for the fatigue behaviour of stainless steel and NiTi alloy

		Stainless steel (304V annealed)	Nickel–titanium (NiTi) alloy (superelastic)
Cyclic strain hardening exponent	(n')	0.334	0.1
Cyclic strength coefficient	(K')	2275 MPa	733 MPa
Fatigue strength exponent	(b)	−0.139	−0.06
Fatigue strength coefficient	(σ'_f)	1267 MPa	705 MPa
Fatigue ductility exponent	(c)	−0.415	−0.6
Fatigue ductility coefficient	(ε'_f)	0.174	0.68

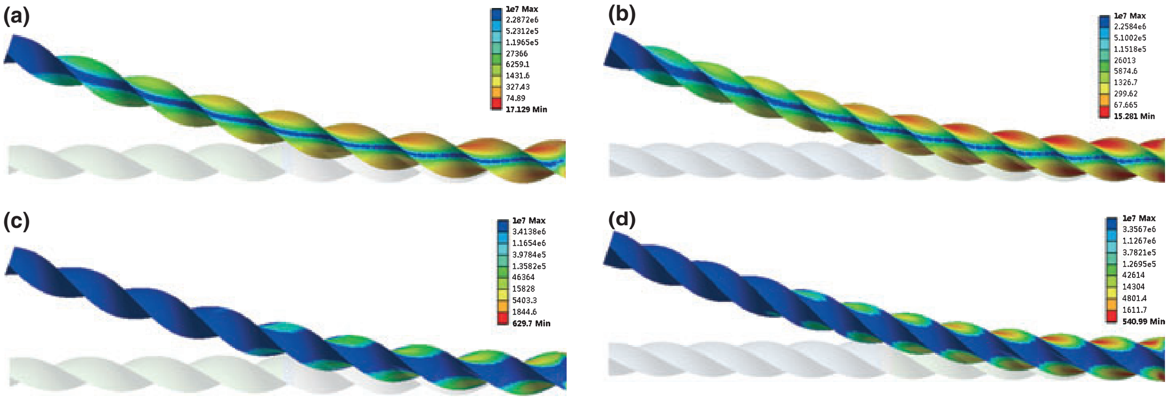

Figure 1 Representative bending fatigue life distribution for four models at 1.0-mm bending displacement at left tip with the right tip fixed. (a) SS-TR(stainless steel file with triangular cross-section) model, (b) SS-SQ(Stainless steel file with square cross-section) model, (c) NiTi-TR(NiTi alloy file with triangular cross-section) model and (d) NiTi-SQ(NiTi alloy file with square cross-section) model.

vs. NiTi). The fatigue behaviour, both LCF (lifetime less than 10^4 cycles) and HCF, was studied in this ANSYS Workbench Environment (ANSYS Inc).

Results

The representative fatigue behaviour for the four combinations of configuration and material properties at the same amplitude of 1.0-mm tip displacement is depicted in Fig. 1. The red region on the surface or in the cross-section of the instrument represented the region experiencing the shortest life (falling in the LCF region), and the blue represented infinite life. Compared to the SS models, NiTi models had more materials in the safety region (the blue region means high fatigue life).

The parts that failed within the LCF region were all situated at the surface of the instrument for each model. The lifetime distribution was found to be strongly related to the distribution of stresses: areas where stress concentration occurred were also the locations with the shortest fatigue life. Instruments of a TR cross-section (Fig. 1a,c) appeared to have a higher fatigue lifetime than the SQ models (Fig. 1b,d) at the same bending amplitude (Fig. 2).

The fatigue lives for the four numerical models at different bending amplitude from 0 to 2.0 mm showed a similar general trend (Fig. 2). With an increasing bending displacement amplitude, the fatigue lifetime of each model decreases rapidly. Both in the HCF and LCF regions, the NiTi material seemed to have a better fatigue resistance than that of SS, compared with the cross-sectional configuration, with the TR cross-section succumbing to a higher lifetime than the SQ group (Fig. 2). Both the cross-section and the material had a significant impact on the fatigue life of the instrument.

Discussion

Three-dimensional finite element analysis has been extensively used in mechanical and structural engineering. Its use has been extended for visualizing the stress distribution and predicting the mechanical behaviours of NiTi root canal instruments under different loading conditions (Berutti *et al.* 2003, Xu &

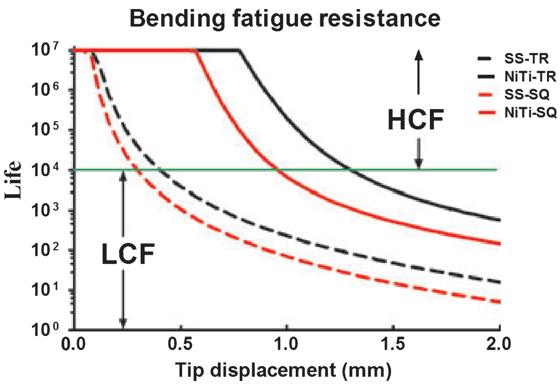

Figure 2 Bending fatigue life of the middle section for different endodontic file models. LCF-low-cycle fatigue; HCF- high-cycle fatigue; SS-TR(stainless steel file with triangular cross-section); SS-SQ(stainless steel file with square cross-section); NiTi-TR(NiTi alloy file with triangular cross-section); and NiTi-SQ(NiTi alloy file with square cross-section).

Zheng 2006), as well as in a computer simulation of clinical use (Kim *et al.* 2008). With a suitably configured package, this numerical method would help with the prediction of fatigue behaviours for rotary files of various designs.

The result of this study indicated that at high alternating load, NiTi instruments had an apparent lifetime higher than their SS counterpart at similar deformation situation. The result is a higher apparent lifetime, compared with SS instrument of the same cross-section, as LCF life is governed by the total alternating strain, not the stress value (Stephens *et al.* 1980). When a rotary file is used to prepare the (curved) root canals, it is being confined to a particular curvature setting (i.e. fixed strain amplitude) during use. Thus, a strain-life approach of analysis may be the best way to examine the fatigue behaviour of NiTi rotary instruments.

It has been suggested that the cross-sectional configuration has little influence on the LCF of NiTi root canal instruments (Cheung & Darvell 2007b). However, this is not supported by the present numerical simulation – the square versus TR configuration demonstrated a significantly different lifetime at both the LCF and the HCF regions. One reason for the different results might be related to the large scatter in actual fatigue experiments (Cheung & Darvell 2007a,b), with the overall lifetime being influenced not only by the strain amplitude but also by the surface condition (e.g. machining grooves) and the microstructure of the underlying material (despite the same composition) of the different brands (Alexandrou *et al.* 2006). On the other hand, the nature of the material seemed to have a greater impact than the cross-sectional configuration on the fatigue behaviour under bending as well as NiTi continued to perform better than SS for instruments of same design (see Fig. 2). At low levels of alternating stress (HCF region), the actual strains and the difference in the strain value between the two materials are also small. That may explain the decreased relative importance of cross-sectional configuration in the HCF property of the rotary instruments. When the displacement is less than a certain value, the model will be in the infinite life region for all models. In this numerical analysis, the same displacement was applied to all models, which means that the surface strain amplitude would be similar for SS versus NiTi instrument. The actual strain amplitude sustained by the instrument is 'masked' by the (elastic modulus of the) material. A high value of the alternating strain would lead to a rapidly decreasing life, that is the LCF region (Stephens *et al.* 1980, Cheung & Darvell 2007a). Thus, in the context of rotary instruments, examination of the fatigue behaviour should be based on the strain value (i.e. unit amount of deformation, be it torsional or flexural). The design of the instrument should also be taken into account, as it is an important determinant of stress concentration (Xu & Zheng 2006) as well as the fatigue lifetime. On the other hand, the operating strain amplitude sustained by the instrument will be confounded by the elastic modulus of the material in the clinical situation. For instance, rotary files made of SS will tend to exert a high reaction (restoring) force on the outer curve of the canal owing to its high modulus of electricity, thus leading to rapid removal of dentine there, reducing the effective curvature as soon as they start to rotate.

Several methods had been proposed to prevent instrument fracture in the clinic (Peter & Fiore 2007). Meanwhile, careful prediction of the fatigue lifetime of rotary files would be useful for the clinicians to avoid premature failure of the instrument (especially when curved root canals are concerned, or where 'autoreverse' or reciprocating motion is used). To simulate the true loading conditions encountered in the clinical situation, a combination of different loading and boundary conditions should be considered, such as the influence of a single overload (e.g. in the case of 'taper lock' (Park *et al.* 2010), or at times when the autoreverse function is activated), as well as the effect of a pre-existing (micro-)crack or surface discontinuity. The finite element model is a useful method to determine the relative importance of various factors for a more reliable prediction, and subsequent verification in actual experimentation, of their effect on the fatigue behaviour.

Conclusions

In summary, a simulated numerical approach was formulated for bending fatigue lifetime prediction for rotary instruments. Bending fatigue behaviour was affected by the material property and the cross-sectional configuration of the instrument. This numerical method would be useful for dentist to predict and prevent premature fatigue fracture of endodontic files.

Acknowledgements

This work was supported by the Beijing Municipal Natural Science Foundation (2082010) and the National Natural Science Foundation of China (No. 51041004).

References

Alexandrou GB, Chrissafis K, Vasiliadis LP, Pavlidou E, Polychroniadis EK (2006) SEM observations and differential scanning calorimetric studies of new and sterilized nickel-titanium rotary endodontic instruments. *Journal of Endodontics* **32**, 675–9.

Anderson ME, Price JWH, Parashos P (2007) Fracture resistance of electropolished rotary nickel-titanium endodontic instruments. *Journal of Endodontics* **33**, 1212–6.

ASM International (1996). ASM handbook, vol. **19**: Fatigue and Fracture.

Bannantine JA, Comer JJ, Handrock JL (1989) *Fundamentals of Metal Fatigue Analysis*. Upper Saddle River: Prentice Hall, 38.

Berutti E, Chiandussi G, Gaviglio I, Ibba A (2003) Comparative analysis of torsional and bending stresses in two mathematical model of nickel-titanium rotary instruments: Protaper versus Profile. *Journal of Endodontics* **29**, 15–9.

Best S, Watson P, Pillian R, Kulkarni GGK, Yared G (2004) Torsional fatigue and endurance limit of a size 30 .06 ProFile rotary instrument. *International Endodontic Journal* **37**, 370–3.

Browell R, Hancq A (2006) Calculating and displaying fatigue results. *ANSYS Inc.*, 2.

Bui TB, Mitchell JC, Baumgartner JC (2008) Effect of electropolishing ProFile nickel-titanium rotary instruments on cyclic fatigue resistance, torsional resistance and cutting efficiency. *Journal of Endodontics* **34**, 190–3.

Cheung GSP (2009) Instrument fracture: mechanisms, removal of fragments, and clinical outcomes. *Endodontic Topics* **16**, 1–26.

Cheung GSP, Darvell BW (2007a) Fatigue testing of a NiTi rotary instrument. Part 1: strain-life relationship. *International Endodontic Journal* **40**, 612–8.

Cheung GSP, Darvell BW (2007b) Low-cycle fatigue of NiTi rotary instruments of various cross-sectional shapes. *International Endodontic Journal* **40**, 626–32.

Cheung GSP, Shen Y, Darvell BW (2007a) Does electropolishing improve the low-cycle fatigue behaviour of a NiTi rotary instrument in hypochlorite? *Journal of Endodontics* **33**, 1217–21.

Cheung GSP, Shen Y, Darvell BW (2007b) Effect of environment on low-cycle fatigue of a nickel-titanium instrument. *Journal of Endodontics* **33**, 1433–7.

Gambarini G (2001) Cyclic fatigue of nickel-titanium rotary instruments after clinical use with low- and high-torque endodontic motors. *Journal of Endodontics* **27**, 772–4.

Kim HC, Cheung GS, Lee CJ, Kim BM, Park JK, Kan SI (2008) Comparison of forces generated during root canal shaping and residual stresses of three nickel–titanium rotary files by using a three-dimensional finite-element analysis. *Journal of Endodontics* **34**, 743–7.

Lopes HP, Moreira EJL, Elias CN, Almeida R, Neves MS (2007) Cyclic fatigue of Protaper instruments. *Journal of Endodontics* **33**, 55–7.

Martín B, Zelada G, Varela P *et al.* (2003) Factors influencing the fracture of nickel-titanium rotary instruments. *International Endodontic Journal* **36**, 262–6.

Park SY, Cheung GSP, Yum J, Hur B, Park JK, Kim HC (2010) Dynamic torsional resistance of nickel-titanium rotary instruments. *Journal of Endodontics* **36**, 1000–4.

Peter M, Fiore D (2007) A dozen ways to prevent nickel-titanium rotary instrument fracture. *Journal of American Dental Association* **138**, 196–201.

Pruett JP, Clement DJ, Carnes DL Jr (1997) Cyclic fatigue testing of nickel-titanium endodontic instruments. *Journal of Endodontics* **23**, 77–85.

Sattapan B, Nervo GJ, Palamara JE, Messer HH (2000) Defects in rotary nickel-titanium files after clinical use. *Journal of Endodontics* **26**, 161–5.

Shen Y, Cheung GSP, Bian Z, Peng B (2006) Comparison of defects in ProFile and ProTaper Systems after use. *Journal of Endodontics* **32**, 61–5.

Spanaki-Voreadi AP, Kerezoudis NP, Zinelis S (2006) Failure mechanism of ProTaper NiTi rotary instruments during clinical use: fractographic analysis. *International Endodontic Journal* **39**, 171–8.

Stephens RI, Fatemi A, Stephens RR, Fuchs HO (1980) *Metal Fatigue in Engineering*, 2nd edn. New York: John Wiley & Sons, 237.

Xu XJ, Zheng YF (2006) Comparative study of torsional and bending properties for six models of nickel-titanium root canal instruments with different cross-sections. *Journal of Endodontics* **32**, 372–5.

Yao JH, Schwartz SA, Beeson YJ (2006) Cyclic fatigue of three types of rotary nickel-titanium files in a dynamic model. *Journal of Endodontics* **32**, 55–7.