Comparison of Cyclic Fatigue Resistance of Five Heat Treated NiTi Rotary Systems in Single and Double Curved Canals.

Mohammad Al-Obaida

King Saud University

Khalid Merdad

King Abdulaziz University

Ali Alkhamis

Ministry of Health

Muneer Khan Mohammed

King Saud University

Rahaf Al-Obaida

Riyadh Elm University

Ebtissam Al-Madi (✉ ealmadi@ksu.edu.sa)

King Saud University

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Abstract

Background

The aim of this study was to compare cyclic fatigue resistance (CFR) and separation patterns during rotating movement of five heat-treated nickel titanium files in both single and double-curved canals.

Methods

CFR was compared between five groups of 24 files each: HyFlex® EDM, HyFlex™ CM, Vortex Blue®, Protaper Next®, and One Curve, by determining the time needed to fracture (TTF) and the number of cycles to failure (NCF) in a cyclic fatigue testing device with a single 5-mm radius of curvature (ROC) and 60° angle, and a double curvature; coronal curvature (5 mm ROC and 60° angle) and apical curvature (2 mm ROC and 70° angle). The separation pattern was evaluated, and file fragment separated length were measured. One-way ANOVA and Tukey's post-hoc were used to compare statistical differences between the groups. Scanning Electron Microscope (SEM) was used to investigate the fracture sites.

Results

HyFlex™ CM files displayed significantly higher CFR, followed by HyFlex® EDM and Vortex Blue® in single curvature canals, and Protaper Next® (PTN) in the double curvature canals, as observed by TTF and NCF. PTN group had the highest tendency for files to extrude apically after separation in both curvatures.

Conclusion

HyFlex™ CM instruments have superior resistance to cyclic flexural fatigue within single canals with single and double curvatures, followed by HyFlex® EDM and Vortex Blue® instruments. Protaper Next® files followed by One Curve had the highest tendency to extrude apically after separation

Clinical relevance

HyFlex™ CM instruments showed the highest safety in preparing canals with single or double curvatures, considering CFR.

Background

Since their introduction into clinical practice, nickel-titanium (NiTi) rotary endodontic instruments have enhanced the effectiveness of endodontic treatment with respect to accuracy, reduction of apical foramen transportation, and procedural time [1]. Their properties of shape memory, super-elasticity, and resistance to corrosion have minimized procedural errors since their use [2]. Despite the apparent advantages and excellent mechanical properties of NiTi alloy, the possibility of sudden fractures as a result of torsional overloading or flexural fatigue remains a major concern in clinical practice [1, 3]. Cyclic

fatigue occurs when the instrument rotates within a curved root canal and is exposed to a large number of tension-compression strain cycles at the maximum curvature of the canal [1]. The reasons for this fracture include operator-related factors [4], variations in the root and canal anatomy [5], and factors related to endodontic instruments such as alloy composition, manufacturing methods, and cross-sectional geometry [6, 7]. To address the instrument-related factors, several manufacturers have developed special thermomechanical processing techniques for NiTi instruments that significantly improve fatigue resistance in comparison with conventional superelastic NiTi alloys [8–10].

HyFlex™ CM files (Coltene-Whaledent, Allstetten, Switzerland) are made from a new type of NiTi wire, namely controlled memory (CM) wire. It is manufactured by a unique process that controls the material's memory [11]. HyFlex® EDM files (Coltene-Whaledent) are fabricated using an electro-discharge machining (EDM) process [12]. Protaper Next® (Dentsply, Maillefer) was developed using the new M-Wire alloy. Its design features include variable tapers and an off-centered rectangular cross section [13]. Vortex Blue® rotary files (Dentsply, Tulsa Dental) process the NiTi wire in a manner claimed to reduce shape memory [14]. The One Curve (Micro-Mega) single-file NiTi system is manufactured from a C-wire by using a proprietary heat treatment that results in a controlled memory and a variable cross-section [15].

The aim of this investigation was to compare the cyclic fatigue resistance and mode of separation between five heat-treated nickel titanium files in rotating movement in single and double curved canals. The null hypothesis is that there is no difference between cyclic fatigue resistance between all files tested, while the alternate hypothesis is that there is a difference between cyclic fatigue between all files tested.

Methods

Five groups; HyFlex® EDM® (EDM), HyFlex™ CM® (CM), Vortex Blue® (VTB), Protaper Next® (PTN), and One Curve (OC), were tested with a cyclic fatigue resistance device manufactured to test cyclic fatigue. A total of 120 files of all systems with the same tip size (0.25 mm) and length (25 mm) with different cross-sections were examined. Twenty-four files were used in each group, subdivided into 2 sub-groups of 12 files each, and their cyclic fatigue resistance was examined in single-curvature and double-curvature artificial canals. A total of 10 groups were tested as follows:

Groups EDM 25/~ in a single-curvature canal (n=12) and a double-curvature canal (n=12).

Groups CM 25/04 in a single-curvature canal (n=12) and a double-curvature canal (12).

Groups VTB 25/04 in a single-curvature canal (n=12) and a double-curvature canal (n=12).

Groups PTN 25/05 in a single-curvature canal (n=12) and a double-curvature canal (n=12).

Groups OC 25/06 in a single-curvature canal (n=12) and a double-curvature canal (n=12).

The device used for cyclic fatigue testing was designed and manufactured by the authors (Fig. 1), as described in Al-Obaida et al [16]. Each instrument was used according to the manufacturer's instructions

and activated by using a 6:1 reduction Sirona handpiece that was powered by a torque-controlled electric motor (X-Smart Plus (Dentsply Maillefer, Ballaigues, Switzerland)). The rpm was set based on the manufacturers' suggestion, which was 300 rpm for PTN, 400 rpm for EDM, and OC, and 500 rpm for CM and VTB. Root canal cream (RC-Plus[®], MEDICEPT UK LTD) was used as a lubricant at room temperature, to minimize the friction of the files in the canal.

Every instrument was rotated until it fractured. The time to fracture (TTF), in seconds, was logged for all samples using Zeiss Loupes (4x power of magnification) by the same observer. Number of cycles to failure (NCF) were calculated by multiplying the number of rotations/cycles per minute by the TTF. The tendency of the separated file to extrude apically 'separation patterns' were compared between the groups, and the fragment length and diameter was measured. Fracture surface characteristics were examined in representative samples from all groups by using SEM at 300X.

SPSS 20.0 software (SPSS Inc., Chicago, IL, USA) was used for analysis. The cyclic fatigue values were evaluated by one-way ANOVA and Tukey's post-hoc test to establish statistical differences between the groups. Significance was established at the 95% confidence level.

Results

Time to fracture

The mean values and standard deviations for the TTF are presented in Table 1. In the single-curvature artificial canal, the CM group showed a significantly higher mean TTF than all other groups ($P < .05$). The mean TTF in the EDM group was significantly higher than those in the remaining groups ($P < .05$), and the VTB group was significantly higher than those in the PTN, and OC groups ($P < .05$). No significant difference was observed among the PTN, and OC groups ($P > 0.05$).

In the artificial canal with double curvatures, the CM group showed the highest mean TTF, which was significantly higher than those in the PTN and OC groups ($P > 0.05$) but not significantly different from the values in the other groups.

Number of cycles to failure

Mean and standard deviation values for NCF are presented in Table 1. In the single-curvature artificial canal, the CM group showed a significantly higher mean NCF than all other groups ($P > 0.05$). The NCF values in the EDM and VTB groups were not significantly different from each other but were significantly higher than the values in the PTN, and OC groups ($P > 0.05$). There were no significant differences between the PTN, and OC groups.

For the artificial canals with double curvatures, the CM group showed the highest mean NCF, followed by the OC, VTB, and EDM groups. The CM group value was significantly higher than those in the PTN groups ($P < .05$). No significant difference was found among the EDM, VTB, or OC groups.

The mean Fragment length and diameter at level of separation are shown in table 2, while the minimum and maximum diameter of the fracture in the tested NiTi instruments in single and double curvatures are shown in Fig 2. The EDM group in the single canal curvature had the significantly higher fragment length than all other groups at 6.46mm ($p=0.00$), while fragment lengths of all other file groups in the single canal (range from 1.42mm to 1.92mm) and the double canal (range 4.29mm to 4.71mm) were not significantly different within the canal curvatures. Accordingly, the diameter at the site of fracture in the EDM group in the single canal (0.71) significantly differed from all other groups ($p=0.00$), while the EDM, PTN and OC in the single curvature did not differ from one another (0.36, 0.37), nor did the CM and VTB in the single curvature (0.42, 0.43) differ from one another. Neither did the CM and VTB diameter at fracture site in the double canal (0.32) differ from each other, nor did the PRN and OC (0.52, 0.53) in the single canal curvature. PTN group was the highest file with tendency to extrude apically after separation in single curvature canals and double curvature canals (12 and 11 out of 12 respectfully), followed by OC in both single and double curvature (11 and 7 out of 12 respectfully), then VTB in double curvature (2/12). EDM, CM in both curvatures and VTB in single curvature did not have tendency to extrude after separation.

SEM Evaluation

The fractographic analysis of the specimens' fracture surface exhibited fatigue crack initiation at two distinct regions. Fatigue striations were observed in (region a) and a dimpled surface (region b) as shown in the Fig 3, 4.

Discussion

Several thermo-mechanical processing and manufacturing techniques have been developed to optimize the microstructure of NiTi alloys and provide superior mechanical properties to the instruments [3, 17]. Thermal treatment may significantly increase the fatigue resistance of NiTi files [18]; the heat treatments change the crystalline disposition of the nickel and titanium atoms, which undergo a main shift from the cubic (austenitic) to tetragonal molecular arrangement (martensitic) phase, inducing different mechanical properties [17, 19–22]. In the present study, five novel heat-treated NiTi files were compared with respect to their cyclic fatigue resistance and separation patterns in single and double curved canals. The main finding of our study was that CM files displayed significantly higher cyclic fatigue resistance in an S-shaped artificial canal, denying the null hypothesis is that there is no difference between cyclic fatigue resistance between all files tested.

Teeth with S-shaped (double curvatures) root canals can be challenging, since the instruments can be vulnerable to deviations in anatomy, loss of working length, and potential for file separation. Fatigue has been implicated to be the main reason for the fracture of clinically used endodontic files [23]. Other studies have tested cyclic fatigue in various instruments *in vitro* in double curvatures [24], however in the present study, two artificial canals (single and double curvatures) were specially manufactured and their cross-sectional measurements were designed to be suitable for all systems to minimize any factors that

may affect the results. Extracted teeth were not used, since imitating clinical conditions and ensuring standardization is difficult with extracted teeth [25]. Nevertheless, the artificial canal has greater volume in comparison to the instruments which allow them to rotate with no low contact area, which is considered a limitation in all studies of this nature but do provide important initial information in file testing.

Fatigue resistance was compared using the TTF and NCF values. In both single- and double-curvature canals, TTF was the longest for CM, followed by EDM, VTB, PTN, and finally OC. CM's TTF was almost double the TTF for EDM and 7 times higher than the lowest values (PTN and OC). CM also showed the highest NCF in the single-curvature assessments and double-curvature assessments. Controlled memory (CM) wire is produced by a special thermo-mechanical process involving the alloy that controls the memory of the material, making the files extremely flexible but without the shape memory, in contrast to conventional NiTi instruments. This imparts high fatigue resistance to the CM [14, 26], allowing it to easily bend during use and recover its original shape when heated above the transformation temperature [27]. Our present results agree with many studies that have demonstrated that CM wire instruments have greater cyclic fatigue resistance than conventional NiTi instruments [14, 26, 28, 29]. However, the standard deviation for the TTF in the CM group was very high. CM showed similar numbers in the double-curve canal, while the numbers differed in the single-curve canal. This could be due to a manufacturer's defect in one batch of the files, or it may indicate that despite the high resistance to fracture in this type of file, its reliability is questionable. It is important to note that all tests were performed by the same operator, and all other standard deviations were low, indicating that the possibility of experimenter error is low.

EDM are also produced with CM wire; however, they are produced with a different fabrication process that uses an electro-discharge machining (EDM) process [12]. In the EDM process, melting and evaporation of the top layer creates a rough, crater-like surface finishing [12, 30]. EDM files are the first endodontic instruments manufactured with this process. The surfaces created through the EDM process could improve the cutting efficiency of tools, as compared to conventional NiTi endodontic files [31]. However, some studies have reported that this surface finish has an effect on the crack initiation process [32] and structural irregularities of the instrument surface may compromise its integrity during clinical use, making the files more susceptible to fracture [7], while others have shown that the cyclic fatigue associated with EDM was significantly greater than that for the conventionally manufactured CM files [20]. In the present study, EDM files showed better resistance to cyclic fatigue than the other files, which is in agreement with the findings of several studies [12, 33, 34], but its resistance was still lower than that of the CM files, which is inconsistent with other findings [35]. On the other hand, the EDM file showed a significantly longer fractured fragment length and separated at a larger diameter than all other files in both single and double canal curvatures. This supports the theory of compromised integrity due to instrument irregularities. Both files showed a reduced tendency to extrude out of the canal once fractured, which might prove to be an important consideration in cases of roots with open apices or enlarged apices due to resorption or presence of a periapical lesion.

A smaller taper and metal mass of the instrument are known to induce better cyclic fatigue resistance [12, 36–38]. Therefore, the NiTi files that were chosen for this study had comparable taper and size and were used for a single file canal preparation. These systems use a reciprocating motion and claim to shape root canals with a single file [39], which amounts to shorter working time; shorter learning curve, and a reduction in the number of instruments needed [2]. However, single-shaping files are exposed to high levels of stress, which might lead to cyclic and torsional fatigue [40]. Therefore, files used in single-file canal preparation systems should have a high resistance to fracture. In addition, cyclic flexural fatigue resistance decreases with extended use, which might be the case if these files are used for single use [41].

A lubricant was used to reduce friction during the test, as its importance was established in a pilot study and other studies [42]. Although current studies have shown that temperature was found to significantly increase the cyclic fatigue of nickel-titanium rotary files, and reduce the NCF, suggesting that cyclic fatigue studies should be conducted at body temperature (Dosanjh et al. 2017; Klymus et al. 2019), our studies were conducted at room temperature for initial testing.

In order to study the failure mechanism of the test files, the cross-sections of the broken files were viewed under the SEM. Although, 3D replicas could be used to compare cyclic fatigue among files with duplicated reconstructed anatomy, the SEM provides important information regarding fatigue failure within the instruments, which is the reason behind the current real-life replica testing apparatus. EDM showed the highest difference between the diameter of fracture in single and double curvature, the highest being in the single curvature, while the smallest difference was in the VTB, and CM files. The analysis revealed fatigue failure of the test files with crack initiation at one or more points. All files exhibited two distinct regions, one with the fatigue striations (region a) and the other with the dimpled surface (region b) as shown in Fig. (3,4). The fatigue striations are the characteristic feature of fatigue crack growth whereas the dimpled surface indicate ductile fracture. The crack originates at the edge due to the presence of high stresses as shown in Fig. (3a, 4a) and it propagates until the fatigue striations. Micro-voids coalescence takes place by the nucleation of micro-voids, which results in weakening of the material, after that ductile fracture occurs until the failure that is evident from the dimpled surface as seen in Fig. (3b, 4b).

Conclusion

Within the limitations of this study, HyFlex™ CM instruments displayed significantly higher cyclic fatigue resistance and therefore, superior fracture resistance, than HyFlex® EDM and Vortex Blue® within single canals with single and double curvatures. ProTaper Next®, and One Curve showed less resistance to cyclic fatigue in the tested canals. Additionally, Protaper Next® files followed by One Curve had the highest tendency to extrude apically after separation, especially in single curve canals, while HyFlex® EDM and HyFlex™ CM did not have any tendency to extrude.

Abbreviations

CFR; Cyclic Fatigue Resistance

TTF; Time needed To Fracture

NCF; Number of Cycles to Failure

ROC; Radius Of Curvature

CM; Controlled Memory wire

EDM; Electro-Discharge Machining process

EDM; HyFlex® EDM ®

CM; HyFlex™ CM ®

VTB; Vortex Blue ®

PTN; Protaper Next®

OC; One Curve

Declarations

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

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Authors' contributions

MO & AK devised the concept. AK & MKM ran the tests and collected the data. MO & EM made the analysis. RO & EM drafted the manuscript. All authors revised the manuscript.

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Tables

Table 1: Mean and standard deviation of time to fracture (TTF) and number of cycles to failure (NCF) in the tested NiTi instruments

Groups		(n)	Mean TTF	Std. Deviation	Mean NCF	Std. Deviation
Single Canal Curvature 60 R 50	HyFlex® EDM	12	258.92	67.67	103,566.67	27069.45
	HyFlex™ CM	12	451.00	114.72	225,500.00	57359.31
	Vortex Blue®	12	167.75	17.70	83,875.00	8847.51
	Pro Taper Next®	12	63.75	7.56	19,125.00	2267.21
	One Curve	12	95.53	8.74	38,133.33	3496.84
Double Canal Curvature S curve	HyFlex® EDM	12	73.17	22.54	29,266.67	9016.89
	HyFlex™ CM	12	107.83	26.35	53,916.67	12173.38
	Vortex Blue®	12	60.42	18.40	30,208.33	9198.46
	Pro Taper Next®	12	37.74	6.62	11,325.00	1986.37
	One Curve	12	76.25	17.38	30,500.00	6951.52

Table 2: Mean Fragment length and diameter at level of separation in the tested NiTi instruments

Groups		(n)	Mean Fragment length (mm)	Std. Deviation	Mean Fragment diameter (mm)	Std. Deviation
Single Canal Curvature 60 R 50	HyFlex® EDM	12	6.46	0.58	0.71	0.02
	HyFlex™ CM	12	4.29	0.66	0.42	0.03
	Vortex Blue®	12	4.58	1.00	0.43	0.04
	Pro Taper Next®	12	4.50	0.71	0.52	0.04
	One Curve	12	4.71	0.33	0.53	0.02
Double Canal Curvature S curve	HyFlex® EDM	12	1.42	0.29	0.36	0.02
	HyFlex™ CM	12	1.71	0.33	0.32	0.01
	Vortex Blue®	12	1.63	0.23	0.32	0.01
	Pro Taper Next®	12	1.92	0.29	0.37	0.02
	One Curve	12	1.79	0.40	0.36	0.02

Figures

Figure 1

Cyclic Fatigue Testing Device

Figure 2

Minimum and Maximum diameter of fracture in the tested NiTi instruments in single and double curvatures.

Figure 3

Micro-voids and fracture showing fatigue striations (a) and dimpled surface (b) in EDM Single Canal, EDM Double canal, CM Single canal, and CM Double canal.

Figure 4

Micro-voids and fracture showing fatigue striations (a) and dimpled surface (b) in VTB Single Canal, VTB Double canal, PTM Single canal, and PTM Double canal.