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Influence of the shape of artificial canals on the fatigue resistance of NiTi rotary instruments

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Abstract

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Aim To investigate the influence of the trajectory of NiTi rotary instruments on the outcome of cyclic fatigue tests.

Methodology Ten ProFile and M*two* instruments tip size 20, taper 0.06 and tip size 25, taper 0.06 were tested in two simulated root canals with an angle of curvature of 60° and radius of curvature of 5 mm but with different shape. Geometrical analysis of the angle and radius of the curvature that each instrument followed inside the two different artificial canals was performed on digital images. The instruments were then rotated until fracture at a constant speed of 300 rpm to calculate the number of cycles to failure (NCF) and the length of the fractured fragment. Mean values were calculated and analysed using two different multivariate linear regression models and an independent sample *t*-test.

Results The shape of the artificial root canal used in cyclic fatigue studies influenced the trajectory of the instrument. This difference is reflected by the NCF measured for the same instrument in the different artificial root canals and by the impact of the type of canal on both the NCF (St.β = 0.514) and fragment length (St.β = −0.920).

Conclusions Small variations in the geometrical parameters of the curvature of an instrument subjected to flexural fatigue could have a significant influence on the results of fatigue tests.

Keywords: angle of curvature, artificial canal, cyclic fatigue test, radius of curvature.

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Introduction

Fracture of instruments used in rotary motion occurs in two different ways: fracture due to torsion and fracture due to flexural fatigue (Serene *et al.* 1995, Sattapan *et al.* 2000, Ullmann & Peters 2005). Torsional fracture occurs when an instrument tip or another part of the instrument is locked in a canal whilst the shank continues to rotate. When the torque exerted by the hand-piece exceeds the elastic limit of the metal, fracture of the tip becomes inevitable (Peters 2004, Parashos & Messer 2006). Instruments fractured because of torsional loads often carry specific signs such as plastic deformation (Sattapan *et al.* 2000).

Fracture due to fatigue through flexure occurs because of metal fatigue. The instrument does not bind in the canal but it rotates freely in a curvature, generating tension/compression cycles at the point of maximum flexure until the fracture occurs (Pruett *et al.* 1997, Haikel *et al.* 1999). As an instrument is held in a static position and continues to rotate, one half of the instrument shaft on the outside of the curve is in tension, whilst the half of the shaft on the inside of the curve is in compression. This repeated tension–compression cycle, caused by rotation within curved canals, increases cyclic fatigue of the instrument over time and may be an important factor in instrument fracture (Pruett *et al.* 1997).

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Resistance of rotary instruments to cyclic fatigue is affected by the angle and radius of canal curvature and the size and taper of the instrument. Increased severity in the angle and radius of the curves around which the instrument rotates decreases instrument lifespan (Pruett *et al.* 1997, Haikel *et al.* 1999, Grande *et al.* 2006). Instruments have been tested in canals having radii of 2 mm, 5 mm and 10 mm, with the conclusion that the smaller the radius, the shorter the life of the instrument when rotating (Pruett *et al.* 1997, Haikel *et al.* 1999, Grande *et al.* 2006). Similarly, several studies have shown that increased diameter at the point of maximum curvature of the instrument, which is determined by tip size and taper, reduces the time to fracture (Pruett *et al.* 1997, Haikel *et al.* 1999, Plotino *et al.* 2006, 2007). Only the study by Yared *et al.* (2000) did not support these findings. Ruddle (2002) has asserted that the position of the curvature of a canal is a factor in instrument safety, a point that was demonstrated in an earlier study (Malagnino *et al.* 1999). When the curvature is localized in a coronal portion of the root canal, the instrument is subjected to the maximum stress in the area in which its diameter is largest.

In nearly all studies reported in the endodontic literature, the rotating instrument was either confined in a glass or metal tube, in a grooved block-and-rod assembly or in a sloped metal block (Plotino *et al.* 2009); there has been no mention of the 'fit' of the instrument in the tube or groove. As the instrument is likely to be fitting loosely, the description of the radius of curvature in those studies is likely to be overstated; that is, the file was actually bent less severely than reported. Previous studies using cylindrical metallic tubes to test the cyclic fatigue life of NiTi rotary instruments reported that the tubes do not sufficiently constrain the shafts of the smaller instruments (Pruett *et al.* 1997, Mize *et al.* 1998, Yared *et al.* 1999, 2000).

The aim of the present study was to investigate the influence of the trajectory of NiTi rotary instruments on the outcome of cyclic fatigue tests. The null hypothesis tested was that there was no difference in the cyclic fatigue resistance of the same instrument tested in two artificial canals with the same radius and angle of curvature but with different shapes.

Materials and methods

Ten ProFile NiTi rotary instruments (Dentsply Maillefer, Ballaigues, Switzerland) tip size 20, 0.06 taper, ten ProFile instruments tip size 25, 0.06 taper, ten M*two* NiTi rotary instruments (Sweden & Martina, Padova, Italy) tip size 20, 0.06 taper and ten M*two* instruments tip size 25, 0.06 taper were selected.

Two simulated root canals with an angle of curvature of 60° and radius of curvature of 5 mm were constructed for each instrument size. The centre of the curvature was approximately 5 mm from the tip of the instrument, the curved segment of the canal was approximately 5 mm in length and the linear segment between the tip of the instrument and the end-point of the curvature was approximately 2.5 mm. The artificial canals with two different shapes were milled in stainless-steel blocks with a precision milling machine.

An artificial canal (A) was constructed with a tapered shape corresponding to the dimensions of the instruments tested (tip size and taper) (Fig. 1a), thus providing the instrument with a suitable trajectory. To ensure the accuracy of the size of each canal a copper duplicate of each instrument was milled increasing the original size of the instrument by 0.1 mm using a computer numerical control machining bench (Bridgeport VMC 760XP3; Hardinge Machine Tools Ltd., Leicester, UK). The copper duplicates were constructed according to the curvature parameters that were chosen for the study. With these negative moulds the artificial canals were made using a die-sinking electrical-discharge machining process (Agietron Hyperspark 3, AGIE Sa, Losone, Switzerland) in a stainless-steel block. The depth of each artificial canal was machined to the maximum diameter of the instrument +0.2 mm, allowing the instrument to rotate freely inside the artificial canal. The blocks were hardened through annealing.

A second artificial canal (B) was constructed with a tapered shape but with larger dimensions that did not match the instrument size and taper; the artificial canal was machined increasing the original size of the instrument by 0.3 mm (Fig. 1b).

Each artificial canal was mounted on a stainless-steel block that was connected to a frame to which a mobile plastic support for the hand-piece was also connected. The dental hand-piece was mounted upon a mobile device that allowed for precise and simple placement of each instrument inside the artificial canal, ensuring three-dimensional alignment and positioning of the instruments to the same depth. The artificial canal was covered with tempered glass to prevent the instruments from slipping out and to allow for observation of the instrument.

Geometrical analysis of the trajectory that each instrument followed inside the two different artificial

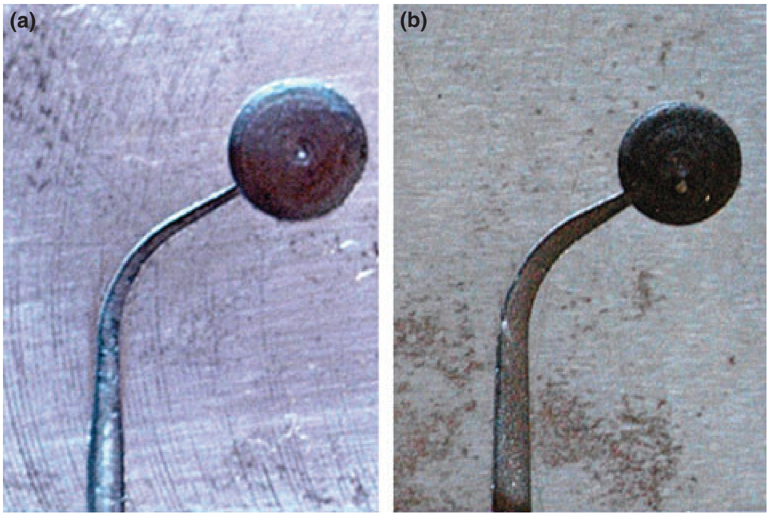

Figure 1 The artificial canals used in the present study. (a) canal A; (b) canal B.

canals was performed on digital images, determining two parameters: angle and radius of the curvature described by the instruments as measured by Pruett *et al.* (1997). A straight line (PQ) was drawn along the long axis of the coronal straight portion of the instrument. A second line (TS) was drawn along the long axis of the apical straight portion of the instrument. There was a point on each of these lines at which the instrument deviated to begin (Q) or end (S) the curvature. The curved portion of the instrument was represented by a segment of a circle (C) with tangents at these points. The most precise circumference that lied on the trajectory of the instrument was geometrically determined using the osculating circumference method (Gray 1997). The osculating circle of a curve at a given point is the circle that best approximate the curve at that point and it is unique. This method was chosen because the curvature followed by an instrument not constrained in a precise trajectory is not a circumference, but a plain curve with a different equation. In these cases, the above described is the most precise method to define a curvature by the parameters of radius and angle of a circumference. It is possible to determine the osculating circle passing through three points of a curve. The points that were chosen on the trajectory of the instruments were the beginning (Q) and the end (S) of the curve and a point B that was chosen as the centre of mass of the triangle resulting from the points Q, S and R that was the point in which the straight coronal and apical portions of the instrument met. The angle of curvature was defined as the number of degrees on the arc of the circle between the beginning and end-points of the curvature; the radius of the circle was defined as the radius of the canal curvature in millimetres (Fig. 2).

The calculation of the radius and angle of curvature determined by the osculating circumference method was repeated for each instrument analysed in the two

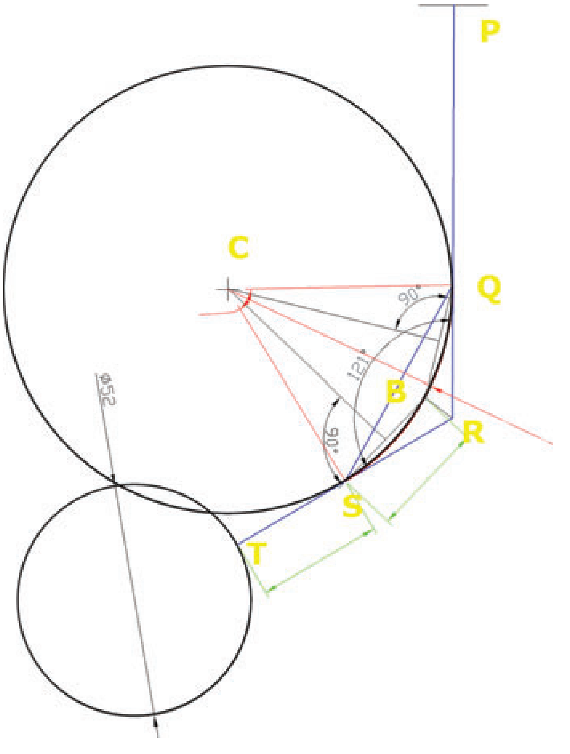

Figure 2 The osculating circumference method to determine the geometrical parameters of the trajectory of the instrument.

different artificial canals. Mean values were then calculated for each instrument size.

ProFile and M*two* instruments were then tested within the two different artificial canals. The instruments were rotated at a constant speed of 300 rpm using a 6:1 reduction hand-piece (Sirona Dental Systems GmbH, Bensheim, Germany) powered by a torque-controlled motor (Silver, VDW GmbH, Munich, Germany). To reduce the friction of the file as it contacted the artificial canal walls, high-flow synthetic oil designed for lubrication of mechanical parts (Super Oil, Singer, Elizabethport, NJ, USA) was applied. All instruments were rotated until fracture occurred. Fracture was easily detectable because the instruments were visible through the glass window. The time to fracture for each file was recorded visually with a 1/100 s chronometer, and the number of rotations was calculated to the nearest whole number. The time to fracture was multiplied by the number of rotations per minute to obtain the number of cycles to failure (NCF) for each instrument. Mean values were then calculated. The length of the fractured tip was also recorded for each instrument and the mean values were then calculated for each instrument type in each group.

Analysed data consisted of NCF and the length of the fractured tip for each instrument tested under the specified artificial canal, and the radius and angle of curvature curvature followed by the instruments in both the artificial root canals tested. The data were processed using SPSS software (SPSS, Oakbrook, IL, USA). Means and standard deviations (SD) were calculated. Two different multivariate linear regression models were performed to investigate the effects of the independent variables considered in the model (size of the instrument, type of the instrument, type of the artificial root canal) on the dependent variables analysed (NCF and fragment length). An independent sample *t*-test was used to analyse significant differences for the angle and radius of curvature measured between the two artificial root canals for each instrument tested. Significance was determined at the 95% confidence level.

Results

Mean values and SD of the radius and angle of curvature described by the instruments in the different artificial canals are displayed in Table 1.

Mean values ± SD expressed as NCF and the mean length of the fractured segment are displayed in Table 2.

In the first model, considering the NCF as dependent variable, the overall regression model was statistically significant ($F = 13.4$; $P = 0.000$; $R = 0.586$). Furthermore, amongst the independent variables canal type (A, B) and instrument size (20, 0.06; 25, 0.06) were statistically significant ($P < 0.05$), whilst the instrument type (M*two*, ProFile) was not ($P = 0.371$). The

Table 1 Mean values ± SD of the radius and angle of curvature described by the instruments in the different artificial canals and *P*-values (*t*-test between canal A and B)

ProFile size 20/0.06 taper	Angle (°)	Radius (mm)	M*two* size 20/0.06 taper	Angle (°)	Radius (mm)
Canal A	60 ± 0.1	4.9 ± 0.3	Canal A	60 ± 0.01	5 ± 0.1
Canal B	51 ± 0.1	5.7 ± 0.3	Canal B	55 ± 0.1	5.9 ± 0.2
ProFile size 25/0.06 taper	Angle (°)	Radius (mm)	M*two* size 25/0.06 taper	Angle (°)	Radius (mm)
Canal A	60 ± 0.1	5 ± 0.2	Canal A	60 ± 0.1	4.9 ± 0,3
Canal B	50 ± 0.1	6.6 ± 0.4	Canal B	54 ± 0.3	6 ± 0,4

Table 2 Mean ± SD expressed in number of cycles to failure (NCF) registered during the cyclic fatigue testing, mean length of the fragments ± SD registered for each group (in mm) and increase of the lifespan between the two groups

ProFile size 20/0.06 taper	NCF	mm	M*two* size 20/0.06 taper	NCF	mm
Canal A	605 ± 52	4.9 ± 0.4	Canal A	617 ± 73	5 ± 0.2
Canal B	677 ± 55	3.3 ± 0.4	Canal B	703 ± 61	3.5 ± 0.3
Difference*	10%		Difference*	12%	
ProFile size 25/0.06 taper	NCF	mm	M*two* size 25/0.06 taper	NCF	mm
Canal A	564 ± 63	4,9 ± 0.3	Canal A	566 ± 84	5.1 ± 0.3
Canal B	645 ± 75	3.1 ± 0.3	Canal B	659 ± 82	3,6 ± 0.3
Difference*	12.5%		Difference*	14%	

*Indicates an increase of the lifespan for canal B compared to canal A.

multivariate linear regression showed that canal type was the independent variable with the greatest impact in the model; canal B positively affected the NCF value (St.β = 0.514, $P < 0.000$) when compared with canal A, whilst an increasing in size negatively affected the outcome variable (St.β = −0.260, $P < 0.000$).

In the second model, considering the fragment length as dependent variable, the overall regression model was statistically significant ($F = 178.9$; $P = 0.000$; $R = 0.935$). Even considering the fragment length the variable with the greater impact in the model was the canal type, canal B negatively affected the length of the fragment (St.β = −0.920, $P < 0.000$) whilst size of the instrument was not statistically significant ($P = 0.844$) and type of instrument has a lower impact on the output variable (St.β = −0.179, $P < 0.000$).

For all the instruments tested a statistically significant difference was found between canal A and canal B for both angle and radius of curvature ($P < 0.000$).

Discussion

Clinically, NiTi rotary instruments are subjected to both torsional load and cyclic fatigue (Gambarini 2001, Ullmann & Peters 2005), and ongoing research aims to clarify the relative contributions of both factors to instrument separation (Peters 2004).

Both cyclic fatigue tests (Pruett *et al.* 1997, Haikel *et al.* 1999) and torsion tests (Camps & Pertot 1995, Yared 2004, Ullmann & Peters 2005) have been performed to investigate how these factors may influence the behaviour of NiTi rotary instruments *in vitro*. In addition, torsional properties of used instruments have been investigated (Yared *et al.* 2003, Yared 2004, Ullmann & Peters 2005) to analyse how the combination of these two factors may influence instrument failure.

The results of the present study showed that the shape of the artificial root canal used in cyclic fatigue studies influenced the trajectory of the instrument; for all the instrument tested both angle and radius of the curve statistically varied between canal A and B ($P < 0.000$). This difference is reflected by the number of cycles to failure measured for the same instrument in the different artificial root canals and in the high impact of the type of canal on both the NCF (St.β = 0.514) and fragment length (St.β = −0.920). The results of the present study showed a statistically significant increase in the number of cycles to failure when instruments were tested in an artificial canal that does not sufficiently restrict the instrument shaft (canal B). In this canal, the instrument would tend to regain its original straight shape, aligning into a trajectory of greater radius and reduced angle; that is, the file was actually bent less severely than reported.

The results of the present study confirmed that the size of the instrument at the point of maximum curvature influenced resistance to fracture for cyclic fatigue: bigger instruments are less resistant than smaller instruments. That is, NCF decreased as the diameter of the instrument increased (Pruett *et al.* 1997, Haikel *et al.* 1999, Grande *et al.* 2006, Plotino *et al.* 2006, 2007). This is due to the fact that when a curved root canal instrument rotates, any points within it in the segment subjected to the maximum stress, except those in the centre (neutral axis), are subjected to repeated tensile or compressive strains. The farther away from the central axis, the greater the imposed strain at that point (Craig 1997). This explains why instruments of a larger diameter are affected by fatigue more than smaller ones.

Analysis of the data regarding the length of the fractured segment revealed a statistically significant difference in the mean size between canal A and canal B for all of the instrument sizes. The centre of the curvature was constructed approximately 5 mm from the tip of the instrument for both canal A and canal B. Instruments subjected to cyclic fatigue fractured at the centre of the curvature or just below this point (Pruett *et al.* 1997, Fife *et al.* 2004). The results of the present study demonstrated that when the instruments were tested in a precise artificial root canal they followed precisely the trajectory established in the construction of the canal. In fact, in the present study instruments tested in canal A fractured at the established point of maximum stress, as expected. This confirms previous findings (Fife *et al.* 2004, Grande *et al.* 2006, Plotino *et al.* 2006, 2007). On the contrary, data demonstrated a significant decrease in the mean length of the fragments for instruments tested in canal B. This was due to the fact that instruments tested in canal B did not followed the trajectory established by parameters with which the artificial canal was constructed and consequently the point of maximum stress were the instrument fracture may vary.

Furthermore, considering the fragment length, there was a minor but statistically significant impact of the type of instrument on this variable (St.β = −0.179). This was because different instruments followed an unpredictable trajectory if the canal in which they were tested did not guide them in a precise trajectory.

As above mentioned, bending properties of different files may determine a different trajectory if the file is not constrained in a precise trajectory. If testing is completed for all different files at a given angle to ensure consistency, the bending properties of the different files determining different angles of curvature, thus bias the results and the comparisons. To limit these problems, Cheung & Darvell (2007a,b,c) constrained the instrument into a curvature using three stainless-steel pins. They used three smooth cylindrical pins of 2 mm diameter from a high hardness stainless steel mounted in acrylic shims, which were adjustable in the horizontal direction; the position of the pins determines the curvature of the instrument. A small V-shaped groove prepared on the lowest pin maintained the position of the tip of the instrument during rotation. The authors reported in detail on the effect of surface strain amplitude on fatigue failure using it as a different indicator of the stress on instruments instead of radius and angle of curvature. It has been reported in a three-point bending test of NiTi wires that such constraints will produce a curvature that is circular (Wick *et al.* 1995). The authors affirmed that although this cannot actually be true, the approximation should be reasonable. Unfortunately, NiTi endodontic files are tapered and with different cross-sectional design. The different bending properties of the different files and the different bending properties between the coronal and apical portion of the same file may determine a different trajectory between the pins, if the file is not constrained precisely.

The present study sought to overcome the limitations of some laboratory studies in terms of the model used for testing. The artificial canal was specifically designed for each instrument in terms of size and taper, giving it a precise trajectory. Cylindrical metallic tubes used in previous studies (Pruett *et al.* 1997, Mize *et al.* 1998, Yared *et al.* 1999, 2000, Melo *et al.* 2002) did not sufficiently restrict the instrument shaft, which would tend to regain its original straight shape, aligning into a trajectory of greater radius and reduced angle (Yared *et al.* 1999, 2000, Melo *et al.* 2002, Bahia & Buono 2005). The results of a previous study (Plotino *et al.* 2009b) reported that an artificial canal manufactured as described in the present to riproduce instrument size and taper seems to guarantee that different NiTi rotary instruments may follow a precise and repeatable trajectory in terms of radius and angle of curvature. On the contrary, if the artificial canal is not identical (in shape and size) to the instrument, its trajectory will not respond to the established parameters, thus having a reduced curvature during the test. The results of the present study demonstrated that the variation in the trajectory followed by the instruments in the artificial canals used to test fatigue resistance could influence the results of cyclic fatigue tests.

Conclusions

The null hypothesis tested in the present study has been rejected. Results of the present study reported that even small variations of the geometrical parameters of the curvature of an instrument subjected to flexural fatigue could determine a significant influence on the results of fatigue tests. The standardization of the parameters and devices used for cyclic fatigue testing of NiTi rotary instruments is lacking. A more precise regulation is required to obtain more consistent and comparable results in different studies.

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