JOURNAL OF ENDODONTICS
Copyright © 2002 by The American Association of Endodontists

Printed in U.S.A.
VOL. 28, NO. 11, NOVEMBER 2002

Fatigue Resistance of Engine-Driven Rotary Nickel-Titanium Endodontic Instruments

Marta Chaves Craveiro de Melo, MSc, Maria Guiomar de Azevedo Bahia, MSc, and Vicente Tadeu Lopes Buono, Dr Eng

A comparative study of the fatigue resistance of engine-driven nickel-titanium endodontic instruments was performed, aiming to access the influence of the cutting flute design and of the size of the files that reach the working length in curved canal shaping. Geometrical conditions similar to those found in practice were used. Series 29 #5 ProFile, together with #6 and #8 Quantec instruments, were tested in artificial canals with a 45-degree angle of curvature and 5-mm radius of curvature. It was observed that the size of the instrument, which determines the maximum strain amplitude during cyclic deformation, is the most important factor controlling fatigue resistance. The effect of heat sterilization on the fatigue resistance of the instruments was also examined. The results obtained indicate that the application of five sterilization procedures in dry heat increases the average number of cycles to failure of unused instruments by approximately 70%.

The concepts of cleaning and shaping of the root canal system (RCS) established by Schilder (1) make up, together with tridimensional obturation, the basis of endodontic therapy. For straight root canals, the stages of cleaning and shaping are relatively simple procedures, but the preparation of curved root canals may lead to ledging, perforation, or even instrument separation. Generally, these procedure failures are caused by the trend of the endodontic instrument to return to its original straight form when inserted into a curved root canal, due to the rigidity of the materials used for its manufacturing. Previously the preparation of root canals was carried out with carbon steel reamers, which in addition to their low flexibility had low resistance to corrosion. The corrosion problems were solved with the use of stainless steel instruments (2), but the elasticity modulus of these materials is still relatively high, and the occurrence of failures during instrumentation of curved root canals continued to depend exclusively on the expertise of the endodontist (3). In 1988, Walia et al. (4) introduced a new material for the manufacturing of endodontic instruments: the nickel-titanium orthodontic wire. The nickel-titanium alloys, with an approximately equiatomic composition, have in addition to high resistance to corrosion and excellent biocompatibility some special features: the shape memory effect (SME) and superelasticity (SE). The SME occurs in specific conditions in which the metal is deformed at a certain temperature in an apparently permanent way, but it recovers its original form when moderately heated. The SE is a particular case of the SME in which the shape recovery temperature is lower than the temperature of deformation. This means that shape recovery happens immediately after deformation interruption and load withdrawal. The term superelasticity is related to the fact that the recoverable strain obtained is much higher than that which may develop in the elastic strain regimen of metals. Both the SME and the SE are associated with the occurrence of a phase transformation in the solid state that has special characteristics: the martensitic transformation, which may be induced by the application of stress and reversed by moderate heating of the material (5).

The manufacturing of endodontic instruments using superelastic nickel-titanium (Ni-Ti) alloys has provided an important development in the techniques of cleaning and shaping of the RCS. The high flexibility associated with the SE allows the use of this material in engine-driven rotary instruments for the preparation of curved root canals. The main advantage of this new technique is the increased efficacy for endodontic treatment. However, despite the evident advantages of the new technique, Ni-Ti rotary instruments may undergo failure by fatigue when used in curved canals due to the tension/compression cycles to which they are subjected when flexed in the region of maximum curvature of the canals (6). The fatigue failure occurs unexpectedly, without any sign of previous permanent deformation; and visual inspection, therefore, is not an adequate method for evaluation of the useful life of these instruments. In fact, there are no test protocols that establish minimum standards regarding their fatigue resistance, which could guide endodontists on their use in clinical practice. Additional studies are necessary to improve the understanding of the criteria that may be used to evaluate the reuse conditions of Ni-Ti engine-driven rotary instruments. Moreover, sterilization of endodontic instruments either for new files or for their reuse involves repeated exposure to heating/cooling cycles. The effect of these thermal cycles on the properties of Ni-Ti instruments has been investigated by several authors (7–10), but results are contradictory.

The objective of this study was to evaluate the influence on fatigue resistance of the design of the cutting flutes and the size of Ni-Ti engine-driven rotary endodontic instruments by using geometrical conditions similar to those found in curved canal shaping.

TABLE 1. NCF of nonsterilized instruments

Instrument	NCF Descriptive Measurements					p	Conclusion
	Minimum	P_{25}	Median	P_{75}	Maximum		
#5 ProFile	2.060	2.251	2.321	2.390	2.528	<0.001	$P_5=Q_6>Q_8$
#6 Quantec	2.158	2.238	2.294	2.434	2.561		
#8 Quantec	1.104	1.168	1.194	1.246	1.300		

The probability significance (p) refers to the Kruskal-Wallis test (11).
P_5 = #5 ProFile; Q_6 = #6 Quantec; Q_8 = #8 Quantec.

Three types of files from two different manufacturers were selected, having as criteria the geometrical characteristics mentioned above, and the fact that in the methodologies proposed by the manufacturers these three instruments are the first to reach the total working length, at which time they are subjected to cyclic deformation during the preparation of curved canals. The effect of multiple sterilizations by dry heat on fatigue resistance of these instruments, in the same simulated working conditions, was also analyzed.

MATERIALS AND METHODS

The instruments evaluated were #5 ProFile Series 29 0.04 taper (Tulsa Dental Products, Tulsa, OK), #6 Quantec 0.04 taper and #8 Quantec .06 taper files (Tycon Inc., Chattanooga, TN), whose differences in the cutting flutes design are well known. The #5 ProFile 0.04 taper and #8 Quantec 0.06 taper files were chosen because they have different sizes and constitute the instruments of greatest size proposed by the respective techniques to be used to working length. Because these two files have different tapers, the #6 Quantec 0.04 taper was also selected so that a comparison could be made among files of different cutting flutes design and same taper. All instruments used in this work were purchased from the usual suppliers, withdrawn from sealed boxes, randomly selected, and then sequentially numbered for reference. The instruments used to evaluate the sterilization effect were selected in the same way, packed in metal boxes, and placed into a sterilizer previously heated at 170°C, where they were kept for 1 h. After the sterilizer was turned off, the instruments remained inside it for approximately 1 h until they reached room temperature. This procedure was applied once for #5 ProFile and five times for #5 ProFile, #6 and #8 Quantec files.

The files were subjected to fatigue tests (10 files for each condition) using a fixation system for the driving equipment and an artificial canal similar to that used by Pruett et al. (6), with the instrument rotating freely inside the artificial canal. The handpiece was fixed on a steel stand with the help of two brass brackets, built in such way as to house the two driving systems used, Tulsa for ProFile files and Tycon for Quantec files. A steel bracket was made for fixation and alignment of the artificial canal. To construct the artificial canals, stainless steel needles, with 1.6 mm of external diameter and 40-mm long, were bent with the help of a gauge to provide the desired radius and angle of curvature. After being bent, the needles were cut to keep straight sections of approximately 4.0 mm before and 1.5 mm after the curvature. Measurements of the radius and the angle of curvature of the artificial canals, according to the method proposed by Pruett et al. (6), as well as the length of the straight sections were made with a profile projector (Mitutoyo, Japan).

To carry out the fatigue tests, the instruments were positioned in such a way that they kept approximately 1 mm of their final length outside the artificial canal, and therefore were visible to the operator. In this way, the maximum curvature region was located at approximately 4.5 mm from the tip of the files. The testing time was registered with a digital chronometer, started at the beginning of the test and stopped at the moment the operator detected instrument separation by observing the displacement of the tip protruding from the artificial canal. The rotation speeds were selected considering, within the range recommended by the manufacturers, those available for the driving systems nearest to each other: 315 rpm for #5 ProFile files and 340 rpm for #6 and #8 Quantec files. The friction of the files with the canal walls was minimized with the use of RC-Prep (Premier, Norristown, PA) as lubricant.

The geometry of the artificial canal was chosen based on preliminary tests, in which the use of a canal having a 5 mm-curvature radius and 45-degree curvature angle gave the best results in terms of repeatability. The parameter used in comparing the behavior of file fatigue was the number of cycles to failure (NCF) determined as the product of the rotation speed used and the test time duration.

The instruments fractured in the fatigue tests were inspected under a stereomicroscope (Wild M8, Germany) in magnifications up to ×50 using a fixation device that allowed them to rotate around their main axis, either in a horizontal position or inclined at 60 degrees. The fracture surfaces were analyzed by scanning electron microscopy (SEM) (Jeol JSM 5410, Japan) with the purpose of determining the characteristics of the fracture process for the test conditions. Three fractured instruments from each group, randomly selected, were prepared for Vickers microhardness tests, involving the following stages: cold mounting, fine grinding, and diamond polishing. The specimens were then submitted to microhardness testing (10 measurements per group of 3 instruments) in a Durimet 2 (Leitz, Germany) apparatus, using a load of 1.961 N.

RESULTS

The results related to fatigue resistance of the investigated instruments, expressed as the NCF are shown in Table 1. The influence of the design of the cutting flutes and the instrument size was evaluated by means of the Kruskal-Wallis test (11), applied to the NCF values determined in the fatigue testing of nonsterilized files. It can be observed that the mean number of cycles to failure of #5 ProFile files does not significantly differ from #6 Quantec files, with both presenting considerably higher values (almost twice) than those observed for #8 Quantec files.

The effect of sterilization, applied once to #5 ProFile instruments and five times to #5 Profile and #6 and #8 Quantec instruments, was analyzed according to the same statistical technique. The results are shown in Table 2. Figure 1 summarizes the results obtained for nonsterilized and sterilized files, in terms of the average NCF values. It shows that there was no appreciable variation in the mean number of cycles to failure for #5 ProFile instruments sterilized in only one procedure. However, when these instruments were subjected to five sterilization procedures, there

TABLE 2. NCF of sterilized and nonsterilized instruments

Instrument	Sterilization	NCF descriptive measurements					p	Conclusion
		Minimum	P_{25}	Median	P_{75}	Maximum		
#5 ProFile	None	2.060	2.251	2.321	2.390	2.528		
	1 time	2.225	2.293	2.379	2.465	2.671	<0.001	$S_0=S_1<S_5$
	5 times	3.612	3.818	3.937	4.120	4.227		
#6 Quantec	None	2.158	2.238	2.294	2.434	2.561		
	5 times	3.693	3.784	3.856	4.090	4.139	<0.001	$S_0<S_5$
#8 Quantec	None	1.104	1.168	1.196	1.246	1.300		
	5 times	1.966	2.030	2.101	2.205	2.302	<0.001	$S_0<S_5$

The probability significance (p) refers to the Kruskal-Wallis test (11).
S_0 = nonsterilized; S_1 = sterilized 1 time; S_5 = sterilized 5 times.

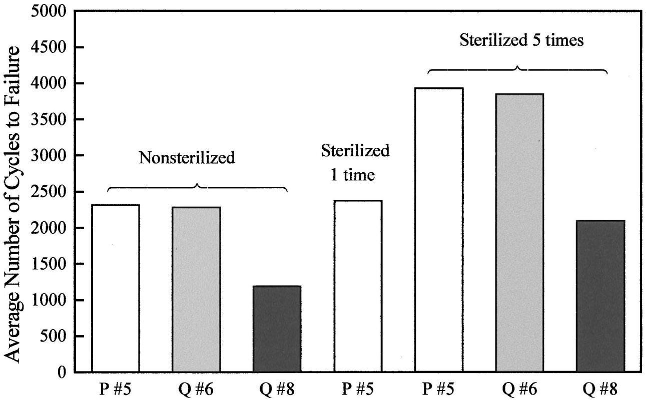

FIG. 1. Average values of the number of cycles to failure of nonsterilized and sterilized instruments.

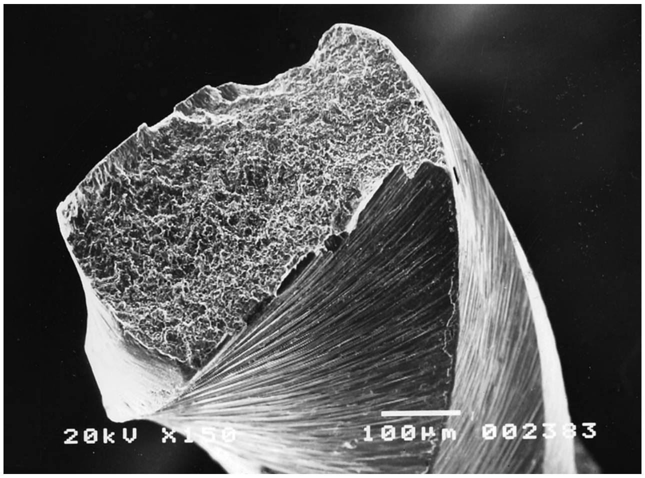

FIG. 2. Fracture surface of a #8 Quantec file, showing smooth regions of nucleation and slow crack propagation at the periphery and a large central fibrous area (original magnification ×150).

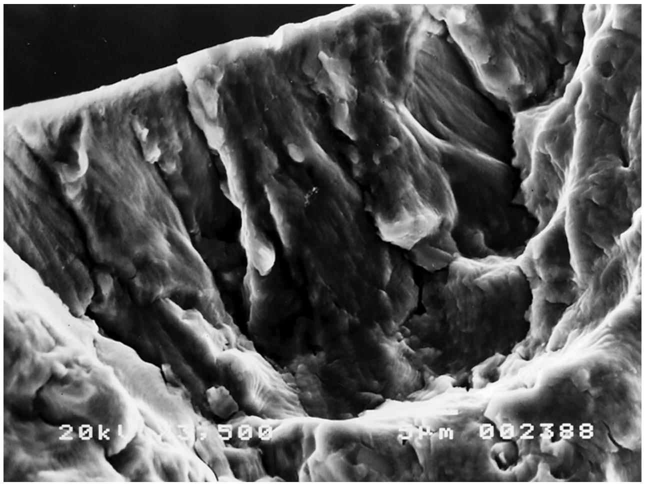

FIG. 3. Region of nucleation and slow crack propagation in the fractured surface of a #8 Quantec file showing multiple cracks (original magnification ×3500).

was an increase of approximately 70% of this parameter. The same was true for #6 and #8 Quantec files, which had increases of 68% and 76%, respectively, in the mean number of cycles to failure after five sterilization procedures.

The examination of the fatigue-tested instruments showed that all files fractured without geometric distortions that could be associated with fracture by torsional overloading. The fracture surfaces of the instruments of different design and size were similar. In fact, no significant differences were found between the nonsterilized instruments and those subjected to one or five sterilization procedures. The appearance of the fracture surfaces, assessed by SEM, indicates that the breakage of the analyzed instruments was due to fatigue. The main characteristics were presence of small areas of nucleation and slow crack propagation, which are called smooth regions, peripherally to the cross section, and large central fibrous areas, associated to final ductile breakage (Fig. 2). Some details of the fracture surfaces, like the nucleation of several cracks and the presence of fatigue striations are shown in Figs. 3 and 4.

The statistical analysis of the results obtained in the Vickers microhardness measurements are shown in Table 3. It can be observed that according to the Mann-Whitney *U* test (11) there is little variation in the mean values of this parameter for the files due to their design and size and an increase of approximately 8% in the mean values after five sterilization procedures.

DISCUSSION

The fatigue behavior of nonsterilized #5 ProFile and #6 and #8 Quantec files observed in this study is in accordance with the pattern reported by Pruett et al. (6), Serene et al. (7), and Haikel et al. (12), in which the largest instruments were more susceptible to fatigue failure. The results also show that the design of the cutting flutes does not influence the fatigue resistance of instruments of the same size, #5 ProFile and #6 Quantec files, which have the same behavior. On the other hand, the instrument size has a strong

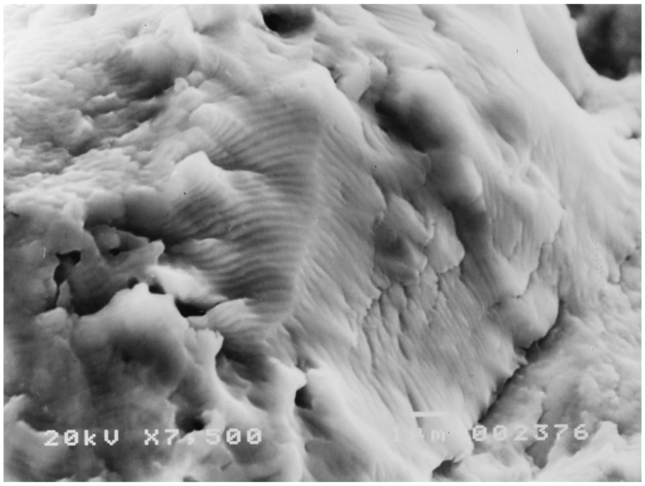

FIG. 4. Fatigue striations in the smooth region of the fractured surface of a #8 Quantec file (original magnification ×7500).

influence on its performance, because the average NCF of the files of smaller size, #5 ProFile and #6 Quantec, is almost twice that of #8 Quantec files. This leads us to the manufacturer's recommendation of using #8 Quantec file up to the working length. When opting for the use of the recommended technique, the difference of behavior between #6 and #8 Quantec in terms of NCF should be taken into consideration. If the two files were to be used at the same length and #8 Quantec file had half of the NCF compared with #6 file, then the largest size instrument should not be used the same number of times as the smaller size but rather be discarded earlier to prevent fatigue failure.

The ADA specification no. 28 evaluates instrument resistance through the determination of the values for maximum torque and maximum angular deflection to fracture. Maximum angular deflection values stipulated by this specification decrease with the increase of instrument gauge. Several authors have compared fracture resistance of Ni-Ti instruments using as a parameter the maximum angular deflection measurements stipulated by this specification. The reported results are, however, controversial; some works show an increase of the maximum angular deflection with the increase of the size of the instruments (13, 14), whereas other studies had both an increase and decrease of this measurement, reaching no conclusive results (15–18). It is important to observe that the maximum torque and the maximum angular deflection do not reflect adequately the mechanical behavior of the material, because they are parameters dependent on the instrument dimensions. On the other hand, the fatigue resistance is under the direct influence of the stress required for the beginning of permanent deformation, i.e. the material yield point, which determines the ease of the nucleation of fatigue cracks. Therefore, there is no way to correlate the results mentioned above with the fatigue resistance measurements carried out in this work.

The fact that #5 ProFile and #6 Quantec files fracture after a number of cycles significantly higher than that of #8 Quantec files may be related to two factors: the first, and the most important, is that the tensile stress on the external surface of the instrument increases in the maximum curvature region, for the same radius of curvature, as the size of the instrument increases. Another factor to be considered, specific to the methodology used, is the greater relaxation of the smaller instruments inside the artificial canal, resulting in their less effective curvature during the tests. These two factors make the larger instruments subjected to greater tensile stress per cycle, which results in their breakage in a fewer number of cycles.

The fatigue behavior of the files subjected to five sterilization procedures, which points to a substantial improvement of fatigue resistance, taken together with the results of the Vickers microhardness tests presented in Table 3, supports the suggestion by Serene et al. (7) that sterilization increases Ni-Ti rotary instruments fatigue life through the increase of hardness and torsional resistance of the material. This correlation is not clearly established in the works of other authors (8, 9, 15). However, considering that the difficulty of nucleation and propagation of fatigue cracks is directly associated with the mechanical strength of the material, the increase of instrument fatigue resistance found in this work after five sterilization procedures may be a direct consequence of the observed increase in hardness.

Because Ni-Ti engine-driven instruments need activation to a predetermined speed before their insertion into the root canal, the test model used, which permits the instrument to rotate freely without its tip being fixed, is more appropriate than the ADA specification no. 28. However, the test used in this work departs from clinical practice by at least two aspects, which deserve consideration. First, in the experiments performed, the files rotated statically in the artificial canal, without incorporating the in and out movement proposed for RCS preparation with these instruments. In other words, maximum deformation always occurred in the same region of the instrument, at the segment located at the maximum curvature of the artificial canal. The in and out movement used in clinical practice makes the segment of the file subjected to maximum fatigue vary continuously, which may increase the useful life of the instruments relative to the results presented in this work. Another important aspect to consider is the use of sodium hypochlorite as an irrigant during RCS preparation, because some studies have shown that Ni-Ti alloys exhibit a tendency to corrosion under simulated clinical conditions in the

TABLE 3. Vickers microhardness (MHV) of the analyzed instruments

Instrument	Sterilization	MHV descriptive measurements					p	Conclusion
		Minimum	P_{25}	Median	P_{75}	Maximum		
#5 ProFile	None	319	341	348	352	360		
	1 time	330	332	338	347	352	<0.001	$S_0=S_1<S_5$
	5 times	353	366	367	377	391		
#6 Quantec	None	323	329	340	357	362		
	5 times	334	354	362	368	371	0.009	$S_0<S_5$
#8 Quantec	None	317	330	342	352	371		
	5 times	343	358	371	380	388	0.002	$S_0<S_5$

The probability significance (p) refers to the Mann-Whitney *U* test (11).
S_0 = nonsterilized; S_1 = sterilized 1 time; S_5 = sterilized 5 times.

presence of this compound (19, 20). Corrosion may cause the loss of material mass, favoring the fracture of endodontic instruments. Therefore, the number of cycles to failure found in this study, in which the instruments did not come in contact with sodium hypochlorite, may be reduced in clinical practice due to the corrosive effect of this compound.

This work was partially supported by Fundacao de Amparo a Pesquisa do Estado de Minas Gerais, FAPEMIG, Belo Horizonte, MG, Brazil.

Drs. Chaves Craveiro de Melo and Guiomar de Azevedo Bahia are affiliated with the Faculty of Dentistry, and Dr. Lopes Buono is affiliated with the Department of Metallurgical and Materials Engineering, Universidade Federal de Minas Gerais, Belo Horizonte, MG, Brazil. Address requests for reprints to Prof. Dr. Vicente T.L. Buono, Departamento de Engenharia Metalurgica e de Materiais, Escola de Engenharia da UFMG, Rua Espirito Santo, 35/206, 30160-030 Belo Horizonte, MG, Brazil

References

1. Schilder H. Cleaning and shaping the root canal. Dent Clin North Am 1974;18:269–96.
2. Scott PA, Lautenschlager EP, Greener EM. The effects of corrosion on two stainless steel files. J Endodon 1994;16:210.
3. Alodeh MHA, Doller R, Dummer PMH. Shaping of simulated root canals in resin blocks using the step-back technique with K-files manipulated in a simple in/out motion. Int Endod J 1989;22:107–17.
4. Walia H, Brantley WA, Gerstein H. An initial investigation of the bending and torsional properties of Nitinol root canal files. J Endodon 1988;14:346–51.
5. Saburi T. Ti-Ni shape memory alloys. In: Otsuka K, Wayman CM, eds. Shape memory materials. Cambridge: Cambridge University Press, 1998:49–96.
6. Pruett JP, Clement DJ, Carnes DL Jr. Cyclic fatigue testing of Ni-Ti endodontic instruments. J Endodon 1997;23:77–85.
7. Serene TP, Adams JD, Saxena A. Nickel-titanium instruments: applications in endodontics. St. Louis: Ishiyaku EuroAmerica, Inc., 1995:112.
8. Silvaggio J, Hicks ML. Effect of heat sterilization on the torsional properties of rotary nickel-titanium files. J Endodon 1997;23:731–4.
9. Mize SB, Clement DJ, Pruett JP, Carnes DL. Effect of sterilization on cyclic fatigue of rotary nickel-titanium endodontic instruments. J Endodon 1998;12:843–7.
10. Svec TA, Powers JM. Effects of simulated clinical conditions on nickel-titanium rotary files. J Endodon 1999;25:759–60.
11. Snedecor GW, Cochcran WG. Statistical methods. Ames: Iowa State University Press, 1989.
12. Haikel Y, Serfaty R, Bateman G, Senger B, Allemann C. Dynamic and cyclic fatigue of engine-driven rotary nickel-titanium endodontic instruments. J Endodon 1999;25:434–40.
13. Camps JJ, Pertot WJ. Torsional and stiffness properties of Canal Master U stainless steel and nickel titanium instruments. J Endodon 1994; 20:395–8.
14. Wolcott J, Himel VT. Torsional properties of nickel-titanium versus stainless steel endodontic files. J Endodon 1997;23:217–20.
15. Canalda-Sahli C, Brau-Aguadè E, Beràstegui-Jimeno E. A comparison of bending and torsional properties of K-files manufactured with different metallic alloys. Int Endod J 1996;29:185–9.
16. Rowan MB, Nicholls J, Steiner J. Torsional properties of stainless steel and nickel titanium endodontic files. J Endodon 1996;22:341–5.
17. Marsicovetere ES, Burges JO, Clement DJ, del Rio CE. Torsional testing of the Lightspeed nickel titanium system. J Endodon 1997;23:141–5.
18. Yared GM, Bou Dagher FE, Machtou P. Cyclic fatigue of ProFile rotary instruments after clinical use. Int Endod J 2000;33:204–7.
19. Sarkar NK, Redmond W, Schwaninger B, Goldberg AJ. The chloride corrosion behaviour of four orthodontic wires. J Oral Rehabil 1983;10:121–8.
20. Busslinger A, Sener B, Barbakow F. Effects of sodium hypochlorite on nickel-titanium Lightspeed instruments. Int Endod J 1998;31:290–4.