Original Article

# Cyclic fatigue resistance of three heat-treated nickel-titanium instruments at simulated body temperature

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## Abstract

**Introduction:** The aim of this study was to evaluate the cyclic fatigue resistance of three heat-treated nickel–titanium (NiTi) systems at simulated body temperature.

**Materials and Methods:** Twelve instruments of similar apical diameter (#25) from three engine-driven NiTi instruments; WaveOne Gold (WOG), Hyflex EDM (HEDM), and M Pro system were tested for cyclic fatigue resistance at 37°C in simulated root canals with 60° angle of curvature and 5 mm curvature radius. All instruments were operated until fracture occurred. Mean and standard deviation of the time to fracture and fragment length were calculated, and statistical significance was set at 5%. The morphological characteristics of the fractured instruments were observed through scanning electron microscopy, and their chemical composition was determined using energy dispersive X-ray analysis (EDXA).

**Results:** HEDM showed the highest resistance to cyclic fatigue at 37°C followed by WOG and M Pro instruments with a statistically significant difference. Scanning electron micrographs confirmed a predominantly ductile mode of fracture for all instruments. EDXA showed that WOG was composed of Ni (45.1 wt%) and Ti (37.0 wt%), HEDM was composed of Ni (52.9 wt%) and Ti (42.4 wt%), and M Pro was composed of Ni (49.7 wt%) and Ti (40.4 wt%).

**Conclusions:** M Pro instrument showed the least cyclic fatigue resistance at 37°C compared to HEDM and WOG.

**Keywords:** Cyclic fatigue, Hyflex EDM, M Pro, nickel-titanium, WaveOne Gold

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## INTRODUCTION

Nickel–titanium (NiTi) mechanical instruments are able to shape root canals faster, with better-centered preparations and less procedural errors than stainless-steel ones.[1] Yet, unexpected instrument fracture still does occur.[2] Two modes of fracture were identified by Sattapan *et al.*:[3] torsional failure and cyclic fatigue. Torsional failure occurs upon reaching the ultimate shear strength. Cyclic fatigue is attributed to metal fatigue when it rotates freely in a curved canal at the point of maximum flexure.[4,5] Factors contributing to the cyclic fatigue of mechanical NiTi instruments rotating in a curvature include root canal anatomy (radius and degree of the curvature),[6] cleaning and shaping techniques,[7] debris accumulation[8] and sterilization procedures,[9] size,[3] taper,[10] cross-section,[11]

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and instrument design,[12] as well as the manufacturing technique.[13] Unfortunately, cyclic fatigue often occurs without any visible sign of plastic deformation.[14]

Introduction of new alloys in addition to the newly developed manufacturing processes aimed to improve the cyclic fatigue resistance of NiTi instruments.[14] Reciprocation motion was also shown to improve the cyclic fatigue resistance.[15-17]

WaveOne Gold (WOG) instruments are the updated version of WaveOne files (Dentsply Tulsa Dental; Tulsa, OK, USA). They are still used in reciprocating motion although with different dimensions, geometry, and cross-section. They possess a parallelogram cross-section with two cutting edges and an off-center design.[18] Gold heat treatment is done through heating followed by slowly cooling of the produced file, unlike M-Wire technology which is done before production.[19]

Hyflex EDM (HEDM) (Coltene/Whaledent; Altstatten, Switzerland) is a single-file system used in continuous rotary motion. Controlled memory (CM) alloy is used for their manufacturing using electric discharge machining technology. The mechanical properties of the HEDM instruments were shown to be significantly improved because of CM wire and method of manufacturing.[18]

M Pro rotary (IMD; ShangHai, China) NiTi instruments are made of X wire, a CM alloy with a special heat treatment to improve flexibility and strength.[20] They showed a convex triangular cross-section with three cutting edges and large core and a progressively increasing pitch along with the blades.[20] No study examining the cyclic fatigue resistance of the M Pro rotary NiTi instrument could be found in the literature. Thus, the aim of the current study was to compare the cyclic fatigue resistance of WOG, HEDM, and M Pro NiTi instruments at simulated body temperature.

## MATERIALS AND METHODS

### Sample selection

Three types of engine-driven NiTi instruments were tested: WOG (Dentsply-Sirona Endodontics, Baillagues, Switzerland), Hyflex EDM (Coltene/Whaledent, Altstatten, Switzerland), and M Pro (IMD, ShangHai, China).

Statistical sample size calculation was performed using the following formula:

$N = (Z_{\alpha})2\ S^2/d^2$, where $Z$ value is 1.64 for 5% level of significance, $s$ is the standard deviation obtained from a previous study,[18] and $d$ is the accuracy of estimate. For each system, 12 instruments of similar tip dimension (# 25) were tested for their cyclic fatigue resistance using a mechanical device used earlier in a previous study.[21]

### Cyclic fatigue test

Instruments were operated according to manufacturer's instructions in a simulated stainless steel canal using a 6:1 reduction handpiece (Reciproc silver, VDW, Germany). The simulated root canal was 18 mm long with a 60° angle of curvature and a 5-mm radius of curvature according to Pruett's method.[4] The curved segment of the canal was 6 mm and the center of curvature was 6 mm away from the instrument tip. After accurate instrument positioning to its full length, it was rotated freely and synchronized with timing by a digital stopwatch (Timex, Middlebury, CT, USA) to the thousandth of a second. The cyclic fatigue apparatus was inserted in a thermocycler water bath at 37°C, and testing of all instruments was performed.

"WaveOne All" program was used for the WOG primary files (tip size 25/0.07 taper in the apical 3 mm and variable taper more coronally). HEDM files (tip size 25/variable taper) were rotated at 400 rpm and torque of 3 Ncm, while M Pro files (tip size 25/0.06 taper) were rotated at a constant speed of 400 rpm and torque of 1.5 Ncm. All tested instruments were rotated until fracture occurred. Timing was initiated as soon as the motion started after accurate positioning of the tested instrument into the canal. Time was calculated till fracture as detected visually and audibly. A ×2.5 magnifying binocular loupes with LED light (Heine; Herrsching, Germany) was used to determine the failure time. Testing of all instruments was performed by one operator. For each instrument, the time to fracture (TtF) in seconds was recorded. The length of the separated fragment was also measured for each instrument with a digital caliper.

### Statistical analysis

Mean and standard deviation (SD) of data obtained were calculated for each group and statistically analyzed using one-way analysis of variance and *post hoc* Tukey test with SPSS version 18.0 (SPSS Inc, Chicago, IL, USA). Statistical significance was set at 5%.

### Scanning electron microscopic evaluation

Random selection of three instruments from each group was made. These instruments were ultrasonically cleaned in absolute alcohol for approximately 120 s and then mounted for fractographic examination by scanning electron microscopy (Philips SEM 515, Eindhoven, Netherlands) at ×200 and ×3000 magnification to evaluate the type of fracture with energy dispersive

X-ray analysis (EDXA) (Philips SEM 515, Eindhoven, The Netherlands) made to identify their metallurgic composition. Analyses were done at 25 kV at room temperature.

## RESULTS

Mean TtF ± SD values after cyclic fatigue testing of WOG, HEDM, and M Pro NiTi instruments are displayed in Table 1. One-way ANOVA revealed a significant difference among the three tested instruments ($P < 0.05$). HEDM showed the highest resistance to cyclic fatigue at simulated body temperature followed by the WOG and the M Pro instruments.

SEM of the fractured surface of the tested instruments confirmed a ductile fracture, evident by the numerous dimples on the fractured surface. These dimples resulted from the formation of microvoids in the center of the metal shaft (overload zone), as it underwent cyclic fatigue. At high magnification (×3000), the dimpled surfaces revealed a characteristic population of microvoids for each instrument type. For HEDM and M Pro instruments, the dimples were fewer and relatively smaller. For WOG instruments, the dimples were numerous and relatively larger [Figure 1].

EDXA showed that WOG instruments were composed of nickel (45.1 wt%), titanium (37.0 wt%), and carbon (15.5 wt%). HEDM instruments were composed of nickel (52.9 wt%), titanium (42.4 wt%), and nitrogen (4.5 wt%). M Pro instruments were composed of nickel (49.7 wt%), titanium (40.4 wt%), oxygen (8.5wt%), and traces of silicon (1.2 wt%) as shown in Figure 2.

## DISCUSSION

Attempts to improve the cyclic fatigue resistance of NiTi instruments were made by changing the metallurgy, design, and kinematics of the instruments.[15] The aim of this study was to evaluate the cyclic fatigue resistance of M Pro NiTi instruments. Pruett's method was chosen for this study to define root canal geometry.

The current study was designed to overcome limitations of other *in vitro* studies through using specifically designed artificial canals for each instrument, thus giving it a precise trajectory during testing.[21,22] Yet, we do not have a standardized technique for cyclic fatigue resistance evaluation of rotary NiTi instruments. The ideal technique

**Table 1: Mean time to fracture in seconds (standard deviation) and fragment length in mm after cyclic fatigue testing of WaveOne Gold, Hyflex EDM, and M Pro rotary files in 60° curved simulated canals**

| | TtF (s) | Fragment length (mm) |
|---|---|---|
| WOG | 167 (28)$^{a}$ | 5.76 (0.57)$^{a}$ |
| HEDM | 266 (33)$^{b}$ | 5.77 (0.52)$^{a}$ |
| M Pro | 102 (21)$^{c}$ | 5.77 (0.55)$^{a}$ |

*Mean values followed by different superscript letters in the same column are statistically significant ($P \leq 0.05$). HEDM: Hyflex EDM, WOG: WaveOne Gold, TtF: Time to fracture

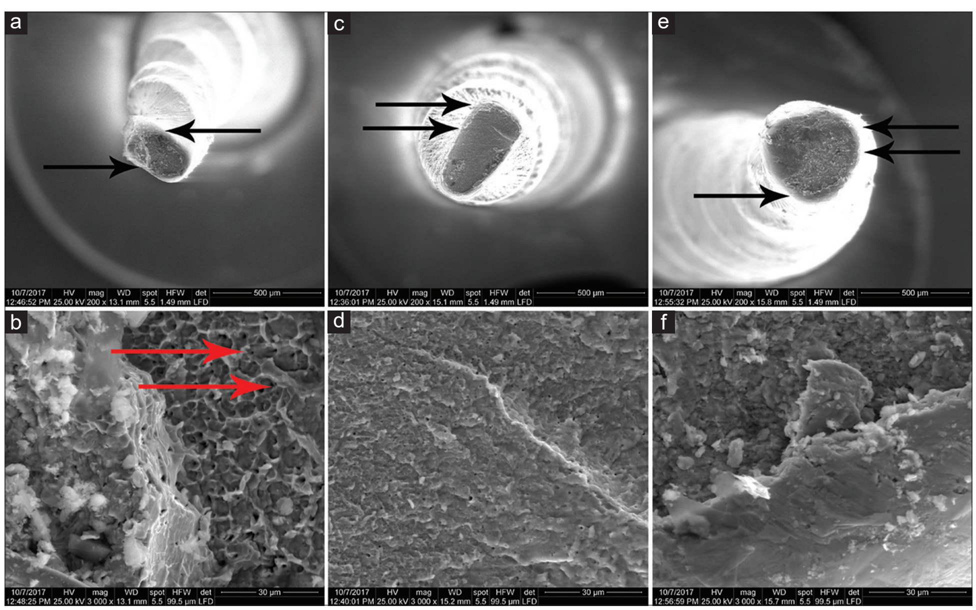


**Figure 1:** Scanning electron micrographs of the fractured surfaces obtained from the instruments after cyclic fatigue testing. At low magnification (×200; a, c, and e), centrally located overload zones with evidence of multiple crack initiation sites (black arrows) around the perimeter of the instrument are shown. At high magnification (×3000; b, d, and f), overload zones revealed evidence of dimpled rupture that occurred due to the coalescence of the microvoids in the overload zone, resulting in the ultimate ductile fracture of the instruments. A large number of microvoids (red arrows) could be seen within the core of the instrument

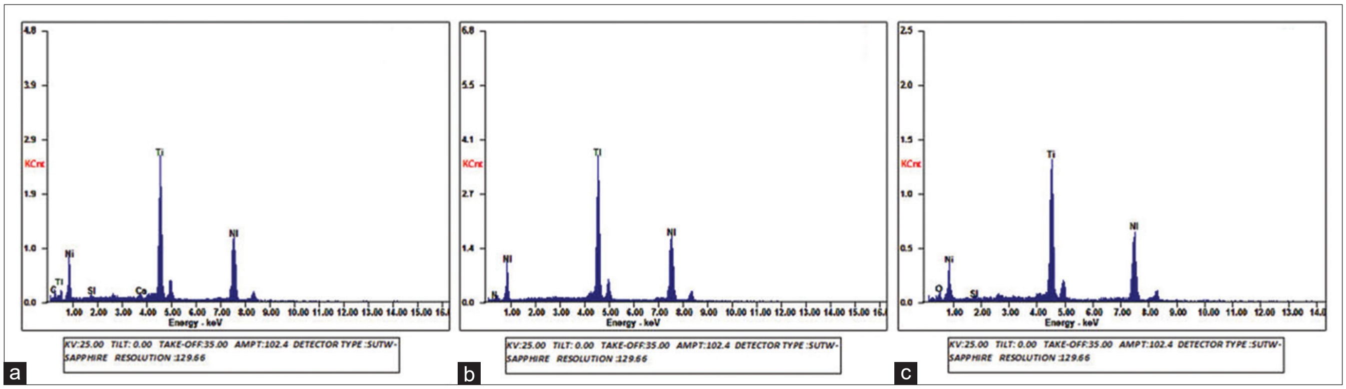


**Figure 2:** Graphic representation of the energy dispersive X-ray analysis results showing the elemental composition of WaveOne Gold (a), Hyflex EDM (b), and M Pro (c) files. KV: 25.00 Tilt: 0.00 Take-off: 35.00 Ampt: 102.4 Detector type: Sutw-Sapphire resolution: 129.55

would use natural curved root canals. However, the tooth will be used only once and standardization of the experimental conditions will be impossible.[23]

A dynamic model for cyclic fatigue testing represents the clinical situation more than a static one; yet, it is more liable to procedural errors and is more difficult to keep the instruments in a precise trajectory.[24]

It has been clearly demonstrated that temperature has a significant effect on cyclic fatigue resistance of all mechanical NiTi endodontic instruments.[25-27] Increase in temperature affects the properties of NiTi alloys.[28] Rotary instruments work at an intracanal temperature of 31°C–35°C[29] rather than room temperature. It was clearly demonstrated that the increase in temperature from room temperature to body temperature affects negatively the cyclic fatigue resistance of rotary NiTi instruments.[24,26,30] This could be explained on the basis of the metallurgical properties of the endodontic instruments. Predominantly, martensitic instruments at room temperature are transformed to a more austenitic phase upon heating, thus decreasing their cyclic fatigue resistance. This is related to the thermomechanical history of the NiTi alloy tested.[30] For this reason, the present study was conducted at body temperature to better simulate the clinical conditions.

The fractured segments' lengths in all groups did not show any significant difference. This indicates correct instruments positioning inside the artificial canal.[18]

M Pro showed the least cyclic fatigue resistance at simulated body temperature. This cannot be directly compared to earlier studies because none could be found in the literature.

Instruments' cross-sectional design, taper, pitch, alloy, manufacturing method, heat treatment, kinematics, and usage speed influence its cyclic fatigue resistance.[11,15-17] The convex triangular cross-section of M Pro possesses more metal mass, and consequently, more stresses concentration than the quadratic cross-section of HEDM and the parallelogram cross-section of WOG. Another contributing factor is the constant taper of M Pro of 6%, compared to the regressing taper of HEDM and WOG, which allows for more instrument-dentin contact, more stress, and cyclic fatigue failure.

WOG showed a superior cyclic fatigue resistance to M Pro which could be easily explained on the basis of kinematics as reciprocation motion increases the cyclic fatigue resistance compared to rotation motion.[15,31,32] Stress concentration at one point of the instrument occurs during continuous rotation motion, rather than at multiple points at each cycle during reciprocation motion. This attenuates the magnitude of stresses built up inside the instrument during operation. An instrument rotating in a curved root canal suffers from alternating compressive and tensile stresses. Upon reciprocation, lower stresses are induced because of the shorter distance traversed in each cycle. This could be added to the gold heat treatment applied in the manufacturing of WOG instruments that was shown to increase its flexibility,[18] and thus increasing its cyclic fatigue resistance.

HEDM showed a superior cyclic fatigue resistance to M Pro as well. Although both files are CM wires used in continuous rotation, they differ in the manufacturing process. HEDM is machined by electrodischarge machining which is a noncontact thermal erosion process that partially melts and evaporates the NiTi wire by high-frequency spark discharges. This technique was proved to enhance the mechanical properties greatly.[33]

Our results showed superior fatigue resistance of HEDM to WOG which come in agreement with Pedullà *et al.*[34] and

Gündoğar and Özyürek.[18] This clearly demonstrates that kinematics is not the only factor that influences cyclic fatigue, but rather the cross-section, alloy type, manufacturing technique, heat treatment, and usage speed influence the cyclic fatigue life of the instrument.[11,15-17] HEDM possesses 8% taper in the apical region and 4% in the coronal region. WOG has 7% taper apically and 3% coronally.

The difference in cross-sectional design might contribute as well. As the tested instruments fractured at D5 to D6 (mean fragment length 5.7 ± 0.5 mm), HEDM changes its cross-section from quadratic to triangular which bears less metal mass and less stress concentration than the parallelogram cross-section of WOG.

Hülsmann *et al*.[24] has shown that cyclic fatigue testing lacks reproducibility as while comparing a particular instrument, WaveOne, for example, a maximal difference between the values published of 200.9% is found. In most of these studies, no clear explanation could be found.

EDXA showed that HEDM instruments were composed of nickel (52.9 wt%), M Pro (49.7 wt%), and WOG (45.1 wt%). The Ni content of a NiTi alloy influences the mechanical properties of endodontic instruments.[35] With the reduction of the Ni content, there is an increased tendency to obtain stable martensite (which is more flexible than austenite) at the working temperature.[36,37] However, it seems that the Ni content was not the most important factor in the superior behavior of HEDM.

The three tested instruments possess different metallurgic properties, manufacturing techniques, heat treatments, cross-section designs, tapers, and kinematics. Therefore, no single parameter could explain our results. Yet, we can conclude that M Pro possesses the least cyclic fatigue resistance followed by WOG and HEDM. Moreover, it is worth mentioning that the clinical situation involves a complex type of stresses, and further studies are deemed necessary to investigate the microstructure and behavior of these instruments.

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## Conflicts of interest

There are no conflicts of interest.

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