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Original Article

Evaluation of cyclic fatigue behavior of RACE EVO rotary Files: In-vitro comparative study

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ABSTRACT

Introduction: Comparative evaluation of the newly introduced; RACE EVO file system to the currently well-performing file systems like HyFlex EDM OneFile, Vortex Blue, ProTaper Gold (PTG) with regards to the cyclic fatigue resistance.

Materials: &Methods.

The endodontic rotary files under evaluation were segregated into four groups as follows:; RACE EVO, PTG, Vortex Blue, and HyFlex EDM OneFile. A detailed physical analysis of the cyclic fatigue resistance was performed in 15 files of each type (n = 60). Under the test conditions of 37 °C the test samples were subjected to continuous motion at the manufacturer recommended speed within an artificial curved canal until it fractured. For all the test samples, with the recording of time of fracture, calculation was done for number of cycles to fracture (NCF). In addition, the length of the fractured segment was determined. The fractured surface was further evaluated with scanning electron microscopic (SEM) images.

Results: Highest significance for NCF was seen in HyFlex EDM OneFile followed by the Vortex Blue, PTG, and; RACE EVO ($p < 0.05$) by analyzing the data statistically. Significant differences among the lengths of the fractured segments were evident among tested files, ranging between 4.73 and 6.3 mm ($p < 0.05$) with HyFlex EDM OneFile uniquely differentiating from the others showing the fracture at 6.3 mm. The common features of cyclic fatigue failure was further substantiated by SEM images.

Conclusions: Compared to the HyFlex EDM OneFile, Vortex Blue, and PTG files; RACE EVO demonstrated significantly lower resistance to cyclic fatigue.

1. Introduction

Successful endodontic treatment envisions a thorough biomechanical preparation to treat or prevent periradicular periodontitis (Kakehashi et al.,1965; TROPE, 2003). NiTi rotary files have been commonly utilized in the field of Endodontics for root canal treatment since their inception (Walia et al.,1988),(Del Fabbro et al., 2018). Nevertheless, the potential for NiTi to fracture during use exists due to various factors, adding complexity to the treatment process.

The likelihood of NiTi fracture is influenced by factors such as the curvature radius and angle, skill of the operator, geometry of canal, instrument size, and the point of maximal instrument flexure, all of which significantly impact the fatigue (Pruett et al.,1997; Sattapan et al.,2000; Parashos et al.,2004). It is crucial to recognize that instrument fractures may sometimes impact the treatment outcome, particularly in the presence of a pathogenic environment (Spili et al.,2005). Therefore, the mechanical properties of the files when evaluated and compared facilitates the clinician's instrument selection according to individual treatment needs of each case.

Flexural/cyclic fatigue and torsional fatigue are the two commonly identified mechanisms of fracture. Tension/compression cycles at the point of maximum flexure is Cyclic fatigue, while torsional fatigue occurs upon locking of an instrument tip or another part in a canal while the shank continues to rotate. Flexural fatigue has been reported as having the highest incidence of failure (Cheung et al.,2005; Plotino et al.,2009).

Aim for advancements in NiTi technology, is to reduce procedural errors, resulting in changes to endodontic files, which could be achieved through surface treatments. Furthermore, manufacturers have extended their efforts to enhance the cyclic fatigue resistance of NiTi instruments

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by the use of heat treated alloys (Bulem et al., 2013). This technology alters the phase-transformation temperature aiming to maintain martensitic phase of the alloy during its operation inside human body temperature leading to improved properties (Oh et al.,2020). The Blue treatment has unique Blue oxide surface layer heat treatment as an advantage along with the gold treatment to increase cyclic fatigue resistance.

Other methods, such as electro polishing, surface coatings, and ion implantation, have also been explored (Plotino et al.,2009) Electro polishing, is a surface treatment method through which the surface irregularities can be removed in addition to cracks and stress areas. This enables the instrument to gain the shiny appearance along with the improvement in flexural fatigue resistance. (Anderson et al.,2007). Since 508 nitinol constituted the M−Wire alloy, undergoes a specific treatment process, the resultant material includes portions in both the martensitic and pre-martensitic R phase, remaining in a pseudoelastic state. Several alteratons related to the core material, particularly the M−Wire alloy, have been introduced. This alloy undergoes a proprietary treatment involving drawing of the raw wire under specified tension and heat treatments at stipulated temperatures. These changes impact the file's cyclic fatigue resistance differently.

The new electropolished RACE EVO (FKG Dentaire SA, La Chaux de Fonds, Switzerland) is similar to its earlier versions with regards to having a triangular cross-sectional design, alternating cutting edges and a rounded tip. However, according to the manufacturer, RaCe instruments have an enhanced cyclic fatigue resistance and flexibility, improved cutting efficiency, lower stress on dentin and lower screwing effect. In addition, the presence of Blue color indicates titanium oxide layer presence, giving rise to superior resistance (Almohareb et al.,2021). The Vortex Blue files (Dentsply Tulsa Dental, Tulsa, OK, USA), produced from Blue wire, result from a proprietary manufacturing process controlling the shape memory property and forming a Blue oxide surface layer (Plotino et al.,2014). ProTaper Gold (PTG) (Dentsply Tulsa Dental, Tulsa, OK, USA) instruments have the same geometry as ProTaper Universal except that it is made from CM-wire (controlled memory wire) and gold alloy giving rise to a superior resistance to cyclic fatigue through heat treatment (Uygun et al.,2016),(Hieawy et al.,2015). HyFlex EDM (Coltene Whaledent, Altstätten, Switzerland), amongst the heat-treated instruments, offers predominantly martensitic phase at intracanal temperature and has higher cyclic fatigue resistance than other martensitic phase files (Harrison,2020), (La Rosa et al.,2023).

There is limited data comparing the fatigue behavior of RACE EVO to other rotary file systems. Therefore, the present study aimed to compare the newly introduced file system, RACE EVO, with well-known fatigue-resistant files, ProTaper gold, Vortex Blue, and HyFlex EDM OneFile.

2. Methodology

In lieu with the evidence of the previous study by Allahem et al., cyclic fatigue resistance test was performed (Allahem et al.,2024). Four different rotary file systems, HyFlex EDM OneFile, PTG F2, Vortex Blue 25.06 and RACE EVO 25.06, were selected for this study for cyclic fatigue resistance comparison. Test sample analysis was done with reference to the previous study (Allahem et al.,2024), (Alfouzan and Jamleh,2018), (Alfawaz et al.,2022) using G-power 3.1.9.4.

New files (n = 15) from each of the selected system with 0.25 mm tip, and 25 mm length were assigned to four different groups. Under the evidence based guidance of the previous study by Alqedairi et al., adopting the same techniques, the artificial canals were made (Alqedairi et al.,2018). The 100 mm × 50 mm × 10 mm measuring stainless steel plates were used to create the artificial canal with laser micromachining technique using a specific laser(Mohammed et al.,2015). The artificial canals were made in correspondence to the tested files with width of + 0.1 mm, depth of + 0.2 mm, 60°angle of, 5 mm radius of curvature, and a 5 mm center of curvature from the instrument tip. The stainless steel block had a frontal transparent glass to aid stabilize the file in the canal during the test and to help in calculating the time for the file to fracture.

The testing started with submersion of the model under distilled water bath at 37 °C degree (Fig. 1). The file attached to X-Smart Plus endodontic motor (Dentsply Maillefer, Ballaigues, Switzerland) was inserted in the artificial canal with 19 mm of the file inside the artificial canal. Subsequently, as per the instructions of the manufacturer, files were rotated in place, at different speeds for each group, 400 rpm for HyFlex OneFile, 300 rpm for ProTaper Gold, 500 rpm for Vortex Blue and 800 rpm for RaceEvo. By multiplying the measured time to fracture with the recommended speed (rpm) for the each of the selected groups, the NCF was calculated.

2.1. Scanning electron microscopy

To analyze the topographic features, one file from each group fractured by cyclic fatigue was randomly selected, cleaned by alcohol to remove debris and room dried. For SEM analysis, vertical mounting of the test file were done with the help of the double-sided carbon tape on 15-mm metal stubs. The mounted samples were placed inside the SEM (6360LV Scanning Electron Micro- scope; JEOL, Tokyo, Japan) with10 kV. The SEM photomicrographs were captured at three magnifications, one revealing the whole surface of the fragment with a range of 150x to 200x magnification and the other two with a close-up photomicrographs to the site of failure with 500x and 1000x magnification respectively.

2.2. Statistical analysis

Mean and standard deviation values were reported as descriptive statistics to summarize the mean number of cycles to failure for each group. The test groups were compared using One-way ANOVA test with Tukey's HSD. Histograms, box-whisker plot and normality test were used to ascertain the normality of the data (Shapiro-Wilk test). Data distribution appears to be normal with normality test p-values > 0.05.

3. Results

The mean number of cycles to fractures, the outer diameter at the D5

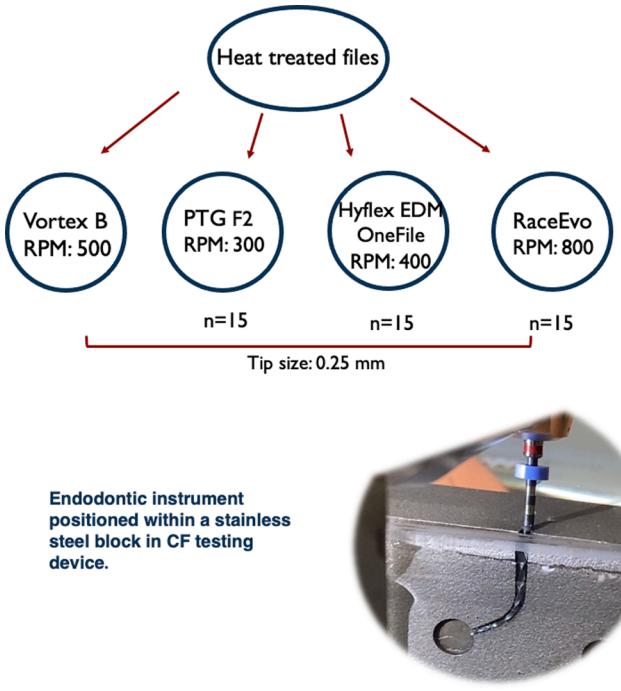

Fig. 1. Flow chart of the experiment method for cyclic fatigue of an instrument in the artificial metal canal.

and surface area of the tested instruments, are presented in Table 1.

Statistically significant difference between groups was found based on one-way ANOVA test, $F(3,56) = 93.53$, $p < 0.001$. Large effect size was found ($\eta 2 = 0.83$) suggesting that group accounts for 83 % variability in number of cycles to failure. Post-hoc test (Tukey's HSD) showed that all groups are significantly different from each other with pairwise comparisons $p < 0.05$. HyFlex EDM has the highest NCF among the tested files followed by Vortex Blue, PTG and RACE EVO. HyFlex EDM has the highest reliability ($M = 1909.07$) while RACE EVO has the lowest ($M = 578.73$). There was a significant difference in the length of the fractured pieces ranging from 4.73 mm to 6.3 mm for HyFlex EDM OneFile ($p < 0.05$). HyFlex EDM OneFile proved to be different from all the other groups, while Vortex Blue, PTG and RACE EVO showed no significant difference.

The SEM images exhibited the typical features of cyclic fatigue behavior (Fig. 2). An area of fatigue striations (a) and another with a dimpled surface (b) were noticed. The crack usually initiated at the edge (A1, white arrow) and propagated to the fatigue striations (a). The instrument was weakened by the coalescence of the microvoids (B3, black arrows) produced, after which ductile fracture occurred, which was evident from the dimpled surface (b), until failure occurred. The round dimples indicated normal rupture patterns caused by tensile stresses.

The taper of each file was measured using a digital microscope (Digital Microscope, Hirox, Tokyo, Japan). For the PTG, a steady increase in the degree of progressive taper was found from D0 to D5, while in the Vortex Blue, a constant increase of 0.04 mm along the tested segment was recorded. On the other hand, the RACE EVO showed an irregular taper pattern, as there was slight taper (0.02) from D1 to D2 and D3 to D4. While an abrupt increase was noticed in the taper between D2 and D3 (0.06), D4 and D5 (0.07). Finally, the HyFlex EDM OneFile showed irregular taper as there was slight taper from D1 to D2 (0.03), followed by an abrupt taper were found from D2 to D3 (0.07) and from D3 to D4 (0.12) then no taper noticed between D4 to D5.

4. Discussion

The newly introduced, blue heat treated RACE EVO files with a claim of high cyclic fatigue resistance was compared with heat-treated files: Vortex Blue, ProTaper gold, and HyFlex EDM which have been used for root canal shaping and cleaning for long time and reported to have high resistance to cyclic fatigue (Plotino et al.,2014; Hieawy et al.,2015; Elnaghy and Elsaka,2018). This study showed that HyFlex EDM has the highest cyclic fatigue resistance followed by Vortex Blue then PTG and RACE EVO.

RACE EVO has been introduced as an improved generation of the RaCe. Recently conducted studies revealed that RACE EVO exhibits greater resistance to cyclic fatigue compared to the traditional RaCe (Basturk et al.,2022). Furthermore, when compared to other newly introduced files namely Tia tornado Blue files and One Curve, RACE EVO shows superior resistance to cyclic fatigue (Ramadan et al.,2023). This enhanced resistance can be attributed to the thermal heating–cooling treatment process applied to RACE EVO resulting in the appearance of Blue titanium oxide layer on the file's surface, resulting in files with improved flexibility. This process influenced the crystallographic state by high austenite transformation finish temperature (Af temperature) close to the human body temperature ensuring that the file remains in the martensitic phase at body temperature, which consequently enhanced its mechanical properties (Yahata et al.,2009; Hou et al.,2020).

In agreement with this study, Khandagale et al. demonstrated greater cyclic fatigue resistance of HyFlex EDM compared with PTG (Khandagale et al.,2021). Furthermore, Uygun et al. showed that Hyfelx EDM perform better than PTG, but different from our study where they did not show significant difference between PTG and Vortex Blue (Uygun et al.,2020). This disparity could be attributed to variations in the test settings, specifically the use of a 3 mm radius in their study, whereas our investigation employed a 5 mm radius. Moreover, Vortex Blue showed significantly higher NCF compared with One Curve, 2shape, Profile Vortex and RaCe rotary instruments (Elnaghy and Elsaka,2018). HyFlex EDM is manufactured from controlled memory alloy, but different than HyFlex CM where the former has been processed by electrical discharge machining (EDM). This process hardens the metal to improve its mechanical performance and provide the file with a superior cyclic fatigue resistance by raising the Af temperature (more than 37 °C degree) (Harrison,2020). Also, HyFlex EDM has unique cross section ranging from rectangular in the apical portion to trapezoidal to triangular in the coronal part (Pedulla et al.,2016). An explanation to be spotlighted is that this unique cross-section design of HyFlex EDM could explain its better performance in this study compared to the triangular design of RACE EVO, Vortex Blue and ProTaper gold.

This study used rotational speed according to the manufacturer's instructions as Pruett et al. reported that rotational speed is safe in terms of cyclic fatigue resistance (Pruett et al.,1997). According to the manufacturing instructions, RACE EVO works effectively on high rotational speed (800 rpm) compared to the other files tested (Elnaghy and Elsaka,2018). Although, Lopes HP reported that an increase in the NiTi file speed will reduce the number of cycles to fracture by 30 % (Lopes et al.,2009). In addition, Li found out that time to failure will be decreased with higher rotational speed (Li et al.,2002). The high rotation speed could explain the inferiority of NCF of RACE EVO compared to the other tested files. However, there is lack in standard protocol or evidence-based technique for the studies that compare cyclic fatigue of different systems of files. The rotational speed employed for any instrument should always be considered in accordance with the manufacturer's recommendations, the clinical situation and the experience of the operator. In this study we used rotational speed recommended by the manufacturers.

To reduce variables that affect the study, files with continuous rotation and the same tip size were selected. Also, the experimental test was performed in 37 °C degree similar to the body temperature to mimic the clinical scenario. In addition, several studies found that the NiTi files at simulated body temperature behave less efficiently in terms of cyclic fatigue (Jamleh et al.,2016; Alfawaz et al.,2018; Savitha et al.,2022). For a closer simulation of the clinical conditions and the complexity of root canal system, a 60 degree angle of curvature is used in the present study. However, Pruet et al. showed no difference between 45 and 60 degree, and it fails at fewer cycles compared to 30 degree (Pruett et al.,1997).

The present study selected static motion as it's preferred model for evaluating cyclic fatigue in terms of comparing with other published studies (Wang et al.,2014; Alfouzan and Jamleh,2018). In Static motion, cyclic stress on a file concentrate on a short area which is the center of the curve. Contrary to the dynamic motion where the file moves inside the canal, stress distributes over a wider area and gives more cyclic fatigue resistance which could generate different result than in static motion (Li et al.,2002).

The objective of fractographic examination is to discern

Table 1
NCF, the diameter and the surface area of the instruments at the level of fracture of the experimental instrument system systems. (n = 15).

Group	Mean ± SD	Outer Diameter (mm)	Surface Area at D5 (mm^2)
[1] RACE EVO	578.73 ± 109.08 a *	2	0.17
[2] PTG	831.60 ± 79.88b	2	0.23
[3] Vortex Blue	1125.00 ± 174.83c	1.9	0.22
[4]HyFlex EDM	1909.07 ± 405.78 d	2	0.25

* Different letters indicate a statistically significant difference ($p \leq 0.05$). NCF: number of cycles.

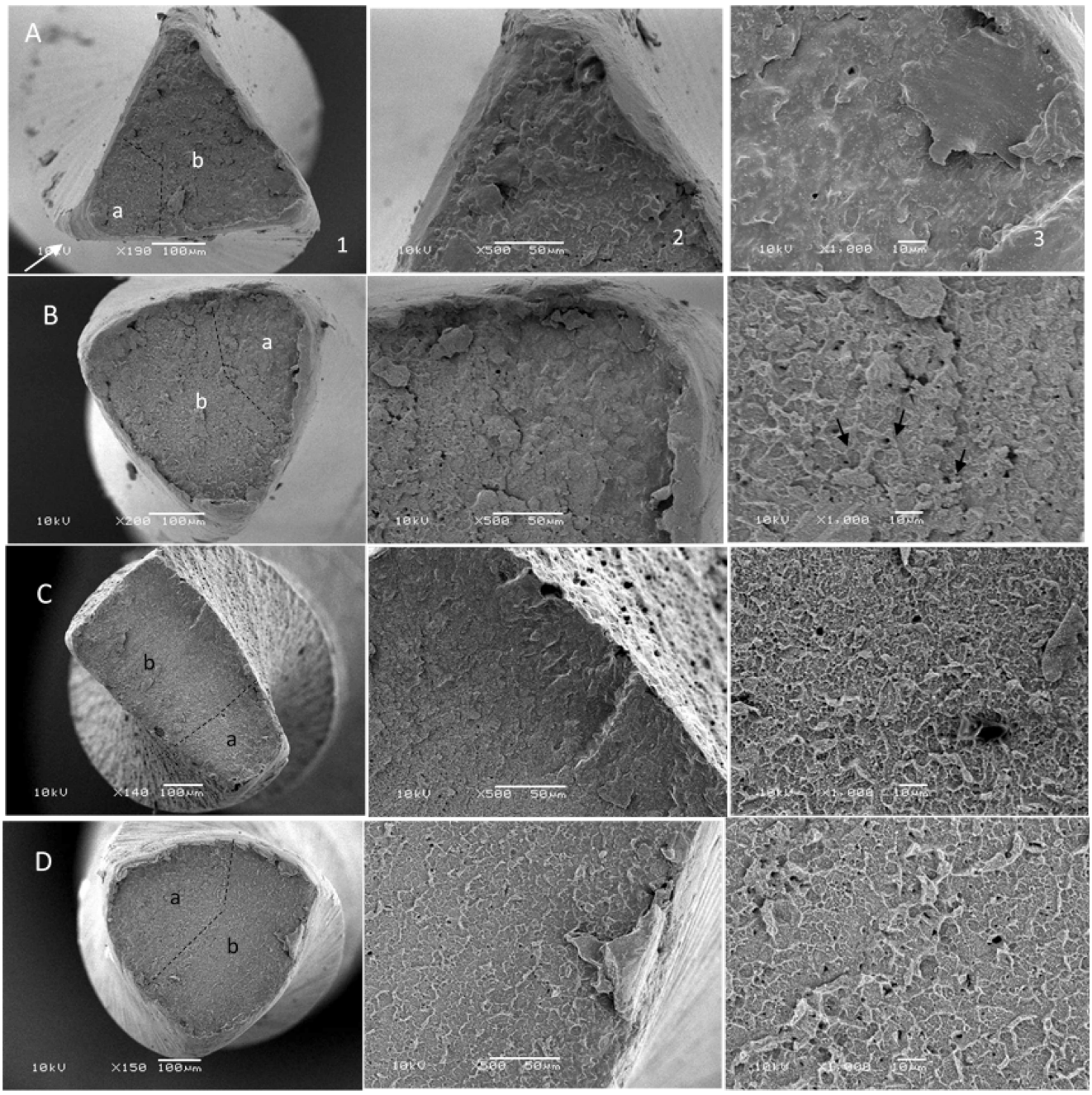

Fig. 2. SEM of the cross-sections of the fractured surfaces. (A) Race Evo. (B) Vortex Blue. (C) HyFlex EDM OneFile. (D) PTG. SEM images exhibited typical features of cyclic fatigue, including (a) striations, (b) dimples, microvoids (black arrows), and initiation of cracks (white arrows).

characteristics on the surface of the file that is fractured that can provide insights into the origin and prpogation of the crack responsible for the material's failure. The fractured surface serves as a visual representation of the actual mechanisms at play in the fracture process. Cyclic fatigue is basically identifiable by the presence of fatigue striations. In the present study, all tested files exhibited similar fractographic features indicative of typical cyclic fatigue behavior.

Different performance results between the files with superiority, as in HyFlex EDM OneFile, could be because of the chemical composition of the alloy, the different design features through the file, the quality of the manufacturing processes (EDM) and the different taper. The instrument cross-section, diameter, and surface area at the level of separation could play a major role in fatigue resistance (McSpadden,2007). As presented in the results, the increases in taper for the RACE EVO at the point of failure from D4 and D5 0.07 mm were larger than those shown in the other tested groups. However, Vortex Blue and PTG were the same, with 0.04, while HyFlex EDM OneFile had no taper which explains the faster failure of the RACE EVO. On the other hand, no taper at the point of failure for HyFlex EDM OnFile enabled the file to be resistant and led to fracture at longer segment 6.2 mm compared to the other tested groups (4.7 to 5.3 mm). It was reported that the fatigue is affected by the increase in taper size as it concentrates the stresses over a short distance with a large taper. This makes the file more susceptible to fatigue (McSpadden,2007). In par, fatigue failure is inversely affected by the wider distance between the stress of tension and the stress of compression, owing to the large total stress area (McSpadden,2007). Flute design, circumference shape, flute depth, and the number of spirals are other factors affecting the cyclic fatigue of the files

(McSpadden,2007).

In future, we recommend having similar rotational speed between different file systems to reduce variables. Also, usage of NaOCl medium instead of distilled water could be more clinically relevant.

5. Conclusion

The RACE EVO failed to show superiority in the cyclic fatigue resistance when compared to ProTaper gold, Vortex Blue and HyFlex EDM OneFile.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Alfawaz, H., Alqedairi, A., et al., 2018. Effects of sodium hypochlorite concentration and temperature on the cyclic fatigue resistance of heat-treated nickel-titanium Rotary instruments. J. Endod 44 (10), 1563–1566.
Alfawaz, H., Alqedairi, A., et al., 2022. Effect of NaOCl and EDTA irrigating solutions on the cyclic fatigue resistance of EdgeTaper platinum instruments. BMC Oral Health 22 (1), 195.
Alfouzan, K., Jamleh, A., 2018. Fracture of nickel titanium rotary instrument during root canal treatment and re-treatment: a 5-year retrospective study. Int. Endod J. 51 (2), 157–163.
Allahem, Z., Bendahmash, M., et al., 2024. Evaluation of the cyclic fatigue resistance of tia tornado blue and tia tornado gold in curved canals. in vitro study. Coatings 14 (1), 15.
Almohareb, R.A., Barakat, R., et al., 2021. Effect of autoclaving cycles on the cyclic fatigue resistance of race and RACE EVO nickel-titanium endodontic rotary files: an in vitro study. Metals 11 (12), 1947.
Alqedairi, A., Alfawaz, H., et al., 2018. Failure analysis and reliability of Ni–Ti-based dental Rotary files subjected to cyclic fatigue. Metals 8 (1), 36.
Anderson, M.E., Price, J.W., et al., 2007. Fracture resistance of electropolished rotary nickel-titanium endodontic instruments. J. Endod 33 (10), 1212–1216.
Basturk, F.B., Ozyurek, T., et al., 2022. Mechanical properties of the new generation RACE EVO and R-motion nickel-titanium instruments. Mater. (basel) 15 (9).
Bulem, Ü.K., Kececi, A.D., et al., 2013. Experimental evaluation of cyclic fatigue resistance of four different nickel-titanium instruments after immersion in sodium hypochlorite and/or sterilization. J. Appl Oral Sci. 21 (6), 505–510.
Cheung, G.S., Peng, B., et al., 2005. Defects in ProTaper S1 instruments after clinical use: fractographic examination. Int. Endod J. 38 (11), 802–809.
Del Fabbro, M., Afrashtehfar, K.I., et al., 2018. In vivo and in vitro effectiveness of rotary nickel-titanium vs manual stainless steel instruments for root canal therapy: systematic review and meta-analysis. J Evid Based Dent Pract 18 (1), 59–69.
Elnaghy, A.M., Elsaka, S.E., 2018. Cyclic fatigue resistance of one curve, 2Shape, ProFile vortex, vortex blue, and RaCe nickel-titanium Rotary instruments in single and double curvature canals. J. Endod 44 (11), 1725–1730.
Harrison, T., 2020. Cyclic fatigue resistance of nickel titanium rotary files in the martensitic state: a systematic review. University of Chester.
Hieawy, A., Haapasalo, M., et al., 2015. Phase transformation behavior and resistance to bending and cyclic fatigue of ProTaper gold and ProTaper universal instruments. J. Endod 41 (7), 1134–1138.
Hou, X.M., Yang, Y.J., et al., 2020. Phase transformation behaviors and mechanical properties of NiTi endodontic files after gold heat treatment and blue heat treatment. J. Oral Sci. 63 (1), 8–13.
Jamleh, A., Yahata, Y., et al., 2016. Performance of NiTi endodontic instrument under different temperatures. Odontology 104 (3), 324–328.
Kakehashi, S., Stanley, H.R., et al., 1965. The effects of surgical exposures of dental pulps in germ-free and conventional laboratory rats. Oral Surg Oral Med Oral Pathol. 20, 340–349.
Khandagale, P.D., Shetty, P.P., et al., 2021. Evaluation of cyclic fatigue of HyFlex EDM, twisted files, and ProTaper gold Manufactured with different processes: an in vitro study. Int. J. Dent 2021, 7402658.
La Rosa, G.R.M., Leotta, M.L., et al., 2023. Cyclic fatigue resistance of different nickel-titanium instruments in single and double curvature at room and body temperatures: a laboratory study. Aust Endod J. 49 (3), 592–598.
Li, U.M., Lee, B.S., et al., 2002. Cyclic fatigue of endodontic nickel titanium rotary instruments: static and dynamic tests. J. Endod 28 (6), 448–451.
Lopes, H.P., Ferreira, A.A., et al., 2009. Influence of rotational speed on the cyclic fatigue of rotary nickel-titanium endodontic instruments. J. Endod 35 (7), 1013–1016.
McSpadden, J.T., 2007. Mastering endodontic instrumentation. Chattanooga, Cloudland Institute.
Mohammed, M.K., Al-Ahmari, A., et al., 2015. Multiobjective optimization of Nd:YAG direct laser writing of microchannels for microfluidic applications. Int. J. Adv. Manuf. Technol. 81 (5), 1363–1377.
Oh, S., Kum, K.Y., et al., 2020. Bending resistance and cyclic fatigue resistance of WaveOne gold, reciproc blue, and HyFlex EDM instruments. J Dent Sci 15 (4), 472–478.
Parashos, P., Linsuwanont, P., et al., 2004. A cleaning protocol for rotary nickel-titanium endodontic instruments. Aust Dent J. 49 (1), 20–27.
Pedulla, E., Lo Savio, F., et al., 2016. Torsional and cyclic fatigue resistance of a new nickel-titanium instrument Manufactured by electrical discharge machining. J. Endod 42 (1), 156–159.
Plotino, G., Grande, N.M., et al., 2009. A review of cyclic fatigue testing of nickel-titanium rotary instruments. J. Endod 35 (11), 1469–1476.
Plotino, G., Grande, N.M., et al., 2014. Blue treatment enhances cyclic fatigue resistance of vortex nickel-titanium rotary files. J. Endod 40 (9), 1451–1453.
Pruett, J.P., Clement, D.J., et al., 1997. Cyclic fatigue testing of nickel-titanium endodontic instruments. J. Endod 23 (2), 77–85.
Ramadan, F., AbuMostafa, A., et al., 2023. Evaluation of cyclic fatigue and bending test for different nickle-titanium files. PLoS One 18 (8), e0290744.
Sattapan, B., Nervo, G.J., et al., 2000. Defects in rotary nickel-titanium files after clinical use. J. Endod 26 (3), 161–165.
Savitha, S., Sharma, S., et al., 2022. Effect of body temperature on the cyclic fatigue resistance of the nickel-titanium endodontic instruments: a systematic review and meta-analysis of in vitro studies. J Conserv Dent 25 (4), 338–346.
Spili, P., Parashos, P., et al., 2005. The impact of instrument fracture on outcome of endodontic treatment. J. Endod 31 (12), 845–850.
Trope, M., 2003. The vital tooth – its importance in the study and practice of endodontics. Endod. Top. 5 (1), 1.
Uygun, A.D., Kol, E., et al., 2016. Variations in cyclic fatigue resistance among ProTaper gold, ProTaper next and ProTaper universal instruments at different levels. Int. Endod J. 49 (5), 494–499.
Uygun, A.D., Unal, M., et al., 2020. Comparison of the cyclic fatigue resistance of HyFlex EDM, vortex blue, ProTaper gold, and onecurve nickel-titanium instruments. Niger J. Clin Pract 23 (1), 41–45.
Walia, H.M., Brantley, W.A., et al., 1988. An initial investigation of the bending and torsional properties of nitinol root canal files. J. Endod 14 (7), 346–351.
Wang, N.N., Ge, J.Y., et al., 2014. Analysis of Mtwo rotary instrument separation during endodontic therapy: a retrospective clinical study. CellBiochem Biophys 70 (2), 1091–1095.
Yahata, Y., Yoneyama, T., et al., 2009. Effect of heat treatment on transformation temperatures and bending properties of nickel-titanium endodontic instruments. Int. Endod J. 42 (7), 621–626.