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ORIGINAL ARTICLE

Influence of Thermal Pretreatments on the Cyclic Fatigue Resistance of Novel Reciprocating Nickel-titanium Files: A Comparison of Low- and High-temperature Modified Systems

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ABSTRACT

Objective: The flexibility and fracture resistance of nickel-titanium (NiTi) files have revolutionised root canal preparation, but file fractures caused by cyclic fatigue or torsional failure are challenging. Thermal pretreatments aim to improve fatigue resistance. This study compared the cyclic fatigue resistance (CFR) of four novel reciprocating NiTi file systems with low- versus high-temperature thermal modification under simulated clinical conditions.

Methods: Four systems (n=50) were investigated in vitro: low heat (LH; EdgeOne R-Utopia (Edge Endo, Albuquerque, New Mexico, USA); Procodile Q (Komet Dental, Lemgo, Germany)) and high heat (HH; Reciproc Blue (VDW GmbH, Munich, Germany); CC One Blue (Bondent, San Clemente, California, USA)). CFR was tested under simulated conditions (35±1°C). Two canal configurations were used: a single-curvature canal (60°, 5 mm radius, curvature centre 6 mm from the tip) and a double-curvature canal (additional 70°, 2 mm radius, curvature centre 2 mm from the tip). The files were tested in a 'pecking' motion (3 mm stroke, 0.5 Hz) until fracture occurred. The time to fracture (TTF), number of cycles to fracture (NCF) and fragment length (FL) were measured. Weibull analysis was performed to assess reliability and predict fracture behaviour. Fracture fragments were analysed using scanning electron microscopy (SEM). Two-factor ANOVA was performed using instrument type and canal configuration as independent variables for each outcome measure (TTF, NCF, FL). Post hoc comparisons were conducted using Tukey-HSD ($\alpha = 0.05$). Normal distribution was confirmed using Shapiro-Wilk testing.

Results: Differences in CFR were not significant between LH and HH systems (p=0.203), however, results were significant between file systems (p<0.001) and canal configurations (p<0.001). CFR was highest with Procodile Q, then Reciproc Blue, and lowest with EdgeOne R-Utopia. FL was similar between LH and HH (p=0.427) but differed between file systems and canal geometries (p<0.05). SEM analyses confirmed fatigue cracks in highly stressed areas.

Conclusion: The temperature range of thermal pretreatment did not affect cyclic fatigue resistance. Instead, file design and alloy composition were the decisive factors. Clinicians should prioritise structural features and mechanical behaviour over heat treatment labels when selecting instruments for complex root canal anatomies.

Keywords: Cyclic fatigue, endodontics, heat treatment, nickel-titanium alloys, reciprocation, scanning electron microscopic analysis

HIGHLIGHTS

- Cyclic fatigue resistance of thermally pretreated reciprocating NiTi files has not been previously reported.
- Low- and high-heat pretreated files showed comparable fatigue resistance under simulated body temperature conditions.
- File design and alloy composition were the primary determinants of cyclic fatigue resistance, with Procodile Q exhibiting superior performance, particularly in complex canal geometries.

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INTRODUCTION

Since their introduction, the use of nickel-titanium (NiTi) files has revolutionised standards in root canal preparation (1). NiTi files were developed to make the mechanical instrumentation of root canals more efficient and faster, offering significant advantages over stainless steel files due to their flexibility, adaptability to canal shapes, and high fracture resistance. Nevertheless, file fractures remain an inherent complication during root canal preparation, even with NiTi files (2, 3). NiTi instruments primarily fracture through two mechanisms: torsional failure and cyclic fatigue (4). Torsional failure occurs when the instrument tip becomes locked in the canal while the shaft continues to rotate, exceeding the elastic limit of the metal. In contrast, cyclic fatigue occurs due to repeated tensile and compressive stresses at the point of maximum canal curvature, ultimately leading to fracture (5, 6).

Recent studies have shown that torsional resistance in NiTi instruments depends not only on material properties, but also on geometric factors such as the polar moment of inertia (7). Notably, instruments with reduced core mass and flat-sided cross-sections can, when combined with advanced heat treatments, achieve both high flexibility and unexpectedly high torsional strength (8). Continuous advancements in NiTi file technology, such as electrolytic polishing and electrical discharge machining, have enhanced their mechanical properties and fatigue resistance (9). A major improvement has been the introduction of reciprocating motion, which optimised conventional rotational kinematics (10). This movement combines a 150° counterclockwise cutting action with a 30° clockwise release at 300 rpm, allowing safe dentin cutting and stress relief. This asymmetric motion reduces cyclic fatigue and the risk of torsional fractures, increasing instrument longevity and safety (11). Nevertheless, reciprocating NiTi files still face limitations in severely curved, narrow, or obliterated canals, especially during extended use (12). To address this, recent focus has shifted to thermal treatments. Alloys like M-Wire, Gold Wire, and Blue Wire undergo targeted heat treatments to further enhance mechanical behaviour (13). The widely used Reciproc Blue system (VDW GmbH, Munich, Germany) was among the first to apply high-temperature processing (450–500 °C), inducing a martensitic phase and forming a blue titanium oxide layer. This improves both flexibility and fatigue resistance compared to conventional NiTi (14, 15). A similar process is used in CC One Blue (Bondent, San Clemente, California, USA), whose M-Wire base is also nano-coated for added flexibility and fracture resistance. In contrast, newer low-temperature-treated files have emerged. EdgeOne R-Utopia (Edge Endo, Albuquerque, New Mexico, USA) undergoes a 'FireWire' process at ~400 °C, creating a brown-golden oxide layer and promoting a martensitic structure. Likewise, Procodile Q (Komet Dental, Lemgo, Germany) receives a modified low-temperature treatment prior to shaping, combining flexibility with high cutting efficiency (12, 16).

To date, there has been no direct comparison between novel low- and high-temperature heat-treated reciprocating NiTi files with respect to their cyclic fatigue resistance (CFR). The question arises whether different manufacturing processes cause different outcomes in terms of clinical application. Therefore, the present study investigated the cyclic fatigue resistance (CFR) of four reciprocating NiTi file systems with different thermal pretreatments—specifically, low- versus high-temperature heat treatment under simulated clinical conditions and two canal curvature configurations. The null hypothesis was that neither the type of instrument (including its specific thermal pretreatment) nor the canal configuration, nor their interaction, has a significant effect on the cyclic fatigue resistance of reciprocating NiTi files.

MATERIALS AND METHODS

Power Analysis and Sampling

The sample size for this CFR study was calculated using G*Power v3.1 (Heinrich Heine University Düsseldorf, Düsseldorf, Germany). A two-way ANOVA analysis with a significance level of 5% and a power of 80% was used. The resulting effect size was determined to be 0.783, suggesting that a sample size of 15 specimens per group would be sufficient to detect statistically significant differences. However, since no published data on the mechanical properties of CC One Blue, EdgeOne R-Utopia, and Procodile Q were available, an additional ten samples per group were included to account for potential unforeseen variations. Consequently, 25 specimens per group were selected for each canal configuration.

This *in vitro* study evaluated four different heat-treated NiTi file systems, divided into two main groups: 1) high-temperature heat treatment (HH): Reciproc Blue (VDW GmbH, Munich, Germany) and CC One Blue (Bondent, San Clemente, California, USA); low-temperature heat treatment (LH): EdgeOne R-Utopia (Edge Endo, Albuquerque, New Mexico, USA) and Procodile Q (Komet Dental, Lemgo, Germany). All files had a uniform tip size of 0.25 mm and a length of 25 mm, with variations in taper.

All tested file systems exhibited a similar S-shaped cross-sectional design with two cutting edges but differed in their tapers. Reciproc Blue files had a regressive taper of 0.08, starting 3 mm from the tip, while CC One Blue files featured a continuous taper of 0.08. EdgeOne R-Utopia files had a variable taper, with a fixed taper of 0.08 in the first apical millimetres (details on cross-sectional design were unavailable). In contrast, Procodile Q files exhibited a variable taper with a decreasing diameter toward the shaft and a taper of 0.06, combined with a double S-shaped cross-section. Before testing, all files were inspected under a digital microscope (VHX-5000, Keyence Corp., Osaka, Japan, 25× magnification) for defects and deformations. No anomalies were detected, and all files were used without restrictions.

Cyclic Fatigue Resistance

CFR testing was conducted under standardised conditions using a custom-made apparatus (Fig. 1) specifically designed by the authors for cyclic fatigue tests. The components were made of durable metal to ensure longevity and precision. The design allowed for flexible handpiece movement, enabling precise and reproducible positioning of files within artificial canals. The apparatus included built-in motors (Micro Motors gear motor, Micro Motors Srl, Verderio, Italy) and heating plates (Tru Components 7.5 Ohm 20W, Tru Components, USA) to simulate realistic conditions. Artificial steel canals with specific geometries were fabricated to simulate various loading

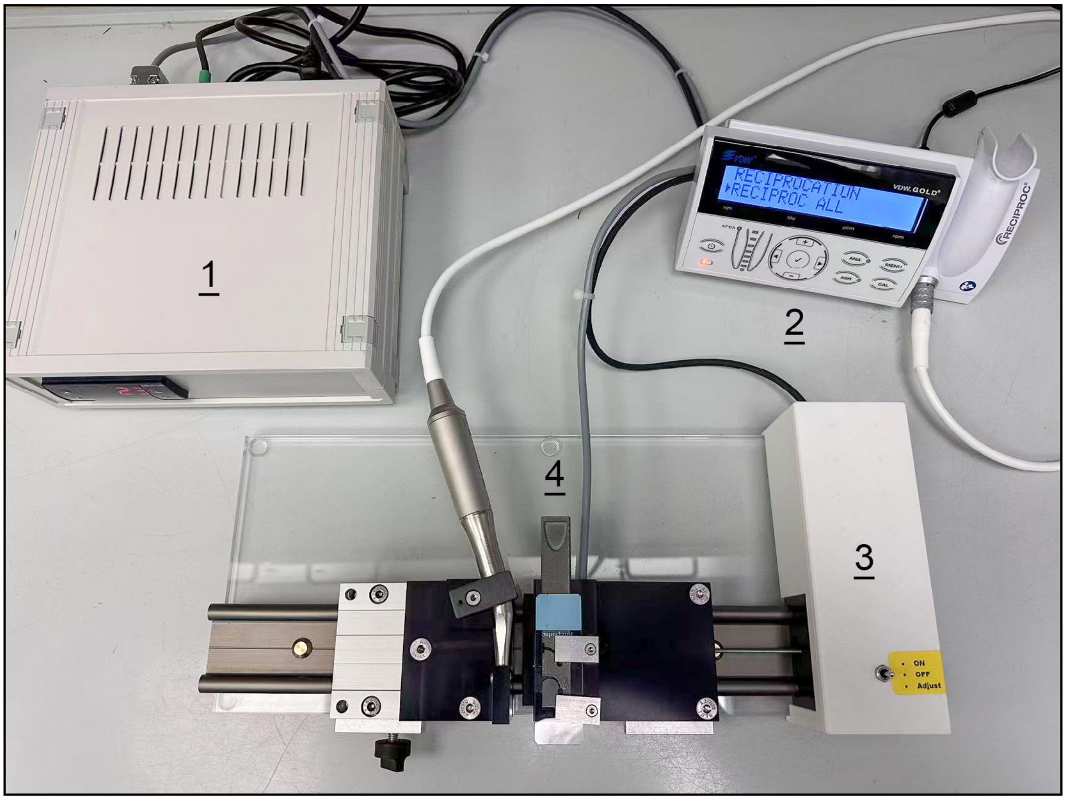

Figure 1. Cyclic fatigue testing device. 1) Temperature controller connected to heating plates (Tru Components 7.5 Ohm 20W, Tru Components, USA) to maintain the desired temperature. 2) Torque-controlled electric motor (VDW Gold, VDW, Munich, Germany). 3) cyclic fatigue resistance testing device equipped with a handpiece and micromotor (Micro Motors Gear Motor, Micro Motors Srl, Verderio, Italy) for pecking motion. 4) Exchangeable artificial root canals to facilitate testing, activated via a 6:1 reduction handpiece (Sirona, Bensheim, Germany)

scenarios (Fig. 2). The first canal had a single curvature with a 60° angle and a 5 mm radius, with the curvature centre located 6 mm from the instrument tip. The second canal featured a double curvature: the first had a radius of 5 mm and an angle of 60° (centred 6 mm from the tip), and the second had a radius of 2 mm and an angle of 70°, located 2 mm from the tip. These configurations correspond to validated protocols from earlier cyclic fatigue studies (17, 18), which standardised canal curvature and radius to allow reproducible comparisons of file performance under clinically relevant mechanical stress. The reference setup has become widely used for benchmarking new systems and was adapted here to ensure compatibility and methodological consistency with published data.

To replicate the ‘pecking’ motion commonly used in clinical practice, the apparatus was modified to enable repeated up-and-down movements of the files in the canals. These movements had an amplitude of 3 mm and a frequency of approximately 0.5 Hz. All files were tested according to the manufacturer’s recommendations using the "RECIPROC ALL" program (300 rpm). A 6:1 reduction handpiece (Sirona, Bensheim, Germany) powered by a torque-controlled electric motor (VDW Gold, VDW, Munich, Germany) was employed. Synthetic oil (WD-40, WD Company, Milton Keynes, UK) was used as a lubricant to minimise friction and ensure smooth file rotation. To simulate oral conditions, the canal temperature was maintained at 35±1 °C, monitored with an infrared thermometer.

Files were operated in the canals until a fracture occurred, which was detected visually and acoustically. Time to fracture (TTF) was recorded using a digital chronometer (Schütt Stopwatch PC-71, Schütt, Erkrath, Germany) with an accuracy of 0.01 seconds. Video recordings were also made for additional verification. The number of cycles to fracture (NCF) was calculated for each file using the following formula:

$$NCF=\frac{(Speed\ of\ rotation\ (rpm)\times TTF(s)}{60}$$

A Weibull analysis was performed to assess the probability of survival and failure characteristics. The shape parameter (β; Weibull modulus) and scale parameter (η; characteristic life) were calculated for each group, including 95% confidence intervals. Survival probabilities were graphically visualized in Weibull plots as described in previous studies (19, 20).

Fragment length (FL) of fractured files was measured using a digital calliper (accuracy 0.01 mm, DIGI-MET 1320 417, Helios-Preisser, Germany). The average FL was calculated to confirm the correct positioning of instruments in the canals and ensure comparable stress distribution during testing. All tests were conducted by the same operator to maintain procedural consistency.

Scanning Electron Microscopy

The surface topography of fractured instruments was examined to investigate fracture mechanisms due to cyclic fatigue.

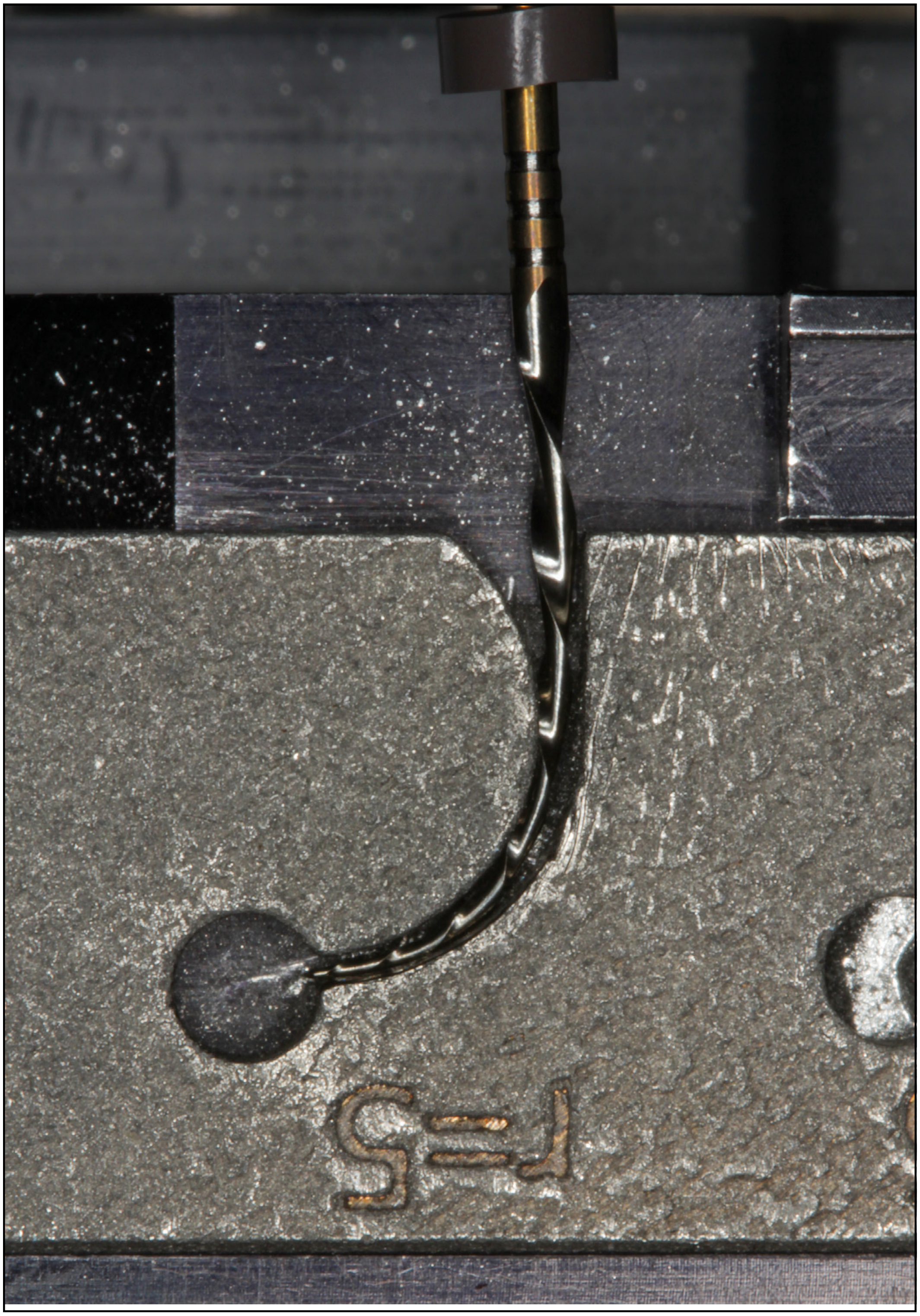

Figure 2. Artificial root canal made of stainless steel, with an inserted test file positioned for cyclic fatigue testing

For each file type, three fragments were randomly selected and analysed using a scanning electron microscope (SEM) (FEI Quanta 400 system, FEI Company, Tokyo, Japan).

Surface Roughness Analysis

The three-dimensional (3D) surface roughness of the files was evaluated using a non-contact optical 3D laser scanning microscope (VK-X3050, Keyence Corporation, Osaka, Japan). Images were acquired in Vertical Scanning Interferometry mode without applying filters. Three central regions of each sample were randomly selected, and their averages were calculated. The analysed parameters included Sa (average surface roughness, providing a general overview of texture) and Sz (maximum vertical difference between the highest and lowest points on the surface). Surface roughness analysis was performed on file fragments after fracture during cyclic fatigue testing, enabling the evaluation of topographical changes associated with material failure.

TABLE 1. Cyclic fatigue resistance: Time to fracture and fragment length in all tested groups

	Single curvature			Double curvature		
	Coronal curvature			Apical curvature		
Group	**TTF (sec)**	**FL (mm)**	**TTF (sec)**	**FL (mm)**	**TTF (sec)**	**FL (mm)**
High heat						
Reciproc Blue	274.2±76.1^{b}	6.16±0.49^{a}	222.3±45.0^{b}	6.32±0.27^{abc}	179.7±30.1^{b}	2.14±0.58^{abc}
CC One Blue	217.8±48.0^{bc}	6.57±0.36^{b}	192±44.1^{b}	6.19±0.67^{abc}	189.2±38.2^{ab}	2.10±0.23^{abc}
Low heat						
EdgeOne R-Utopia	184±66.2^{c}	6.28±0.94^{c}	126.5±18.8^{c}	5.59±1.15^{abc}	102.8±39.3^{c}	2.26±0.43^{abc}
Procodile Q	339.1±35.6^{a}	7.25±1.57^{a}	343.2±74.3^{a}	6.10±0.53^{abc}	239±46.1^{a}	2.25±0.34^{abc}

Results presented as mean±standard deviation. Different superscript letters within a column indicate statistically significant differences between groups ($p<0.05$, Tukey HSD). Identical letters indicate no significant difference. TTF: Time to fracture, FL: Fragment length

TABLE 2. Weibull parameters of NiTi endodontic instruments (under single and double curvature conditions)

Group	**Mean Life (NCF)**		**Shape parameter β (95% CI)**		**Scale parameter η (95% CI)**	
	Single curvature	**Double curvature**	**Single curvature**	**Double curvature**	**Single curvature**	**Double curvature**
High heat						
Reciproc Blue	1368.25±380.47	1023±221.26	4.81 (3.34–7.54)	5.26 (4.18–6.80)	1500 (1329–1641)	1111 (1007–1210)
CC One Blue	1084±239.92	953.25±203.82	5.29 (4.13–6.92)	5.58 (4.31–7.50)	1176 (1055–1289)	1034 (943–1119)
Low heat						
EdgeOne R-Utopia	918±331.02	576.75±156.59	3.41 (2.51–4.90)	4.43 (3.33–7.05)	1024 (863–1170)	632 (559–699)
Procodile Q	1696.75±177.75	1585.25±408.27	12.78 (9.15–17.39)	4.56 (3.50–6.81)	1766 (1695–1835)	1739 (1532–1936)

Weibull analysis based on number of cycles to fracture (NCF). β: shape parameter (Weibull modulus), CI: Confidence interval, η: Scale parameter (characteristic life)

Statistical Analysis

Statistical analysis was performed using a Weibull analysis to assess reliability and fracture behaviour (β, η), followed by a two-way ANOVA in SPSS 29.0 (IBM Corp., Armonk, NY, USA) to assess the influence of file type and canal geometry on TTF and FL. Separate ANOVA analysis were conducted for each dependent variable. Normal distribution was confirmed using the Shapiro-Wilk test prior to analysis. A significance level of 5% was defined, and pairwise differences between groups were analysed using Tukey-HSD post hoc tests.

RESULTS

Cyclic Fatigue Resistance

Table 1 presents the results of the mechanical *in vitro* tests for TTF and FL under simulated physiological conditions (body temperature), including pairwise comparisons. There were significant effects of the file systems on TTF ($F(3)=72.09$, $p<0.001$, $\eta^2=0.538$) and of the canal configurations ($F(1)=27.59$, $p<0.001$, $\eta^2=0.069$). However, no significant interaction between these factors was detected ($F(3)=2.11$, $p=0.101$, $\eta^2=0.016$).

The Procodile Q system exhibited the longest TTF across all canal configurations, achieving similar values in the double-curvature canal to those of the established gold standard (Reciproc Blue) in the single-curvature canal. In contrast, the EdgeOne R-Utopia system demonstrated the shortest TTF in both canal configurations. Weibull survival analyses (Table 2, Figs. 3, 4) graphically highlighted these differences: Procodile Q exhibited a notably flatter survival curve compared to other systems, indicating superior fatigue resistance. Reciproc Blue followed with a relatively flat curve, whereas CC One Blue showed a steeper decline. EdgeOne R-Utopia exhibited the steepest decline, with nearly complete fracture probability observed after only a few cycles in the double-curvature canal. Across both canal geometries, Procodile Q demonstrated the highest scale (η) and shape (β) parameters, indicating superior fatigue resistance combined with high reliability. Reciproc Blue and CC One Blue showed moderate η values and acceptable β ranges, reflecting good overall performance with consistent failure behaviour. In contrast, EdgeOne R-Utopia exhibited the lowest values for both parameters under single- and double-curvature conditions, suggesting earlier fracture and greater variability in cyclic fatigue behaviour. Regarding FL, no significant differences were found between the different heat treatments (LH vs. HH, $p=0.427$). However, significant differences were observed between file systems ($p=0.023$) and canal configurations ($p<0.01$).

Surface Roughness

The surface roughness analysis revealed moderate differences between file systems (Table 3 and Fig. 5). Procodile Q exhibited lower Sa values in single-curvature canals compared to other systems, whereas CC One Blue showed the highest Sa values in double-curvature canals. EdgeOne R-Utopia displayed consistently low Sz values, regardless of curvature.

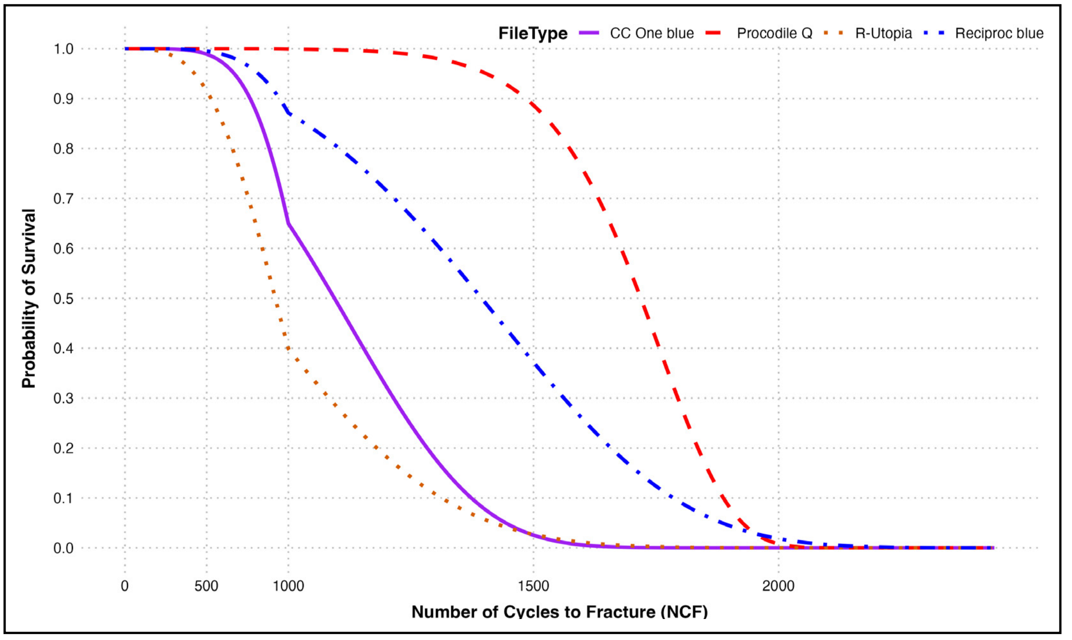

Figure 3. Weibull distribution of survival probabilities (number of cycles to fracture) for tested NiTi-file systems in a single-curved canal configuration

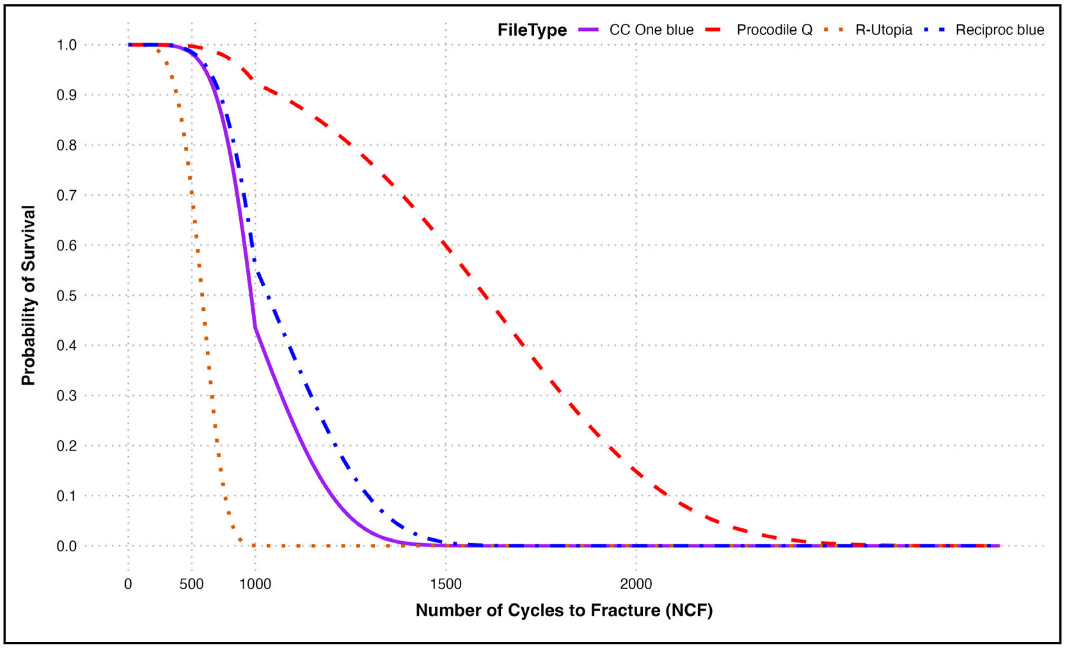

Figure 4. Weibull distribution of survival probabilities (number of cycles to fracture) for tested NiTi-file systems in a double-curved canal configuration

SEM Analysis

Fractographic analysis revealed that the fracture surfaces of NiTi files displayed typical fatigue patterns (Fig. 6). Fatigue cracks originated from one or more initiation points and propagated across the fracture surface. Two characteristic zones were identified: areas with visible fatigue striations and regions with a knobby, irregular surface texture.

DISCUSSION

NiTi file fractures during root canal preparation represent a significant complication that should be avoided whenever possible (18). In cases where a fracture occurs, several approaches can be considered, including bypassing the fragment, integrating the broken instrument into the filling material, or complete removal (21). Regardless of the chosen method, this issue places a considerable burden on the clinician due to the additional time required and the need to involve a specialist consultation (22). Moreover, the prognosis of the affected tooth is significantly reduced, as the fragment cannot always be retrieved, and successful bypassing is not guaranteed. To enhance fracture resistance, novel NiTi file systems with thermal treatments across varying temperature ranges (high versus low) have been introduced in recent years. The thermal treatment of NiTi files aims to modulate the transformation

Table 3. Surface roughness of NiTi endodontic instruments (under single and double curvature conditions)

Group	Sa (μm)		Sz (μm)	
	Single curvature	Double curvature	Single curvature	Double curvature
High heat				
Reciproc Blue	17.19±1.4	26.93±2.21	153.53±14.08	309.83±39.16
CC One Blue	24.9±1.67	31.56±1.65	152.91±12.47	243.97±35.43
Low heat				
EdgeOne R-Utopia	24.07±1.93	25.72±3.11	152.14±8.72	158.08±13.58
Procodile Q	20.94±1.76	19.96±2.16	158.62±14.04	268.78±20.92

Results presented as mean±standard deviation. Sa: Average surface roughness, Sz: Maximum vertical difference between the highest and lowest points on the surface

behaviour between the austenitic and martensitic phases (23). An increased proportion of the martensitic phase is associated with greater flexibility and improved CFR (9).

This is the first study to evaluate the CFR of the newly introduced heat-treated file systems CC One Blue, EdgeOne R-Utopia and Procodile Q. Our findings partially rejected the null hypothesis, as both the type of file system and the canal geometry had a statistically significant effect on cyclic fatigue resistance. However, this study confirmed that the specific temperature range of thermal pretreatment (low versus high) did not significantly influence CFR, supporting this part of the hypothesis. No interaction between instrument type and canal curvature was found. Instead, the results of this study suggest that the interplay between file design, thermal modification, and alloy composition is the key determinant of CFR (3). The lack of differentiation between the two thermal treatment methods suggests that the induction of the martensitic phase in the NiTi core—a common effect of both approaches—has a critical influence on fatigue resistance, while the precise temperature range of the treatment appears to play a less dominant role than previously assumed. Nevertheless, this study demonstrated that the file system and canal geometry (simple versus double curvature) had significant effects on the TTF. These findings align with previous studies emphasizing the role of canal morphology complexity in instrument stress (5, 17). The file systems tested reflect technological advancements in endodontics. While Reciproc Blue was introduced in 2016 (14), CC One Blue, EDGEOne R-Utopia and Procodile Q were introduced to the market later. Since its release, Reciproc Blue has often

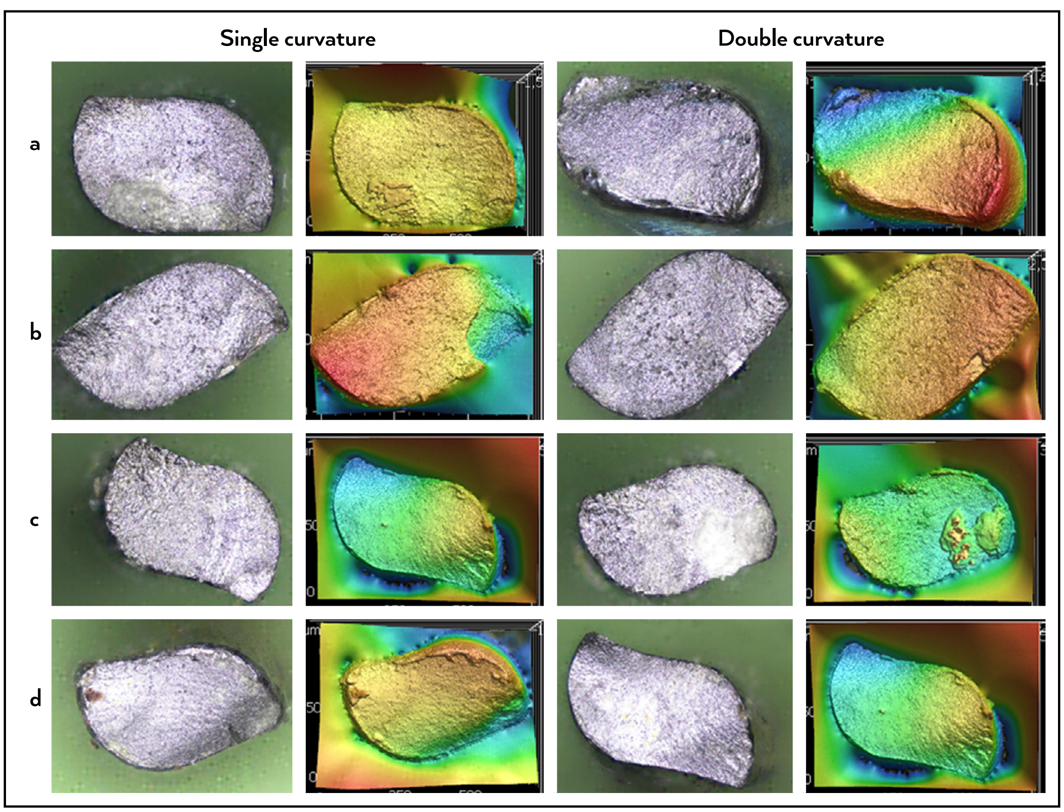

Figure 5. Surface roughness analysis. Laser-optical images of the fracture surfaces (left, black and white) alongside the corresponding 3D profilometric representations (right, colour). (a) Reciproc Blue; (b) CC One Blue; (c) Procodile Q; (d) EdgeOne R-Utopia

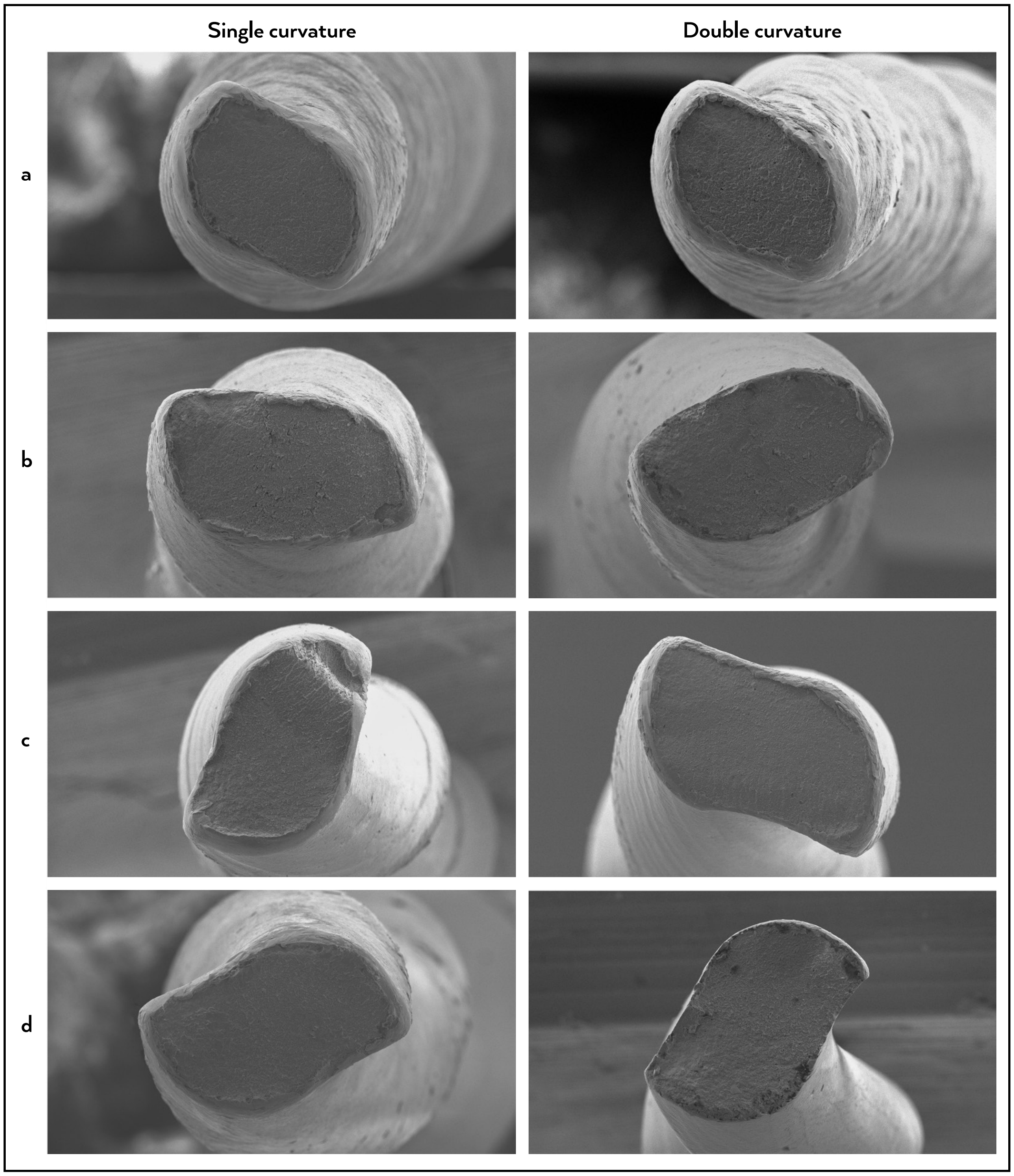

Figure 6. Scanning electron micrographs of tested files (magnification 600x) in single and double curvature. (a) Reciproc Blue; (b) CC One Blue; (c) EdgeOne R-Utopia; (d) Procodile Q

been regarded as the 'gold standard' for thermally optimised NiTi instruments (3). Reciproc Blue utilises Blue Wire technology, which involves a specific heat treatment that promotes martensitic phase formation at body temperature (24).

This study confirmed the high CFR of Reciproc Blue. Notably, in simply curved canals where mechanical stress was moderate, this file demonstrated high TTF values. The measured values of 274 s for simple curvature and 222 s and 179 s for double curvature canals are consistent with values reported by Keleş et al. (25) (253 s) and Klymus et al. (9) (303 s) for simply curved root canals. Comparable values of (251s) for complex canal configurations, reported by Al-Obaida et al. (17), further suggest the validity of the experimental setup used in our study. The data also highlight advancements in thermally treated NiTi instruments in which the newer Procodile Q system achieved superior results in CFR, indicating that recently developed systems can compete with established instruments despite their shorter time on the market. Procodile Q exhibited a 23.72% increase in resistance compared to Reciproc Blue in simple curvatures, and increases of 54.50% and 33.52% in the coronal and apical regions in complex curvatures, respectively. CC One Blue showed reduced fatigue resistance compared to Reciproc Blue but still demonstrated clinically relevant performance values within an acceptable range. In contrast, EdgeOne R-Utopia files exhibited the shortest lifespan, possibly due to their less robust alloy composition. In addition to alloy properties, cross-sectional design is another critical factor for CFR (26). Instruments with S-shaped or double S-shaped cross-sections can better distribute stress during bending (17). This was particularly evident in Reciproc Blue and Procodile Q, whose S-shaped designs positively influenced CFR. In double curved root canals, where instruments are subjected to significant bending stress in the apical region while simultaneously adapting to the coronal section, these additional loads often result in marked reductions in TTF values (17). The current results confirm this trend, as all tested instruments showed lower CFR in double curved canals compared to simply curved ones. Nonetheless, Procodile Q maintained relatively high fracture resistance even in these demanding scenarios, suggesting an optimal combination of heat treatment, alloy structure and file architecture. While Reciproc Blue exhibited slightly reduced CFR in comparison, it still performed reliably.

The dynamic experimental setup provided a realistic simulation by incorporating reciprocating movements and axial load changes, which distribute fracture risk more evenly and enhance overall CFR (27). The maintenance of body temperature ensured that temperature-dependent phase transitions in the NiTi material were considered, resulting in clinically relevant findings (28). Profilometer data indicated that surface roughness might be less critical for fatigue resistance than other material properties. Surface roughness analysis was performed after fracture, which offers the advantage of characterising the surface in its final, clinically relevant failure state. However, this approach does not account for potential roughness changes occurring progressively during instrumentation, thereby limiting insight into the fatigue process itself. Additionally, the analysis of FL provided valuable insights into fracture dynamics and underscored the influence of canal geometry (5). No statistically significant differences in FL were observed between the two thermal treatments (LH vs. HH). This suggests that FL is primarily influenced by the specific properties of the file systems and the geometry of canal curvature. The fracture area was often localised near the most pronounced curvature, where the highest bending moment occurs. This finding aligns with previous studies, such as Al-Obaida et al. (17), which reported that FL, irrespective of cross-sectional shape or thermal treatment, is typically concentrated in regions of maximum curvature. All of these findings are clinically significant, as they suggest that the selection of a file system should be guided more by its design and specific application conditions rather than solely by the temperature range of its thermal treatment. For highly curved or obliterated canals, choosing a system with higher fatigue resistance, such as Procodile Q, may minimise the risk of instrument fracture.

This study has methodological limitations that should be considered when interpreting the results. The use of rigid, stainless-steel canals with standardised curvatures only partially simulated the variable and complex geometries of natural root canals, limiting the generalisability to clinical conditions. The *in vitro* design also lacked critical biological factors such as tissue pressure, moisture and debris, which could influence the mechanical properties and fatigue resistance of NiTi files *in vivo*. Additionally, while the constant temperature of 35±1°C mimicked oral conditions, it did not account for potential temperature fluctuations from irrigants or thermal loads during clinical application. Future studies should integrate these factors and other dynamic parameters, such as cutting performance and centring ability, to provide a more comprehensive understanding of the clinical performance of heat-treated reciprocating NiTi instruments.

CONCLUSION

The mechanical performance of heat-treated reciprocating NiTi files depends more on instrument design and alloy characteristics than the specific temperature of thermal pretreatment. While all systems experienced reduced fatigue resistance in complex canals, Procodile Q consistently demonstrated superior performance. These results suggest that design-driven enhancements can outweigh thermal modifications—highlighting the importance of structural and mechanical properties over thermal treatment labels when selecting instruments for demanding clinical situations.

Disclosures

Informed Consent: Informed consent was obtained from all participants.

Conflict of Interest Statement: The authors declared that this study was conducted as an Investigator-Initiated Trial (IIT). Gebr. Brasseler GmbH & Co. KG (Komet, Lemgo, Germany) provided the technical equipment for the scanning electron microscopy (SEM) analysis. The company had no influence on the study design, data collection, analysis, or interpretation of the results.

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