Original Article

An *in vitro* comparative evaluation of cyclic fatigue resistance of two rotary and two reciprocating file systems

G. P. V. Srikumar, Vaishnavi Gadbail, Arvind Kumar Alexander[1], Geeta Nishad, Shripriya Rahane[2], J. S. Beautlin[1]

Department of Conservative Dentistry and Endodontics, Triveni Institute of Dental Sciences, Hospital and Research Centre, Bilaspur, Chhattisgarh, [1]Department of Conservative Dentistry and Endodontics, Rajas Dental College and Hospital, Tirunelveli, Tamil Nadu, [2]Department of Conservative Dentistry and Endodontics, Rajesh Ramdasji Kambe Dental College and Hospital, Akola, Maharashtra, India

Abstract

Context: Root canal instrumentation is one of the important procedures for successful endodontic therapy. Unexpected fracture of files occurs during root canal instrumentation without any visible signs of deformation compromising the success of root canal treatment.

Aims: The aim of the study was to evaluate and compare cyclic fatigue resistance (CFR) of rotary and reciprocating files in simulated canals with 45°, 60°, and 90° angle of curvature.

Settings and Design: The study design was an *In vitro* study.

Subjects and Methods: Sixty nickel–titanium files, 30 each of rotary and reciprocating files were selected and divided into four groups ($n = 15$) of Neoendo Flex, ProTaper Next, WaveOne Gold (WOG), and Reciproc Blue (RPB) files. Each group was further subdivided into three subgroups containing five samples each based on their use in simulated canals with 45°, 60°, and 90° angle of curvature. To simulate root canals with 45°, 60°, and 90° angle of curvature, three artificial canals were designed in a stainless steel metal block. Each file was autoclaved, immersed in 3% sodium hypochlorite (NaOCl), and coated with 17% ethylenediaminetetraacetic acid (EDTA). Each file was tested for CFR using a torque-controlled reduction handpiece by instrumenting in a simulated canal for 10 s until fracture. The cycle of autoclaving, exposure to NaOCl, EDTA, and testing of CFR for 10 s per canal as per groups and subgroups was repeated again and again until the respective file fracture. The time taken to file fracture was recorded using a digital chronometer. The time taken for each file fracture (in minutes) was multiplied by the number of rotations per minute to attain the number of cycles to failure (NCF).

Statistical Analysis Used: The obtained results were subjected to statistical analysis using one-way analysis of variance and independent *t*-test.

Results: One-way ANOVA test showed a statistically significant difference between the four groups, $P < 0.001$. Independent "*t*"-test between individual subgroups showed a statistically significant difference, as $P < 0.05$.

Conclusions: WOG and RPB reciprocating file systems showed superior CFR, more especially in canals with abrupt 90° angle of curvature compared to both rotary file systems tested. Among rotary file systems tested, Neoendo Flex showed greater CFR than ProTaper Next.

Keywords: Angle of curvature; cyclic fatigue resistance; file; simulated canal

Address for correspondence:
Dr. J. S. Beautlin,
CSI Bishop Bungalow, Palace Road, Nagercoil,
Kanyakumari - 629 001, Tamil Nadu, India.
E-mail: beautlin.js@gmail.com

Date of submission : 02.01.2024
Review completed : 11.02.2024
Date of acceptance : 10.06.2024
Published : 08.07.2024

Access this article online

Quick Response Code:

Website: https://journals.lww.com/jcde

DOI: 10.4103/JCDE.JCDE_2_24

How to cite this article: Srikumar GP, Gadbail V, Alexander AK, Nishad G, Rahane S, Beautlin JS. An *in vitro* comparative evaluation of cyclic fatigue resistance of two rotary and two reciprocating file systems. J Conserv Dent Endod 2024;27:774-9.

INTRODUCTION

Root canal instrumentation is considered the most important and challenging step in endodontic therapy. Walia *et al*. suggested the use of Nickel–Titanium (Ni-Ti) alloy named "Nitinol" in the manufacturing of rotary files owing to its innovative file design, superelasticity, and shape memory making root canal instrumentation faster, easier, and effective.[1] The mechanical properties of Ni-Ti alloy mainly depend on their chemical composition and thermomechanical processing.[2] Despite great development in the design and technology involved in the manufacturing of Ni-Ti rotary files, unexpected fractures of these files occur during root canal instrumentation without any visible signs of deformation compromising the success of root canal treatment.[3] Sattapan *et al*. reported fracture of Ni-Ti files due to torsional failure in 55.7% and flexural or cyclic fatigue in 44.3% of all fractured files.[4] Cyclic fatigue is defined as stress, strain, and deformation induced in a material by cyclic loading.[5] Cyclic fatigue failure is the leading cause in more than one-third of fractures of Ni-Ti files without any previous signs of permanent deformation.[6]

In our study, four different Ni-Ti file systems were selected based on the criteria that they were manufactured by different metallurgical processes and cross-sectional designs. ProTaper Next file (PTN; Dentsply Maillefer, Ballaigues, Switzerland), Neoendo Flex (Orikam Healthcare Private Limited, India), WaveOne Gold (WOG; Dentsply Maillefer, Ballaigues, Switzerland), and Reciproc Blue (RPB; VDW, Munich, Germany).

An ideal cyclic fatigue resistance (CFR) testing would involve instrumentation of curved root canals in human teeth with rotary and reciprocating files for accurate evaluation of CFR; however, in such tests, a root canal can be used only once as the shape of canal changes during instrumentation, making it impossible to standardize experimental settings.[7]

The rotational bending is the method used in endodontics for testing cyclic fatigue of Ni-Ti rotary files permitting them to rotate until fracture using different geometric curvatures.[8] Pruett *et al*. described the angle and radius of canal curvature using two parameters independent of each other: First, a straight line is drawn along the long axis of the coronal straight portion and a second line is drawn along the long axis of the apical straight portion of the root canal meeting at a point, at which the canal begins to deviate with the curved portion of the canal represented by a circle with tangents at these two points. The angle of curvature is the angle (number of degree) formed by these two perpendicular lines drawn from the points of deviation that intersect at the center of the circle and the length of these lines is the radius of the circle defining the radius of canal curvature in millimeters representing how abruptly a specific angle of curvature occur, as the canal deviates from a straight line. The smaller the radius of curvature, the more abrupt is the canal deviation. Stress on the file is inversely proportional to the radius of curvature.[9]

Given this, the aim of the present research was a comparative evaluation of CFR of Ni-Ti Rotary file systems (Neoendo Flex and ProTaper Next) and Reciprocating file systems (WOG and RPB) in artificial simulated canals with 45°, 60°, and 90° angle of curvature.

SUBJECTS AND METHODS

After obtaining Institutional ethical committee clearance certificate: TIDSHRC/IEC/2023/D0020. The sample size was estimated using the G*Power version 3.1.9.4 (Franz Faul Universitat, Kiel, Germany) adopting alpha (α) level of 5% (0.05), beta level of 20% (0.20), that is power of the test is 80% and an effect size (*d*) of 0.6 (8). Hence, it was calculated as 15 samples per group. A total of sixty Ni-Ti files, 30 each of rotary and reciprocating files were used for the cyclic fatigue static test in this study. All files were first examined for any surface defects under a stereomicroscope (Olympus, Tokyo, Japan) at ×20 magnification, only the files with no surface defects were included in the study. Of 30 rotary files; 15 Neoendo Flex files (size 0.25 mm/6% taper) (Group 1) and 15 PTNs (size 0.25 mm/6% taper) (Group 2). Of 30 reciprocating files, 15 WOG files (size 0.25 mm/7% taper) (Group 3) and 15 RPB files (size 0.25 mm/8% taper) (Group 4) with all the files having identical tip size of 0.25 mm.

To simulate root canals with 45°, 60°, and 90° angle of curvature, three artificial canals were engraved in a 36.8 mm × 25.4 mm × 9.5 mm custom-made 316-series stainlesssteel metal block/jig (Tata Steel Ltd., Jamshedpur, India) [Figure 1] specifically designed for the purpose as illustrated by Pruett *et al*. and already used in previous

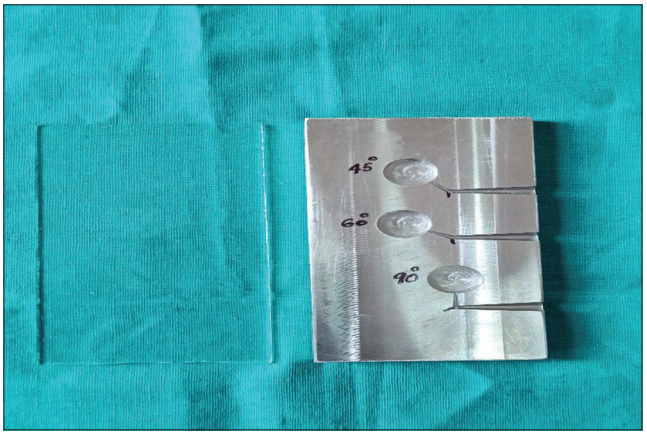


Figure 1: Stainless steel metal block/jig with simulated canals at 45°, 60°, and 90° angle of curvature

studies of Plotino *et al*. and Grande *et al*.[8-10] Simulated canals were milled by electrical discharge wire cutting machine (Accutex Technologies Co., Ltd., Taiwan) using Auto Computer Aided Design 2022 software (Autodesk) in the Department of Metallurgy at Visvesvaraya National Institute of Technology, Nagpur, India, having an inner diameter of 1.5 mm, length of 25 mm, and 5 mm radius of curvature providing a suitable trajectory with the curved segment of each canal 6 mm in length. The depth of each simulated canal was machined to the maximum diameter of the selected Ni-Ti files +0.1 mm, allowing the file to freely rotate inside. A circular well was also custom-designed at the apical end of each simulated canal within the metal jig for easy retrieval of fractured files during cyclic fatigue testing.

All files were first autoclaved (UniqueClave C79, Nashik, India) at 121°C, 15lb pressure for 15 min in self-seal sterilization pouches (Abbott Healthcare Pvt. Ltd., Mumbai, India) having a color changing indicator for depicting complete sterilization. The cutting flutes of the files were then immersed in Dappen dish (Golden Bird International Limited, Meerut, India) containing 3% sodium hypochlorite solution (NaOCl; Smyan Biomed, Kolkata, India) for 30 s. Each group (Groups 1, 2, 3, and 4) was further divided into three subgroups with 5 files each to be tested for CFR in artificial simulated canals with 45°, 60°, and 90° angle of curvature [Table 1].

All rotary and reciprocating files were then tested for CFR using a 16:1 reduction contra-angle handpiece powered by a torque-controlled electric motor (E-Connect S-Pro Cordless, Changzhou Eighteeth Medical Technology Co. Ltd., Changzhou, China) mounted on a custom-made stable wooden platform allowing for simple, precise, and reproducible placement of each file inside the artificial canal up to its full length of 25 mm [Figure 2]. A marker with permanent black ink was placed at 19 mm in all three simulated canals to ensure three-dimensional alignment of the file constrained in a precise trajectory. All rotary and reciprocating files were used according to their manufacturer's recommendations; Neoendo Flex file at 350 rpm (revolutions per minute) and 1.5N.cm torque, PTN file at 300 rpm and 1.5N.cm torque, WOG file at 350 rpm and 1.5N.cm torque, and RPB file at 300 rpm and 1.00N.cm torque. To reduce the friction of the file as it contacted the artificial canals made in stainless steel metal block, the cutting flutes of files were coated with 17% ethylenediaminetetraacetic acid (EDTA) gel (Prime Dental Products, Pvt. Ltd., Mumbai, India) as lubricant.

Each file was instrumented in a simulated canal for 10 s until fracture, considering an average time required either by a rotary or reciprocating file for instrumentation of a curved root canal. The files were then again autoclaved, immersed in 3% NaOCl, coated with 17% EDTA, and tested for CFR. This cycle of autoclaving of files, immersion in 3% NaOCl, 17% EDTA, and testing of CFR in simulated canals as per the groups and subgroups [Table 1] with similar experimental settings was repeated again and again until the respective file fracture.

The metal block with simulated canals was covered with snugly fitting tempered glass allowing clear observation of rotating files during cyclic fatigue testing, and fracture of the file was easily detectable through the glass cover, and it also helps in preventing the fractured files from slipping away facilitating for their easy retrieval. A single endodontist conducted the cyclic fatigue testing of all files. The time taken to fracture of each rotary and reciprocating file was recorded using a digital chronometer (Royals, VVT, China) and video camera to an accuracy of 0.1 s by the same endodontist, and the number of cycles to fracture of each file was calculated using the following formula: Number of cycles to fracture (NCF) = Time taken for file separation in minutes × Number of rotations per minute.[11] The collected data were recorded and tabulated.

Table 1: Rotary and reciprocating files used in simulated canals with 45°, 60°, and 90° angle of curvature

Groups: Ni-Ti files used	Sample size	Number of files used at 45°, 60°, and 90° angle of curvature
Group 1: Neoendo Flex rotary file	15	Subgroup: 1a (45°) (*n*=5) Subgroup: 1b (60°) (*n*=5) Subgroup: 1c (90°) (*n*=5)
Group 2: PTN rotary file	15	Subgroup: 2a (45°) (*n*=5) Subgroup: 2b (60°) (*n*=5) Subgroup: 2c (90°) (*n*=5)
Group 3: WOG reciprocating file	15	Subgroup: 3a (45°) (*n*=5) Subgroup: 3b (60°) (*n*=5) Subgroup: 3c (90°) (*n*=5)
Group 4: RPB reciprocating file	15	Subgroup: 4a (45°) (*n*=5) Subgroup: 4b (60°) (*n*=5) Subgroup: 4c (90°) (*n*=5)

Ni-Ti: Nickel-titanium, RPB: Reciproc Blue, WOG: WaveOne Gold, PTN: ProTaper Next

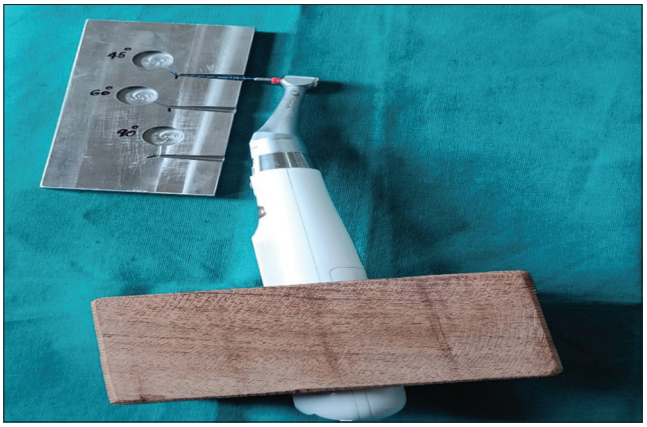


Figure 2: Cyclic fatigue testing of files with mounted endomotor handpiece

Statistical analysis

Data analysis was carried out using SPSS (the Statistical Package for the Social Sciences) software (Version 18.0, Chicago, IL, USA). One-way analysis of variance (ANOVA) test was used to compare between the four groups. Independent *t*-test was used between any two individual subgroups. Mean values ± standard deviation of NCF were calculated for all groups and subgroups.

RESULTS

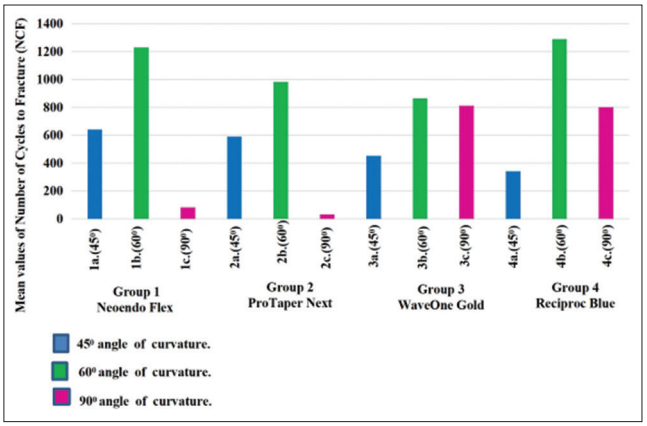
In our study, files with greater CFR showed higher NCF values. One-way ANOVA test revealed statistically significant difference exists between the four groups tested, as $P < 0.001$ [Table 2]. Mean values of NCF were calculated for all four groups, RPB (810) and WOG (709) reciprocating file systems showed the highest mean NCF values compared to Neoendo Flex (650) and PTN (534) rotary file systems.

In simulated canals with 45° angle of curvature, Neoendo Flex files exhibited greater CFR and at 60° angle of curvature RPB files exhibited greater CFR. At abrupt, 90° angle of curvature, WOG files exhibited greater CFR. Independent "*t*"-test showed a statistically significant difference between all individual subgroups, as $P < 0.05$. However, there was no statistically significant difference seen (Mean values of NCF) between the subgroups of 1a and 2a, 1b and 4b, 1c and 2c, and 3c and 4c, as $P > 0.05$ [Graph 1].

DISCUSSION

In our study, a custom-made stainless steel metal block with simulated canals that guaranteed a fixed 45°, 60°, and 90° angle of curvature and 5 mm radius of curvature was used to keep the experimental settings standardized to avoid bias and for better control of variables in the evaluation of CFR of Ni-Ti files deemed to be clinically relevant to simulate curved root canals of teeth. This is based on a method described by Pruett *et al*., accurately explaining the root canal curvature based on angle of curvature (α) and radius of curvature (r).[9]

In our study among the rotary files tested, Neoendo Flex showed higher CFR compared to PTN in canals with 45°, 60°, and 90° angle of curvature. The CFR of Neoendo Flex was also found to be higher than WOG and nearly equal to RPB reciprocating file systems in canals with 60° angle of curvature. This could be due to its triangular cross-sectional design, lower metal mass, the metal predominantly remains in the austenite phase at room temperature, and proprietary gold thermal treatment prevents opening of flutes of the file under stress during canal instrumentation rendering them highly flexible with greater CFR.[11] Hayashi *et al*. reported higher CFR or bending load values of rotary files with triangular cross-sectional shape than files with rectangular cross section.[12] However, Gayatri *et al.* in a previous study reported that the NeoEndo flex files exhibited minimal CFR compared to Edge files and Neolix Neoniti files tested in the artificial canal with 60° angle of curvature.[11] In the present study, PTN rotary files showed the least CFR in canals with 90° angle of curvature compared to all other file systems tested and this could be due to its off-centered rectangular cross-sectional design, larger metal mass. Riyahi AM *et al*., in a previous study, reported that PTN files showed the least CFR compared to TruNatomy and Twisted files tested in artificial canals with 60° angle of curvature.[13]



Graph 1: Vertical bar graph of cyclic fatigue resistance of rotary and reciprocating files in simulated canals

Table 2: Comparison of number of cycles to fracture between all the groups using one-way analysis of variance

Groups	Sub-groups (angle of curvature)	Sample size	Mean±SD	*F*	*P*
Group 1 (*n*=15) Neoendo Flex rotary files	1a (45°)	5	640.46±3.99	19008.376	<0.001
	1b (60°)	5	1230.8±9.78		
	1c (90°)	5	82.88±6.01		
Group 2 (*n*=15) PTN rotary files	2a (45°)	5	589.6±8.08		
	2b (60°)	5	983±5.7		
	2c (90°)	5	31.4±3.05		
Group 3 (*n*=15) WaveOne Gold reciprocating files	3a (45°)	5	453.4±5.46		
	3b (60°)	5	864±5.1		
	3c (90°)	5	812.4±7.92		
Group 4 (*n*=15) RPB reciprocating files	4a (45°)	5	342.2±3.35		
	4b (60°)	5	1289.8±8.56		
	4c (90°)	5	801.3±7.31		

SD: Standard deviation, RPB: Reciproc Blue, WOG: WaveOne Gold, PTN: ProTaper Next

However, both the reciprocating file systems showed significantly greater CFR compared to rotary file systems tested in canals with abrupt 90° angle of curvature. A probable explanation of the outcome of our study could be due to the differences in the metallurgical characteristics, cross-sectional design, and movement kinematics of the four Ni-Ti file systems tested.

The findings of our study are in accordance with previous studies of Plotino *et al*., Pedullà *et al*., and De-Deus *et al*. reported that the reciprocating files were significantly more effective in CFR than rotary files in abrupt root canal curvatures.[14-16] The higher CFR of WOG files in canals with 90° angle of curvature could be attributed to its off-centered parallelogram cross-sectional design, lower metal mass, has two cutting edges with a reduced number of contact points between the file and canal wall. WOG is made with special heat treatment technology, in which the file is continually heated and slowly cooled, after the heat treatment, a layer of titanium oxide in thickness of 100–140 nm remains covered on the surface of these files giving them a characteristic gold color, thus known as WOG files rendering them with greater flexibility and CFR.[5,17] Higher CFR of RPB files in canals with 90° angle of curvature is due to its unique S-shaped cross-sectional design with minimal two cutting blades, they are manufactured with heat treatment technology, in which the file is continually heated and slowly cooled with a layer of titanium oxide in thickness of 60–80 nm remains covered on the surface of these files giving them a characteristic blue color rendering them with greater flexibility and CFR.[17] However, the influence of cross-sectional design of Ni-Ti files on its CFR is controversial and has been the subject of a number of investigations.[8]

Pruett *et al*. concluded that when the angle of curvature of the root canal increases and/or the radius of curvature decreases, the NCF of the file reduces.[9] Iqbal *et al*. reported the fracture of most rotary Ni-Ti files in the apical third of the canal at the point of maximum curvature and smallest diameter.[18] Both WOG and RPB files were manufactured with M-Wire-based alloy in austenite phase with little amounts of martensite, thus exhibiting greater flexibility, better mechanical properties, and CFR compared to conventional rotary Ni-Ti files.[19] Plotino *et al*. and Gambarini *et al.,* in their study, explained that during one reciprocating motion, the file turns 150° clockwise (CW) direction, thus engaging the root canal dentin followed by 30° counter-CW (CCW) direction that would immediately disengage the file minimizing the risk of fracture, the degree of CCW rotation is designed to be smaller than the elastic limit of the Ni-Ti alloy. It is only after three reciprocating motions; the file completes one full rotation (360°) and this movement kinematics of reciprocating files significantly increases their CFR reducing the risk of file fracture compared to rotary files with continuous 360° rotation.[5,20]

In our study, all files were subjected to autoclaving, exposure to 3% NaOCl solution and 17% EDTA during their testing of CFR to closely simulate clinical situations of instrumentation in root canals of teeth during endodontic treatment. The main purpose of autoclaving endodontic files is to completely eliminate microbial contamination, as autoclaving do not compromise the mechanical behavior of Ni-Ti files, assuring the possibility of their re-use after sterilization, thereby preventing cross infection between patients and increasing the success rate of endodontic therapy.[21] Pedullà *et al.* reported autoclaving reduced the CFR of rotary files used in the artificial canal with 60° angle of curvature,[22] whereas Zhao *et al*. reported an increase in CFR of rotary files used in the artificial canal with 60° angle of curvature after autoclaving.[7] Hayashi *et al*. have shown that additional heat treatment by autoclaving increases the flexibility of Ni-Ti rotary files.[12]

Nair *et al*. investigated Mtwo and ProTaper Ni-Ti rotary files under atomic force microscopy and concluded that roughness on the surface of files became more pronounced with multiple autoclave cycles.[23] With the findings of our study, it is plausible to say that autoclaving might have contributed to the lower CFR of Neoendo Flex and PTN rotary files compromising their mechanical behavior compared to both reciprocating file systems tested, as there was a statistically significant difference in NCF in the simulated canal with abrupt 90° angle of curvature.

The use of NaOCl as a root canal irrigant is currently the golden standard for tissue dissolution and disinfection during endodontic therapy. However, it is found to be highly corrosive to Ni-Ti files ultimately reducing their cyclic fatigue.[24] Berutti *et al*. reported that immersion of Ni-Ti files in 5% NaOCl at 50°C significantly reduced their CFR.[25] In our study, all files were immersed in 3% NaOCl for 30 s, thereby simulating *in vivo* situation of a molar tooth having three root canals irrigated with NaOCl, 10 s per root canal. When ProTaper Ni-Ti rotary files are immersed in NaOCl, a decrease in the weight% of nickel and titanium with a corresponding increase in the weight% of sodium and chlorine elements were observed in energy-dispersive X-ray spectroscopy (EDS) analysis, as EDS identifies and characterizes semi-quantitatively the chemical elements present in deposits on instrument surfaces.[26]

In many previous studies, lubricants in the form of high-flow synthetic oils, petroleum jelly, cold spray, and glycerin were used in artificial canals made in stainless steel metal blocks to reduce friction and prevent overheating of endodontic files during testing of CFR. To closely simulate *in vivo* conditions, in our study, 17% EDTA gel, a most commonly used root canal irrigant was used as lubricant. Cyclic fatigue static tests aim to investigate a particular mechanical property of files and are more favored over dynamic tests, because dynamic tests cannot replicate real

clinical conditions and their results cannot be used to infer aspects of the mechanical behavior of Ni-Ti files.[27]

The limitation of our study is that testing of CFR of rotary and reciprocating files was conducted in artificial simulated canals designed in stainless steel metal blocks; however, these files may behave differently during instrumentation of curved root canals in human teeth with slightly varying results. As both rotary and reciprocating files are widely used for root canal instrumentation, there is an urgent need for a universally accepted testing device for experimental evaluation of CFR of files ensuring uniformity in methodology and comparable results for a safer, efficient clinical use during root canal treatment.

CONCLUSIONS

Within the parameters of this *in vitro* study, WOG and RPB reciprocating file systems showed superior CFR compared to both rotary file systems tested, more especially in canals with abrupt 90° angle of curvature. Among rotary file systems tested at 45°, 60°, and 90° angle of curvatures, Neoendo Flex showed greater resistance to cyclic fatigue than PTN. However, in canals with moderate angles of curvatures (45° and 60°), Neoendo Flex files exhibited greater CFR than all other file systems tested, except RPB at 60°. Finally, reciprocating files can be used more safely even in severely abrupt root canal curvatures. Therefore, movement kinematics should be included among the factors determining cyclic fatigue failure of Ni-Ti files. Hence, further studies are required for the comparative evaluation of the CFR of these files and to examine their performance in clinical situations.

Financial support and sponsorship
Nil.

Conflicts of interest
There are no conflicts of interest.

REFERENCES

1. Walia HM, Brantley WA, Gerstein H. An initial investigation of the bending and torsional properties of Nitinol root canal files. J Endod 1988;14:346-51.
2. Alshwaimi EO. Effect of sterilization on cyclic fatigue resistance of proflexendo endodontic rotary files. Saudi J Med Med Sci 2019;7:151-5.
3. Alapati SB, Brantley WA, Svec TA, Powers JM, Nusstein JM, Daehn GS. SEM observations of nickel-titanium rotary endodontic instruments that fractured during clinical Use. J Endod 2005;31:40-3.
4. Sattapan B, Nervo GJ, Palamara JE, Messer HH. Defects in rotary nickel-titanium files after clinical use. J Endod 2000;26:161-5.
5. Plotino G, Grande NM, Testarelli L, Gambarini G. Cyclic fatigue of reciproc and WaveOne reciprocating instruments. Int Endod J 2012;45:614-8.
6. Testarelli L, Grande NM, Plotino G, Lendini M, Pongione G, Paolis GD, *et al.* Cyclic fatigue of different nickel-titanium rotary instruments: A comparative study. Open Dent J 2009;3:55-8.
7. Zhao D, Shen Y, Peng B, Haapasalo M. Effect of autoclave sterilization on the cyclic fatigue resistance of thermally treated nickel-titanium instruments. Int Endod J 2016;49:990-5.
8. Plotino G, Grande NM, Cordaro M, Testarelli L, Gambarini G. A review of cyclic fatigue testing of nickel-titanium rotary instruments. J Endod 2009;35:1469-76.
9. Pruett JP, Clement DJ, Carnes DL Jr. Cyclic fatigue testing of nickel-titanium endodontic instruments. J Endod 1997;23:77-85.
10. Grande NM, Plotino G, Pecci R, Bedini R, Malagnino VA, Somma F. Cyclic fatigue resistance and three-dimensional analysis of instruments from two nickel-titanium rotary systems. Int Endod J 2006;39:755-63.
11. Gayatri K, Tammineedi S, Bolla N, Vemuri S, Basam RC, Sunil CR. Effect of autoclaving on the cyclic fatigue resistance of nickel-titanium rotary instruments: An *in vitro* study. J Conserv Dent 2021;24:440-4.
12. Hayashi Y, Yoneyama T, Yahata Y, Miyai K, Doi H, Hanawa T, *et al.* Phase transformation behaviour and bending properties of hybrid nickel-titanium rotary endodontic instruments. Int Endod J 2007;40:247-53.
13. Riyahi AM, Bashiri A, Alshahrani K, Alshahrani S, Alamri HM, Al-Sudani D. Cyclic fatigue comparison of TruNatomy, twisted file, and ProTaper next rotary systems. Int J Dent 2020;2020:1-4.
14. Plotino G, Ahmed HM, Grande NM, Cohen S, Bukiet F. Current assessment of reciprocation in endodontic preparation: A comprehensive review – Part II: Properties and effectiveness. J Endod 2015;41:1939-50.
15. Pedullà E, Grande NM, Plotino G, Gambarini G, Rapisarda E. Influence of continuous or reciprocating motion on cyclic fatigue resistance of 4 different nickel-titanium rotary instruments. J Endod 2013;39:258-61.
16. De-Deus G, Moreira EJ, Lopes HP, Elias CN. Extended cyclic fatigue life of F2 ProTaper instruments used in reciprocating movement. Int Endod J 2010;43:1063-8.
17. Dablanca-Blanco AB, Castelo-Baz P, Miguéns-Vila R, Álvarez-Novoa P, Martín-Biedma B. Endodontic rotary files, what should an endodontist know? Medicina (Kaunas) 2022;58:719.
18. Iqbal MK, Kohli MR, Kim JS. A retrospective clinical study of incidence of root canal instrument separation in an endodontics graduate program: A PennEndo database study. J Endod 2006;32:1048-52.
19. Gao Y, Gutmann JL, Wilkinson K, Maxwell R, Ammon D. Evaluation of the impact of raw materials on the fatigue and mechanical properties of ProFile vortex rotary instruments. J Endod 2012;38:398-401.
20. Gambarini G, Gergi R, Naaman A, Osta N, Al Sudani D. Cyclic fatigue analysis of twisted file rotary NiTi instruments used in reciprocating motion. Int Endod J 2012;45:802-6.
21. Sundaram KM, Ebenezar RA, Ghani MF, Martina L, Narayanan A, Mony B. Comparative evaluation of the effects of multiple autoclaving on cyclic fatigue resistance of three different rotary Ni-Ti instruments: An *in vitro* study. J Conserv Dent 2013;16:323-6.
22. Pedullà E, Benites A, La Rosa GM, Plotino G, Grande NM, Rapisarda E, *et al.* Cyclic fatigue resistance of heat-treated nickel-titanium instruments after immersion in sodium hypochlorite and/or sterilization. J Endod 2018;44:648-53.
23. Nair AS, Tilakchand M, Naik BD. The effect of multiple autoclave cycles on the surface of rotary nickel-titanium endodontic files: An *in vitro* atomic force microscopy investigation. J Conserv Dent 2015;18:218-22.
24. O'Hoy PY, Messer HH, Palamara JE. The effect of cleaning procedures on fracture properties and corrosion of NiTi files. Int Endod J 2003;36:724-32.
25. Berutti E, Angelini E, Rigolone M, Migliaretti G, Pasqualini D. Influence of sodium hypochlorite on fracture properties and corrosion of ProTaper rotary instruments. Int Endod J 2006;39:693-9.
26. Prasad PS, Sam JE, Kumar A, Kannan. The effect of 5% sodium hypochlorite, 17% EDTA and triphala on two different rotary Ni Ti instruments: An AFM and EDS analysis. J Conserv Dent 2014;17;5:462 6.
27. Keleş A, Eymirli A, Uyanık O, Nagas E. Influence of static and dynamic cyclic fatigue tests on the lifespan of four reciprocating systems at different temperatures. Int Endod J 2019;52:880-6.