Cyclic fatigue, torsional failure, and flexural resistance of rotary and reciprocating instruments

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Abstract

Aim: The aim was to compare cyclic fatigue, torsional failure, and flexural resistance of NiTi endodontic files: Hyflex CM (HYF), Genius files (GEN), WaveOne Gold (WOG), and ProTaper Universal (PTU).

Materials and Methods: Fifteen files of each brand were used in cyclic fatigue test and other fifteen files for flexural test and torsional failure test. To the cyclic fatigue test, used torque limit and revolutions per minute were set according to the respective manufacturer guidelines. The test was performed under deionized water at 36°C, and all files were tested in a 3 mm radius of curvature with an angle of curvature of 60°, time of the fracture was recorded. Torsional fatigue test was performed in the torsional machine (Instron MT, USA), recording the fractured time and torque data by the machine software. Flexural fatigue test was performed in 60° of curvature. All data were statistically analyzed by one-way analysis of variance, and Tukey test for multiple comparisons.

Results: Cyclic fatigue (seconds) = HYF: 744.1 ± 231.9/GEN: 477.3 ± 220.5/WO: 278.4 ± 57.0/PTU: 152.4 ± 65.2; torsional failure (N × cm) = HYF: 6.85 ± 1.484/GEN: 6.55 ± 0.828/WOG: 5.73 ± 0.360/PTU: 4.43 ± 0.900; flexural resistance (N × mm) = HYF: 0.33 ± 0.294/GEN: 0.19 ± 0.136/WOG: 0.98 ± 0.216/PTU: 1.85 ± 0.276.

Conclusion: HYF and GEN showed the best results for cyclic fatigue, torsional failure, and flexural resistance, followed by WOG and PTU.

Keywords: Cyclic fatigue; endodontic files; flexural resistance; torsional failure

INTRODUCTION

Endodontic files’ performance has been improved over time; however, its fracture continues to be a challenge.[1] Nickel-titanium files have a high flexibility given by the physical transformation of the austenitic and martensitic phases. Still, fracture occurs due to cyclic flexural fatigue or torsional failure.[2]

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The cyclic fatigue test is used to count the cycles of each file until fracture[3] as it continuously rotates freely in a curved canal generating tension/compression cycles at the point of maximum flexure, which corresponds to the point of greatest curvature within the simulated root canals.[4] However, the flexural resistance is important too, as the greater the degree of flexing that a rotary NiTi file is subjected to when used in curved canals, the shorter the files’ life expectancy (flexural resistance failure).[5]

Torsional failure occurs when a file tip or body is locked in the canal while the shank continues rotating, once the torque exerted by the handpiece exceeds the elastic limit of the metal, the file fracture becomes unavoidable.[6]
The alloy nature and the manufacturing process greatly affect the files’ mechanical performance. Several novel approaches for rotary NiTi files have been introduced to enhance resistance of fatigue fracture using new alloys with different thermal treatments, cross-sectional designs, and kinematics, as well, pre- or postmanufacturing processes that enhance the mechanical properties of files. Recently, many surface and bulk treatments have been tested to evaluate their effect on failure parameters.

The use of reciprocating motion has been suggested to curved canals and has shown to increase the files’ useful life and their resistance to fatigue. Reciprocation motion is claimed to work under the files elastic limit continuously, to prolong the cyclic fatigue life, that is already proved when compared to conventional NiTi alloys.

Genius (GEN) files (Ultradent, South Jordan, UT, USA) according to the manufacturer has a combination of rotary and reciprocating motion, which first uses asymmetric reciprocation motion to open space safely and then uses rotation to remove debris, with the same file. It can enlarge the apical third without over flaring the canal with a super tapered file, giving the maximum taper possible without removing sound dentin unnecessarily. In the 90°/30° reciprocation setting, GEN files safely create access to the working length while minimizing cyclic and torsional fatigue. In the 360° rotation setting, the files refine the canal walls while shaping and removing the debris from the canal.

The aim of the present study was to compare the cyclic fatigue resistance of NiTi endodontic files in simulated 60° curved canals; torsional failure and the flexural resistance of NiTi endodontic files, two used in reciprocating motion: WaveOne Gold (WOG) and GEN, and two in rotary motion: HYF and ProTaper Universal (PTU) (control).

**Materials and Methods**

**Endodontic files**

Four different NiTi files were used including HYF CM (#25/0.06; Coltene-Whaledent, Allstetten, Switzerland), GEN files (only reciprocation movement was tested) (#25/0.04-Ultradent, South Jordan, UT, USA), WOG (PRIMARY-size #25/0.07-Dentsply Maillefer, Ballaigues, Switzerland), and PTU (F2-#25/0.08-Dentsply Maillefer, Ballaigues, Switzerland). Fifteen files of each brand were used in cyclic fatigue test and fifteen in both flexural and torsional fatigue.

**Cyclic fatigue**

The torque limit and revolutions per minute (rpm) used were set according to the respective manufacturer guidelines (2.5 Ncm and 500 rpm for HYF CM, 3.0 Ncm and 300 rpm for PTU, factory reciprocation motion for WOG, and factory reciprocation motion for GEN). A plastic base with three adjustable stainless steel pins (6 mm in diameter, 4 cm long, 0.5-mm wide V-shaped notch) was used to simulate the curvature of the root canal in which the files were tested according to de Vasconcelos et al. [1] Figure 1a. The electric motor VDW silver endodontic motor (VDW Dental, Munich, Germany) for HYF CM, PTU and WOG. And Genius endodontic motor (Ultradent, South Jordan, UT, USA) for GEN was used to run the test respecting the rpm and torque limit of each file, and the handpiece was hung on the same plastic base. Then, to adjust the temperature, a glass container was filled with 200 ml. deionized water inside a heating chamber (Kasvi, Taiwan) and placed on a hot plate until the water temperature was stabilized at $37 \pm 0.5°C$; during all tests using an infrared thermometer. The plastic base with pins, the file, and two connected clips were positioned inside the glass container and fixed with a clamp, and sufficient time after immersion of the base was allowed to equilibrate temperature. All files were tested in a 3-mm radius of curvature with an angle of curvature of 60° according to Pruett et al. [3] At the moment of the file separation, a chronometer verified the time of separation.

**Flexural fatigue test**

Fifteen files of each brand were tested using the universal machine (Shimadzu, model AG-X, Japan). A load was applied over the file until its tip reaches the 60° of curvature, and then the test stopped [Figure 1b]. A camera was fitted to the test machine to assist and check the desired angle. The software Trapezium X coupled to the test machine reads the data of the applied load and the needed time to reach the angle of curvature.

**Torsional failure test**

The test was performed in a torsional machine (Instron MT, model 229013-3A, USA). The file handle was clamped in the mandrel using a custom-made apparatus, which remained static during the test. Five millimeters of the file tip was clamped in another mandrel [Figure 1c]. The machine was activated, promoting the rotating motion of the file up to separation, in constant speed, at 2 rpm. The rotation direction was clockwise for PTU, HYF CM, and GEN, and counterclockwise for WaveOne Gold, because of the machining direction of the files. The separated tip was measured with a pachymeter and the time, angle, and torque data, at the time of fracture, were presented by the machine software.

**Scanning electron microscope**

The fractured files were examined under a scanning electron microscope (SEM) (Inspect S50, PT Multi Teknindo Infotronika, Jakarta, Indonesia) to evaluate the fractures. They were cleaned using absolute alcohol for 3 min and fixed on a metallic stub and examined at magnification ($\times 500$).

**Statistical analysis**

All data were submitted to normality test, then the
parametric test of one-way ANOVA was selected, followed by the Tukey test for multiple comparisons, with significance level 5%.

RESULTS

Cyclic fatigue
There was no significant difference between the means of the WaveOne (mean: 278.4 ± 57) and PTU (mean: 152.4 ± 65.2) groups. However, HYF (mean: 744.1 ± 231.9) presented the best results, followed by the GEN group (mean: 477.3 ± 220.5) [Figure 2a].

Flexural fatigue test
One-way ANOVA presented HYF (0.33/0.29) and GEN (0.19/0.13) as the most flexible groups, respectively, followed by WaveOne (0.98/0.21) and PTU (1.85/0.27), but HYF and GEN had no significant difference [Figure 2b].

Torsional failure test
HYF (mean: 6.851 ± 1.48) presented the best results with the greater tensile strength among the tested groups, followed by GEN (mean: 6.55 ± 0.82), WOG (mean: 5.73 ± 0.36), and PTU (mean: 4.435 ± 0.90) [Figure 2c].

Scanning electron microscope analysis
SEM analysis of fractured surfaces of all the groups revealed crater-like formation along with numerous dimples, circular abrasions, and microbubbles indicative of the ductile mode of fracture. After the cyclic fatigue test, those files showed the presence of crack initiation areas and overloaded fast fracture zones [Figure 3]. After the torsional test, those fragments demonstrated shear failure, including concentric abrasion marks and fibrous microscopic dimples at the center of rotation [Figure 3].

DISCUSSION

The present study tried to evaluate the cyclic fatigue (in deionized water at body temperature), torsional failure, and flexural resistance of two reciprocating and two rotating files. Comparing two different motions was tested previously in the literature testing diverse file systems.[6,13]

The manufacturing process (CM wire) seems to play a major role in the superior fatigue resistance of the HYF files. In this study, there was no difference between HYF and GEN, when tested by three different stress conditions: cyclic fatigue, torsional failure, and flexural resistance. However, in cyclic fatigue, there was no significant difference between GEN and WOG [Figure 2a], also in torsional failure, there was no significant difference among HYF, GEN and WOG [Figure 2b].

GEN, even if not treated thermomechanically, was the most flexible, probably due its taper 0.04 against 0.06 of HYF;
0.07 WOG and 0.08 of PTU, or due to its rhombus-like with rounded angle cross section, which different of WOG that has acute angles as appeared in SEM analysis, as well as to the fact that reciprocation movement gives more flexibility to the file. However, being thinner was unfavorable for GEN for torsional and cyclic fatigue tests. GEN files when compared to WOG files showed the highest cyclic and bending resistance.\[14\] Recently, it was related that GEN promotes efficient three-dimensional preparation as BioRace and ProTaper Next\[15\] and that reciprocating motion could reduce cyclic and torsional fatigue of the file and increase its resistance to cyclic fatigue, also reducing chair time and appointments.\[16\] HYF CM group has higher cyclic fatigue resistance than the PTU group according to our results, and it was indicated for severely curved canals.\[17\] Recent studies showed that the HYF CM group was superior to the PTU group regarding cyclic fatigue resistance,\[18\] which agree with the results of the present study. Another study comparing pathfinding files reported that HYF GPF (#15 and a 0.02 taper) was more resistant to cyclic fatigue than PathFile (#16 and a 0.02 taper), G-File(#12and0.03taper),ScoutRace(#15and0.02taper), and ProGlider (#16 with a mean taper of 0.04 and a 0.02),\[19\] confirming the high alloy resistance of HYF. However, a recent study showed a reciprocating glide path R-Pilot with greater cyclic fatigue resistance than HYF EDM.\[16\]

Manufacturers have been developing processes to increase cyclic fatigue resistance as well as flexibility, one example is M-wire alloy, which is prepared by a special thermal process to increase flexibility and resistance to cyclic fatigue.\[20\] A thermal process is one of the fundamental approaches toward adjusting the transition temperatures of NiTi alloys, and several novel thermomechanical processing and new technologies have been developed to optimize the microstructure of NiTi alloys. Several factors such as cross-sectional design, the chemical composition of the alloy, and manufacturing techniques of endodontic instruments could have a significant effect on their clinical performance and resistance to fracture.\[21\]

According to a recent study,\[26\] WOG instruments had a higher torsional resistance compared with reciproc and twisted file adaptive, and this finding could be attributed to the different cross-sectional design. WOG instruments have a parallel gram-shaped design with cutting edges and alternate one-point contact. It has been reported that the greater cross-sectional area would have higher torsional stiffness and flexural strength.\[22\] Elsaka et al.\[19\] (2017) emphasize that WOG combines the metallurgical advancements of gold wire thermal treatment and the original WaveOne reciprocating instrument technique, due to the heat treatment process performed after manufacturing. In this study, WOG was better than PTU, but not the same with HYF and GEN, which their cross section and type of motion, seems to improve their resistance to fracture.

The CM-wire has made the NiTi instruments more resistant to cyclic fatigue than conventional super-elastic NiTi instruments and is expected that instruments treated thermo-mechanically maintain the same torsional properties as conventional super-elastic NiTi instruments.\[23\] HYF is manufactured by a unique process that controls the material’s memory, making the files extremely flexible, however, unlike conventional files, which exhibit a stress-induced phase transformation.\[24\] Heating transforms the metal temporarily into the austenitic phase, which makes it possible for the file to regain its

Figure 3: Scanning electron micrographs of the fracture surface of separated fragments: Hyflex; Genius; WaveOne Gold; ProTaper Universal. The first row shows images after cyclic fatigue test, indicating the crack initiation origin and the area of overload fast fracture zone. The second row shows the images after torsion failure test, indicating the concentric abrasion mark and showing the fibrous dimples.
original shape before cooling down again and analysis of used HYF instruments indicated that most of the files showed visible plastic deformation such as unwinding and curving.[23] Al-Sudani[25] observed that the majority of these files could be restored after autoclaving, however, de Vasconcelos et al.[1] evaluated the resistance to fracture of NiTi endodontic instruments under different temperature conditions observed that temperature increases up to 37°C, substantially decrease the fracture resistance, for all tested instruments (PTU, HYF CM, TRUShape, and Vortex Blue), greater to less reduction was verified for TRUShape, Vortex Blue, HYF CM, and PTU, respectively. The same study suggested that PTU is in an austenitic state at many temperatures tested, whereas HYF CM is in varying degrees of martensitic condition at room temperature and move to a much more austenitic state at body temperature.

According to Pereira et al.,[26] fatigue life in the air is shorter than water at room temperature, and a possible reason is that martensitic phase transformation renders crack propagation because of the larger number of interfaces, so a complex array of secondary cracks is formed, dissipating the energy required for crack propagation. In our study, HYF CM showed higher cyclic fatigue resistance. On the other hand, GEN had a similar performance in cyclic fatigue test when compared with HYF CM, as well as in torsion test. Gündoğar and Özyürek[27] using the new HYF EDM showed better cyclic fatigue resistance over Reciproc Blue, WOG, and OneShape, respectively. Another issue is cut efficiency of the highly flexible instruments, beyond the fact they are not recommended to be used in a reciprocating motion, the recent study shows that flexible instruments like HYF EDM and WOG caused less resin remotion that Reciproc (M-Wire). However, the possibility of dentinal crack formation is greater in less flexible instruments, as shown in anterior study,[27] comparing One Shape, F6 SkyTaper, HYF EDM, WaveOne, Reciproc, and WOG. HYF EDM and WOG caused fewer microcracks than the other instruments tested. In our study, HYF CM showed higher cyclic fatigue resistance. On the other hand, GEN had a similar performance in cyclic fatigue test when compared with HYF CM, as well as in torsion test.

The tested files have different size, design, manufacturing process, and operation mode, and as the fracture mechanism of the endodontic NiTi files involves both torsional stress and cyclic fatigue, and these two forces influence each other,[28] this represents a significant problem under clinical conditions.[29] The mechanical properties, shape, and dimensions can have a crucial effect on the mechanical performance of endodontic files, especially in fatigue and torsional resistance.[30] Successive torsion loads, occurring together with flexural fatigue, reduce the mechanical resistance of NiTi file.[31] Then, it is very difficult to attribute the differences among the tested files to an isolated factor as many factors are involved.[29]

**CONCLUSION**

HYF and GEN showed the best results in cyclic fatigue and torsional failures, followed by WOG and PTU. GEN was the most flexible instrument, without a significant difference to HYF, followed by WOG and PTU.

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**Conflicts of interest**

There are no conflicts of interest.

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