International Journal of Enhanced Research in Medicines & Dental Care (IJERMDC),
ISSN: 2349-1590, Vol. 9 Issue 12, December 2022, Impact Factor: 7.125

Evaluation of Cyclic Fatigue Resistance of Four Heat Treated Nickel-Titanium Rotary Instruments in a Canal with a Double Curvature – An in-vitro Study

Mrunalini Vaidya[1], Swati Thongire[2], Vibha Hegde[3]

[1]Professor, Department of Conservative Dentistry and Endodontics, Dr G D Pol Foundation's YMT Dental College and Hospital, Maharashtra, India
[2]PG Student, Department of Conservative Dentistry and Endodontics, Dr G D Pol Foundation's YMT Dental College and Hospital, Maharashtra, India
[3]Professor and Head, Department of Conservative Dentistry and Endodontics, Dr G D Pol Foundation's YMT Dental College and Hospital, Maharashtra, India

ABSTRACT

Intracanal separation of rotary endodontic files is a concern for endodontist as it may affect the long-term prognosis of the tooth. New generation thermally treated rotary files are claimed to have enhanced cyclic fatigue resistance. This study evaluated the cyclic fatigue resistance (CFR) of Hyflex CM (Coltene Whaledent, Altstatten, Switzerland), Twisted file (SybronEndo, Orange, CA), V-Taper 2H (SS White, Lakewood, CA) and 2Shape (Micro-mega, Besançon, France) instruments used in an artificial S-shaped canal.A total of 80 files were tested in an S-shapedcanal. Time and Number of cycles to fracture (NCF) were observed. Fragments were measured and fractured surface was evaluated using scanning electron microscope (SEM). V Taper 2H showed significantly greater CFR than Hyflex CM, Twisted file and 2Shape. Heat treatment increased resistance to cyclic fatigue differently for each type of instrument. Controlled memory alloy presented better cyclic fatigue resistance than R-phase and T wire with heat treatment.

Keywords: Cyclic fatigue, s-shaped canal, Nickel-Titanium, thermal treatment

INTRODUCTION

Nickel Titanium alloys were developed by metallurgist W F Buehler in 1960s for Naval Ordinance Laboratoy in Maryland USA and hence were named NiTiNOLalloys[1]. Due to their shape memory, superelasticity and superior resistance to torsional fracture, the NiTi alloy was introduced to the field of endodontics for rotary endodontic instruments by Walia et al.[2,3]. Despite their favourable qualities, they are susceptible to unexpected separation due to torsional failure and cyclic fatigue.[3-6]

Separation of the endodontic files is multifactorial phenomenon as various factors predispose to its fracture. The predisposing factors can be classified as parameters related to metallurgy, instrument design and manufacturing defects; canal configuration [5] parameters such as length, diameter, curvature,especially double curvatures, radius and canal types; mechanics related parameters such as torque and speed settings[4,6], glide path, lubrication, debris removal, irrigation, type of motion, technique, number and frequency of use, sterilisation protocol etc. Newer technological advancements and manufacturing processes such as CM wire, EDM technology, M wire, Max-wire, T wire, C wire with surface treatments, thermal treatmentsalong with instrument designare being investigated to overcome these challenges.[7,8,9]

Heat treatment (thermal processing) is one amongst the foremost fundamental approaches toward adjusting the transition temperatures of NiTi alloys and affecting the fatigue resistance of NiTi endodontic files. Heat treatment of NiTi alloy produces a better arrangement of the crystal structure, thereby resulting in increased flexibility and improved fatigue resistance or plastic behavior.[10] In recent years, several thermomechanically processed endodontic NiTi files like HyFlex CM (Coltene Whaledent, Altstatten, Switzerland), Twisted file (SybronEndo, Orange, CA), V -Taper 2H (SS White, Lakewood, CA) and 2Shape (Micro-mega, Besançon, France) are introduced. According to the manufacturers, new generation thermally treated rotary files have enhanced cyclic fatigue resistance. This claim should be experimentally verified because it relates to instrument selection and the desired outcome. Therefore, the aim of this study was to evaluate and compare the cyclic fatigue resistance of four heat treated nickel titanium rotary files mentioned above in a canal with a double curvature.

MATERIALS AND METHOD

The study design was approved by the Institutional Ethics Committee. Based on data from a previous study[11], power calculations indicated that the sample size for each file system must be a minimum of 20 files. Therefore, a total of 80 heat treated rotary files with apical diameter of 0.25mm and taper 0.06% were selected and divided into four groups according to the file system.

Group I: Hyflex CM (Coltene Whaledent, Altstatten, Switzerland)
Group II: Twisted file (SybronEndo, Orange, CA)
Group III: V-Taper 2H (SS White, Lakewood, CA)
Group IV: 2Shape (Micro-mega, Besançon, France).

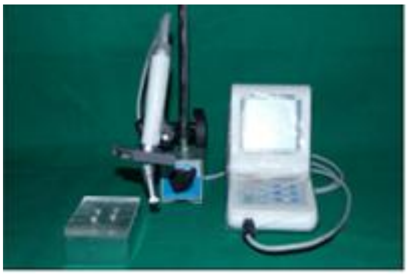


Fig 1 The assembly to measure the cyclic fatigue resistance

Each file was evaluated under stereomicroscope at 10x and 30x magnification for defects and deformities such as cracks, pits, fins. Any defective instrument found was discarded and replaced by another instrument devoid of any defects. The cyclic fatigue testing assembly consisted of a steel platform with a rod fixed vertically that acted as a mount with a clamp. Provision was made for stainless steel block with double curvature for precise and reproducible placement of each instrument inside handpiece which allows file rotation freely in the simulated canal of stainless-steel block. WD 40 oil was sprayed inside the S shaped canal of the stainless-steel block as a lubricant to reduce friction and minimize the generation of heat. The experimental procedure was performed by a single operator to avoid inter-operator variability. Silicon stopper of the file placed inside the handpiece was adjusted to get standardize 18mm working length. The X smart reduction handpiece (DENTSPLY^{TM}) was activated at constant speed of 400 rpm and torque recommended by the manufacturer (Group I- 2.4 N-cm, group II - 5.2Ncm, group III - 4.5Ncm and group IV- 2Ncm) for the file. Simultaneously, digital chronometer was started and the test procedure was timed. The file was allowed to rotate freely inside the artificial canal. The digital chronometer was stopped as soon as a fracture was visually detected and the time to fracture (TtF) in seconds from the start of the test until the moment of breakage was recorded and registered to the nearest whole number with a chronometer to an accuracy of 0.1. Using the time data, the number of cycles to fracture (NCF) for the file was calculated using the formula: **Number of cycles to fracture (NCF) = revolutions per minute (rpm)/60 * time of fracture (sec).** The length of each instrument fragment was measured using a digital calliper with an accuracy to 0.01 mm. The fractured surfaces of the fractured instruments were analysed under a scanningelectron microscope to confirm the type of fracture.

STATISTICAL ANALYSIS

Data obtained was compiled on a MS Office Excel Sheet (v 2010, Microsoft Redmond Campus, Redmond, Washington, United States). Data was subjected to statistical analysis using Statistical package for social sciences (SPSS v 21.0, IBM). Normality of numerical data was checked using Shapiro-Wilk test & was found that the data followed a normal curve; hence parametric tests have been used for comparisons. Inter group comparison (>2 groups) was done using one way ANOVA followed by pair wise comparison using post hoc test. For all the statistical tests, $p<0.05$ was considered to be statistically significant, keeping α error at 5% and β error at 20%, thus giving a power to the study as 80%.

RESULTS

Table I

	Groups	N	Mean	Std. Deviation	Std.Error	Minimum	Maximum
Time toFracture in SEC	HyflexCM	20	252.21	40.306	9.013	188	321
	TwistedFile	20	205.44	49.842	11.145	96	279
	V-Taper2H	20	426.60	126.735	28.339	182	627
	2Shape	20	204.99	77.980	17.437	36	302
	Total	80	272.31	121.335	13.566	36	627

Intergroup comparison for the mean time to fracture values of four heat-treated nickel titanium rotary instrumentsinseconds

Table II

DependentVariable	(I) groups	(J) groups	Mean Difference(I-J)	Std. Error	p value
NCFsec	I	II	311.750	170.779	.270#
	I	III	-1162.650*	170.779	.000**
	I	IV	314.800	170.779	.261#
	II	III	-1474.400*	170.779	.000**
	II	IV	3.050	170.779	1.000#
	III	IV	1477.450*	170.779	.000**

Pair wise comparison of NCF values of four heat treated nickel titaniumrotaryinstruments insecondsusing Tukey's Post Hoc Test

There was a statistically highly significant difference seen for the values between I vs III, IIvsIIIandIIIvsIV($p<0.01$, 0.05)asshown in table II

The mean and standard deviations of time to fracture, number of cycles to fracture and length of fractured fragments are presented in the table 1, 2 and 3. Group III had significantly higher mean cyclic fatigue resistance followed by Group I, Group II, Group IV. There was a statistically significant difference between group I and III, II and III and III and IV. In terms of fractured fragment length, no statistically significant difference was found among the tested groups. Scanning electron microscopic evaluation revealed typical characteristic of ductile fracture on the fractured surfaces

Table III

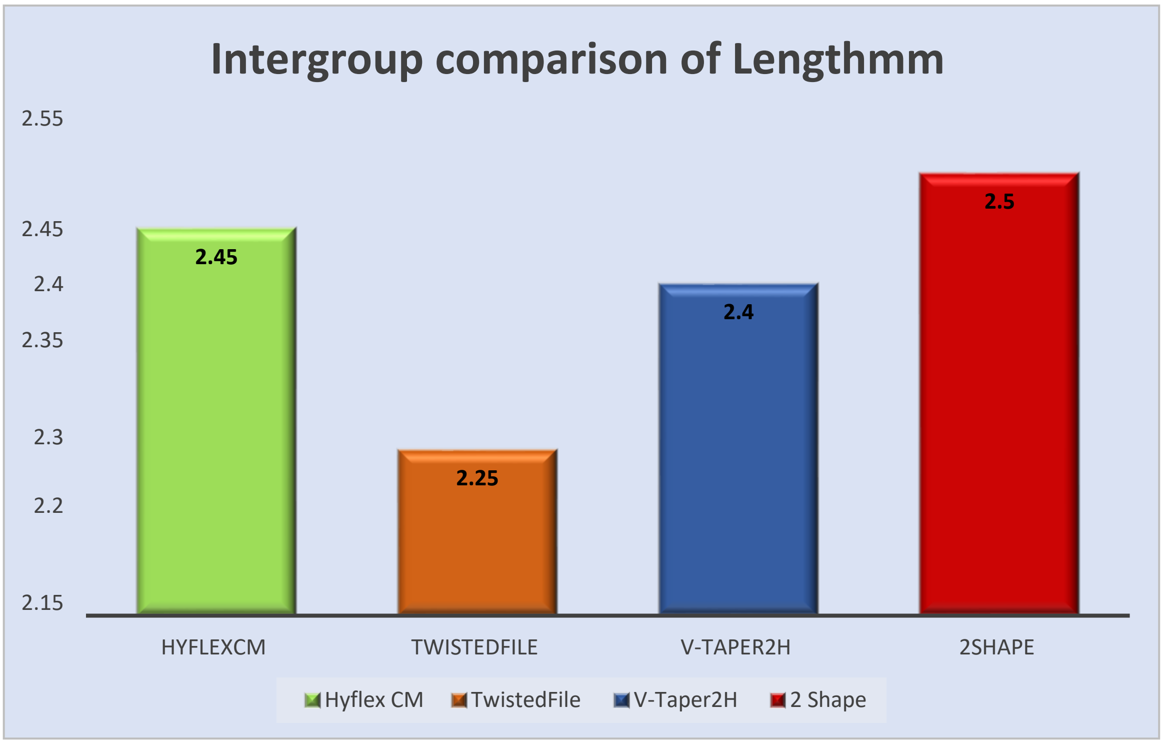
.

	Groups	N	Mean	Std. Deviation	Std.Error	Minimum	Maximum
NCF (Sec)	HyflexCM	20	1681.45	268.796	60.105	1252	2142
	TwistedFile	20	1369.70	332.271	74.298	642	1861
	V-Taper2H	20	2844.10	844.846	188.913	1213	4180

	2Shape	20	1366.65	519.800	116.231	243	2016
	Total	80	1815.48	808.886	90.436	243	4180

Intergroup comparison for the mean NCF values of four heat treated nickeltitanium rotary instrumentsinseconds

Graph I



Comparison of length of fractured fragment of four heat treated nickeltitanium rotary instruments

DISCUSSION

The embedment of the oxide particle in the alloy, during the manufacturing of the Ni-Ti rotary endodontic files, results in weaknesses at the grain boundaries and susceptibility to propagation of the cracks. Surface defects and irregularities such as cracks, grooves, pits, metal roll overs act as areas of crack initiation and the embedded dentin debris propagate it further during clinical use. [11, 12, 13-18]As eachdefect can act as an area of stress concentration making the alloy more susceptible to fatigue; all the eighty specimen files were evaluated under stereomicroscope at 10x and 30x magnification. Those files with defects were replaced with appropriate files. Studies by Pruett et al and Peters OA concluded that cross sectional diameter and core size, metal mass affects the cyclic fatigue resistance of the files, hence the same size of files (0.25 apical size and 0.06 taper) of four brands were selected for the study. These instruments will have same diameter at the point of maximum curvature because of their tip diameter and taper, thereby standardizing the procedure and removing the confounding factor.[20]

Radiographic studies that examined the degree and frequency of canal curvature reported that almost all root canals have secondary curvature. Such curvatures in buccolingual plane cannot be detected in a 2D radiograph[7,21] and may increase the cyclic fatigue causing instrument separation.[22]One of the foremost studies to assess the fatigue resistance of endodontic files in a double curvature canal, Al-Sudani et al (2012)[23] showed that the instruments fractured earlier when the Vortex and ProFile files were tested in double curvature versus single curvature canals. However, the detailed information about the exact size of the artificial canal and the trajectory of the different files was not reported. S shaped canals influence the cyclic fatigue of rotary NiTi instruments with the number of cycles to fracture being statistically lower in double curvature canals when compared with single curvature canal.[23]

Though extracted teeth simulate clinical condition,the use of simulated artificial canal minimizes the confounding factors such as canal length, radius of curvature and its position.[23]Grande et al. [24] stated that lesser the adaptation of the instrument to the artificial canal more the variation in the parameters of the curvature. Therefore, in the present study, two precisely defined artificial double curvature paths were designedin terms of size and taper.

Each file was rotated inside the double curvature canal at a constant speed of 400 rpm and torque settings recommended by the manufacturer until fracture occurred. The recommended torque values depend on the manufacturing process, metallurgy, the core diameter, surface treatments, flexibility of the files. The elastic limit of the file should not exceed the torque values [25].The concept of slow-speed, high-torque NiTi rotary instrumentation led to many iatrogenic errors. If a high-torque motor is used, the instrument-specific limit torque (fracture limit) is often exceeded, thus increasing the risk of intracanal failure.A possible solution of this problem is to use a low-torque endodontic motor that operates below the maximum permissible torque limit of each rotary instrument. As a consequence, new endodontic electric motors with low-torque values (Endostepper, SET, Emmering, Germany) have recently been developed[26.] It has been reported that instruments used with low-torque motors are more resistant to fracture than those used with high-torque motors (>3 N/ cm2)[27-30]

There are two aspects of checking cyclic fatigue resistance, time to fracture and number of cycles to fracture. Topçuoglu et al. [31] evaluated time to fracture instead of number of cycles to fracture, as the results could be more related to the conditions how the instruments are used clinically. But a more appropriate method would be to evaluate both parameters, time to fracture and number of cycles to fracture. In various studies, the speed for files was kept according to manufacturer's recommendation.[23, 32-34]. NCF should be used as an independent variable for statistical analysis. In the present study, the speed of 400 rpm was kept constant.

In the present study, V taper 2H showed the highest value for number of cycles to fracture followed by Hyflex CM, Twisted file and least was seen for 2 Shape (table III). These findings are in accordance with studies done by Chang et al. (2016)[35] who reported that V-taper 2H showed significantly higher cyclic fatigue resistance and torsional resistance than V-taper. Study by Hye-jin et al. (2017)[36] showed the highest NCF value for Hyflex EDM followed by V Taper 2H and Hyflex CM. From the above-mentioned studies, it is clear that V Taper 2H shows increased cyclic fatigue resistance. This result could be attributed to a higher flexibility of V Taper 2H. V Taper 2H has control memory wire technology. These files have austenite finish temperature (A_f) above room temperature, therefore mixed phases of austenite and martensite are present at room temperature. This property makes control memory wire more flexible than conventional wires.[37]

When an instrument is machined, plastic deformation occurs at the surface of the metal, resulting in residual stresses that remain at the surface that might accelerate the crack initiation and propagation process. Differential scanning calorimetry results suggests that thermal treatment received by V Taper 2H reduce the residual internal stress produced in mechanical processes like milling and an austenite finish temperature of 33.25ºC implying that at room temperature martensite or R phase could be mixed with an austenite phase. The presence of martensite phase could explain the increase cyclic fatigue resistance of V Taper 2H. [38]

V-Taper 2H file system obtained better results compared to Hyflex CM system even when the two system presents the same CM heat treatment. This finding could be attributed to the safe core™ parabolic design of V-Taper 2H which provides flexibility and reduces the chance of instrument fracture. A neutral rake angle as opposed to positive rake angle of Hyflex CM that will result in digging and gouging of the dentin, which can lead to separation.[39,40]

However, examination of cross sections at 3mm from the tip of instrument found the area of V-Taper 2H as 0.1373 $mm^2$and Hyflex CM as 0.0677 mm^2.[26] It is stated that more the core and Cross-Sectional area, less is the CFR.[41,42]With respect to this finding the area of V-Taper 2H is more compared to Hyflex CM and therefore the CFR of V-Taper 2H should be less when compared to Hyflex CM. The present study, however, reported an increased CFR value for V-Taper 2H. As, V-Taper 2H file system also has a variable (V) decreasing taper design from tip to shaft that allows file to remain flexible even in the most curved canals.[39] Similar results demonstrating superior value of V-Taper 2H have been obtained by Hye-jin et al. (2017).[36]

The present study showed increased NCF value for V-Taper 2H when compared to Twisted file.The result obtained can be attributed to CM wire alloy, safe core parabolic cross section and neutral rake angle of V-Taper 2H that enhances the flexibility of the file system.[39]Austenite finish temperature is in the range 17.62-18.88°C for twisted file and 33.25°C for V-Taper 2H. [[43]]When the working environment is below austenite finish temperature, the nitinol microstructure comprises martensite which exhibits higher flexibility and lower stiffness of than austenite. The lower stiffness of martensitic instruments can be attributed to the lower Young's modulus of martensite (30-40 GPa) whereas austenite (80-90 GPa) at ambient temperature.[44]An instrument becomes more flexible and fatigue resistant due to more martensitic properties.[45]There are no studies in the literature comparing CFR of V-Taper 2H and Twisted file system. However, endodontic instruments manufactured with CM wire alloy are expected to have more flexibility and to be more resistant to fatigue than those made from R phase.

In the present study, 2Shape showed the least value for the number of cycles to fracture (table III). This is in accordance with the study performed by Saeed et al. (2019).[46] The study evaluated cyclic fatigue restance at body temperature and 2Shape showed statistically significant reduction in fatigue. The 2Shape instruments undergoes a different thermomechanical process, including post machining electropolishing followed by heat treatment, which is a proprietary process undisclosed by the manufacturer. According to the manufacturer, T wire treatment results in instruments with better flexibility and cyclic fatigue resistance compared with instruments manufactured using the traditional austenite Ni Ti alloy. Despite the gold colour of 2Shape, scanning calorimetric test found to have A_f of 17°C. Therefore, it is an austenite file. The A_f might confer greater stiffness to the file.[47]

Uslu et al (2018)[48]studied and compared the cyclic fatigue resistance of 2Shape, Twisted file and Endosequence Xpress (ESX) NiTi rotary files at intracanal temperature (35ºC). All the instruments were rotated in artificial canals of diameter 1.5mm, 60º angle of curvature and a radius curvature of 5mm until fracture occurred. Number of cycles to fracture values revealed that 2Shape had significantly the highest cyclic fatigue resistance followed by Twisted file and ESX. T wire treatment might enable the file to have a higher austenite finish temperature and softer structure at test temperature which might be the reason for higher fracture resistance of 2Shape file in the study. The authors also believed that rotation speed of 2Shape might also play a role in its increased cyclic fatigue resistance values. The interpreted it to increase in the temperature of file surface with an increase in rotation speed, causing a thermomechanical stress on the file and decreasing the cyclic fatigue resistance.

The study done by Taha et al (2018)[49]showed no statistically significant difference in terms of cyclic fatigue resistance between wave one gold file in reciprocating motion and that of 2Shape file running on continuous rotation. Authors speculated that the smaller core volume given by the triple helix cross section of 2Shape might play role in these results. T wire alloy heat treatment might have also contributed to these results.

In a study by Elnaghy AM. et al.(2018),[50] 2Shape displayed superior cyclic fatigue resistance than Profile Vortex and Race instrument. It has been postulated that thermal processing raised the austenite transformation temperature of NiTi alloy and enhanced the arrangement of crystal structure, which increased the performance of instrument.

All files in the present study fractured in the apical curve. It could be due to abrupt apical curvature (a radius of 2 mm) compared to the coronal curvature (a radius of 5 mm). This finding is in agreement with previous studies that showed that fatigue life of NiTi instruments is considerably affected by the radius and/or angle of the curvature.[23,31,51]
The current study showed no significantdifference in the mean length of fractured fragments of theinstruments tested. Fracture of the instruments occurred at or justbelow the centre of the curve, which confirms the precise trajectorypositioning of the files.

Fractured fragments showed the typical feature of ductile fracture with microvoids and an area of microscopic dimples on fracture surface confirming that the rotary files fractured due to cyclic fatigue.

Since this is an in vitro study performed on a simulated stainless-steel model. The angulation and inclination of the teeth present in the oral cavity might produce varying results in CFR. Hence, further evaluation of the clinical performance of the tested brands in vivo, at intracanal temperature are needed to give reliable recommendations for endodontists. There is no specification or standard for testing fatigue resistance. Recently, Park et al. (2010)[52]proposed an alternative test method for torsional resistance. Similarly, there is a need for international standard and clinically relevant test methodology to evaluate the resistance to cyclic fatigue fracture.

CONCLUSION

Based on the results obtained under experimental condition and taking into account the limitations of this study, it can be concluded that –

1. V-Taper 2H file system showed significantly higher values of Number of cycles to fracture than Hyflex CM, Twisted file and 2Shape file systems.
2. The current study showed no significant difference in the mean length of fractured fragments of the instruments tested.

Financial support and sponsorship: Nil
Conficts of interest: there are no conflicts of interest.

REFERENCES

[1]. Ingle JI, Bakland LK. Endodontics. 5th ed. London: BC Decker Inc; 2002.
[2]. Walia H, Brantley W, Gerstein H An initial investigation of the bending and torsional properties of NiTi root canal files Journal of Endod 1988; 14(7):346-51

[3]. 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 Sep;17(5):462-6. doi: 10.4103/0972-0707.139842. PMID: 25298649; PMCID: PMC4174708.
[4]. Parashos P, Messer HH. Rotary NiTi instrument fracture and its consequences. Journal of endodontics. 2006 Nov 1;32(11):1031-43.
[5]. Cheung GS, Shen Y, Darvell BW. Effect of environment on low-cycle fatigue of a nickel–titanium instrument. Journal of endodontics. 2007 Dec 1;33(12):1433-7.
[6]. Martin B, Zelada G, Varela P, Bahillo JG, Magán F, Ahn S, Rodríguez C. Factors influencing the fracture of nickel-titanium rotary instruments. International Endodontic Journal. 2003 Apr;36(4):262-6.
[7]. Willershausen B, Kasaj A, Röhrig B, Marroquin BB. Radiographic investigation of frequency and location of root canal curvatures in human mandibular anterior incisors in vitro. Journal of endodontics. 2008 Feb 1;34(2):152-6.
[8]. Sattapan B, Nervo GJ, Palamara JE, Messer HH. Defects in rotary nickel-titanium files after clinical use. Journal of endodontics. 2000 Mar 1;26(3):161-5.
[9]. Shen Y, Zhou HM, Zheng YF, Peng B, Haapasalo M. Current challenges and concepts of the thermomechanical treatment of nickel-titanium instruments. Journal of endodontics. 2013 Feb 1;39(2):163-72.
[10]. Zupanc J, Vahdat-Pajouh N, Schäfer E. New thermomechanically treated NiTi alloys–a review. International endodontic journal. 2018 Oct;51(10):1088-103.
[11]. 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
[12]. Marsicovetere ES, Clement DJ, Del Rio CE. Morphometric video analysis of the engine-driven nickel-titanium Lightspeed instrument system. J Endod 1996;22:231–5.
[13]. Marending M, Peters OA, Zehnder M. Factors affecting the outcome of orthograde root canal therapy in a general dentistry hospital practice. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 2005;99:119 –24.
[14]. Eggert C, Peters O, Barbakow F. Wear of nickel-titanium Lightspeed instruments evaluated by scanning electron microscopy. J Endod 1999;25:494 –7.
[15]. Kuhn G, Tavernier B, Jordan L. Influence of structure on nickel-titanium endodontic instruments failure. J Endod 2001;27:516 –20.
[16]. Tripi TR, Bonaccorso A, Tripi V, Condorelli GG, Rapisarda E. Defects in GT rotary instruments after use: an SEM study. J Endod 2001;27:782–5.
[17]. Alapati SB, Brantley WA, Svec TA, Powers JM, Mitchell JC. Scanning electron microscope observations of new and used nickel-titanium rotary files. J Endod 2003;29:667–9.
[18]. Alapati SB, Brantley WA, Svec TA, Powers JM, Nusstein JM, Daehn GS. Proposed role of embedded dentin chips for the clinical failure of nickel-titanium rotary instruments. J Endod 2004;30:339 – 41. and reference number 6.
[19]. Topçuoglu HS, Topçuoglu G. Cyclic fatigue resistance of Reciproc Blue and Reciproc files in an s-shaped canal. Journal of endodontics. 2017 Oct 1;43(10):1679-82.
[20]. Plotino G, Grande NM, Sorci E, Malagnino VA, Somma F. A comparison of cyclic fatigue between used and new Mtwo Ni–Ti rotary instruments. International Endodontic Journal. 2006 Sep;39(9):716-23.
[21]. Sakkir N, Thaha KA, Nair MG, Joseph S, Christalin R. Management of Dilacerated and S-shaped Root Canals-An Endodontist's Challenge. Journal of clinical and diagnostic research: JCDR. 2014 Jun;8(6):ZD22.
[22]. Jain N, Tushar S. Curved canals: ancestral files revisited. Indian Journal of Dental Research. 2008 Jul 1;19(3):267.
[23]. Al-Sudani D, Grande NM, Plotino G, Pompa G, Di Carlo S, Testarelli L, Gambarini G. Cyclic fatigue of nickel-titanium rotary instruments in a double (S-shaped) simulated curvature. Journal of endodontics. 2012 Jul 1;38(7):987-9.
[24]. Plotino G, Grande NM, Mazza C, Petrovic R, Testarelli L, Gambarini G. Influence of size and taper of artificial canals on the trajectory of NiTi rotary instruments in cyclic fatigue studies. Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology, and Endodontology. 2010 Jan 1;109(1):60-6.
[25]. Yared G, Kulkarni GK. Accuracy of the DTC torque control motor for nickel-titanium rotary instruments. International endodontic journal. 2004 Jun;37(6):399-402.
[26]. Gambarini G. Rationale for the use of low-torque endodontic motors in root canal instrumentation. Endod Dent Traumatol. 2000 Jun;16(3):95-100. doi: 10.1034/j.1600-9657.2000.016003095.x. PMID: 11202872.
[27]. Madarati AA, Watts DC, Qualtrough AJ. Factors contributing to the separation of endodontic files. Br Dent J. 2008 Mar 8;204(5):241-5. doi: 10.1038/bdj.2008.152. PMID: 18327187.
[28]. Yared GM, Dagher FE, Machtou P, Kulkarni GK. Influence of rotational speed, torque and operator proficiency on failure of Greater Taper files. Int Endod J. 2002 Jan;35(1):7-12. doi: 10.1046/j.1365-2591.2002.00443.x. PMID: 11858204.
[29]. Sattapan B, Palamara JE, Messer HH. Torque during canal instrumentation using rotary nickel-titanium files. J Endod. 2000 Mar;26(3):156-60. doi: 10.1097/00004770-200003000-00007. PMID: 11199710.

[30]. Gambarini G. Cyclic fatigue of nickel-titanium rotary instruments after clinical use with low- and high-torque endodontic motors. J Endod. 2001 Dec;27(12):772-4. doi: 10.1097/00004770-200112000-00015. PMID: 11771588.

[31]. Topçuoglu HS, Topçuoglu G. Cyclic fatigue resistance of Reciproc Blue and Reciproc files in an s-shaped canal. Journal of endodontics. 2017 Oct 1;43(10):1679-82.

[32]. Pedullà E, Savio FL, Boninelli S, Plotino G, Grande NM, La Rosa G, Rapisarda E. Torsional and cyclic fatigue resistance of a new nickel-titanium instrument manufactured by electrical discharge machining. Journal of endodontics. 2016 Jan 1;42(1):156-9.

[33]. Al-Sudani D, Plotino G, Grande N, Rengo S, Simeone M. Cyclic Fatigue of Glide Path Rotary NiTi Files in a Double (S-Shaped) Simulated Curvature. Dentistry. 2016;6(355):2161-1122.

[34]. Olcay K, Eyuboglu TF, Erkan E. Cyclic fatigue resistance of waveone gold, protaper next and 2shape nickel titanium rotary instruments using a reliable method for measuring temperature. Nigerian journal of clinical practice. 2019 Oct 1;22(10):1335.

[35]. Chang SW, Shim KS, Kim YC, Jee KK, Zhu Q, Perinpanayagam H, Kum KY. Cyclic fatigue resistance, torsional resistance, and metallurgical characteristics of V taper 2 and V taper 2H rotary NiTi files. Scanning. 2016 Nov;38(6):564-70.

[36]. Goo HJ, Kwak SW, Ha JH, Pedullà E, Kim HC. Mechanical properties of various heat-treated nickel-titanium rotary instruments. Journal of endodontics. 2017 Nov 1;43(11):1872-7.

[37]. Pereira ÉS, Viana AC, Buono VT, Peters OA, de Azevedo Bahia MG. Behavior of nickel-titanium instruments manufactured with different thermal treatments. Journal of endodontics. 2015 Jan 1;41(1):67-71.

[38]. Kaloustian M, Nehme W, El Hachem C, Zogheib C, Ghosn N, Michetti J, Naaman A, Diemer F. Evaluation of Two Shaping Systems and Two Ultrasonic Irrigation Devices in Removing Root Canal Filling Material from Mesial Roots of Mandibular Molars: A Micro CT Study. Dentistry journal. 2019 Mar;7(1):2.

[39]. V Taper 2H Rotary Files. Available from: http://www.sswhitedental.com/content/v-taper%E2%84%A22h-rotary-files. [Last accessed on 2016 Jan 03].

[40]. Poggio C, Dagna A, Chiesa M, Beltrami R, Bianchi S. Cleaning effectiveness of three niti rotary instruments: a focus on biomaterial properties. Journal of functional biomaterials. 2015 Mar;6(1):66-76.

[41]. Parashos P, Gordon I, Messer HH. Factors influencing defects of rotary nickel-titanium endodontic instruments after clinical use. *J Endod.* 2004;30:722–5.

[42]. Sekar V, Kumar R, Nandini S, Ballal S, Velmurugan N. Assessment of the role of cross section on fatigue resistance of rotary files when used in reciprocation. Eur J Dent. 2016 Oct-Dec;10(4):541-545. doi: 10.4103/1305-7456.195171. PMID: 28042272; PMCID: PMC5166313.

[43]. Shim KS, Oh S, Kum K, Kim YC, Jee KK, Chang SW. Mechanical and metallurgical properties of various nickel-titanium rotary instruments. BioMed research international. 2017;2017.

[44]. Johnson WB, inventor. Fatigue-resistant Nitinol instrument. United States patent US 8,714,976. 2014 May 6.

[45]. Santoro M, Nicolay OF, Cangialosi TJ. Pseudoelasticity and thermoelectricity of nickel-titanium alloys: A clinically oriented review. Part I: Temperature transitional ranges. Am J Orthod Dentofacial Orthop. 2001 Jun 1;119(6):587–93.

[46]. Saeed DH, Rafea FA. Evaluation of the effect of temperature on cyclic fatigue resistance of three types of Nickel-Titanium rotary files with various alloy properties: An in vitro study. Erbil Dental Journal (EDJ). 2019 Jun 6;2(1):157-63.

[47]. Brantley WA, Svec TA, Iijima M, Powers JM, Grentzer TH. Differential scanning calorimetric studies of nickel-titanium rotary endodontic instruments after simulated clinical use. Journal of endodontics. 2002 Nov 1;28(11):774-8.

[48]. Uslu G, Özyürek T, Gündoğar M, Yılmaz K. Cyclic fatigue resistance of 2Shape, Twisted File and EndoSequence Xpress nickel-titanium rotary files at intracanal temperature. Journal of dental research, dental clinics, dental prospects. 2018;12(4):283.

[49]. Ozyurek T, Gundogar M, Uslu G, Yılmaz K, Staffoli S, Grande NM, Plotino G, Polimeni A. Cyclic fatigue resistances of Hyflex EDM, WaveOne gold, Reciproc blue and 2shape NiTi rotary files in different artificial canals. Odontology. 2018 Oct 1;106(4):408-13.

[50]. Elnaghy AM, Elsaka SE. Cyclic Fatigue Resistance of One Curve, 2Shape, ProFile Vortex, Vortex Blue, and RaCe Nickel-Titanium Rotary Instruments in Single and Double Curvature Canals. Journal of endodontics. 2018 Nov 1;44(11):1725-30.

[51]. Duke F, Shen Y, Zhou H, Ruse ND, Wang ZJ, Hieawy A, Haapasalo M. Cyclic fatigue of ProFile Vortex and Vortex Blue nickel-titanium files in single and double curvatures. Journal of endodontics. 2015 Oct 1;41(10):1686-90.

[52]. Park SY, Cheung GS, Yum J, Hur B, Park JK, Kim HC. Dynamic torsional resistance of nickel-titanium rotary instruments. Journal of endodontics. 2010 Jul 1;36(7):1200-4.