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Research Article

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Comparison of the cyclic fatigue resistance of One Curve, F6 Skytaper, Protaper Next, and Hyflex CM endodontic files

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Conflict of Interest
No potential conflict of interest relevant to this article was reported.

Author Contributions
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ABSTRACT

Objectives: This study compared the cyclic fatigue resistance of One Curve (C wire) and F6 Skytaper (conventional austenite nickel-titanium [NiTi]), and 2 instruments with thermo-mechanically treated NiTi: Protaper Next X2 (M wire) and Hyflex CM (CM wire).
Materials and Methods: Ten new instruments of each group (size: 0.25 mm, 6% taper in the 3 mm tip region) were tested using a rotary bending machine with a 60° curvature angle and a 5 mm curvature radius, at room temperature. The number of cycles until fracture was recorded. The length of the fractured instruments was measured. The fracture surface of each fragment was examined with a scanning electron microscope (SEM). The data were analyzed using one-way analysis of variance and the *post hoc* Tukey test. The significance level was set at 0.05.
Results: At 60°, One Curve, F6 Skytaper and Hyflex CM had significantly longer fatigue lives than Protaper Next X2 ($p < 0.05$). No statistically significant differences were found in the cyclic fatigue lives of One Curve, F6 Skytaper, and Hyflex CM ($p > 0.05$). SEM images of the fracture surfaces of the different instruments showed typical features of fatigue failure.
Conclusions: Within the conditions of this study, at 60° and with a 5 mm curvature radius, the cyclic fatigue life of One Curve was not significantly different from those of F6 Skytaper and Hyflex CM. The cyclic fatigue lives of these 3 instruments were statistically significantly longer than that of Protaper Next.

Keywords: Cyclic fatigue; Scanning electron microscopy; Endodontics; Nickel-titanium alloy; Rotary files

INTRODUCTION

Nickel-titanium (NiTi) has remarkable properties, such as a shape memory effect and superelasticity, which confer its high elasticity [1-3]. It also exhibits good biocompatibility, which enables its use for medical devices [4]. In the field of endodontics, NiTi was first used for its superelasticity. The introduction of conventional equiatomic austenitic NiTi rotary instruments has facilitated endodontic procedures by reducing the time for

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chemo-mechanical preparation and minimizing procedural errors associated with hand instrumentation [5,6]. However, the main problem of NiTi instruments in clinical use is their unexpected fracture due to torsion or flexural fatigue [7]. For this reason, manufacturers are constantly attempting to improve instruments. Different strategies have been developed, such as the improvement of their geometrical parameters, the proposition of a new reciprocating working motion, the use of single disposable instruments, the application of surface treatments as electropolishing, and the use of new machining procedures (twisting and electrical discharge machining) to reduce surface micro-cracks and the use of thermomechanical treatment to obtain NiTi alloys containing the R-phase or martensite [8-14]. Thermomechanically treated NiTi alloys have been reported to be more flexible and to have an improved cyclic fatigue resistance thanks to their modified phase composition. They contain different percentages of R-phase and martensite at room or body temperature [15]. One of the first thermomechanical treatments was M-Wire treatment, which led to a NiTi alloy containing austenite with small amounts of R-phase and martensite [16].

Protaper Next instruments (size: 0.25 mm, 6% taper) (Dentsply Sirona, York, PA, USA) are made of M-wire, resulting in increased flexibility and an extended fatigue life beyond the conventional NiTi alloy [17,18]. Protaper Next is a sequence of rotary instruments that are designed with variable tapers on each instrument and an off-centered rectangular cross section.

The F6 Skytaper (size: 0.25 mm, 6% taper) (Komet Brasseler, Lemgo, Germany) is characterized by a constant 6% taper and by a S-shaped cross-section [19]. This file is made of a conventional equiatomic austenitic Ni-Ti alloy and is electropolished after machining. Another feature of F6 Skytaper is that a single instrument is used for the entire root canal shaping before being discarded.

The F6 Skytaper instrument shares this feature with the One Curve instrument (Micro Mega, Besançon, France). One Curve is a rotary system, which is produced with a diameter of 0.25 mm. It presents a variable cross-section (triple-helix section at the tip and an S-section closer to the shank), a constant 6% taper and a variable pitch. It has undergone a NiTi heat treatment called C Wire, which confers a shape memory effect to the file [20]. This file has been subjected to electropolishing, in order to enhance its resistance in cyclic fatigue.

Hyflex CM (Coltene-Whaledent, Allstetten, Switzerland) is another generation of a rotary file sequence with thermomechanical treatment. These instruments are made using a reduced percentage weight of nickel (52% Ni by weight) compared with the great majority of commercially available NiTi rotary instruments (54.5%–57% Ni by weight) [21]. For this reason and because of its specific thermomechanical treatment, Hyflex CM mainly contains martensite and exhibits shape memory [15]. Hyflex CM instruments (size: 0.25 mm, 6% taper) are electropolished and present a symmetrical triangular convex cross-section and a constant 6% taper [22,23].

To the authors' knowledge, the cyclic fatigue resistance of One Curve and F6 Skytaper have rarely been compared, and on a more general level, although there are a few publications on One Curve fatigue, the mechanical behavior of this file has not yet been extensively studied. The purpose of this study was to compare the cyclic fatigue resistance of the One Curve new single instrument (C wire, electropolishing) with the cyclic fatigue resistance of F6 Skytaper single instrument (conventional austenite superelastic NiTi alloy, with electropolishing) and 2 instruments with thermo-mechanically treated NiTi alloys: Protaper Next X2 (M wire) and Hyflex CM (CM wire, with electropolishing).

MATERIALS AND METHODS

As this study involved *in vitro* experiments, no ethics committee approval or informed consent was required.

Instrument samples

A total of 40 instruments were tested.

The instruments selected were Protaper Next X2 (size: 0.25 mm, 6% taper), F6 Skytaper (size: 0.25 mm, 6% taper), One Curve (size: 0.25 mm, 6% taper) and Hyflex CM (size: 0.25 mm, 6% taper). Ten new instruments of each group were tested.

Experimental cyclic fatigue tests

Each instrument was subjected to a rotary bending fatigue test with a 60° curvature angle and a 5 mm curvature radius, thanks to a special fatigue machine adapted to the size of endodontic files (**Figure 1**).

This device (**Figure 1**) was composed of a rotating engine axis with a chuck (clamping jaw A) to hold the instrument and by a bending axis with a clamping jaw (clamping jaw B) linked to a stainless-steel tube (with an inner diameter of 0.68 mm) for the tip of the instrument. The 2 axes were at a distance of 16 mm and the rotation center was located 10 mm from the rotating chuck. The tip of each instrument (4 mm) was inserted into the tube, whereas its shaft was inserted into the rotating chuck at 5 mm. An optical angular transducer connected to a controller monitored the bending angle until it achieved 60° of deflection; then, the instrument was put in rotation at 400 rpm, with a torque of 2.5 N·cm, in air at room temperature. To reduce friction and prevent overheating, grease (Molykote 33 Medium™; Dow Corning GMBH, Wiesbaden, Germany) was used for lubrication. The bending torque until fracture of the instrument was measured with a load cell of 20 N·cm (Buster 8625-4200; A-instruments Ltd, Toronto, Canada). A decrease in the value of this bending torque indicated fracture. This fracture time was recorded (seconds) and the number of cycles to fracture (NCF) was calculated. The lengths of the instruments were measured using a digital caliper (Facom, Morangis, France).

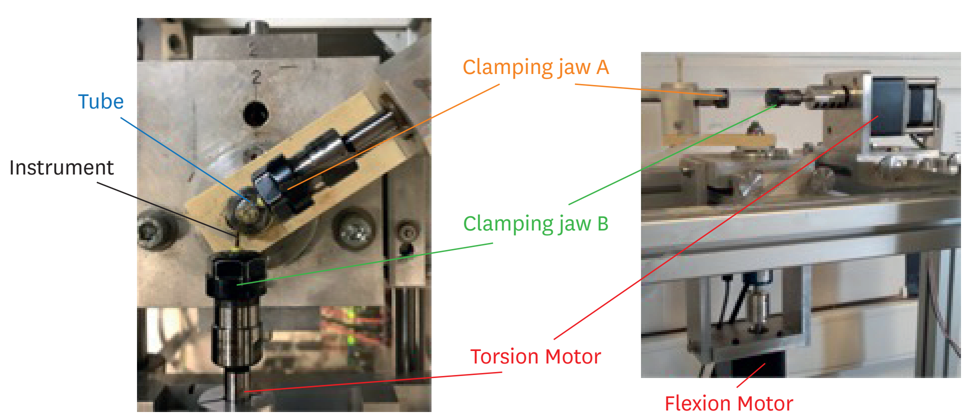

Figure 1. Photographs of the experimental set-up of the rotary bending fatigue machine.

Scanning electron microscopy (SEM) observations

Five instruments were randomly selected per group of instruments fractured during the tests and cleaned in an ultrasonic bath before observations under SEM (JSM-IT300LV; JEOL, Tokyo, Japan). The fractured surfaces were examined under magnification settings up to ×500 in order to investigate their topographic features. The objective was to confirm that the fracture occurred by a cyclic fatigue mechanism.

Statistical analysis

Collected data were statistically analyzed with dedicated software (Statistica; Tibco Software Inc, Palo Alto, CA, USA). After testing for normality, the NCF of the 4 groups (Protaper Next, F6 Skytaper, One Curve, and Hyflex CM) was compared using one-way analysis of variance (ANOVA). When ANOVA indicated a significant difference, the Tukey HSD test was performed for *post hoc* multiple comparison. An alpha risk of 0.05 was set as the limit of statistical significance ($p > 0.05$).

RESULTS

Experimental cyclic fatigue tests

The NCF and fragment lengths of the fractured instruments for Protaper Next, F6 Skytaper, One Curve, and Hyflex CM are presented in **Table 1**.

At 60°, F6 Skytaper, One Curve and Hyflex CM had significantly higher NCF than Protaper Next ($p < 0.05$). There was no statistically significant difference between F6 Skytaper, One Curve, and Hyflex CM ($p > 0.05$).

SEM observations

SEM images of the fracture surfaces of the different instruments (**Figure 2**) showed similar and typical features of fatigue failure, with a zone of crack initiation, a crack propagation zone, and a final fracture zone. In some of them, it was still possible to observe the dimples.

DISCUSSION

This study compared the resistance to rotational bending of 4 different instruments using a rotary bending machine. As there are no standards (neither ANSI/ADA nor ISO) to study the cyclic fatigue resistance of endodontic instruments, we chose this device because it enables the boundary conditions to be controlled. Moreover, it was checked to ensure that the instruments did not fracture in the tube or the jaws. A stainless-steel tube with a 0.68 mm inner diameter was used. Friction between the instrument and the walls of the tube during the procedure could cause a certain amount of heat to be generated [24]. Therefore, a lubricant was used, as recommended, to control the local temperature [25].

Table 1. Cyclic fatigue resistance results of the 4 NiTi instruments

Group	No.	NCF 60	FL (mm)	Time to fracture
Protaper Next	10	731 ± 108^{b}	13.502 ± 0.47^{a}	1 min 48 sec
F6 Skytaper	10	887 ± 100^{a*}	13.152 ± 0.55^{a,b}	2 mins 12 sec
One Curve	10	984 ± 122^{a}	12.509 ± 1.01^{b,c}	2 mins 27 sec
Hyflex CM	10	1,009 ± 110^{a}	12.07 ± 0.12^{c}	2 mins 30 sec

*Different lowercase letters in the same column represent a statistically significant difference between groups (Tukey test).
NCF, number of cycles to failure; FL, fragment length.

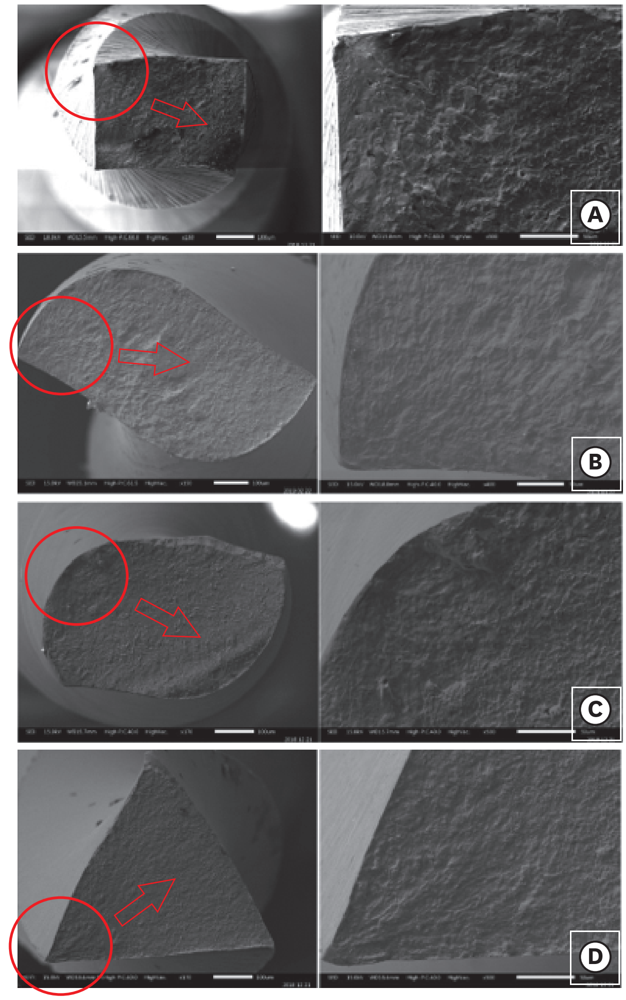

Figure 2. Fracture surfaces of the 4 different instruments, with 2 magnifications. The red circle indicates a zone of crack initiation, and the arrow shows the direction of crack propagation. (A) ProTaper Next, with a magnification of ×160 and ×500. (B) F6 Skytaper, with a magnification of ×150 and ×400. (C) One Curve, with a magnification of ×170 and ×500. (D) Hyflex CM, with a magnification of ×170 and ×500.

The results of our study showed that the cyclic fatigue life of One Curve was not statistically significantly different from those of F6 Skytaper and Hyflex CM. The cyclic fatigue lives of One Curve, F6 Skytaper and Hyflex CM were significantly longer than that of Protaper Next. These results can be mainly explained by the differences in the cross-section and heat treatment of the instruments, although the manufacturing process may have also played a role. As a matter of fact, Vadhana *et al.* [26] reported that an S-section would reduce mechanical stress at the canal walls, due to a smaller contact area between the instrument and the canal compared to a triangular section. Another reason could be that the core size of the S section is smaller than that of a triangular cross-section [27]. Thus, cyclic fatigue resistance would be increased. This could explain why the cyclic fatigue life of F6 Skytaper instrument (S cross-section) did not show a statistically significant difference from those of One Curve (triple helix at the tip of the instrument and "S" at the handle) and Hyflex CM (triangular cross-section), although these latter 2 instruments are made of thermomechanically treated NiTi. The results comparing the cyclic fatigue resistance of One Curve and F6 Skytaper are concordant with the literature [28]. The S-cross section could account for the statistically higher fatigue life of F6 Skytaper in comparison with Protaper Next. The S-cross-sectional design of the F6 Skytaper instrument could be the most important factor contributing to the good cyclic life span of this instrument [19,29]. In their study published in 2019, Rubio *et al.* [29] also observed that the S-shaped F6 Skytaper obtained better results than the M-Wire Protaper Next instrument. Moreover, Cheung *et al.* [30] determined that instruments with a triangular cross-sectional design possessed greater cyclic fatigue resistance than those with a square cross-sectional design. This difference is related to the reduced metal mass of the files with a triangular cross-section compared with files with a square cross-section and similar diameter [31]. This can explain why Hyflex CM (triangular cross-section) and One Curve (triple helix at the tip of the instrument and "S" at the handle) had longer fatigue lives than Protaper Next (rectangular cross-section) in our study. For One Curve, this explanation is also mentioned in the study by Elnaghy *et al.* [32]. Another explanation of the higher cyclic fatigue resistance of Hyflex CM compared to that of Protaper Next could be the thermomechanical treatment of this instrument. Protaper Next is made of M-wire, which contains the austenite phase with small amounts of martensite and R-phase at body temperature [16,17,33]. It exhibits greater flexibility than conventional NiTi wire [16,32,33]. However, it mainly contains the austenite phase and remains superelastic [15]. CM-Wire is a mixture of austenite and martensite with small amounts of R-phase at room temperature, [21,34,35]. The alloy mainly contains martensite and would seem to have greater flexibility than M-Wire and conventional NiTi instruments [22,36-41]. The improved flexibility is mainly attributed to the fact that the critical stress required to induce martensite reorientation in martensitic instruments, is much lower than the critical stress needed to induce superelastic transformation (austenite to deformed martensite) in austenitic instruments [42]. Because of the reorientation ability of the twinned phase structure, martensite has a higher fatigue life than austenite [19]. Other studies have investigated the resistance to rotary bending between Protaper Next and Hyflex CM at 60° and have found that was that Hyflex CM had significantly higher fatigue resistance. This was the case for the studies conducted by Capar *et al.* [43] Pedullà *et al.* [44] and Palma *et al.* [45]. More recently, a dynamic cyclic fatigue study with different conditions of NaOCl immersion has shown that Hyflex CM performed significantly better than Protaper Next, regardless of the immersion conditions [46].

There is still a lack of information about the C-wire alloy of One Curve in the literature, but this heat treatment allows the One Curve to remain martensitic at room temperature, like the CM-wire, even though differences in the exact phase composition between the 2 alloys can exist. In our study, we found that the NCF of One Curve was higher than that of Protaper Next. This finding appears to be consistent with the literature, which reports that martensitic alloys confer a higher cyclic fatigue resistance than austenitic and M-wire alloys [15]. A recent study compared the cyclic fatigue resistance of One Curve with that of Protaper Next and Hyflex CM [45]. The conclusions of that study, which was conducted at room temperature, are fully consistent with our results.

To our knowledge, only one previous study in the literature has compared One Curve and F6 Skytaper, even if these 2 files are both single-use rotary files that enable the shaping of the full canal length with a single instrument [28]. It is worth confirming that there is no statistically significant difference between these 2 instruments. This study could be augmented in the future by investigating the cyclic fatigue behavior of the instruments under dynamic conditions.

CONCLUSIONS

Within the conditions and limitations of the current study, the cyclic fatigue life of One Curve did not show statistically significant differences from those of F6 Skytaper and Hyflex CM. These 3 instruments had significantly longer cyclic fatigue lives than Protaper Next.

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