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Original Article

Bending resistance and cyclic fatigue resistance of WaveOne Gold, Reciproc Blue, and HyFlex EDM instruments

Soram Oh [a†], Kee-Yeon Kum [b†], Hyun-Jung Kim [a], Su-Young Moon [c], Hyeon-Cheol Kim [d], Antonis Chaniotis [e], Hiran Perinpanayagam [f], Eugenio Pedullá [g], Seok Woo Chang [a,h*]

[a] Department of Conservative Dentistry, KyungHee University Dental Hospital, 23 Kyungheedaero, Dongdaemun-gu, Seoul 02447, Republic of Korea
[b] Department of Conservative Dentistry, Dental Research Institute, Seoul National University Dental Hospital, Seoul National University School of Dentistry, 101 Daehak-ro, Jongro-gu, Seoul 03080, Republic of Korea
[c] Korea Research Institute of Chemical Technology, 141 Gajeong-ro, Yuseong-gu, Daejeon 34114, Republic of Korea
[d] Department of Conservative Dentistry, School of Dentistry, Pusan National University, Geumo-ro 20, Mulgeum, Yangsan, Gyeongnam 50612, Republic of Korea
[e] Private Practice, 140 Eleftheriou Venizelou Str, 17676, Kalithea, Greece
[f] Schulich School of Medicine & Dentistry, University of Western Ontario, 1151 Richmond Street, London, ON N6A3K7, Canada
[g] Department of General Surgery and Surgical-Medical Specialties, University of Catania, Via Cervignano, 29, 95129, Catania, Sicily, Italy
[h] Department of Conservative Dentistry, Kyung Hee University School of Dentistry, 23 Kyungheedaero, Dongdaemun-gu, Seoul 02447, Republic of Korea

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KEYWORDS
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Abstract *Background/purpose:* Several single-file systems manufactured using different heat treatment and operated by different kinematics have been released. This study compared the bending resistance and cyclic fatigue resistance of three NiTi files, and examined their phase-transformation behavior.
Materials and methods: WaveOne Gold Primary (WOG), Reciproc Blue R25 (RPB), and HyFlex EDM OneFile (HDM) were tested (N = 40/instrument). A vertical load was applied to a point 3 mm from the tip, and the stress was measured until a displacement of 3 mm. Tests were

* Corresponding author. Department of Conservative Dentistry, Kyung Hee University School of Dentistry, 23 Kyungheedaero, Dongdaemun-gu, Seoul 02447, Republic of Korea. Fax: +82 2 960 5108.
E-mail address: swc2007smc@khu.ac.kr (S.W. Chang).
† Soram Oh and Kee-Yeon Kum contributed equally as first authors to this study.

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conducted at either room temperature (RT: 22 °C) or body temperature (BT: 37 °C) (n = 10). Cyclic fatigue resistance tests were performed in an artificial canal, which had a curvature angle of 40° and a 5-mm radius. Tests were conducted at either RT or BT (n = 10). Instruments were operated according to the manufacturers' instructions. Test results were analyzed using the Kruskal–Wallis and the Mann–Whitney tests. Additional three instruments of each brand were subjected to differential scanning calorimetry (DSC).

Results: At RT the bending resistance of three files were not significantly different. However, at BT the bending resistance of RPB was highest, followed by WOG, and HDM ($P < 0.05$). At RT, RPB demonstrated the longest fracture time, followed by HDM, and WOG ($P < 0.05$). At BT, HDM had the longest fracture time, followed by RPB, and WOG ($P < 0.05$). The WOG, RPB consisted of austenite in a considerable proportion, whereas HDM was mainly martensite state at BT.

Conclusion: HDM presented superior flexibility and cyclic fatigue resistance at BT.

Introduction

For root canal preparations with a single-file system only one instrument is used to prepare the entire coronal to apical canal system. Therefore, the nickel-titanium (NiTi) files that are used as single-file systems need greater flexibility, strength and fracture resistance. NiTi instruments have been developed with enhanced fracture resistance through strategies that include reciprocating kinematics instead of continuous rotation, modification of instrument design, and heat treatment of the NiTi alloy.[1] Reciprocating rotation increases the cyclic fatigue resistance of NiTi files, compared to continuous rotation.[2,3] WaveOne Gold (Dentsply Maillefer, Ballaigues, Switzerland) and Reciproc Blue (VDW GmbH, Munich, Germany) are recently released reciprocating files manufactured with heat treatment. For WaveOne Gold, heat treatment of the NiTi alloy involves a slow heating-cooling process, which generates Ti_3Ni_4 precipitates dispersed over the surface,[4] and provides greater resistance to cyclic fatigue than M-wire reciprocating files.[5,6] Blue treatment of Reciproc Blue involves a proprietary heating-cooling process that creates a blue colored titanium oxide layer.[1,7] These heat-treated Reciproc Blue demonstrated greater flexibility and resistance to cyclic fatigue fracture when compared to the identical Reciproc (VDW GmbH) files made of M-wire.[8,9]

HyFlex EDM (Coltène/Whaledent Inc., Altstäten, Switzerland) are a single-file system that uses continuous rotation. They are manufactured by electrical discharge machining of a controlled memory (CM) wire,[10] which uses spark erosion to shape the file without direct contact, and thereby eliminates the mechanical stress created by traditional grinding and twisting procedures.[11] HyFlex EDM exhibited greater resistance to cyclic fatigue fracture, micro-hardness, maximum torque, and distortion angle than HyFlex CM (Coltène/Whaledent Inc.).[12,13]

For all NiTi instruments their mechanical properties are largely affected by their crystallographic state. When the NiTi alloy is in the austenitic crystallographic state it is stiffer, harder and has a higher elastic modulus than in the martensitic state.[1] However, austenite exists at higher temperatures and martensite at lower, with progressive phase transformations that occur with temperature. Thermomechanical treatments of NiTi alloy are used to modify the phase-transformation temperature of NiTi instruments, and thereby control their phase composition at operating temperatures, to optimize the mechanical and metallurgical properties of NiTi files.[14,15] Arias et al. reported that cyclic fatigue resistance of HyFlex EDM, consisted of martensite and R-phase, was not affected by temperature change (22 °C vs. 37 °C).[16] Whereas, according to Plotino et al. cyclic fatigue resistance of Reciproc Blue was higher as the environmental temperature decreased.[17] WaveOne Gold, Reciproc Blue, and HyFlex EDM are single-file systems manufactured using different heat treatment and operated by different kinematics. The fatigue fracture resistance of these three NiTi files needs to be evaluated at body temperature.

Since the bending resistance of martensite is lower than that of austenite, the stiffness of NiTi instruments may vary with their phase composition.[18] However, there have not been any study of bending resistance at body temperature. Therefore, the objective of this study was to evaluate the effect of body temperature on the bending resistance and cyclic fatigue resistance of WaveOne Gold, Reciproc Blue, and HyFlex EDM, and to examine the relationship between the variation in cyclic fatigue resistance and bending resistance with the temperature and phase transformations.

Materials and methods

The three brands of NiTi instruments (N = 43/brand) of 25 mm length with tip size #25 were carefully inspected under a dental operating microscope (G3; Global, St. Louis, MO, USA) at 12.8 magnification to detect any defects or deformities. The WaveOne Gold Primary (#25/07 taper) (WOG), Reciproc Blue R25 (#25/08 taper) (RPB), and HyFlex EDM OneFile (#25/variable taper) (HDM) were then assessed for their bending resistance (N = 20/brand) and resistance to cyclic fatigue (N = 20/brand). Their phase transformations with temperature were analyzed by differential scanning calorimetry (DSC, N = 3/brand).

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Bending resistance

The bending resistance of the instruments (N = 20/brand) were assessed by a cantilever-bending test as previously reported.[19,20] Each file was inserted into the contra-angle of an endodontic motor (X-smart motor, Dentsply Maillefer) that was mounted vertically in a universal testing machine (AGS-X STD, Shimadzu, Kyoto, Japan) with vinyl polysiloxane impression material (Fig. 1a). The file shank was then inserted into a standardized groove that had been prepared in a heat-resistant plastic container and submerged in distilled water (DW) (Fig. 1b). DW temperatures were either 22 ± 1 °C (RT, N = 10/brand) or 37 ± 1 °C (BT, N = 10/brand). The load cell was 20 N, and the cross-head speed was 2 mm/min. Load was applied at a point 3 mm from the tip of the NiTi file using a stainless-steel blade, which was connected to the crosshead of the universal testing machine (AGS-X STD, Shimadzu). When the blade was depressed 3 mm, the stress was recorded to evaluate the bending resistance.

Cyclic fatigue resistance

The cyclic fatigue resistance of the instruments (N = 20/brand) were assessed by a static model (Fig. 1c). Each file was inserted into an artificial canal that had a 40° curvature and 5 mm radius (Fig. 1d), until the file tip was 6 mm past the center of curvature (Fig. 1e). This model was submerged in DW at either RT (N = 10/brand) or BT (N = 10/brand). A wooden block firmly held the electric handpiece, which was driven by an endodontic motor (Reciproc Silver, VDW GmbH). NiTi rotary files were rotated in the artificial canals according to the manufacturers' instructions. WOG and RPB were operated in a reciprocating motion using the WaveOne and Reciproc modes respectively, whereas HDM were rotated at 500 rpm. When each file fractured, the time until fracture was recorded and the fragment length was measured by digital calipers (Digimatic, Mitutoyo Co., Kawasaki, Japan). After cyclic fatigue test, fractured files were cleaned with 70% ethanol, and the fractured surfaces were examined by scanning electron microscopy (SEM) (Hitachi S-4700; Hitachi, Tokyo, Japan).

Statistical analysis

The bending resistance, fracture time, and fragment length for WOG, RPB and HDM at RT and BT were compared by the Kruskal–Wallis and the Mann–Whitney tests with Bonferroni correction. The correlation between fracture time and bending resistance was evaluated by Pearson correlation analysis. All statistical analyses were performed by SPSS version 22 (IBM Corp, Somers, NY, USA) ($\alpha = 0.05$).

DSC

The phase transformation behavior of the instruments (N = 3/brand) were analyzed by DSC (Q1000; TA Instruments, New Castle, DE, USA). For DSC analysis, 2–3 mm

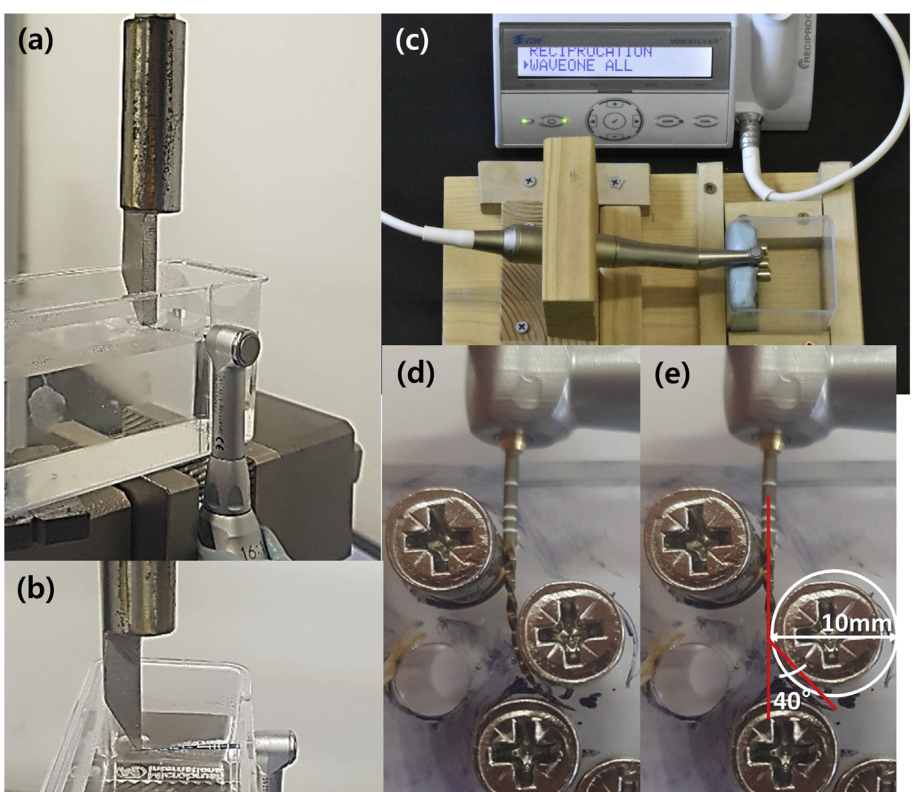

Figure 1 Apparatus used for the bending resistance test (a, b) and the cyclic fatigue fracture test (c, d, e). The angle and radius of curvature of the artificial canal is depicted in (e).

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Table 1 Mean (±standard deviation) of bending resistance, fracture time, and fragment length of three brands of NiTi file.

		WaveOne Gold	Reciproc Blue	HyFlex EDM
Bending resistance (N)	RT	0.3556 (0.0464)[c]	0.3518 (0.0445)[c]	0.3165 (0.0822)[c]
	BT	0.7053 (0.1050)[b]	1.1192 (0.1697)[a]	0.3974 (0.0924)[c]
Fracture time (s)	RT	261.4 (26.1)[f]	1117.5 (251.0)[d]	596.4 (102.7)[e]
	BT	149.1 (23.5)[g]	291.8 (107.1)[f]	599.6 (108.5)[e]
Fragment length (mm)	RT	5.38 (0.29)	5.50 (0.59)	5.41 (0.39)
	BT	5.50 (0.30)	5.73 (0.53)	5.50 (0.38)

Different superscript letters indicate significant difference for bending resistance (a–c) and fracture time (d–g), respectively.

of tip region of the sample was used, alumina was used as a reference pan. Each instrument was heated from 25 °C to 100 °C, and then cooled to −85 °C at a rate of −10 °C/min, which was followed immediately by a heating cycle at 10 °C/min up to 80 °C. These heating and cooling cycles were repeated three times for each instrument and the heat flow recorded. These heating and cooling curves were analyzed to identify phase-transformation temperatures.

Results

The means and standard deviations of the bending resistance, fracture time, and fragment length for the WOG, RPB, and HDM instruments are presented in Table 1. For the bending test performed at RT, there was no significant difference in bending resistance between the three brands of NiTi files (Table 1). In contrast, when the bending resistance was tested at BT, the bending resistance of RPB was the highest, followed by WOG, and then HDM ($P < 0.05$). The bending resistance of RPB and WOG were higher at BT than at RT ($P < 0.05$), whereas that of HDM did not change with the temperature.

At RT, RPB demonstrated the longest fracture time, followed by HDM, and then WOG ($P < 0.05$). At BT, HDM had the longest fracture time, followed by RPB, and then WOG ($P < 0.05$). The fracture times of WOG and RPB at BT were significantly less than RT ($P < 0.05$), whereas temperature did not influence the fracture time of HDM. There was no significant difference in the fragment length between the tested files (Table 1).

The fracture surfaces of tested files demonstrated typical features of cyclic fatigue fracture (Fig. 2). Crack initiation areas were observed along the outer surfaces of the instruments. Both multiple fatigue striations and circular abrasions were observed. There was no difference in microscopic features of fracture surface according to experimental condition (RT vs. BT).

A moderate negative correlation was identified between the fracture time and the bending resistance at BT by using Pearson correlation analysis ($P < 0.05$; Pearson r = −0.5). More flexible instruments (i.e., less bending resistance) can withstand longer to the cyclic fatigue. By contrast, no significant correlation was found between the fracture time and the bending resistance at RT ($P > 0.05$).

Representative DSC curves of each NiTi file are presented in Fig. 3. DSC curves for WOG and RPB showed single

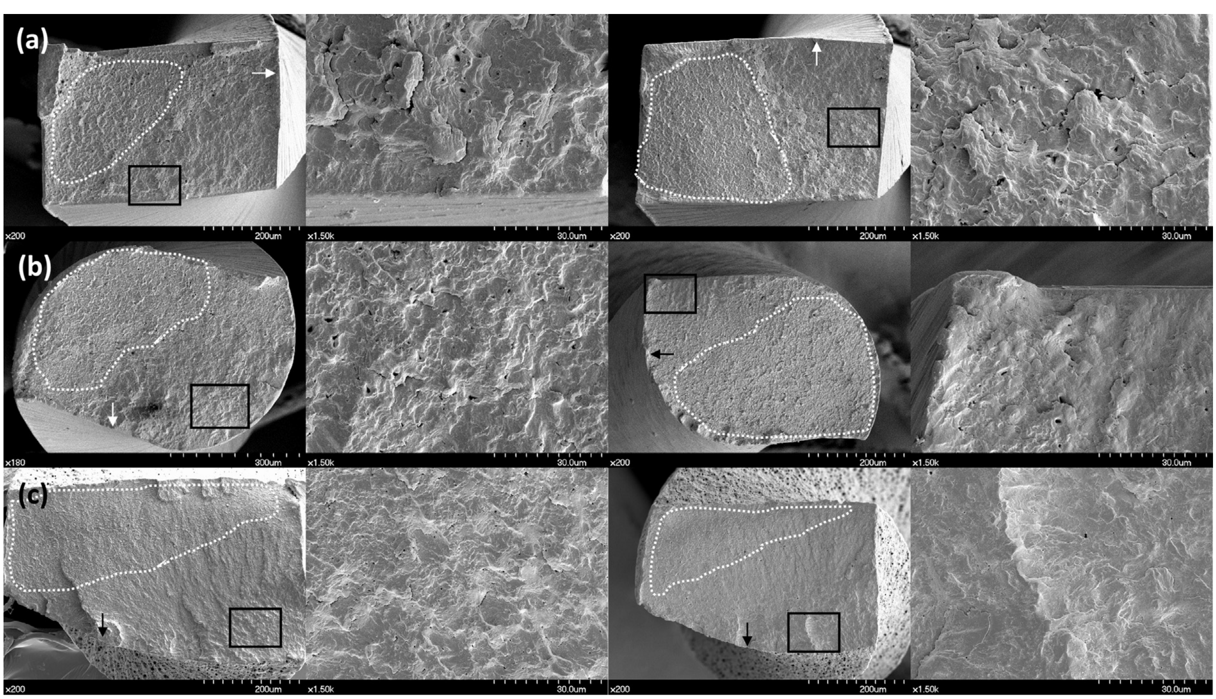

Figure 2 SEM images of fractured surface after cyclic fatigue of WaveOne Gold (a), Reciproc Blue (b), and HyFlex EDM (c), respectively. From left to right each column shows fractured surface of NiTi instrument tested at RT; the magnified view of box area; fractured surface of NiTi instrument tested at BT; and the magnified view of box area, respectively. Cracks were indicated as arrows, and circular abrasion pattern was marked as dotted line. Multiple fatigue striations are examined in the magnified images.

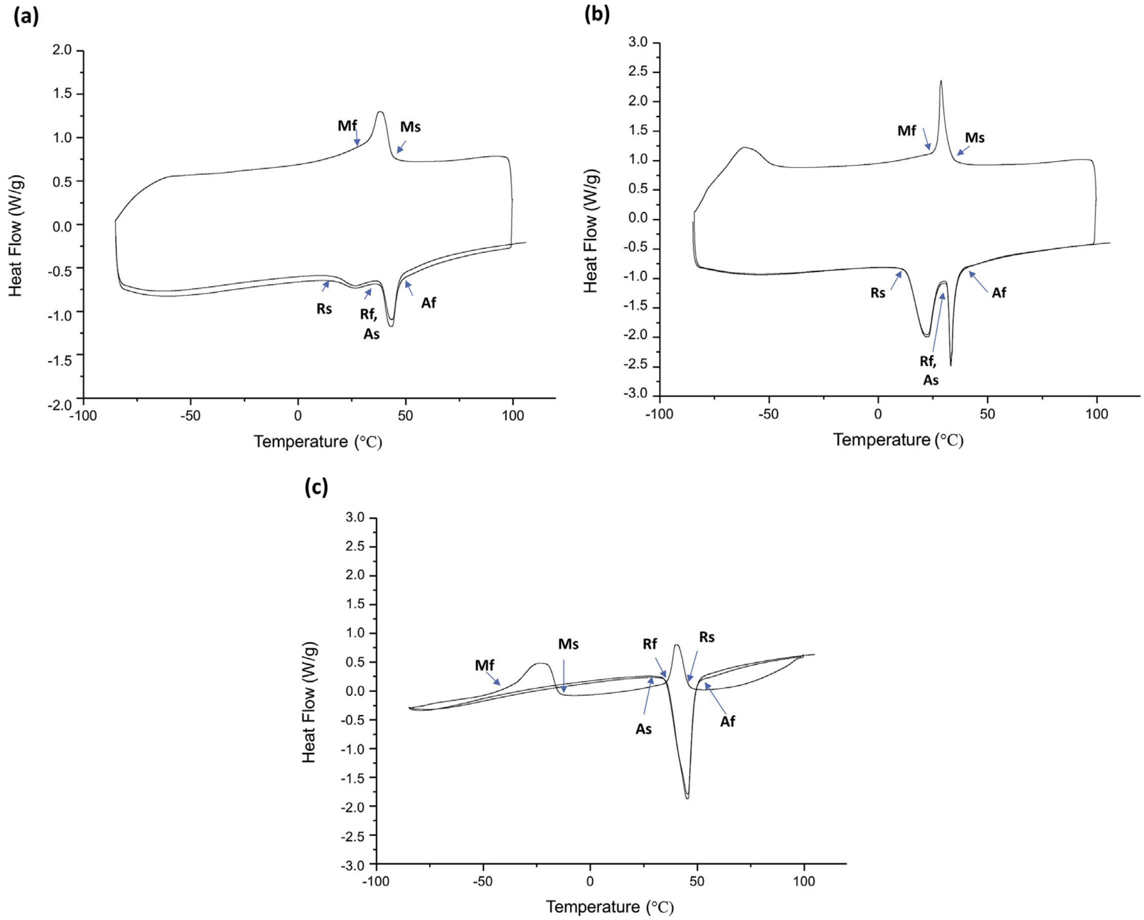

Figure 3 Representative heating (lower) and cooling (upper) curves from differential scanning calorimetry of (a) WaveOne Gold Primary; (b) Reciproc Blue R25; and (c) HyFlex EDM OneFile. As: austenite start temperature; Af: austenite finish temperature; Ms: martensite start temperature; Mf: martensite finish temperature; Rs: R-phase start temperature; Rf: R-phase finish temperature.

peaks on the cooling curves and double peaks on heating curves (Fig. 3a, b), whereas the DSC curve for HDM showed double peaks on the cooling curve and a single peak on the heating curve (Fig. 3c). The austenite finish temperatures (Af temperatures) of tested files were determined by locating the intersection of the tangent of the steepest endothermic slope at the austenitic-end with the baseline extension of the heating curve: Af of WOG, RPB, and HDM were 49, 38 and 51 °C, respectively.

Discussion

This study has been the first to evaluate the bending resistance within water at 37 °C for BT. The working part of the instrument was immersed in DW to control the temperature. The bending test was conducted after waiting approximately five minutes with the instrument immersed in DW; the temperature of DW was measured by a thermometer. The bending resistance of WOG and RPB increased with the increase in temperature from RT to BT, which was mainly due to a phase transformation of the instruments caused by temperature.[21] The phase composition of WOG at BT was a mixed state of R-phase and austenite, whereas, WOG at RT was mainly R-phase (Fig. 3a). The Af of RPB was 38 °C, and the phase composition of RPB at BT was almost pure austenite, whereas a mixture of R-phase and austenite existed together at RT (Fig. 3b). R-phase is considerably more flexible than austenite, and the transformation strain for the R-phase to martensite transformation is less than one-tenth of that of the austenite to martensite transformation.[22] Therefore, the bending resistance of a NiTi file that was mainly in the R-phase was lower than when it was in the austenite phase.

The bending resistance of HDM was unchanged by the temperature change. HDM had a phase composition that was martensite at RT and a mixed state of martensite with some austenite at BT (Fig. 3c). Its bending resistance increased slightly from RT to BT, which was not statistically significant (Table 1). HDM showed the lowest bending resistance (increased flexibility) and the longest fracture time at BT. This finding is attributed to that electrical discharge machining process during manufacturing as well as phase composition of the CM-wire.[7]

The cyclic fatigue resistance of WOG and RPB decreased with the temperature increase from RT to BT. Phase transformations of WOG and RPB in response to temperature contributed to the difference in their fracture times. In contrast, the cyclic fatigue resistance of HDM did not change with the increase in temperature, which is in agreement

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with a previous study.[16] There was a moderate negative correlation between the fracture time and the bending resistance at BT. The differences in fracture time are affected by additional factors beyond the bending resistance of the instrument. The cyclic fatigue resistance tests subject the instruments to tension and compression repeatedly within the artificial canal. Surface cracks and defects may occur in the early stage of flexural fracture, which then propagate.[23] The martensitic transformation and dissipation of energy required for crack formation and/or propagation during cyclic fatigue testing are altered by thermal treatment during manufacture.[15] At the same stress intensity, the fatigue crack propagation speed of austenitic microstructures is much faster than that of martensitic ones.[24]

Resistance to cyclic fatigue was greater in RPB than WOG, as reported in prior studies.[7,9,25–27] Their cyclic fatigue were both unaffected by rotation rates, despite the difference in their reciprocating angles.[28] Cyclic fatigue can be influenced by cross-sectional area,[2,29] instruments with smaller cross-sections have better resistance.[30] In the present study, however, RPB (8% taper) that have larger cross-sectional areas within the 3-mm tip than WOG (7%), had greater resistance to cyclic fatigue. Therefore, their resistance to cyclic fatigue may be due to the post-machining Blue thermal treatment.[7] Whereas RPB are ground prior to a Blue thermal treatment, WOG are mechanically ground after a Gold thermal treatment.[1,31]

Most published studies on bending resistance and cyclic fatigue fracture resistance of NiTi rotary and reciprocating instruments were performed at RT. The studies at RT may be of limited clinical relevance as the instruments are normally utilized at temperatures closer to BT, and therefore their conclusions should be interpreted with caution. It appears that the transformation temperature (Af) of NiTi instruments might alter their behavior when utilized clinically at BT. When the Af of a NiTi instrument is around BT, the instrument may become stiffer and less fatigue resistant at BT, despite its flexibility and resistance at RT. The Af of HyFlex EDM was found to be far above BT, which results in instruments that are always in the martensitic state in clinical relevant temperature.

WOG, RPB, and HDM are single-file systems manufactured using different heat treatment and operated with different kinematics. Among the three single-file systems tested in this study, a martensitic structure in BT, i.e. HyFlex EDM, will exert superior flexibility and fatigue fracture resistance and might be a better option for the root canal treatment of highly curved canals. Additional studies of torsional resistance and clinical use of WOG, RPB, and HDM are needed.

In conclusion, temperature influenced the bending resistance and cyclic fatigue resistance of WOG and RPB, whereas HDM was not affected by temperature. When root canal shaping is performed using NiTi files, one should consider the flexibility and cyclic fatigue fracture resistance at the temperature at which they are worked.

Declaration of Competing Interest

The authors deny any conflicts of interest related to this study.

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