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ORIGINAL ARTICLE/ARTICOLO ORIGINALE

Wear analysis and cyclic fatigue resistance of electro discharge machined NiTi rotary instruments

HyFlex EDM: caratteristiche superficiali e resistenza alla fatica ciclica di innovativi strumenti rotanti NiTi prodotti per elettroerosione

F. Iacono [a], C. Pirani [a,*], L. Generali [b], P. Sassatelli [c], C. Nucci [a], M.G. Gandolfi [a], C. Prati [a]

[a] *Endodontic Clinical Section, Master Program for Clinical Endodontics, Department of Biomedical and Neuromotor Sciences (DIBINEM), University of Bologna, Bologna, Italy*
[b] *Department of Surgery, Medicine, Dentistry and Morphological Sciences with Transplant Surgery, Oncology and Regenerative Medicine Relevance (CHIMOMO), School of Dentistry, Endodontic Section, University of Modena and Reggio Emilia, Modena, Italy*
[c] *Department of Engineering Enzo Ferrari (DIEF), University of Modena and Reggio Emilia, Modena, Italy*

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KEYWORDS
CM-wire;
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Wear;
SEM analysis;
Cyclic fatigue.

Abstract
Aim: To evaluate the wear of new rotary instruments produced via electro discharge machining and to test their fatigue resistance.
Methodology: Twenty-one HyFlex EDM (Coltène/Whaledent, Switzerland) files were used for laboratory instrumentation of curved root canals of extracted teeth. Superficial characteristics were analyzed pre- and postoperatively by scanning electron microscopy (SEM) (JSM-5200, JEOL, Tokyo, Japan) at same points and with same angulations to identify the wear features. Number of fractures, microcracks blunt/disruption of cutting edge and tip deformations were reported.

* Corresponding author at: Endodontic Clinical Section, Department of Biomedical and Neuromotor Sciences (DIBINEM), University of Bologna, Alma Mater Studiorum, Bologna, Italy. Tel.: +39 051 2088126; fax: +39 051 225208.
E-mail: chiara.pirani4@unibo.it (C. Pirani).
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Twenty HyFlex EDM and 20 HyFlex CM (Coltène/Whaledent, Switzerland) were subjected to cyclic fatigue test in a 70° artificial metal canal. Results were statistically analyzed using Mann–Whitney tests.

Results: No fractures were registered during laboratory canal instrumentation. No wear and no degradation of the 25.12 and 25.08 files were reported. Slight plastic deformations were only observed in three 10.05 files. The cyclic fatigue test revealed a significant increase of fatigue resistance of EDM files compared to CM ($p = 0.0001$).

Conclusions: The typical irregular surface of HyFlex EDM remained unaffected after multiple uses, confirming a high wear resistance. The new manufacturing process of electrical discharge machining had a substantial impact on fatigue lifetime of EDM files when compared with HyFlex CM. Within limitations of the present *in vitro* results, EDM files appeared suitable in shaping severely curved canals.

PAROLE CHIAVE
Strumenti endodontici;
Nichel Titanio;
Elettroerosione;
Analisi superficiale;
Fatica ciclica.

Riassunto

Obiettivo: Esaminare la morfologia superficiale e l'usura di strumenti HyFlex EDM usati *in vitro* e testare la loro resistenza in fatica ciclica.

Materiali e Metodi: Ventuno strumenti HyFlex EDM sono stati utilizzati per la strumentazione *in vitro* di canali curvi. La morfologia di superficie e i fenomeni di usura sono stati investigati pre e post operativamente con un Microscopio Elettronico a Scansione (SEM) (JSM-5200, JEOL, Tokyo, Japan). Ulteriori 20 HyFlex EDM sono stati poi testati in fatica ciclica in un canale artificiale con angolo di curvatura di 70° e comparati con strumenti HyFlex CM. I dati ottenuti sono stati validati con il test di Mann-Whitney.

Risultati: Le indagini al SEM hanno rivelato una specifica struttura irregolare caratterizzata da una superficie con morfologia a ''cratere'' legata alla capacità erosiva generata dalle scariche elettriche del processo produttivo. Tutti gli strumenti, dopo diversi utilizzi, hanno preservato il loro peculiare aspetto crateriforme e non hanno mostrato appiattimento dell'angolo di taglio delle lame. Non si è verificata nessuna frattura. I test di fatica ciclica hanno evidenziato una resistenza statisticamente significativa degli HyFlex EDM rispetto agli HyFlex CM ($p = 0.0001$).

Conclusioni: Gli HyFlex EDM hanno dimostrato un affidabile comportamento *in vitro* quando sottoposti a strumentazione di canali molto curvi. La superficie crateriforme si è ben conservata dopo ripetuti utilizzi. Gli strumenti di diametro minore sono apparsi quelli maggiormente stressati. La resistenza in fatica ciclica di strumenti della stessa lega sembra essere notevolmente aumentata dal differente processo di produzione.

Introduction

Introduction of nickel titanium (NiTi) rotary instruments has favored endodontic procedures by minimizing procedural errors associated with hand instrumentation and reducing time for chemo-mechanical preparation.[1,2] Despite many advantages of the NiTi instruments, unexpected intracanal separation due to torsion or flexural fatigue of the instruments is still a major concern.[3,4] In recent years, several novel thermo-mechanical processing and manufacturing technologies have been developed to optimize the microstructure of NiTi alloys.[5] In 2010, CM (controlled memory) NiTi files have been introduced using a special thermo-mechanical process of the alloy that controls the memory of the material, making the files extremely flexible but without the shape memory of other NiTi files, as opposed to what is found with conventional NiTi instruments. This imparts to the HyFlex CM (Coltene/Whaledent, Switzerland) a high fatigue resistance[6,7] and the possibility to be easily bended during use, recovering its original shape heating above the transformation temperature.[8] Recently a patented fabrication process was introduced in the manufacturing of new files obtained by the same CM wire. In fact, HyFlex EDM (Coltene/Whaledent, Switzerland) instruments are manufactured via electro discharge machining (EDM) process. In the EDM process an electric spark is used to cut the workpiece, which takes the shape opposite to that of the cutting tool or electrode. The electrode and the workpiece are both submerged in a dielectric fluid, which is generally light lubricating oil.[9] The electrical sparks causes a local melting and partially evaporation of small portion of material that is removed from this local area living a typical crater-like surface finishing.[10] Despite EDM is a common fabrication process for miniaturized components in medical technology,[11–13] HyFlex EDM files are the first endodontic instruments manufactured with this process.

The aim of this study was to evaluate the wear of new rotary instruments produced via electro discharge machining and to test their fatigue resistance in comparison with the conventionally manufactured HyFlex CM.

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Materials and methods

Twenty-one brand new HyFlex EDM were subjected to *in vitro* wear tests. Tests were performed using severely curved canals selected from a pool of extracted human multi-rooted teeth according with Kosti et al.[14] Once that canal patency was verified with a #10 K-file, the working length was determined by subtracting 1 mm. HyFlex EDM files were used with a 16:1 reduction handpiece X-Smart (Dentsply Maillefer, Baillagues, Switzerland) following the manufacturer's recommendation, at 500 rpm and 2.5 N cm, in pecking motion. The operative sequence was: 25/12 at 2/3 of the WL, 10/05 and 25/08 at WL. Irrigation was performed with 3 ml of 5% NaOCl (Niclor 5, Ogna, Muggiò, Italy) and 3 ml of 10% EDTA (Tubuliclean, Ogna, Muggiò, Italy). Each instrument was used in 10 curved canals, washed in an ultrasonic bath containing detergent for 10 min and then autoclaved at 134 °C.

Scanning electron microscope (JSM-5200, JEOL, Tokyo, Japan) was used to evaluate brand new HyFlex EDM instruments, and the same samples after canals instrumentation at same points and with same angulations to identify the wear features.

Micrographs were taken at increasing magnification from 35× to 5000×, on the tip of the instruments, and on cutting edges at 5 mm from the tip. The wear degradation was evaluated comparing the pre- and post-operative micrographs, in order to verify fractures and the presence of unwinding, microcracks, blade disruption and tip deformation.

Cyclic fatigue tests were performed on 20 brand new HyFlex EDM 25.08 (n = 10) and 40.04 (n = 10) using an artificial stainless steel canal with 5.0 mm radius of curvature, 70° angle of curvature and the center of the curvature at approximately 5.0 mm from the tip of the instrument and an overall length of 18.0 mm. A stainless steel apparatus provided a standardized placement of the NiTi instruments in the artificial canal.[15] All the files were rotated until the fracture and time was visually recorded with a digital stop-watch (3M ESPE, St. Paul, MN, USA). The number of cycles to fracture (NCF) was calculated using the following formula: NCF = time (s) failure × rotational speed/60.

The same test was also performed on 25.04 (n = 10) and 40.04 (n = 10) brand new HyFlex CM, whose results has been taken as a benchmark.

Results

Superficial investigations conducted by SEM on new EDM files disclosed the presence of the typical irregular surface texture derived from the manufacturing process (Fig. 1a). In fact, high magnification micrographs disclosed a non-uniform structure were voids caused the "spark-machined" surface (Fig. 1b). During root canal instrumentation, no files fractured (Table 1). All the instruments, after multiple uses, well preserved the "spark-machined" surface without cutting edge or blunt disruption. All used instruments presented no surface defects and only three 10.05 files showed microcracks perpendicularly to the axis of the instrument, near the tip. Spiral distortions and microcracks were absent in severely stressed 25.12 and 25.08, when a comparison was made between new and used files (Fig. 2). A spiral unwinding was observed at high magnification in one 10.05 file. The incidence of detected metal defects is represented in Table 1. Only three used instruments presented wide areas of debris on the instruments surface.

HyFlex EDM files exhibited a statistically higher cyclic fatigue resistance when compared with CM (Fig. 3). Mann–Whitney was performed; α-level was *a priori* set at 0.05. When 40.04 EDM was compared with 40.04 CM, a significant increase was observed (p = 0.0001).

Discussion

Improvement in the manufacturing process of NiTi endodontic files has been proposed over last years and thermomechanical processing procedures have been adopted providing superior mechanical properties to the instruments.[3] HyFlex EDM are produced with the well-known controlled memory (CM) wire but with a different fabrication process that use the ability of electrical sparks to partially melt and evaporate small portion of material in a dielectric medium.[10] Despite EDM being a common fabrication process already

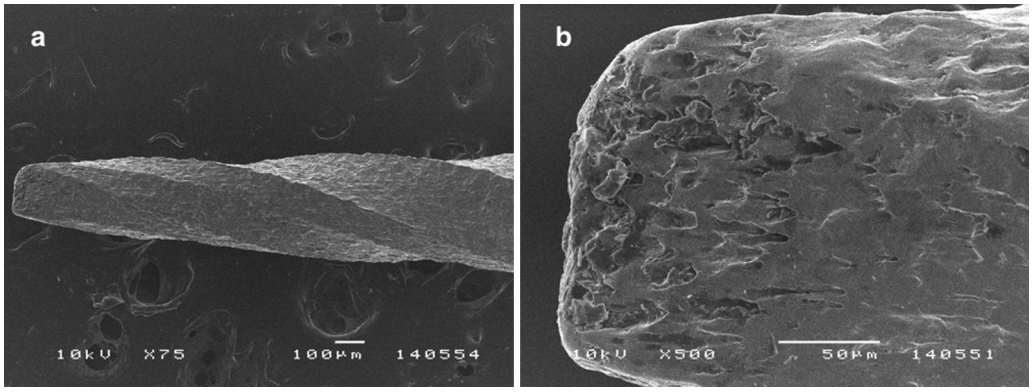

Figure 1 New HyFlex EDM 25.12 instrument at 75× (a) showed the typical irregular surface texture derived from the electro discharge machining. (b) High magnification micrographs (500×) of the tip of the same instrument disclosed a non-uniform structure where pits, pores and voids cause the peculiar aspect of a "spark-machined" surface.

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Table 1 Number of defects after 10 root curved canals instrumentation.

HyFlex EDM	Fractures	Unwinding	Microcracks	Tip deformation	Blade disruption
25.12 ($n = 7$)	0	0	0	0	0
10.05 ($n = 7$)	0	3	3	2	0
25.08 ($n = 7$)	0	0	0	0	0

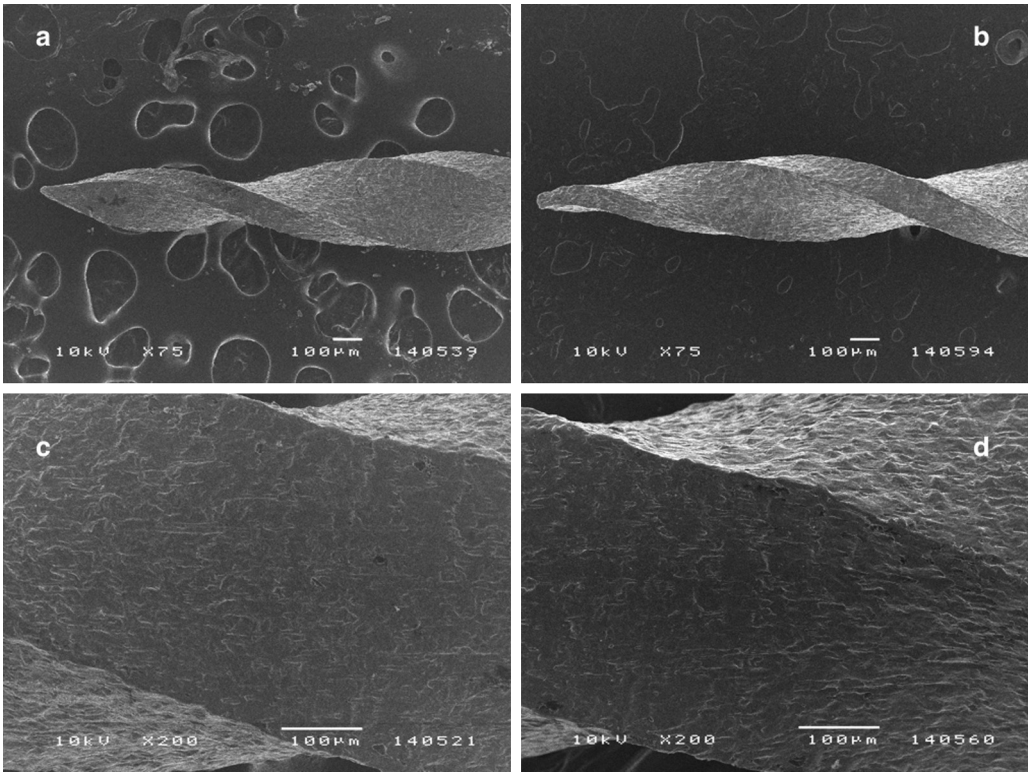

Figure 2 HyFlex EDM 25.08 at 75× before (a) and after use in 10 canals (b). Micrographs were taken at the same magnification revealing the absence of deformations or spirals unwinding. At higher magnification (200×), at 5 mm from the tip, the comparison between new (c) and used file (d) showed the preservation of the ''spark-machined'' without alteration of the outline and no blade disruption and microcracks.

used for NiTi alloys for surgical applications,[12,13] HyFlex EDM are the first endodontic instruments manufactured with this procedure. It is known that EDM process creates a rough and hard surface that could improve the cutting efficiency of tools[16] and SEM micrographs on HyFlex EDM files revealed a rough ''spark-machined'' surface that is the typical superficial morphology of the electro discharge machined materials. This superficial rough aspect represents a surprising innovation in comparison with conventional NiTi endodontic files. In the present study no fractures, plastic deformations or microscopic signs of wear were reported in large instruments (25.12 and 25.08) during *in vitro* instrumentation of multiple curved canals. All the instruments well-preserved the ''spark-machined'' irregular surface without cutting edge alterations. Only minor defects were reported on the tip region of three used 10.05 files. This could be explained by a supposed higher susceptibility to torsional stresses of small CM-treated files than larger instruments[17,18] and caution would be recommended regarding reuse of small HyFlex rotary files.

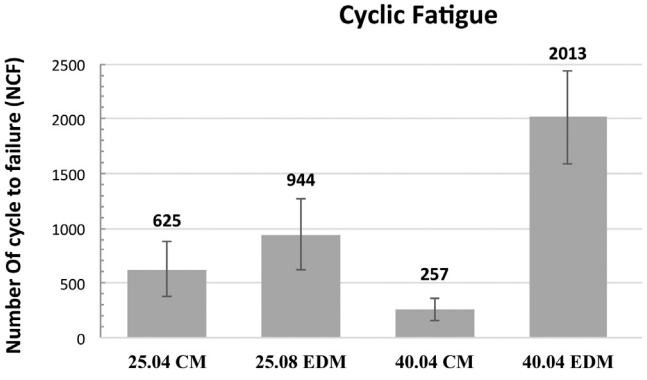

Figure 3 The chart reports numbers of cycles to failure (NCF), for HyFlex EDM and HyFlex CM.

Several studies reported that surface finish has an effect on the crack initiation process[19] and structural irregularities of the instrument surface may compromise its integrity during clinical use, making the files more susceptible to fracture.[20] In contrast with these findings, the remarkable irregularities observed on the surface of the HyFlex EDM did not compromise the instruments integrity after multiple

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uses. Surprisingly, the cyclic fatigue tests demonstrated a significant greater resistance of the ''irregular'' EDM instruments compared with the conventionally manufactured CM files. This is particularly unexpected since both EDM and CM files are manufactured with the same controlled memory wire and such great improvement is likely to be related to the electro discharge machining manufacturing process. A remarkable increase in cyclic fatigue resistance of the thermal treated CM wire instruments compared with conventional NiTi files has been extensively documented.[6,7,21,22] It may therefore be supposed that thermomechanical treatment procedures performed on the EDM instruments during the manufacturing process cause changes of the phase composition of the wire influencing the mechanical properties of the instruments. The low degradation after multiple uses and the improved mechanical properties, due to the innovative fabrication process, could have an important clinical relevance in order to minimize the risk of fracture of the instruments.

Conclusions

The electro discharge machining manufacturing process creates a spark-machined surface unaffected after multiple uses. Cyclic fatigue tests demonstrated that the thermomechanical treatment procedures had an important impact on fatigue lifetime of HyFlex EDM.

Conflict of interest

The authors declare to have no conflict of interest related to this study.

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