The Effect of Robotic Cyclic Fatigue on the Torsional Properties of the K3 Ni-ti Rotary Files

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ABSTRACT

The purpose of this study is to compare torsional properties including torque levels and angle of rotation at separation between new and stressed Ni-Ti rotary instruments. The instruments will be stressed using a newly proposed robotic procedure.

Summary: During root canal treatment using the Ni-Ti rotary files a significant percentage of files are stressed nearly to their deformation limit with no visible signs of metal fatigue making them more vulnerable to separation (fracture) even during their first clinical use. The authors are proposing a more standardized robotic system stressing files just up to the yield point (maximum value at which deformation is still reversible) before separation testing, to provide more clinically relevant data to preset the electronic torque control motor.

Results: When comparing paired new and stressed instruments (Table), the results indicate that the torque and angle of rotation at the yield point and at separation of size 15 instruments were not significantly different at $p=0.05$. For all the other sizes, the angle of rotation at yield of stressed instruments was not significantly different from that of new instruments. However, the remaining three variables (angle of rotation at separation and torque at yield and separation) were significantly different between new and stressed files.

Discussion and Conclusions: Under the study conditions, it can be concluded that robotically stressed instruments gain in torsional flexibility, but their ability to tolerate torque stress (torque level at yield and separation) decrease when compared to new instruments.

During root canal treatment using the Ni-Ti rotary files with an electronic torque control motor, a significant percentage of files are stressed nearly to their deformation limit with no visible signs of metal fatigue making them more vulnerable to separation (fracture) even during their first clinical use. The value of resin blocks and extracted teeth in simulating clinical use is limited. The authors are proposing a more standardized robotic system stressing files just up to the yield point (maximum value at which deformation is still reversible) before separation testing, to provide more clinically relevant data to preset the electronic torque control motor. The purpose of this study is to compare torsional properties including torque levels and angle of rotation at separation between new and stressed Ni-Ti rotary instruments. The Nitinol nickel-titanium (NiTi) alloy has been introduced as an alternative to stainless steel, in order to overcome the stiffness of the stainless steel material (Laurichesse 1996). It is generally believed that engine-driven or manually used nickel-titanium instruments produce better prepared root canals than their stainless steel counterparts (Schäfer & Schlingemann, Thompson 2003). Clinically however, such instruments, and in particular the rotary types, have a higher risk of separation (Barbakow & Lutz 1997). Specifically, retrospective analysis of routinely discarded NiTi instruments indicated two distinct fracture mechanisms, namely, torsional (when the tip of the file is locked) and flexural separation (when the file is entering a curve) (Sattapan et al. 2000a).

According to ANSI/ADA Specification no. 28 (ANSI/ADA 1988), the torsional properties of endodontic instruments can be evaluated as torque and angle of rotation required to cause instrument separation. Sattapan et al. 2000 evaluated the torque at separation of Quantec Series 2000 rotary Ni-Ti instruments (Tycom Corp, Irvine, CA, USA). The instruments separated at torque values varying from 2.26 to 19.63 Nmm. The torque at separation of Lightspeed instruments (Lightspeed Technology, Inc., San Antonio, TX, USA) ranged from 1.96 to 41.96 Nmm (Hübscher 2003). The angle of rotation at separation varied from 637.2 to 1710° (Marsicovetere et al. 1996). Peters & Barbakow 2002 tested selected Ni-Ti ProFile 0.04 rotary instruments (Maillefer Dentsply, Ballaigues, Switzerland), the torque and angle of rotation at separation for sizes 15, 35 and 60 ranged from 3.59 to 31.68 Nmm and from 514.3° (size 60) to 614.1° (size 35), respectively.

MATERIALS AND METHODS

Evaluation of new instruments (Part 1)

Ni-Ti rotary files .06 Taper, K3 (triple edge K3 design) (Fig. 4) rotary instruments (SDS Sybron Endo, Anaheim, CA) in sizes 15-20-25-30-35-40, were evaluated. In Part I, 10 new instruments of each size were tested for torsional properties according to ANSI/ADA Specification no. 28. The torque value and angle of rotation at the yield point and at fracture were calculated for all instruments. In Part II, 10 new instruments were stressed in a standardized robotic system applying 10 cycles of angular rotation (value of the angle of rotation at the yield point obtained in Part I). Subsequently, the stressed instruments were tested for torsional properties similarly to the new instruments in Part I. Then the torsional characteristics of the new and old instruments were compared using the Duncan's multiple-range test to detect significant differences between paired sizes. The relation between size of instrument and torsional properties were subjected to regression analysis.

Apparatus and test

A calibrated digital torque metre memocouple (A-Tech Instruments Limited, Scarborough, Ontario, Canada) allowing measurement of torque with an accuracy of ±0.1 Nnm and angle of rotation with an accuracy of ±2° was used. Prior to testing, each instrument's handle will be removed with a suitable wire cutter at the point where the handle is attached to the instrument shaft (Fig. 5). The shaft end was clamped in a chuck connected to a reversible geared motor revolving at a speed of 2rpm (Aerotech, Pittsburgh, Pennsylvania, USA). This speed setting is applied according to the ANSI/ADA no. 28 regulation to allow adequate numbers of data recordings prior to separation. Speeds above 2rpm result in an earlier occurrence of the separation rendering the recording of the torque and angle of fracture difficult to accurately find on the graph tracing (Fig. 6).

Figure . Chart applicable to the K3 NiTi rotary instruments, where the torque level is recorded along with the angle of rotation.

Motor speed is set at 2rpm allowing a large number of recordings prior to separation (ANSI/ADA Regulation 28). Separation has occurred at a torque value of 50 g/cm and the angle of separation is of 3,451 degrees (red line). The pink line represents the average values of the recorded data. The initial linear section of the pink line corresponds to the reversible phase of deformation in which the increase in angular deflection is proportional to the increase in torque values. Beyond this linear pattern, angular deflection increases exponentially with the increasing torque indicating that the instrument deformation is in its irreversible phase. Yield strength was measured as the torque and angle of rotation defining the maximal levels at which instrument deformation is still reversible (green line). To determine the yield strength value, a line coinciding with the initial segment of the yellow line was drawn (blue line). The point at which the 2 lines separate indicates the yield strength value (50g/cm, 691 degrees).

A digital display amplifier controls the operation of the motor. Three millimetres of the tip of the instrument were clamped tightly in another chuck with brass jaws connected to the digital torque meter memocouple and to a computer for measurement recording using the LabView software (National Instruments, Austin, Texas, USA) (Fig. ??).

Once the tip of the instrument

is locked in the torque meter, the motor will initiate clockwise rotation applied at the shaft resulting in increasing levels of torque at the tip. Progressive torque levels (NTS) and angle of rotation (NAS) were recorded until file separation (Fig. 9).

A small detail: the jaws of the torque meter (Fig. ??) have to be made of soft copper in order to have a good and firm grip on the tip of the file, because this is where the torque will be recorded, and any slip from the file will result in a false reading. the jaws are to be changed frequently with every different group of files.

Statistical analysis

Analysis of variance were used to compare the torque (NTS) and angle of rotation (NAS) at fracture amongst the different sizes of the new instruments. Pair-wise comparisons using Duncan's multiple-range test were applied to detect significant differences between (among) sizes. The relation between size of instrument and torque at fracture were subjected to regression analysis. Significance was determined at the 95% confidence level.

Evaluation of used instruments (Part 2)

The yield strength of the new instruments were determined using the chart of the new K3 instruments obtained in Part 1. Twenty new .06 K3 new instruments in sizes 15-20-25-30-35-40 were individually prepared and mounted as per Part 1. The testing equipment was prepared such that the motor can be run in a clockwise as well as counter-clockwise fashion. The torque meter was programmed so that the instrument was subjected to a set angular rotation corresponding to the rotational angle of the yield strength (obtained in Part 1) in a clockwise fashion and then reversed to an angular deflection of zero degrees. This procedure was performed on each instrument 10 times simulating extreme clinical usage.

The instrument was rotated as per Part 1 to the point of separation. The values of the yield, torque (UTS) and angle of rotation (UAS) at fracture were recorded as previously described.

Statistical analysis

Analysis of variance was used to compare the yield, torque and angle of rotation at fracture amongst the different sizes of the used instruments. Pair-wise comparisons using Duncan's multiple-range test were performed to detect significant differences between used instruments of different sizes and differences between new and used instruments of the same size. The relationship between torque at fracture and size of instrument were determined with regression analysis. Significance was determined at the 95% confidence level.

RESULTS

The torsional properties including torque values and angle of rotation at the yield point and at separation for both new and stressed instruments are reported in Table ??.

When comparing paired new and stressed instruments (Table 2), the results indicate that the torque and angle of rotation at the yield point and at separation of size 15 instruments were not significantly different at p=0.05. For all the other sizes, the angle of rotation at yield of stressed instruments was not significantly different from that of new instruments. However, the remaining three variables (angle of rotation at separation and torque at yield and separation) were significantly different between new and stressed files.

Table : Paired t-test comparing the torsional properties of paired new and stressed instruments (mean?SD). The p values reported indicate the statistical significance when comparing new and stressed instruments of similar dimensions.

Analysis of variance (Table 3) indicated that for both stressed and new files, the angle of rotation at yield was not significantly different between the various instrument sizes. In contrast, the variables, angle of rotation at separation and torque at yield and separation were significantly different among sizes.

New files

Variable	ANOVA P value
Angle at yield	.218
Angle at separation	.000
Torque at yield	.000
Torque at separation	.000

Table : Analysis of variance comparing the torsional properties of different sizes of new files (15-20-25-30-35-40).

Stressed Files

Variable	ANOVA P value
Angle at yield	.596
Angle at separation	.029
Torque at yield	.000
Torque at separation	.000

Table : Analysis of variance comparing the torsional properties of different sizes of stressed files (15-20-25-30-35-40).

When applying the Duncan's test in a pair wise comparison of variables with statistically significant difference, the angle at separation of stressed instruments size 25 was significantly higher than that of the other sizes. Within the new instruments, the mean values for sizes 15 and 20 were significantly higher than the other sizes while the means for sizes 25 and 30 were significantly lower than all the others.

In both types the Y angle is not significantly different among the different sizes. However, there are differences in the other three variables (S angle, Y torque and S torque) between the different sizes within each type. For the variables with significant difference, we use Duncan's test as the pairwise comparison method. Results are summarized as follows:

S angle: Within type C, the S angle mean for size 25 is significantly higher than all that of the other. Within type N, the means for sizes 15 and 20 are significantly higher than all the other and the mean S angles for sizes 20 and 25 are significantly lower than all the others.

Y torque: For type N, there was a significant increasing trend for the torque with size, except that sizes 15 and 20 are not statistically significant different from each other. Similar trend was observed for type C, except that size 20 was significantly higher that both sizes 15 and 25 which were significantly not different.

S torque: For type N, the lowest torque for sizes 15 and 20 are not different. The highest torque for sizes 30 and 40 are not significantly different. A significant increasing trend is observed for type N, with the exception that 15 and 25 have nonsignificant different mean S torque.

For the variable torque at yield for the new files, there was a significant trend of torque increasing with size; however the difference between sizes 15 and 20 was not statistically significant. Similar trend was observed for stressed files, except that size 20 was significantly higher that both sizes 15 and 25 which were not significantly different.

Torque at separation for new files, the lowest torque values were recorded for sizes 15 and 20 and were not significantly different. The highest torque values were found for sizes 30 and 40 and were also not significantly different. A significantly increasing trend with sizes was observed for stressed files, with the exception that 15 and 25 had non-significant different means.

According to Table , a linear association between each of the four variables and the instrument size could be established for new files. The angle of rotation (both at yield and at separation) decreased as the instrument size increased while the torque (whether at yield or at separation) followed a reverse pattern (increased as size increased). The strongest association was found between torque at yield and size ($R2$=.947).

For stressed files, no change in the angle variables was observed with the increasing instrument size. The torque variables followed a pattern similar to that observed with the new files. It should also be noted that the torque variables had larger slopes with size in new files than in stressed files.

	New Files			Stressed files		
Variable	P value	R 2	Equation of the line	P value	R 2	Equation of the line
Angle at yield	.064	.153	Y=-.72X+187.83	.534	.026	Y=-4.3X + 189.48
Angle at separation	.011	.272	Y=-13.16X +733.86	.412	.038	Y= -4.18X +802.52
Torque at yield	<.001	.947	Y= 9.39X - 120.07	<.001	.817	Y= 7.87X - 81.36
Torque at separation	<.001	.481	Y=20.39X - 215.37	<.001	.765	Y= 7.33X - 70.47

Table : Regression analysis reporting the presence of a linear association between dependent and independent variables (angle and torque at yield and separation with the instrument sizes), the R2 and the slope for each regression line.

DISCUSSION

Several studies have evaluated the influence of various factors on the separation of NiTi rotary instruments (Barbakow & Lutz 1997; Pruett et al. 1997; Silvaggio & Hicks 1997; Thompson & Dummer 1997; Baumann & Roth 1999; Mandel et al. 1999; Kum et al. 2000; Thompson & Dummer 2000; Yared et al. 2001a,b; Ruddle 2002; Schäfer & Florek 2003; Yared & Kulkami 2003). It is important for the clinician to have detailed research information to provide a rational basis for instrument selection and instrumentation sequence.

Separation of rotary NiTi instruments is associated with variations in canal dimensions and anatomy, such as merging, curving, re-curving, dilacerating or dividing canals (Ruddle 2000). Dentin quality has also been reported to affect the rate of file separation (Ruddle 2000). Another factor associated with separation of NiTi instruments is the design and diameter of the file itself (Marsicovetere et al. 1996; Silvaggio & Hicks 1997; Sattapan et al.

2000; Peters & Barbakow 2002; Yared et al. 2003; Schäfer & Florek 2003). Design of different brands of Ni-Ti files include variations in the helical angle, the rake angle, and the inner mass (Turpin, F Chagneau, J.M Vulcain 2000).

Instrument taper has also been advocated as a potential factor influencing file separation (Yared et al 2003). Finally, motor settings mainly torque level settings, have been demonstrated to have an impact on the rate of file separation (Yared & Kulkami 2003). Various separation percentages have been reported in the literature (Thompson & Dummer 1997; Baumann & Roth 1999; Kum et al. 2000; Thompson & Dummer 2000; Schäfer & Florek 2003).

According to Schäfer & Florek (2003), separation occurred in 23% of the 28∫-curved and 35∫-curved canals prepared with 0.04 taper K3 files. In this study, canals were prepared in resin blocks with all instruments used to enlarge one canal only. Lower fracture rates were reported by other authors with (Thompson & Dummer 1997; Baumann & Roth 1999; Kum et al. 2000; Thompson & Dummer 2000; Schäfer & Florek 2003). Torque settings play a major role in controlling instrument separation during root canal preparation (Yared & Sleiman).

A higher incidence of instrument deformation and separation was found with the air and high torque control motors versus low torque control motors (Yared & Kulkami 2003). Data published in previous studies (Marsicovetere et al. 1996, Sattapan et al. 2000, Hübscher. 2003) provide manufacturers with helpful information related to the settings of electronic torque control motors. The new generations of electronical torque controlled motors (ETCM) are equipped with an autoreverse system that is automatically activated when the stress levels resulting from friction between the file and the dentin reach the preset torque level. This process allows to draw the file out of the canal thus preventing instrument separation.

Questions have been raised as to whether repeated use of Ni-Ti rotary instruments adversely affects their torsional properties and renders them more prone to separation. Use of instruments can be considered when an instrument is utilized to prepare a single canal with multiple strokes or multiple canals in the same tooth. Instruments are subjected to cyclic fatigue (i.e. flexural fatigue) and torsional stress during clinical use (Sattapan et al. 2000). Separation resulting from cyclic fatigue is likely to occur when instruments are rotated in root canals with abrupt curvatures (Pruett et al. 1997).

Recent studies have shown that cyclic fatigue is not the main reason for Ni-Ti rotary instrument separation (Yared et al. 1999; Sattapan et al. 2000; Yared et al. 2000; Peters & Barbakow 2002). When instruments are locked into a canal, they are subjected to high levels of torsional stress, leading to deformation and separation (Yared et al. 2001a). Findings reported by Yared et al. 2003, suggested that the torque and angle of rotation at fracture were significantly affected by the repeated use of 0.06 K3 instruments in resin blocks. An SEM study of Ni-Ti rotary instruments demonstrated a high incidence of surface defects where cracks are usually initiated (Kuhn et al. 2001).

Flexural or torsional fatigue caused by the use of instruments in a curved canal and by the repeated locking of the files in the canal could facilitate the initiation and propagation of a crack (Kuhn et al. 2001), and therefore could affect the torque of the instruments at fracture.

Schäfer & Florek 2003 reported high separation rates following a single use of Ni-Ti files in one canal. Usually, motor torque settings recommended by manufacturers are based on torque values applied to new instruments. The results of the abovementioned studies along with the finding that torque at fracture is significantly higher than torque during instrumentation (Sattapan et al. 2000) emphasize the need to revisit motor torque values when working with Ni-Ti files.

Resin blocks and extracted teeth have been utilized to simulate instrument use and measure torsional properties (Lim & Webber 1985; Blum et al. 1998a; Schäfer & Florek 2003; Schäfer & Schlingemann 2003; Yared et al. 2003). The results of such studies cannot be extrapolated to clinical situations because resin blocks have a different structure than dentin, and extracted teeth are subject to numerous human errors and variations related to shape selection of canal morphology (Garip et al. 2001; Gluskin et al. 2001). Peters & Barbakow (2002) demonstrated that higher torque levels were generated in canals prepared in resin blocks compared to canals in extracted teeth. A major drawback of resin blocks is heat generation resulting in softening of the resin material (Kum et al. 2000) and binding of cutting blades and instrument separation (Thompson & Dummer 1997; Baumann & Roth 1999). In addition, instruments may not be subjected to high levels of stress at their tip during root-canal preparation in resin blocks (Yared et al. 2003). This may significantly affect the values of torque at failure.

The selection of 10 alternating rotations in the robotic cycle to stress the instruments was based on the mechanical concept of endurance. Materials usually show diminishing effects of stress loading. For example, the first time a material is loaded to maximum stress before irreversible deformation (torque at yield), it may lose 10% of its ultimate strength, the next time it is loaded, it might lose only 8% of its strength, then 6%, then 5%, then 4% after repeated stress loadings. Most materials have what is called an Endurance Limit, which is the minimum strength the material will have regardless of the number of stress cycles it has withstood.

While some materials such as aluminum, do not have this Endurance Limit (they keep getting weaker and weaker each time they are stressed), all materials do exhibit smaller and smaller changes in strength during repeated stress cycling. Ten cycles of NiTi up to its yield strength will have a significant effect on the material. With additional cycles beyond 10, say up to 20, the additional decrease in strength would be much less than originally seen after the first 10 cycles. Therefore, testing up to 10 cycles will allow the most significant effect (and probably have more statistical significance) because the relative changes will be the greatest. The selection of the clockwise direction of rotation is based on the fact that the instrument was designed to be used in clockwise manner and will therefore only be torsionally stressed in that direction.

Stress cycle number 1

Fig. . The above graphs show the level of torque reached after the first, fifth, tenth, and fifteenth cycles of robotic stress at 170 degrees (angle at yield). Note that the changes in the torque values were significantly different between the first, fifth and tenth cycles. After the 15th cycle, the differences become non-significant.

T-test results showed that the angle of rotation at yield for all instrument sizes was not significantly different, when comparing new and stressed files. This could be interpreted as follows: the stressed files maintain unaffected their angle of rotation at yield after robotic stress which means that they do not show any macroscopic shape alteration after the 10th cycle.

In contrast, the other three variables (torque at yield and separation and angle of rotation at separation) of the stressed instruments are affected by robotic stress, meaning that the files lose their ability to tolerate stress and torque and, therefore, clinical damage such as file separation may occur. Clinically, this would implicate that lower values of torque (based on data from stressed files and not from those of new files) should be applied in the settings of the torque control motor to activate the auto reverse system when critical torque values are reached in order to avoid file separation.

Although the number 15 files were an exception as they did not show significant differences in all variables when comparing new and stressed instruments at p=0.05, a statistical difference between new and stressed 15 files was, however, recorded when the level of confidence was lowered to 90%.

The analysis of variance showed that the angle of rotation at yield was not significantly different between files of different sizes in the same group (stressed or new). This would indicate that regardless of the size of the instrument, the angle of rotation at yield remains constant. This also substantiates the application of this angle in the robotic stress model and as potential reference in future studies.

When considering the angle of rotation at separation for new instruments of different sizes, the 15 and 20 files showed the highest values while larger files 25 through 40 exhibited lower angles. This would indicate that the larger instruments are less flexible than smaller ones. After robotic stress, the trend changed and the values of the angle of rotation at separation did not decrease with increasing sizes indicating that larger stressed instruments were not less flexible than smaller stressed files.

For new and stressed instruments, the torque at yield and separation showed a trend towards increasing values with increasing file size, indicating that larger files have a better tolerance to torque.

A similar pattern was found when applying regression analysis. The new instruments became less flexible with increasing size but tolerated torque better. For stressed files, the larger instruments did not lose in flexibility compared to smaller sizes but their ability to withstand torque diminished when compared to small files.

Torsional stress is still the major cause for file separation, cyclic fatigue will lower the properties of the Ni-Ti alloy and may cause some internal micro crack that can reduce the tolerance to stress without any macro evidence on the file, during root canal shaping we must avoid locking the tip of the file, even when the file is enlarging a very narrow canal the tip will rotate at a different speed then the rest of the file. The proper choice of file sequence, very low torque setting, speed between 350 and 450 rpm, small 1 to 2mm amplitude of works, and each file reaching a little bit farther than the previous one, - these recommendations can help us achieve a more secure root canal enlargement and actually tell us about the anatomy of the root canal system. Torque control motors should be equipped with values related to stressed files and not new ones.

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Oral Health welcomes this original article.

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Fig. . The above graphs show the level of torque reached after the first, fifth, tenth, and fifteenth cycles of robotic stress at 170 degrees (angle at yield). Note that the changes in the torque values were significantly different between the first, fifth and tenth cycles. After the 15th cycle, the differences become non-significant.

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