Effect of different kinematics and operational temperature on cyclic fatigue resistance of rotary NiTi systems

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Abstract

Background: The aim of this study was to compare the effect of different kinematics and operational temperature on cyclic fatigue resistance of Protaper Next, WaveOne Gold, and Twisted File Adaptive files in a static model.

Methodology: An artificial canal, made of stainless steel with an inner diameter of 1.5 mm, a 60° angle of curvature, and a curvature radius of 2 mm, was used for the cyclic fatigue test immersed in a water bath for temperature adjustment (37 °C and 20 °C). A total of 120 files were divided into three groups according to the type of motion continuous rotation motion (CRM), adaptive motion (AM), and reciprocation motion (RM). Each group was further subdivided into two subgroups according to the operational temperature (37 °C and 20 °C). All instruments were operated until fracture occurred, and the time to fracture was recorded in seconds. Mean number of cycles to failure and standard deviations were calculated for each group, and data were analyzed statistically using two-way ANOVA followed by Tukey’s post hoc test (P ≤ 0.05).

Results: The continuous rotation motion exhibited significantly lower cyclic fatigue resistance than reciprocating or adaptive motion (P ≤ 0.001) at 37 °C and 20 °C.

Conclusions: Cyclic fatigue resistance of NiTi files was affected by the motion used during root canal preparation. Reciprocation motion and adaptive motion resulted in extended fatigue. The operational temperature affects the cyclic fatigue resistance of the twisted file.

Keywords: Adaptive motion, Body temperature, Continuous rotation, Cyclic fatigue, Kinematics, Reciprocation, Metallurgy, Alloys

Introduction

The introduction of rotary nickel-titanium (NiTi) instruments in endodontic practice has revolutionized the concept of root canal instrumentation in the last two decades. This is because of the alloy’s superelasticity associated with the reversible phase transformation between austenite and martensite phases (Shen et al. 2013; Pereira et al. 2012; Brantley et al. 2009).

The clinical behavior of these two phases is remarkably different and temperature dependent (Otsuka and Ren 2005). Originally, the development of NiTi systems has been focused on changes in file design together with the simplification of the instrumentation sequences without changing the basic properties of the alloy (Shen et al. 2013; Peters and Pague 2010). More recently, new heat treatment methods together with novel manufacturing procedures have been introduced to improve the cyclic fatigue resistance of the rotary files (Plotino et al. 2017; Gambarini et al. 2008; Rodrigues et al. 2011).

Another approach adopted by the manufacturers to improve the cyclic fatigue resistance of the instruments is changing the rotation kinematics during root canal preparation (Çapar and Arslan 2016). Reciprocation motion was introduced to reduce stress values attained by

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the instrument during rotation through travelling to a shorter angular distance than rotation motion do (Silva et al. 2016; Plotino et al. 2015). Meanwhile, the adaptive motions is composed of both continuous and reciprocation motion. When the amount of stress on the file is kept to minimal, the file continues in constant rotation until substantial load is applied; hence, reciprocation motion is executed (Marks Duarte et al. 2018).

Fracture of endodontic rotary instruments occurs due to combination between torsional and flexural fatigue. Torsional fracture occurs due to locking of the tip or any part of the instrument in the canal, while the shaft continues to rotate. Flexural fatigue occurs when the instrument rotates inside a curved root canal and is subjected to an excessive number of tension-compression strain cycles in the region of maximum root canal curvature (Pedullà et al. 2018). The environmental temperature dramatically affects fatigue resistance of nickel-titanium rotary files (Plotino et al. 2017; Grande et al. 2017).

The aim of the present study was to compare the effect of different kinematics on cyclic fatigue resistance of Protaper Next (PTN), WaveOne Gold (WOG), and Twisted File Adaptive (TFA) files in room temperature.

Materials and methods

Based on data from previous studies (Plotino et al. 2017; De Vasconcelos et al. 2016), a power calculation was performed using the G*Power 3.1 software (Faul et al. 2007) (Heinrich Heine University, Dusseldorf, Germany). The calculation indicated that the sample size for each group should be a minimum of 20 files. A total of 120 files were tested for cyclic fatigue failure, twenty files from each system; TFA; SM2 (SybronEndo, Orange, CA, USA), PTN; X2 (Dentsply Maillefer, Ballaigues, Switzerland); and WOG; primary file (Dentsply Maillefer, Ballaigues, Switzerland). The instruments were inspected for any manufacturing defects using a stereomicroscope (Olympus BX43; Olympus Co, Tokyo, Japan).

A specially designed custom-made cyclic fatigue testing device was used in this study (Fig. 1). This device consisted of curved stainless steel canal 19 mm in length with 60° angle of curvature and 2 mm radius, which were stuck on an acrylic surface where the headpiece was also fixed. The radius and angle of curvature were determined according to Pruett et al. (Pruett et al. 1997). To reduce friction between the instrument and the metal canal walls, a synthetic oil was used as a lubricant. The artificial canals were covered with glass to prevent the instruments from slipping out.

The method described by De Vasconcelos et al. (De Vasconcelos et al. 2016) was used to adjust the operating temperature. The device was placed in a glass water container, with rotating the instruments until fracture in air.

The glass container was filled with 200 mL water and immersed in ice until the water temperature was stabilized at 20 ± 1 °C or placed on a hot plate until the water temperature was stabilized at 37 ± 1 °C, and the temperature was continuously monitored using an infrared thermometer (Etekcity Corporation, CA, USA).

The files were divided into three groups (n = 20), and the following procedures were performed:

**Group (RM): reciprocation motion**

The WOG primary files 25/.07 (n = 20) were inserted into the artificial canal and operated using a torque-controlled endodontic motor (x-smart plus, Dentsply, Maillefer) following the instructions given by the manufacturer at 350 rpm, reciprocating motion until fracture.

**Group (AM): adaptive motion**

The TFA files SM2 25/.06 (n = 20) were inserted into the artificial canal and operated with the “TF Adaptive”
program, using one-way ANOVA followed by Tukey's post hoc test to cross-check the time of file separation.

**Group (CRM): continuous rotation motion**
The PTN X2 files (*n* = 20) were inserted into the artificial canal and operated using a torque-controlled endodontic motor (x-smart plus, Dentsply, Maillefer) following the instructions given by the manufacturer at 300 rpm, continuous rotation motion until fracture.

The time to fracture was recorded in seconds using a stopwatch and stopped as soon as a fracture was detected visually, and a video recording was performed to cross-check the time of file separation.

The number of cycles to failure (NCF) was calculated by multiplying the rpm (in seconds) with the time taken to fracture (in seconds). NCF data were analyzed by using one-way ANOVA followed by Tukey's post hoc test. Statistical analysis was performed using the software SPSS (Statistical Packages for the Social Sciences 20.0; IBM, Armonk, NY).

**Results**
The mean NCF and standard deviations for all groups are shown in Table 1.

There was a statistically significant difference between (AM), (RM), and (CRM) (*p* ≤ 0.001) at 37 °C and 20 °C.

At 20 °C, the highest fatigue resistance was recorded in group (RM) Wave One gold followed by group (AM), TF adaptive without significant difference, whereas the lowest fatigue resistance was recorded in group (CRM) Protaper Next which was significantly lower.

At 37 °C, the highest fatigue resistance was recorded in group (RM) Wave One Gold followed by group (AM), TF adaptive with significant decrease, whereas the lowest fatigue resistance was recorded in group (CRM) Protaper Next which was significantly lower.

Regarding the effect of temperature, the RM group (Wave One Gold) and RCM group (Protaper Next) showed no significant decrease in NCF with raising the temperature to 37 °C. However, the AM group (Twisted file) recorded significant decrease in NCF at 37 °C.

| Temperature | Group (AM) | Group (RM) | Group (RCM) | P value |
|-------------|------------|------------|-------------|---------|
| 20 ± 1 °C   | 728 ± 151AB | 850 ± 130AB | 388 ± 40A    | ≤ 0.001 |
| 37 ± 1 °C   | 568 ± 63AB  | 833 ± 139AB | 347 ± 29A    | ≤ 0.001 |
| P value     | P ≤ 0.001  | P = 0.397   | P ≤ 0.085    |

*Significant at *p* < 0.05*

Different superscript small letters indicate statistically significance difference between different groups in the same row
Different superscript capital letters indicate statistically significance difference between different subgroups in the same column

**Discussion**
Several factors affect NiTi file fracture during endodontic treatment of curved root canals such as kinematics, speed used, structural characteristics, method of manufacturing, geometric designs, radius, and angle of the curvature of the canal (Castelló-Escrivá et al. 2012; Kim et al. 2008).

The aim of the present study was to compare the effect of different kinematics on cyclic fatigue resistance of Protaper Next, WaveOne Gold, and TF Adaptive files in a static model at different operational temperatures.

According to Yao et al. (Yao et al. 2006), to decrease the influence of other variables, standardized artificial canals in custom made device should be used. Therefore, in the present study, a standardized artificial canal was used for the cyclic fatigue test, and this was in full agreement with De-Deus et al. (De-Deus et al. 2010).

A static model was used in this study rather than a dynamic model. Although the dynamic model could mimic the clinical brushing or pecking motion, it has limitations because the instruments are not constrained in a precise trajectory. Moreover, the speed and amplitude of the axial movements are subjective because this up and down motion is manually controlled (Pedullà et al. 2018; Higuera et al. 2015).

The results of this study showed that the highest cyclic fatigue resistance was associated with the reciprocation motion followed by adaptive motion then continuous rotation. This might indicate that the motion plays a major role in cyclic fatigue resistance. These findings might be attributed to the release of the reaction stresses built up in the material by reversing the rotational direction (Gavini et al. 2012; You et al. 2010). Plotino et al. (Plotino et al. 2014) concluded that reciprocating movement can improve cyclic fatigue resistance of NiTi instruments by reducing torsional loads and torsional failure.

On the other hand, the adaptive motions are composed of continuous and reciprocation motion. When the amount of stress on the file is minimal, the file uses continuous rotation till load is applied, and it then uses reciprocation motion (Higuera et al. 2015); thus, TFA has been shown to be elastic and resistant to cyclic fatigue than continuous rotation motion did (De-Deus et al. 2010; Bhagabati et al. 2012).

A number of studies (Gambarini et al. 2012; Karataş et al. 2016; Keskin et al. 2017; Gündoğar and Özüyrek 2017) reported that, regardless of the file type, reciprocation motion increased the cyclic fatigue resistance of files more than continuous rotation did. Karatas et al. (Karataş et al. 2016) concluded that fatigue life is associated with the number of times that a crack in an instrument closes and opens. During reciprocation motions, the instrument needs to complete one full rotation (360°) in more time when compared with continuous rotation.
Therefore, the number of times that a crack closes and opens in reciprocation motions is expected to be less when compared with continuous rotation or adaptive motions over the same time. This may explain the extended fatigue life of reciprocation motion. This was in full agreement with the results of the present study as the PTN showed the least cyclic resistance among the tested groups.

WOG file has a parallelogram cross-sectional design with only two cutting edges, and this design in addition to high austenitic finish value and 2-stage transformation behavior decreases the torsional stress on the file and extends its cyclic fatigue resistance as described by Özyürek (Gündoğar and Özyürek 2017; Özyürek 2016). Although TFA file has a triangular cross-section design with three cutting edges that thought to increase the torsional stress on the file decreasing its cyclic fatigue resistance, yet, the unique heat treatment (R-phase) coupled with electropolishing (Castelló-Escrivá et al. 2012) might maintain the natural grain structure resulted in decreased crack initiation and propagation process. Hence, the file has comparable cyclic fatigue resistance coupled with the novel adaptive motion operational mode.

Although PTN file has the same parallelogram cross-section design as WOG, it showed significant difference in cyclic fatigue resistance than WOG and TFA files. These results emphasized that the motion plays a major role in cyclic fatigue resistance than the design do.

Another important issue to be emphasized is the operational temperature. It was found that the temperature inside the root canal is buffered within few minutes to 31–35 °C as stated by De Hemptonne et al. (De Hemptonne et al. 2015). So, our study was performed comparing the two environmental temperatures. It was found that raising the temperature from room temperature to body temperature considerably reduced the cyclic fatigue resistance for both PTN and TFA rotary systems. These findings are in agreement with recent previous studies (Plotino et al. 2017; Grande et al. 2017; De Vasconcelos et al. 2016; Yılmaz et al. 2018).

The considerable decrease in fatigue resistance might be due to the interrelated transformation temperatures, austenitic finish temperature, in which raising the temperature to around 37 °C suggests that the instrument is typically in an austenitic state. This is evident for TFA in which the austenitic finish temperature was identified to be about 20 °C (Braga et al. 2013), whereas in Wave One Gold and the M-Wire Protaper Next, the transformation temperature obviously above body temperature is about 50 °C (Ye and Gao 2012; Hieawy et al. 2015); accordingly, the files were not affected by the increase of temperature during cyclic fatigue testing in the present study which was in full agreement with Plotino et al. (Plotino et al. 2017)

Conclusion
Under the conditions of this study, it can be concluded that:

1. The operational temperature at which the instruments are tested has a considerable effect on cyclic fatigue testing and varies according to the type of alloy.
2. Gold heat treated alloys and M-wire alloys are not readily affected by the intracanal temperature because their austenitic temperature is obviously above body temperature, whereas Twisted file is influenced by intracanal temperature because its austenitic finish is below body temperature.
3. The mode of rotation greatly affects the cyclic fatigue, whereas both the reciprocation and adaptive motions exhibited higher cyclic fatigue resistance than continuous rotation.

Abbreviations
NI:q: Nickel titanium; PTN: Protaper Next; WOG: WaveOne Gold; TFA: Twisted File Adaptive; SPSS: Statistical Packages for social sciences; ANOVA: Analysis of variance; CRM: Continuous rotation motion; AM: Adaptive motion; RM: Reciprocating motion; NCF: Number of cycles to failure; RPM: Revolutions per minute

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Authors’ contributions
Amira Galal Ismail prepared specimens and analyzed and interpreted data. Manar Galal wrote the manuscript, Mohamed Mokhtar Nagy analyzed the data and substantively revised the work. The authors read and approved the final manuscript.

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No competing interest in this section.

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