INTRODUCTION

The separation of rotary nickel-titanium (NiTi) has always been unpleasant for clinical dentists because it may jeopardize the outcome of root canal treatment. Cyclic fatigue may be the main reason for separation of a NiTi instrument. When instruments continuously rotate in a curved root canal and are exposed to repeated compression and tension cycles, cyclic fatigue fracture occurs. To reduce cyclic fatigue fracture, researchers of root canal instruments have innovated materials, processing technology, cross-sections, blades, pitch design and taper angles.

Technological advances in NiTi instruments in endodontics and different kinematics have increased the cyclic fatigue resistance of the instruments. Various NiTi instruments have been gradually applied in root canal treatment. ProTaper Universal (PTU; Dentsply Maillefer, Ballaigues, Switzerland) is a classic type of NiTi instrument that uses a traditional manufacturing process and is designed with a variable progressive taper, convex triangular cross-section, and noncutting tips. ProTaper Next (PTN; Dentsply Maillefer) is made with the M-Wire and manufactured by a thermal treatment process. It is also designed with an off-centered rectangular cross-section and a variable regressive taper to increase cyclic fatigue resistance and flexibility. WaveOne Gold (WOG; Dentsply Maillefer) is also an M-wire manufactured with gold treatment, aiming to increase the flexibility and cyclic fatigue resistance. It is designed as a parallelogram cross-section with two cutting edges. HyFlex CM (HCM; Coltene Whaledent, Altstätten, Switzerland) is made with controlled memory (CM) by a special thermomechanical procedure that increases flexibility. HyFlex CM has two cross-sections, including a triangular cross-section with three blades and three flutes as well as a quadrangular cross-section with four blades and four flutes. HyFlex EDM (HEDM; Coltene Whaledent) is manufactured with a variable cross-section design and the innovative use of CM alloy by an electrical discharge machining (EDM), which has been claimed to improve cutting efficiency and result in superior fatigue resistance. Twisted File Adaptive (TFA; SybronEndo, Orange, CA, USA) works by adaptive motion, allowing for either continuous rotation or reciprocal motion. TFA has some distinctive designs: R-phase heat treatment, twisting of the metal wire, equilateral triangular cross-section, and special surface conditioning to optimize its strength and flexibility.

The six NiTi instruments are extensively used in the clinic, and their resistance to cyclic fatigue has been examined in some studies. The angle and radius of curvature of the root canal are generally considered the two key factors for the fatigue resistance of NiTi instruments. Root canals with a curvature of 25–70° and S-shape curvature are classified as severely curved root canals. A root canal with a curvature radius greater than 5 mm and less than 25 mm was considered moderate curvature. Therefore, to evaluate the effect of the angle and radius of curvature of the root canal on cyclic fatigue for the six types of NiTi instruments, artificial canals with curvature angles of 45°, 60°, and double 45° as well as radii of curvatures of 8, 6, and 4 mm were considered in this study.
MATERIALS AND METHODS

The six types of nickel-titanium rotary instruments

In this study, two single-file systems, WaveOne Gold Primary (25/.07~) and HyFlex EDM OneFile (25/.08~) and four multiple-file systems, ProTaper Universal F2 (25/.08~), ProTaper Next X2 (25/.06~), HyFlex CM (25/.06), and Twisted File Adaptive SM2 (25/.06) were selected. The six instruments were normalized to the taper of .06 and size 25# and 25 mm in length, except for the TFA, which was 27 mm in length. PTU, PTN, WOG, HCM, and HEDM were rotated in an electric motor (X-smart; Dentsply Maillefer) according to the manufacturer’s recommendations as follows: PTU at 250 rpm and 3 N/cm torque, PTN at 300 rpm and 2 N/cm torque, WOG at 350 rpm and 2 N/cm torque in WaveOne All mode (350 rpm), HCM and HEDM at 500 rpm and 2.5 N/cm torque. TFA was used with patented TFA motion at 400 rpm at the TFA setting in an element motor (SybronEndo). All instruments were inspected with a stereomicroscope (M205A, Leica, Germany) at 25× before examination to discard those with defects and deformities.

Three curvature angles of artificial canals

Three groups of artificial canals were made out of a testing block of stainless steel with an inner diameter of 1.5 mm, a curvature radius of 2 mm, and a curvature site located 10 mm from the top of the canal (Figs. 1a, b). The curvature angles of the artificial canals were 60° (Canal 1), 45° (Canal 2), and double 45° (S-shape curvature, Canal 3). Thirty files were tested for each nickel-titanium rotary instrument, and each curvature angle was repeated 10 times. All the NiTi instruments were operated according to the manufacturers’ recommendations with the same work length of 18 mm.

Three radii of curvature of artificial canals

Three groups of artificial canals were made out of a testing block of stainless steel with an inner diameter of 1.5 mm, 90° angle of curvature, and initial site of curvature located 10 mm from the top of the canal. The radii of curvature of the three artificial canals were 8 mm (Canal 4), 6 mm (Canal 5), and 4 mm (Canal 6, Figs. 1c, d). Thirty files were tested for each nickel-titanium rotary instrument, and each radius of curvature was repeated ten times. All the NiTi instruments were inserted to 10 mm length and then entered a quarter circle of each curvature in the artificial canals; thus, the work length of each instrument was 10 mm+1/4 2πR. The instruments were operated at the manufacturer’s recommendations.

All tests were performed at room temperature during the day in August and September in Guangzhou City, China. To decrease the effect of the environmental temperature, the room temperature was limited to a range of 30°C to 35°C by examination of a thermometer according to the possible work temperature during a root canal by Hemptinne et al. 20). To prevent the instruments from slipping out, the testing block of stainless steel was covered with glass and tightly clamped. The fracture time (FT) was recorded to an accuracy of 0.1 s from the start of the test until the moment of breakage. The number of cycles to fracture (NCF) was calculated according to the following formula: NCF = time (s) to fracture×rotational speed/60 s.

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Fig. 1  The diagrammatic sketches of the different angle, initial site and radius of curvature of artificial canals for this study.  
Three angles of curvature, 60° angle (Canal 1), 45° angle (Canal 2) and S-shaped curvature (Canal 3, both angles were 45°) were devised in artificial canals (a, b); the three radii of curvature were 8 mm (Canal 4), 6 mm (Canal 5) and 4 mm (Canal 6), respectively (c, d). The artificial canals were made from a testing block of stainless steel with an inner diameter of 1.5 mm and a depth of 3 mm, and the testing block of stainless steel was covered with glass and tightly clamped by a vise to prevent the instruments from slipping out (e). The six 25# NiTi instruments, PTU, PTN, WOG, HEM, HEDM and TFA were operated at a according to the manufacturers’ recommendations.
Table 1 Description for FT and NCF of six nickel-titanium rotary instruments of the canals with 60° angle, 45° angle and S shape curvature (both angles were 45°)

| NiTi instrument | 60° FT | NCF | 45° FT | NCF | Double curvature FT | NCF |
|-----------------|-------|-----|--------|-----|---------------------|-----|
| PTU             | 15 (2)a | 61 (10)a | 22 (4)a | 92 (16)a | 24 (7)a | 101 (28)a |
| PTN             | 43 (9)bc | 215 (47)b | 64 (7)b | 318 (37)b | 62 (13)b | 312 (67)b |
| WOG             | 44 (11)bc | 255 (65)b | 112 (27)c | 653 (158)b | 96 (21)c | 560 (125)b |
| HCM             | 56 (2)c | 466 (20)c | 111 (23)c | 927 (189)c | 69 (10)c | 575 (87)c |
| HEDM            | 22 (4)ad | 186 (30)b | 97 (16)bc | 807 (134)bc | 73 (18)bc | 611 (149)c |
| TFA             | 32 (9)bd | 215 (63)b | 106 (31)c | 709 (201)bc | 84 (20)bc | 560 (137)c |

The mean and standard deviations of FT and NCF of fracture were given and statistically analyzed using one-way ANOVA and post-hoc Tukey’s test at the same curvature condition (α=0.05). The same superscript letters indicated no statistically significant difference among different kinds of NiTi instrument at the same curvature angle (p>0.05). No same superscript letters indicated statistically significant difference among different kinds of instruments at the same curvature angle (p<0.05).

Table 2 Description for FT and NCF of six nickel-titanium rotary instruments of the canals with different curvature radius (mm)

| NiTi instrument | 8 mm FT | NCF | 6 mm FT | NCF | 4 mm FT | NCF |
|-----------------|--------|-----|--------|-----|--------|-----|
| PTU             | 68 (11)ab | 283 (44)a | 61 (4)ab | 255 (15)a | 31 (9)a | 129 (36)a |
| PTN             | 80 (9)b | 402 (46)a | 57 (18)a | 284 (92)a | 30 (6)a | 148 (31)a |
| WOG             | 129 (19)c | 751 (108)b | 126 (24)c | 733 (137)bc | 135 (15)b | 786 (89)b |
| HCM             | 118 (22)c | 987 (180)c | 111 (24)bc | 927 (203)c | 102 (11)c | 726 (318)b |
| HEDM            | 46 (15)a | 381 (123)p | 82 (10)ab | 680 (86)bc | 42 (2)a | 353 (19)a |
| TFA             | 124 (18)c | 825 (120)bc | 73 (22)ab | 488 (148)ab | 27 (6)a | 181 (39)a |

The mean and standard deviations of FT and NCF of fracture were given and statistically analyzed using one-way ANOVA and post-hoc Tukey’s test at the same curvature condition (α=0.05). The curvature radius is 8, 6 mm and 4 mm, respectively. The same superscript letter indicated no statistically significant difference between six groups of instrument at the same curvature radius (p>0.05), and no same superscript letters indicated a statistically significant difference (p<0.05).
of PTU and PTN ($p<0.05$). In the S-shape, the NCF of WOG, HCM, HEDM, and TFA was significantly higher than that of PTU and PTN ($p<0.05$).

**Cyclic fatigue resistance for the three radii of curvature**

HEDM showed the longest FT and the highest NCF at a 6 mm radius of curvature, and FT or NCF of WOG showed no significant difference among the 8, 6, and 4 mm radii of curvature. At an 8 mm radius of curvature, WOG, HCM, and TFA presented significantly longer FT and higher NCF than PTU, PTN, and HEDM ($p<0.05$). At 6 or 4 mm radius of curvature, both WOG and HCM showed longer FT and higher NCF than PTU, PTN, HEDM, and TFA ($p<0.05$, Table 2).

**The appearance of fractured fragments**

The length of the fractured fragments of the six instruments was unanimous at a 60° angle of curvature, and therefore, the cross-section of the six fractured fragments was captured and measured under SEM. PTU had the largest area (approximately 947,253 μm²), followed by HEDM (approximately 856,693 μm²), WOG (approximately 717,760 μm²), HCM (approximately 666,186 μm²), and PTN (approximately 567,786 μm²), whereas TFA had the smallest area (approximately 459,146 μm²). The morphological characteristics of the cross-section and side of the six NiTi instruments represented their respective structure and machining process (Figs. 2, 3). The morphological characteristics

![Fig. 2](image_url)
of cyclic fatigue were exhibited on all of the fracture surfaces. The cutting edges of the cross-section of the six instruments showed breakages, and the fibrous fatigue zones with dimples and cones were representative of the fracture surface of PTU, WOG, and TFA (Fig. 2). Some cracks were found in the lateral view of the fractured fragments of PTU, WOG, HCM, and HEDM (Fig. 3).

**DISCUSSION**

The fatigue resistance of an endodontic instrument depends on multiple factors, such as movement kinematics, material and processing technology, cross-section, variable regressive taper design, and different cutting edges. Furthermore, environmental temperature was reported to influence the fatigue resistance of NiTi instruments. Our studies were performed in August and September in Guangzhou, Guangdong Province, China, and the room temperature during the daytime is generally within the range of 30°C to 35°C, close to the working temperature of NiTi instruments during root canals. NiTi instruments first operating in the root canals did not immediately reach body temperature. The NiTi instruments generally work in the root canals from 1 to 2 min, and the working temperature at short times is generally less than body temperature. Therefore, the room temperature in our test is relatively close to the working temperature of NiTi instruments in the body.

The purpose of this study was to evaluate the cyclic fatigue resistance of six NiTi instruments under different curvature conditions at the same room temperature. In our studies, PTN, WOG, HCM, TFA, and HEDM, through the modification of the NiTi alloy and structure as well as rotation motions, had higher cyclic fatigue resistance than the conventional NiTi alloy of PTU. First, the movement kinematics of NiTi instruments influenced the cyclic fatigue resistance, and reciprocating motion increased the cyclic fatigue resistance of NiTi instruments in contrast to continuous rotary motion.

Second, the instruments made by special material processing techniques exhibited high cyclic fatigue resistance. PTN, made of M-wire alloy, showed higher cyclic fatigue resistance than PTU but was not as good as WOG, TFA, HCM, and HEDM in this study. M-Wire showed superior physical and mechanical properties compared to conventional NiTi for manufacturing rotary endodontic instruments and thereby possesses more resistance to cyclic fatigue resistance. M-Wire contains an austenite phase with small amounts of martensite and R-phase at body temperature, and the technologies of thermomechanical treatments may make M-Wire inferior to CM wire, the EDM process, and gold and blue heat treatment in fatigue resistance. The high fatigue resistance of CM wire HCM is mainly due to its tendency for martensite-induced reorientation when confronted with critical stress. HEDM is another NiTi instrument manufactured from CM wire and is the first instrument to feature the use of EDM technology. HEDM is made up of martensite and substantial amounts of the R-phase, and the absence of austenite increases cyclic fatigue resistance at room or body temperature.

WOG and TFA not only operate by reciprocating movement, but their alloy materials, gold technology, and R-phase wire modify the transitional temperature
of martensitic transformation to generate a high percentage of the martensitic phase, which increases their flexibility and improves their cyclic fatigue resistance\(^{21,31}\). WOG instruments are made by means of a gold thermal treatment procedure by heating the file and then cooling it slowly after production, in contrast to the premanufacturing heat treatment of M-Wire technology. The postmanufacturing process provides WOG with superelastic NiTi metal properties\(^{35}\). TFA is named after its twisting process conducted by transforming a raw NiTi wire in an austenitic state through a proprietary thermal process into the R-phase, which has high resistance to cyclic fatigue. The conventional NiTi PTU showed low cyclic fatigue resistance in the present study. In the case of the alloy material, the conventional NiTi mainly consists of the austenite phase, and only a grinding process is used\(^{34}\).

Although movement kinematics and alloy processes influence the fatigue resistance of NiTi instruments, varied cross-sections may also affect the cyclic fatigue resistance. Cross-sectional areas and shape may have a significant impact on the torsional and bending resistance and thereby influence resistance to cyclic fatigue\(^{29}\). PTU has larger cross-sectional areas than HEDM, PTN, HCM, and TFA, which is one of the factors of low cycle fatigue resistance. Although WOG had a relatively larger cross-sectional area, it exhibited a high cyclic fatigue resistance. Fatigue resistance is influenced by multiple factors. The cyclic fatigue resistance of WOG is related to the gold technology, reciprocating motion, off-centered, and parallelogram-shaped cross-section design.

Apart from the rotation and materials, the taper design may influence the cyclic fatigue resistance of NiTi files\(^{36,37}\). To reduce the effect of the taper, the six tested files were controlled to the above taper of .06. PTU had the largest taper of .08 in the test NiTi files and the lowest cyclic fatigue resistance. Although HEDM also had a tip taper of .08, manufacture from CM wire and the use of EDM technology significantly improved its fatigue resistance. HCM (25/.06) and TFA (25/.06) had a relatively smaller taper and showed high cyclic fatigue resistance. Furthermore, the single or multiple file systems may affect the application of the file and is related to their actual fatigue properties in the clinic. In the multiple file system, the thin root canal widened by the small size of files will decrease the cyclic fatigue of the large size of files. Our research used a unified artificial root canal model with an internal diameter of 1.5 mm, whose width ensured that the test NiTi files were freely inserted into the canal. The design of a single file requires high fatigue resistance without the small size of file assistance, which is a possible factor because WOG and HEDM showed relatively higher fatigue resistance at the same size #25 in this study.

In testing the different radii of curvature, the working length of all files was limited to the quarter of curvature. In this condition, WOG as well as HCM performed with longer PT and higher NCF than for the others for the 8, 6, or 4 mm radius of curvature canals. HEDM showed the longest PT and highest NCF at a 6 mm radius of curvature. All instruments except HEDM showed decreasing PT and NCF from 8 to 4 mm. These results illustrate that the influence of the radius of curvature on the cyclic fatigue fracture of NiTi instruments was closely related to their respective materials, processing technology, and cross-sectional design. The flexibility of the CM wire, EDM technology, and gold thermal treatment procedure may account for the higher cyclic fatigue resistance of HCM, HEDM, and WOG in canals with different radii of curvature, as mentioned above, which is similar to a previous study\(^{33,38,39}\). Each file should have its applicable curved root canals due to their different materials, processing techniques, cross-sectional design, etc. Furthermore, the six NiTi files generally showed lower fatigue resistance at 60° than at 45° angles of curvature, which indicates that the angle of curvature was larger and that the fatigue resistance of the NiTi files was lower.

The fatigue resistance of an endodontic instrument may be influenced by a few potential factors. Technological advancements achieved in recent years have significantly improved the mechanical properties of endodontic instruments. However, to date, there is still no instrument capable of meeting all the requirements for root canal preparation. An instrument that possesses more technological innovations would potentially be better when applied in the clinic.

**CONCLUSION**

Advances in materials and processing technology, cross-sectional design, etc. have enhanced the cyclic fatigue resistance of NiTi files. Within our study and in vitro conditions, the use of M-wire, R-phase wire, and CM-wire; the invention of gold technology and EDM technology, and reciprocating movement are beneficial to enhance the cyclic fatigue resistance of NiTi files in the curved root canal. The data of this study provide information for the application of these instruments in curved root canals.

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