



Article

Impact of Metallurgical and Geometric Features on the Cyclic Fatigue Strength of Reciprocating Endodontic Files

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Abstract

Background: Nickel–titanium (NiTi) endodontic instruments have undergone significant improvements in heat treatment processing and geometric design, aimed at enhancing flexibility, cutting efficiency, and fatigue strength. Reciprocating motion was introduced to increase cyclic fatigue resistance, which remains the predominant mode of failure in NiTi endodontic file systems. Although these instruments are widely used in both clinical practice and research, few comparative studies have integrated geometric, metallurgical and mechanical evaluations of the most commonly used reciprocating systems. **Methods:** In the present study, four single-file reciprocating NiTi systems (Reciproc Blue, WaveOne Gold, EdgeOne Fire, and Easy-File Flex) were evaluated for their geometric design, metallurgical composition, and cyclic fatigue strength. Stereomicroscopy and scanning electron microscopy were employed to assess active blade length, spiral configuration, and surface finish, while elemental composition and phase transformation temperatures were analyzed using energy-dispersive X-ray spectroscopy and differential scanning calorimetry. Ten instruments from each group were tested for cyclic fatigue using a standardized curved stainless-steel canal at room temperature, and the time to fracture was recorded. Fatigue data were statistically analyzed using Mood’s median test, with significance set at $p < 0.05$. **Results:** Reciproc Blue exhibited the longest active blade length, highest spiral density, and superior surface finish. R-phase start and finish temperatures were highest in WaveOne Gold and lowest in Easy-File Flex. Reciproc Blue demonstrated the higher cyclic fatigue strength, whereas Easy-File Flex showed the lowest. **Conclusions:** These findings suggest that the metallurgical and geometric characteristics of the Reciproc Blue file significantly enhance its strength to cyclic fatigue compared with the other instruments evaluated.



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1. Introduction

Root canal anatomy often presents significant challenges, including curvatures, isthmuses, lateral ramifications, and apical deltas [1]. These anatomical complexities require instruments capable of achieving effective mechanical debridement while minimizing the risk of iatrogenic complications such as canal transportation, ledging, and perforation. The

concept of mechanical instrumentation in endodontics has been fundamentally transformed by the advent of nickel–titanium (NiTi) instruments. Nonetheless, ongoing advancements in geometric design, metallurgy, and heat treatment processing continue to improve these instruments, enhancing their cutting efficiency and safety [2,3].

Metallurgical developments have been particularly transformative, as modifications in phase transformation properties through heat treatments, introducing NiTi wires such as M-Wire, Gold-Wire, Blue-Wire, and Fire-Wire technologies, have substantially improved the mechanical performance by increasing flexibility and cyclic fatigue strength without compromising cutting efficiency [4–6]. To further improve cutting efficiency, debris removal, and adaptability to curved canals, manufacturers have introduced geometric modifications in cross-sectional profile, helical angulation, taper configuration, and tip design. Despite these major advances, instrument fracture remains a clinical possibility [7–9].

During canal instrumentation, cyclic fatigue and torsional failures are the two predominant modes of instrument separation, with cyclic fatigue accounting for the majority of intracanal separations, particularly in anatomically challenging cases involving severe curvatures and limited access [10–12]. Cyclic fatigue strength has therefore emerged as the most critical mechanical property determining the instrument longevity and safety of NiTi instruments [13]. This form of failure results from repeated cycles of tensile and compressive stress as the instrument rotates or reciprocates within curved canals, leading to crack initiation and propagation until fracture occurs [10,14]. Unlike torsional failure, which typically occurs when an instrument binds within the canal and can be prevented through proper clinical technique, cyclic fatigue develops progressively and unpredictably during routine use, making it the primary concern for assessing instrument reliability [11,15].

Reciprocating kinematic was introduced to mitigate cyclic fatigue and extend instrument longevity [16]. This motion pattern reduces continuous rotational stress, modifies debris extrusion dynamics, and prolongs the functional lifespan of instruments compared to continuous rotation [17]. Consequently, reciprocating systems have gained substantial clinical acceptance, with numerous commercially available variants differing in metallurgical composition and geometric design. However, due to variations in alloy treatment, cross-sectional geometry, manufacturing precision, and overall design concept and performance variability exists among these systems. Given that cyclic fatigue strength is a key factor influencing clinical safety and predictability, this variability justifies the need for a comprehensive comparative evaluation.

Currently, four reciprocating NiTi systems, WaveOne Gold (Dentsply Sirona Endodontics, Ballaigues, Switzerland), Reciproc Blue (VDW, Munich, Germany), EdgeOne Fire (EdgeEndo, Johnson City, TN, USA), and Easy-File Flex (Access, Shenzhen, China), are widely used in clinical practice. Each system possesses distinctive design characteristics, including proprietary Gold-Wire technology, Blue-Wire heat treatment, Fire-Wire heat treatment processing, and variable taper configurations. Despite their widespread use, few studies have provided integrated comparative assessments encompassing geometric, metallurgical, and mechanical analyses, with particular emphasis on cyclic fatigue strength. Therefore, the present study aims to evaluate these four reciprocating file systems, with cyclic fatigue testing serving as the primary mechanical assessment parameter. The null hypothesis would be that no difference exists between instruments regarding their cyclic fatigue strength.

2. Materials and Methods

Four reciprocating nickel–titanium (NiTi) instruments (WaveOne Gold Primary [Dentsply Sirona Endodontics, Ballaigues, Switzerland], Easy-File Flex Regular 25 [Access, Shenzhen, China], EdgeOne Fire Primary [EdgeEndo, Johnson City, TN, USA], and Reciproc

Blue R25 [VDW, Munich, Germany]) were randomly chosen for evaluation. Each instrument featured a 0.25 mm tip diameter, variable taper, and a length of 25 mm. These files were assessed in terms of their geometric configuration, metallurgical properties, and cyclic fatigue strength. Prior to testing, all instruments were examined under $13.6\times$ magnification (Opmi Pico, Carl Zeiss Surgical, Jena, Germany) to detect any significant deformations or manufacturing flaws that could compromise their inclusion in the study. None of the instruments were excluded from the analysis.

A comprehensive evaluation of the instrument design ($n = 4$ for each group) was carried out using both stereomicroscopy and scanning electron microscopy (SEM). The stereomicroscopic analysis (Opmi Pico) aimed to quantify specific parameters of the active portion of the instruments, including the active blade length, the number of spirals, and spiral density (spirals per millimeter). These measurements were obtained from high-resolution images captured with a Canon EOS 500D (Canon, Tokyo, Japan) and analyzed using image processing software (Image J v1.50e, Laboratory for Optical and Computational Instrumentation, Wisconsin, WI, USA). SEM examination (Hitachi S-2400, Hitachi, Tokyo, Japan) was employed to detect potential microstructural irregularities such as blade disruptions, signs of early crack initiation, or metal rollovers. Additionally, this analysis provided insights into the spiral blade geometry, assessing symmetry and the presence of features like radial lands or flattened surfaces, as well as tip configuration (active vs. passive) and surface finishing features.

The metallurgical profile of the instruments was characterized using energy-dispersive X-ray spectroscopy (EDS) and differential scanning calorimetry (DSC). For EDS analysis ($n = 3$ per group), a Hitachi S-2400 scanning electron microscope, equipped with a tungsten filament electron source and a Bruker Quantax EDS detector (Bruker Corporation, Billerica, MA, USA), was used to identify elemental composition. Operating parameters included an accelerating voltage of 20 kV, a current of 3.1 A, and a working distance of 25 mm. Prior to data acquisition, a 10 min vacuum was applied, followed by a 60 s collection period. Each analysis covered a $400\text{ }\mu\text{m} \times 400\text{ }\mu\text{m}$ area. Elemental quantification was conducted using semi-quantitative analysis with ZAF correction, processed via dedicated analytical software (Systat Software Inc., San Jose, CA, USA). DSC testing adhered to the guidelines established by the American Society for Testing and Materials [18]. Small samples (approximately 5–10 mg) were collected from the active portion of each file and pretreated in a chemical bath composed of 25% hydrofluoric acid, 45% nitric acid, and 30% distilled water for 2 min, followed by neutralization in distilled water. Each treated sample was placed into an aluminum pan, with an empty pan used as a reference, and analyzed using a differential scanning calorimeter (DSC 204 F1 Phoenix, Netzsch—Gerätebau GmbH, Selb, Germany). The thermal cycle ranged from $-150\text{ }^{\circ}\text{C}$ to $150\text{ }^{\circ}\text{C}$, with a heating/cooling rate of $10\text{ }^{\circ}\text{C}$ per minute, under a nitrogen (N_2) gas environment. Phase transformation temperatures were determined using dedicated analysis software (Netzsch Proteus Thermal Analysis, Netzsch—Gerätebau GmbH, Selb, Germany).

The calculation of the sample size was based on the two instruments that showed the greatest difference after six preliminary tests. Using a power of 80%, a significance level (α) of 0.05, and an effect size of 177.50 ± 94.37 (comparing Reciproc Blue R25 and Easy-File Flex Regular 25), it was determined that six instruments per group would be sufficient. However, to strengthen the analysis, the final sample size was increased to ten instruments per group. The instruments were operated using a 6:1 reduction handpiece (VDW/Sirona Dental Systems, Bensheim, Germany), powered by a Silver Reciproc motor (VDW GmbH, Munich, Germany). This setup was mounted onto a custom-made tube model device (Odeme Dental Research, Luzerna, Santa Catarina, Brazil), designed to standardize the testing conditions across all samples. The instruments were tested within a stainless-steel

artificial canal featuring a curvature of 86 degrees, a 6 mm radius, an internal diameter of 1.4 mm, and a total length of 9 mm. The area of peak mechanical stress was located at the midpoint of the curvature. Cyclic fatigue resistance was assessed using a static model. Glycerin was used as a lubricant, and the instruments operated in an asymmetric, oscillatory counterclockwise motion, using the WAVEONE ALL setting (for WaveOne Gold, Easy-File Flex, and EdgeOne Fire) or the RECIPROC ALL setting (for Reciproc Blue). All tests were performed at room temperature (20 °C), in accordance with ASTM standards for testing the tensile properties of superelastic NiTi alloys [19]. Instruments were allowed to rotate freely within the canal until fracture occurred, which was identified both visually and audibly. The time until fracture was recorded with a digital stopwatch.

The results were presented using both mean with standard deviation and median with interquartile range. To assess the distribution of the data, the Shapiro–Wilk test was employed. Since normality could not be assumed, the non-parametric Mood’s median test was used to compare the time to fracture between groups (SPSS software, version 22.0 for Windows; SPSS Inc., Chicago, IL, USA). Statistical significance was established at a *p*-value of less than 0.05.

3. Results

The stereomicroscopic analysis of the instruments revealed a greater active blade length (18 mm), number of spirals (8), and spiral pitch (0.44 spirals/mm) in the Reciproc Blue files, whereas a lower spiral pitch (0.35 spirals/mm) was observed in both Easy-File Flex and EdgeOne Fire instruments (Table 1).

Table 1. Tested instruments geometric characteristics and time to fracture results expressed as means (standard deviation) and medians (interquartile range).

Instrument	Instruments Design				Time to Fracture (Seconds)
	Tip Size/Taper ¹	Active Blade Length	Number of Spirals	Spirals Pace (Spirals/mm)	
WaveOne Gold Primary	0.25/.07v	17 mm	7	0.41	155.7 (±46.0) ^a 145.0 [121.0–178.3]
Easy-File Flex Regular 25	0.25/.07v	17 mm	6	0.35	39.4 (±19.4) ^b 33.5 [24.5–61.0]
EdgeOne Fire Primary	0.25/.07v	17 mm	6	0.35	94.7 (±13.3) ^c 98.5 [85.0–102.3]
Reciproc Blue R25	0.25/.08v	18 mm	8	0.44	225.4 (±24.2) ^d 217.0 [212.0–236.3]

¹ Information provided by the manufacturer. ^{a,b,c,d} different superscript letters represent statistical significance (*p* < 0.05).

In the SEM inspection, all instruments exhibited a symmetrical blade design with non-active tips (Figure 1). All files showed parallel manufacturing marks on their surfaces, and although surface irregularities were present in all instruments, WaveOne Gold and Reciproc Blue exhibited the fewest (Figure 2).

All instruments were composed of an alloy with a near-equiatomic proportion of nickel and titanium elements (Table 2), without traces of other metallic elements. The analysis of phase transformation temperatures showed that the highest R-phase start (Rs) (45.2 °C) and R-phase finish (Rf) (28.8 °C) temperatures were observed in WaveOne Gold, while the lowest were recorded in Easy-File Flex (24.8 °C and 2.2 °C, respectively) (Figure 3).

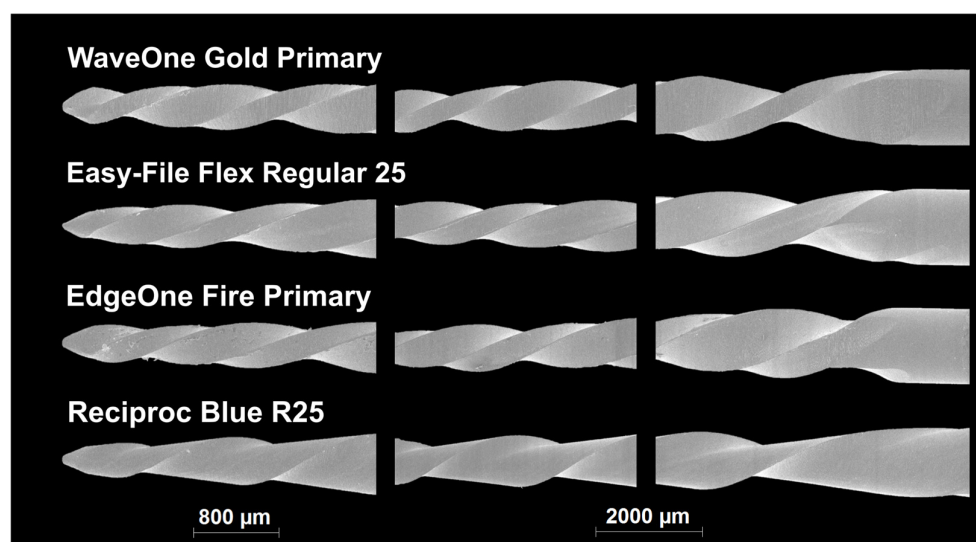


Figure 1. Representative SEM images of the evaluated reciprocating instruments showing the tip geometry and active blade sections (coronal, middle and apical). The transition angles to the blade and the overall geometry of the tips varied amongst instruments.

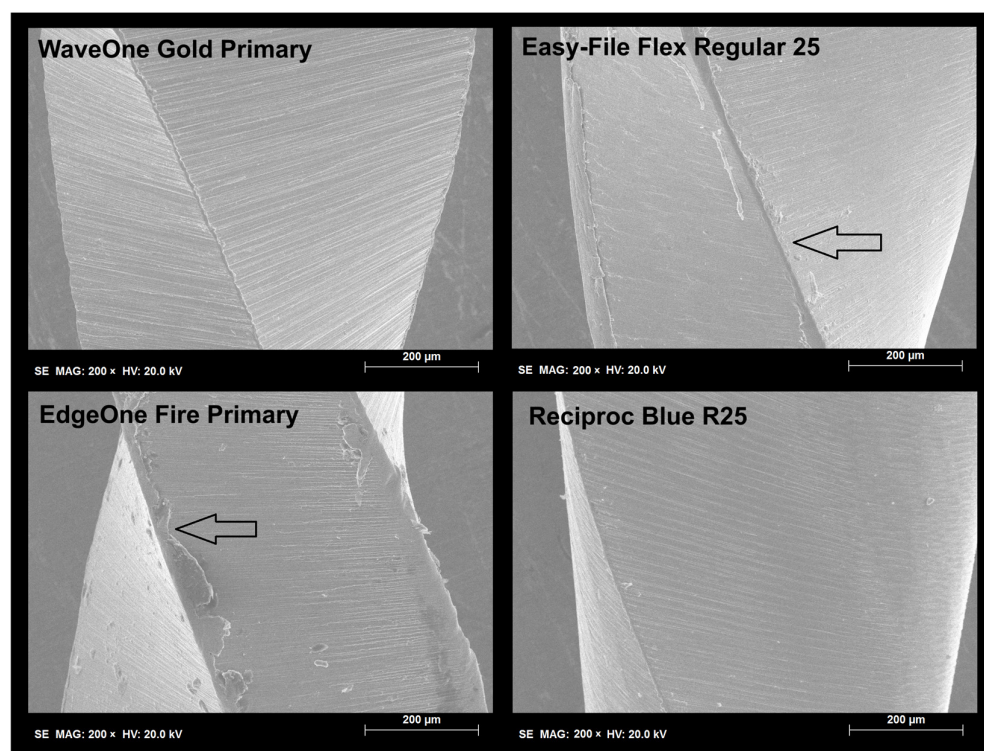


Figure 2. Representative SEM images of the instruments' surface. Visible parallel manufacturing marks were observed in all systems surfaces, with WaveOne Gold and Reciproc Blue having the least surface irregularities (arrow in figure shows the irregularities).

At the mechanical testing temperature, WaveOne Gold is expected to have a fully martensitic crystallographic structure, whereas the other instruments are expected to present a mixture of R-phase and austenitic phase, with a higher proportion of the austenitic phase likely in Easy-File Flex (Table 2). The time to fracture was highest for Reciproc Blue files (225.4 s) and lowest for Easy-File Flex instruments (39.4 s) ($p < 0.05$) (Table 1).

Table 2. Tested instruments' metallurgical features.

Instrument	Phase Transformation Temperatures (°C)				Ni/Ti Ratio
	Rs	Rf	As	Af	
WaveOne Gold Primary	45.2	28.8	8.9	51.4	1.036
Easy-File Flex Regular 25	24.8	2.2	−18.1	27.9	1.024
EdgeOne Fire Primary	35.1	17.6	19.7	36.9	1.026
Reciproc Blue R25	32.5	19.6	11.7	37.2	1.018

Abbreviations: Rs, R-phase start; Rf, R-phase finish; As, Austenitic start; Af, Austenitic finish.

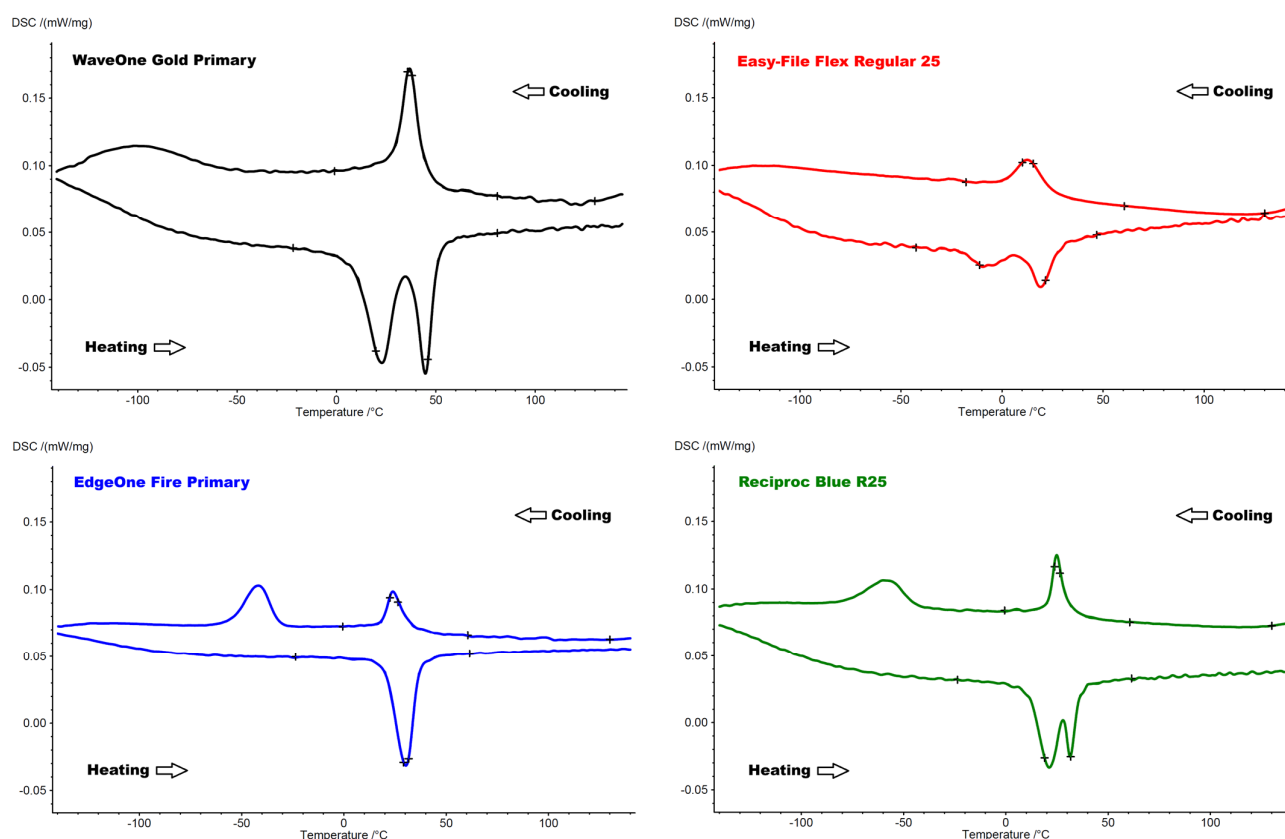


Figure 3. DSC charts illustrating the phase transformation temperatures during cooling (upper lines, reading from right to left) and heating (lower lines, reading from left to right). The analysis of phase transformation temperatures revealed the highest R-phase start and finish temperatures were observed in WaveOne Gold files, while the lowest were recorded in Easy-File Flex.

4. Discussion

The present study evaluated four commercially available reciprocating NiTi file systems through an integrated assessment of their geometric design, metallurgical properties, and cyclic fatigue strength. The findings revealed significant differences among the tested systems, particularly in active blade length and spiral configuration. Reciproc Blue demonstrated the longest active blade and the highest spiral density, features that may help distribute mechanical stresses more uniformly along the instrument's length and reduce localized fatigue stress concentrations. In contrast, Easy-File Flex exhibited a lower spiral density, a design characteristic that may contribute to less favorable stress distribution under cyclic loading. Although EdgeOne Fire also presented a relatively low spiral density, its overall fatigue performance did not deteriorate to the same extent, suggesting that its metallurgical properties may compensate for potential geometric disadvantages.

DSC analysis of the instruments provides critical insight into the phase transformation behavior underlying their mechanical performance [20]. Generally, endodontic files ex-

hibit distinct crystallographic phases: a superelastic phase at higher temperatures, termed the austenitic phase; a more flexible phase that appears under stress or cooling, known as the martensitic phase; and an intermediate R-phase, which enhances flexibility and fatigue resistance [21]. Both Reciproc Blue and EdgeOne Fire exhibited mixed R-phase and austenitic structures at the testing temperature, a condition associated with increased flexibility and enhanced fatigue strength. WaveOne Gold showed the highest R-phase transformation temperatures, indicating a fully martensitic structure during testing, a state known for its flexibility and capacity to accommodate strain without fracture [15]. Conversely, Easy-File Flex demonstrated the lowest R-phase transformation temperatures, suggesting a predominantly austenitic structure at room temperature. This phase condition, while generally supporting cutting efficiency, is associated with greater stiffness and a reduced ability to withstand cyclic strain.

Differences were observed in the mechanical performance of the tested endodontic instruments, thereby rejecting the null hypothesis. The superior cyclic fatigue strength of the Reciproc Blue file corroborates previous findings demonstrating the enhanced fatigue performance conferred by Blue-wire heat treatment technology [22,23]. This heat treatment process alters the phase transformation characteristics of NiTi alloys, improving flexibility and resistance to crack initiation under cyclic loading conditions [21]. In contrast, WaveOne Gold exhibited intermediate cyclic fatigue performance, whereas Easy-File Flex demonstrated markedly lower fatigue strength, fracturing approximately 5.7 times faster than Reciproc Blue under identical testing conditions. The results of the DSC analysis provide a clear explanation for this lower performance, which relates to the fact that Easy-File Flex displayed the lowest R-phase transformation temperatures among all instruments. At the mechanical testing temperature of 20 °C, the file was expected to possess more austenitic crystallographic structure with less R-phase content. The austenitic phase, while promoting cutting efficiency, is associated with increased stiffness and reduced flexibility compared with R-phase or martensitic arrangements [15,24]. The increased rigidity likely amplified stress concentration at the point of maximum canal curvature, accelerating crack initiation and propagation. Additionally, the lower spiral density of Easy-File Flex may have contributed to uneven stress distribution along the active blade, further compromising its fatigue strength. These findings suggest that conventional austenitic NiTi alloys, despite their simplified manufacturing process, may be unsuitable for demanding clinical situations characterized by severe canal curvatures, where cyclic fatigue represents the predominant failure mechanism [25]. Nonetheless, it is important to recognize that the relationship between phase transformation behavior and cyclic fatigue strength is complex and influenced by multiple interacting factors, including cross-sectional geometry, surface finish quality, and manufacturing consistency [10,11].

The combined use of DSC and mechanical testing was fundamental to elucidating the intricate relationship between metallurgical characteristics and mechanical behavior under clinically relevant conditions. Although all instruments were produced from near-equiatomic NiTi alloys, the marked differences in phase transformation temperatures significantly influenced their crystallographic structures at operative temperatures. This finding underscores that interpreting mechanical tests performed at a single temperature can be limited; however, the DSC analysis conducted in this study helps contextualize the thermally dependent phase behavior of the alloys and supports a more informed interpretation of the results obtained at 20 °C [26,27] while allowing a comprehensive understanding of possible changes at other relevant temperatures as these instruments tend to work on a service temperature range and not so much on specific temperatures. The use of room temperature for cyclic fatigue testing was intentionally adopted to ensure methodological standardization, as there is currently no consensus in the literature

regarding the superiority of body-temperature testing, particularly given the dynamic and variable thermal conditions encountered clinically. Furthermore, previous investigations have demonstrated that intracanal temperatures during clinical instrumentation are highly dynamic and variable, often fluctuating below core body temperature [27] due to irrigation, canal anatomy, and intermittent file engagement, rather than remaining constant at 37 °C. This variability challenges the assumption that body temperature testing necessarily offers superior clinical relevance [26,27]. Importantly, several authors have cautioned that testing exclusively at body temperature may make harder comparisons between instruments with different phase transformation ranges, favoring alloys specifically engineered to perform optimally at higher temperatures. In the present study, the combined use of DSC analysis and mechanical testing at a controlled temperature allowed a more accurate interpretation of the relationship between metallurgical phase behavior and cyclic fatigue performance [26]. Nonetheless, it is acknowledged that testing at additional temperatures could further elucidate the thermomechanical behavior of these instruments and should be considered in future studies.

In this study, a static cyclic fatigue testing protocol was selected to ensure strict standardization and reproducibility. While dynamic models incorporating axial pecking motion have been advocated as more clinically representative, they introduce uncontrolled variables such as inconsistent contact patterns, fluctuating load distribution, and intermittent stress relief, which hinder reliable intergroup comparison [11,14]. The primary objective of *in vitro* fatigue testing is not to replicate the clinical scenario in full, but to establish consistent reference points that allow objective comparison of different designs under controlled conditions. Accordingly, the static approach adopted herein ensured that all instruments were subjected to identical stress concentration at a fixed curvature point, thus permitting robust comparative assessment of their intrinsic fatigue resistance. Mood's median test was selected instead of the Kruskal–Wallis test because it is more robust to unequal variances and differences in distribution shape between groups, allowing a conservative comparison of central tendency when normality assumptions are violated. Nonetheless, some limitations should be acknowledged when extrapolating these results to clinical practice. Despite rigorous control of experimental variables, several factors inherent to real-world endodontic treatment, such as anatomical irregularities, dentin microhardness variability, operator-dependent technique, and temperature changes during irrigation, were not replicated in the present setup, also only reciprocating files were included in the current study without comparing with the rotary systems. Future investigations should therefore integrate micro-computed tomographic analysis of canal shaping with multimodal mechanical testing and temperature-controlled fatigue assays, to achieve a more comprehensive and clinically meaningful evaluation of instrument performance.

5. Conclusions

Although all tested instruments were manufactured from near-equiatomic NiTi alloys, their cyclic fatigue performance varied markedly according to differences in geometric designs and possible crystallographic arrangements. Among them, Reciproc Blue exhibited the greatest cyclic fatigue strength, reflecting the combined benefits of its optimized geometry, refined surface finish, and thermally enhanced metallurgical characteristics. Overall, these findings confirm that the mechanical reliability of reciprocating NiTi endodontic instruments is dictated not by alloy composition alone, but by the synergistic interplay between metallurgical processing and geometric design which ultimately affects the durability and reliability of these files in clinical use, emphasizing the value of integrated comparative assessment when evaluating instrument performance.

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