



Design, Metallurgical Features, and Mechanical Behavior of Five Reciprocating NiTi Endodontic Systems: A Multimethod Analysis

Gustavo Oliveira Campos ^{a*} , Jéssica Dornelas Silva ^b , Vicente Tadeu Lopes Buono ^b , Leandro de Arruda dos Santos ^b , Isabella Faria da Cunha Peixoto ^a , Ana Cecília Diniz Viana ^a

^a Department of Restorative Dentistry, School of Dentistry, Universidade Federal de Minas Gerais (UFMG), Belo Horizonte, MG, Brazil; ^b Department of Metallurgical and Materials Engineering, School of Engineering, Universidade Federal de Minas Gerais (UFMG), Belo Horizonte, MG, Brazil

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*Corresponding author: Gustavo Oliveira Campos, Restorative Dentistry Department, School of Dentistry, Universidade Federal de Minas Gerais (UFMG), R. Prof. Moacir Gomes de Freitas, 688-Pampulha; CEP. 31270-901, Belo Horizonte, MG, Brazil.

E-mail: gustavocampos03@hotmail.com

Abstract

Introduction: This work aimed to examine the geometrical, metallurgical, and static mechanical properties of five reciprocating NiTi endodontic files with similar cross-sectional geometries. **Materials and Methods:** Reciproc Blue, ProDesign R, V File, V+ File, and Univy One systems were evaluated using a multimethod approach including geometrical analysis, scanning electron microscopy, energy-dispersive spectroscopy, differential scanning calorimetry, X-ray diffraction, bending resistance, and torsional tests. **Results:** R-phase was predominant in most instruments, while the Univy One system showed indications of a combined martensitic and R-phase structure. ProDesign R demonstrated superior flexibility, whereas Reciproc Blue and V File exhibited greater torsional resistance. Cross-sectional area was an important factor influencing the mechanical characteristics of the instruments, although metallurgical aspects appeared to influence the behavior of specific systems. **Conclusion:** Geometry and metallurgical characteristics influenced the observed static mechanical behavior of the evaluated reciprocating instruments. Instruments exhibiting higher proportions of martensite and R-phase demonstrated enhanced flexibility, while bending resistance was also strongly affected by cross-sectional geometry, highlighting the combined influence of material properties and design on mechanical performance. However, the findings should be interpreted within the limitations of static mechanical evaluation, since cyclic fatigue testing was not performed.

Keywords: Dental Alloys; Equipment Failure; Endodontics; Nickel-titanium; Torque

Introduction

The introduction of Nickel-titanium (NiTi) alloy in endodontics has led to the production of instruments that are more flexible and resistant to fracture when compared to their stainless steel counterparts [1]. NiTi alloy has also enabled mechanized instrumentation, resulting in more predictable outcomes, particularly in canals with pronounced curvatures. However, the use of mechanized NiTi instruments has raised concerns about the risk of fracture, as these instruments can break even below their yield strength without exhibiting visible signs of deformation [2]. An instrument fragment lodged in the root canal

may represent a significant problem for endodontic therapy [3, 4]. It impacts the outcome of the treatment since, apart from shaping, it is essential to reduce the number of bacteria and their by products below the threshold that triggers apical pathologies [5].

Among the initial generations of instruments, geometry was reported to be the main factor that influenced their clinical performance [6, 7]. Today, in addition to design aspects, alloy characteristics, and applied heat treatments expand the potential for differing behavior among file systems [2, 8, 9]. Nevertheless, it remains unclear whether alloy treatment has become the principal factor in modifying the mechanical properties of the instruments or if geometry continues to play the main role in preventing failures.



To mitigate the risk of fractures, various adjustments have been made in endodontic files, such as the adoption of reciprocating kinematics [10]. Reciprocating motion extends the fatigue life of the instrument [11] and enhances torsional resistance [12]. The Reciproc Blue system (VDW GmbH, Munich, Germany), an evolution of the Reciproc instrument with added heat treatment to optimize certain properties [13, 14], has become one of the most widely adopted and researched systems in the market. Due to its success, other manufacturers have introduced similar instruments, capitalizing on features such as reciprocating motion, diameters, and the S-shaped cross-section. Despite their similarities, these replica-like systems are marketed without the support of scientific evidence regarding their mechanical and clinical attributes. Examples of such replica-like systems include the ProDesign R system (Bassi Endo, Belo Horizonte, Brazil), Univy One system (Universo Odonto, São Paulo, Brazil), and V File and V+ File systems (TDK, Shenzhen, China). While these instruments are already available in several countries worldwide, there is limited or non-existent scientific evidence concerning their behavior and properties.

Although cyclic fatigue is considered one of the most clinically relevant failure modes of reciprocating NiTi instruments, the present study focused specifically on the relationship between geometrical features, metallurgical characteristics, and static mechanical behavior, including bending and torsional properties. These parameters are clinically relevant because they directly influence instrument performance during root canal preparation. Torsional overload is one of the main causes of instrument separation, especially in narrow and constricted canals, while bending resistance is directly related to flexibility and the ability to maintain the original canal anatomy. The present work aims to assess the geometrical characteristics, metallurgical aspects, and mechanical properties of these reciprocating instruments and compare them with Reciproc Blue, which has well-established records of use and safety. The results are discussed in terms of the role played by geometry and metallurgy on the mechanical behavior of the files.

Materials and Methods

A total of 185 reciprocating heat-treated instruments, divided into five groups, including Reciproc Blue (RB), ProDesign R (PDR), V File (VF), V+ File (V+), and Univy One (UO), were used in this research.

To assess the dimensional characteristics based on the American National Standards Institute/American Dental Association Specification No. 101, five instruments ($n=5$) of each system were randomly selected and photographed using a high-resolution digital camera (EOS 20D; Canon, Tokyo, Japan). Subsequently, digital lines were superimposed on the instrument

images, and the outermost diameters D3, D9, and D16 (3, 9, and 16 mm from the tip, respectively) were determined using ImageJ 1.48V software (National Institutes of Health, Bethesda, MD, USA).

The cross-sectional area at 3 mm from the tip (A3) for each system was analysed by ImageJ through images obtained through scanning electron microscopy (SEM) using a Jeol JSM 6360 (Jeol, Tokyo, Japan) microscope. The samples were prepared by cutting sections from the instruments near the 3 mm mark, followed by a metallographic grinding until this exact mark. The images had 400 \times magnification, and five instruments ($n=5$) from each group were analysed. Then, lines were traced on the images obtained by SEM to demarcate and measure the cross-sectional areas of the instruments at D3. Moreover, SEM images of the active part and the tip of the instruments were also obtained with magnifications of 50 \times and 400 \times , respectively.

Energy-dispersive spectroscopy (EDS) was employed to measure the chemical composition of the five groups using a TN-M3055 spectrometer (Noran, Middleton, WI, USA). During EDS analysis, ten small areas were analyzed for each type of system ($n=1$). The transformation temperatures were determined as the beginning and end of exothermic/endothemic peaks on the heating and cooling curves recorded by differential scanning calorimetry (DSC). DSC analyses were performed at a heating/cooling rate of 10 $^{\circ}\text{C}/\text{min}$, ranging from -100 $^{\circ}\text{C}$ to 100 $^{\circ}\text{C}$ in a Shimadzu DSC-60 calorimeter (Shimadzu, Kyoto, Japan). The tests were performed in triplicate ($n=3$) by cooling each specimen from room temperature to -100 $^{\circ}\text{C}$, followed by heating to 100 $^{\circ}\text{C}$, cooling back to -100 $^{\circ}\text{C}$, and finally, heating the specimens to room temperature again.

Three instruments ($n=3$) from each group were subjected to X-ray diffraction (XRD) to evaluate the atomic structure of each system. XRD analyses were carried out using Cu-K α radiation and a scan speed of 0.02 $^{\circ}/\text{s}$ in an Empyrean diffractometer (PANalytical, Amelo, Netherlands). Data, available by the International Committee for Diffraction Data (ICDD), were used to identify the phases present in the samples.

The static mechanical properties of the systems were evaluated through bending and torsional resistance tests. Resistance to bending was determined using an apparatus constructed according to ISO 3630-1 (International Organization for Standardization, 1992). Although originally developed for stainless steel endodontic instruments, this standard remains widely used as a standardized laboratory method for comparative evaluation of the mechanical behavior of NiTi instruments. The use of a standardized testing protocol allows direct comparison among systems with different geometric and metallurgical characteristics. Ten instruments ($n=10$) from each group were tested using a machine (Analogica,

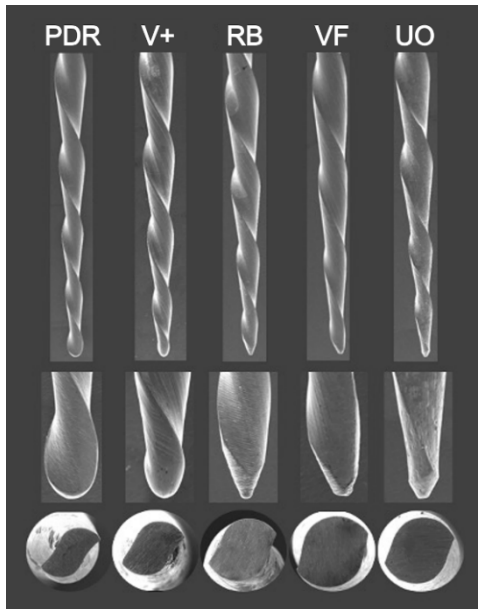


Figure 1. SEM images of the five studied instruments showing (from top to bottom of the figure) the active blade (50× magnification), tip (400× magnification), and cross-section view at 3 mm from the tip (400× magnification)

Belo Horizonte, Brazil) with the instruments clamped at 3 mm from the tip, oriented perpendicular to the geared motor's axis. The bending angle was controlled by a resistive angular transducer connected to a process controller. A specially designed computer program aligned the angular position to zero when the bending lever contacted the instrument shaft and initiated the motion until the instrument reached a 45° bend relative to its long axis, with a rotation speed of 0.5 rpm. Subsequently, the bending moment was automatically measured and recorded by the load cell. Torsion tests were similarly conducted on ten instruments ($n=10$) from each group, utilizing a torsional machine (AN8050; Analogica, Belo Horizonte, MG, Brazil). The rotation speed was set to 2 rpm in a clockwise direction. One end of the file was clamped in a chuck connected to a reversible geared motor, while the other end was clamped in another, positioned 3 mm from the tip. Continuous monitoring of torque and angular deflection was performed by a custom computer program. More details about the bending and torsion tests were published by Santos *et al.* [15]. Statistical analysis was performed using a significance level of 5% ($\alpha=0.05$). Data normality was assessed using the Shapiro–Wilk test. Variables showing normal distribution were analyzed by one-way analysis of variance (ANOVA), whereas non-normally distributed data were analyzed using the Kruskal–Wallis test. Multiple comparisons were performed using the Student–Newman–Keuls post hoc test. Statistical analyses were applied to both geometric and mechanical data.

Results

SEM images of the active parts, tips, and cross-sections of the five systems are shown in Fig. 1. Machining marks are visible on the surface of all instruments, which is expected from this type of manufacturing process. Nevertheless, VF and UO instruments presented more surface irregularities in comparison with the other systems. All instruments have an S-shaped cross-section, but present noticeable differences in terms of cross-sectional area at 3 mm from the tip. The RB file has an intermediate area when compared with the other instruments. The PDR instrument has the lowest cross-section area value, followed by the V+ group. The VF and UO groups have the highest area values among the instruments observed. The mean values of the cross-sectional area and respective standard deviation are shown in Table 1. Significant statistical differences were found among all the groups, except between VF and UO, which are statistically alike ($P>0.05$). Furthermore, the images suggest differences among the tip geometries.

In the apical third part, all instruments had values smaller than the nominal diameter reported by the manufacturers, and the diameter of RB was similar to all other groups except PDR ($P<0.05$), which had the smallest diameter. All instruments had a variable taper along their active part, except PDR instruments, which had a fixed taper of 6% up to the wire limit diameter. EDS results showed similar chemical composition for all instruments, an approximately equiatomic percentage between nickel and titanium elements (Ni-Ti ratios: RB 1.03; V+ 1.04; VF 1.06; PDR 1.04; UO 1.03). DSC curves and respective transformation temperatures for each system group can be verified in Fig. 2. Considering a room temperature of 22 °C, it is estimated that most of the groups (RB, PDR, VF, and V+) presented predominantly R-phase in their crystalline structure. The DSC results for the UO group suggested the possible coexistence of R-phase and martensite B19' at room temperature, based on the overlap between the transformation peaks of R-phase (Rs-Rf) and martensite (Ms-Mf) under cooling. The XRD patterns (Fig. 3A) obtained at room temperature were consistent with the crystalline structures suggested by the DSC analysis. Martensite was detected in small quantities for RB, VF, and PDR, probably due to stress induction during the manipulation of the specimens. Fig. 3B shows, qualitatively, that the UO system presents the highest apparent deformation after a certain amount of bending. It is associated with the higher quantity of martensite B19' detected in this system. For all the systems, the apparent deformation showed qualitative visual recovery after heating. Only the V+ system presented an integral superelastic behavior, with no need for heating to recover the deformation.

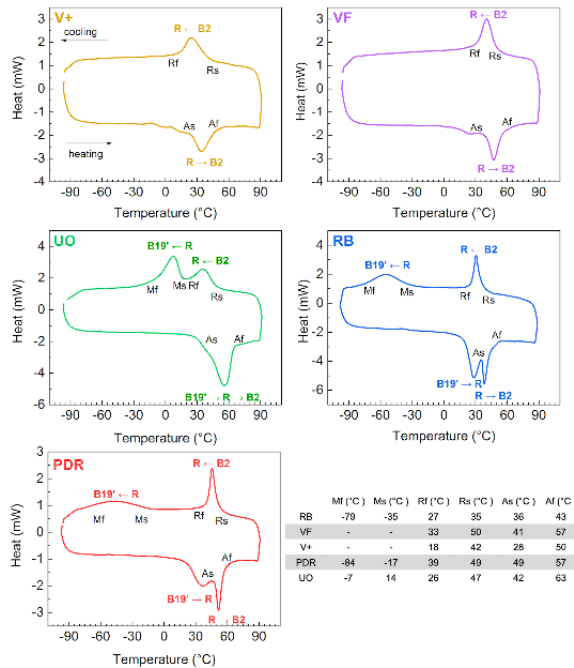


Figure 2. DSC curves for the five systems studied and their respective transformation temperatures. Under cooling, it is seen a two-step transformation: start of R-phase transformation from parent B2 (Rs) and its ending (Rf), followed by the start of B19' transformation from R-phase (Ms) and its ending (Mf). Under heating, it is depicted a one-step transformation: start of austenite B2 transformation from martensite (As) and its ending (Af)

The results of the bending and torsion tests can be seen in Table 2 and Fig. 4. It is seen that the PDR group had the lowest bending moment (Fig. 4A), being considered the most flexible, followed by the UO, V+, RB, and VF systems. An association between geometric characteristics (Table 1) and flexibility can be observed since more flexible instruments were the ones that presented smaller values of cross-sectional area and diameter at 3 mm from the tip. The only exception was UO, whose behavior may be associated with the presence of martensite in its structure at room temperature. Statistical differences in terms of flexibility were found among all the groups ($P < 0.05$).

Regarding the torsional resistance, RB and VF groups ($P > 0.05$) presented higher values of maximum torque until fracture, being considered the most resistant to torsion, followed by UO, V+, and PDR. The greatest angular deflection was observed in the UO group, followed by the RB, PDR, VF, and V+.

Discussion

The production and market presence of endodontic instruments has experienced substantial growth in recent years, notably fuelled by the influx of replica-like instruments [16]. These files generally exhibit characteristics similar to those already established in the

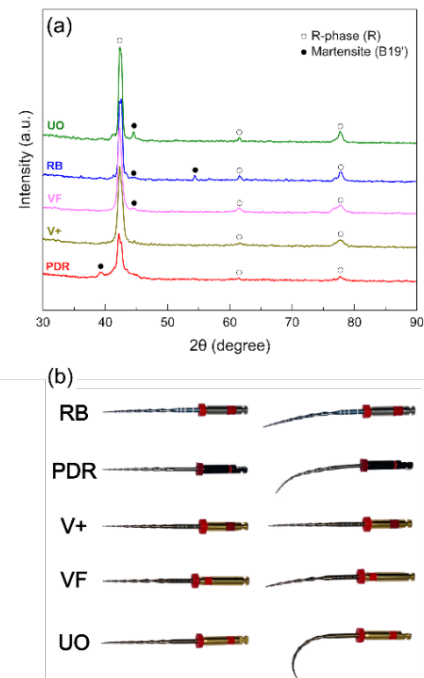


Figure 3. A) XRD test and peaks of R-phase and martensite B19' of each group: Green for UO; Blue for RB; Purple for VF; Yellow for V+ and Red for PDR; B) Representative images of the five studied instruments as received and after bending deformation

global market [17]. Two pivotal factors influencing the mechanical properties of these instruments are their design [18], and thermomechanical treatment [19]. The scientific importance of this theme is emphasized by the growing number of studies about it published by different authors recently [20-23]. In the present work, a multimethod approach to evaluate these two factors was employed to analyze the features and properties of the Reciproc Blue system and four replica-like instruments.

All instruments studied in the present work share a similar cross-sectional design but differ in cross-sectional areas. The PDR group stands alone with a consistent 6% taper, while the V+ group boasts a 7% taper, and the remaining groups (RB, VF, and UO) exhibit an 8% taper. Noteworthy is the conformity of nominal values reported by manufacturers to those found at 3 mm from the tip diameters. A regressive taper is discernible for RB, VF, V+, and UO, resulting in similar diameter values at D9. However, at D16, the PDR group displays lower values due to its unique manufacturing with a smaller wire diameter (1.01 mm versus 1.18 mm for other systems).

Concerning the atomic structure of NiTi alloys, the martensite phase, possessing a lower modulus of elasticity than austenite and R-phase, implies that instruments with a higher martensite content at room temperature exhibit greater flexibility compared to those predominantly composed of austenite and R-phase [24]. DSC

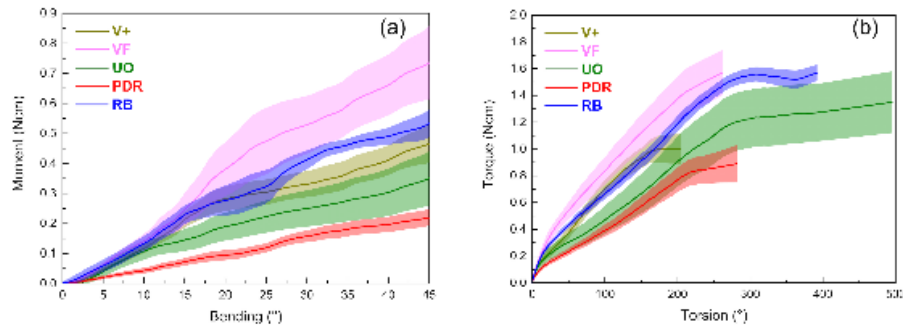


Figure 4. Bending and torsion test curves for the five studied instruments

Table 1. Cross-sectional area at 3 mm from the tip, and mean values and respective standard deviations (SD) of the diameter of the instruments in D3, D9, and D16. Different superscript letters represent statistically significant differences in the same column ($P < 0.05$)

Groups	Area A3 (mm ²)	Diameter D3 (mm)	Diameter D9 (mm)	Diameter D16 (mm)
RB	0.13 (0.00) ^A	0.48 (0.03) ^{A,B}	0.80 (0.02) ^A	1.12 (0.04) ^A
PDR	0.08 (0.01) ^B	0.44 (0.01) ^C	0.81 (0.02) ^A	1.01 (0.01) ^B
VF	0.15 (0.02) ^C	0.50 (0.01) ^A	0.78 (0.01) ^A	1.16 (0.01) ^C
V+	0.10 (0.00) ^D	0.46 (0.01) ^{B,C}	0.80 (0.01) ^A	1.15 (0.02) ^{A,C}
UO	0.15 (0.00) ^C	0.51 (0.02) ^A	0.81 (0.03) ^A	1.17 (0.02) ^C

Table 2. Mean (SD) of the mechanical tests performed in the groups. Different superscript letters represent statistically significant differences in the same column ($P < 0.05$)

Groups	Bending (N.cm)	Angular deflection (degrees)	Maximum torque (N.cm)
RB	0.55 (0.05) ^A	392 (19.08) ^A	1.57 (0.06) ^A
PDR	0.22 (0.02) ^B	282 (38.87) ^B	0.89 (0.14) ^B
VF	0.73 (0.12) ^C	262.6 (27.56) ^B	1.57 (0.17) ^A
V+	0.45 (0.04) ^D	204.4 (17.45) ^C	1.00 (0.11) ^B
UO	0.34 (0.09) ^E	495 (85.28) ^D	1.35 (0.23) ^C

results reveal the prevalence of R-phase as the crystalline structure at room temperature for all instruments, with the UO group presenting a combination of R-phase and martensite. Notably, the V+ group is the only instrument having austenite in its structure at room temperature, indicating a mixed structure of austenite and R-phase. However, these findings should be interpreted with caution, since the XRD analysis was performed only at room temperature and no quantitative phase analysis was conducted.

Flexibility assumes paramount importance in evaluating endodontic instruments, particularly when one evaluates the shaping of curved root canals. This property correlates with the ability of an instrument to navigate the original path of the root canal with minimal restorative force, thereby reducing the risk of iatrogenic errors during preparation [6, 25]. While alloy characteristics exert a significant influence on instrument flexibility, the correlation of bending test results with instrument cross-sectional area values suggests that geometry is an important factor influencing flexibility. Instruments with smaller areas than RB (PDR and V+) exhibited greater flexibility, whereas VF, which presented one of the largest cross-sectional areas, showed greater bending resistance. Although UO and VF exhibited similar cross-

sectional areas and no statistical difference in area values, minor differences in geometric parameters, including tip diameter, taper, and cross-sectional design, may also contribute to their mechanical behavior. Therefore, cross-sectional area alone does not fully characterize instrument geometry. Nevertheless, the substantially lower bending resistance observed for UO is unlikely to be explained solely by these small geometric differences. The DSC results suggested the coexistence of martensite and R-phase at room temperature in this system, indicating that metallurgical characteristics likely played a major role in its enhanced flexibility and more pronounced shape memory effect (Fig. 3B).

Torsion tests assess two key aspects: angular deflection and maximum supported torque before rupture. Angular deflection refers to the capacity of a specimen to rotate about its long axis before fracturing during rotating cycles with a fixed end [7]. In this study, the UO group was the only instrument surpassing RB in angular deflection values ($P < 0.05$), establishing both as reliable instruments in terms of torsional fracture resistance, as they endure substantial deformations before fracturing. This behavior is attributed to the heat treatments applied to this instrument and the resultant martensite in its crystalline composition, enhancing

the flexibility and deformability of the alloy. However, the UO group exhibited notably high standard deviation values, underscoring low standardization in its properties. Conversely, the V+ group, the only one featuring an austenitic structure at room temperature, demonstrated lower toughness, evidenced by its lower angular deflection values ($P < 0.05$).

Torque, defined as the force required for an instrument to continue rotating despite encountering resistance during movement [7, 12], represents the stress that an instrument can withstand under torsion before fracturing [26]. Torsion tests revealed that groups with larger cross-sectional areas (RB, VF, and UO) supported higher torque values, aligning with previous findings correlating mass with maximum torque endurance [27, 28]. Besides the design, alloy composition, and applied heat treatments also exert an influence on the torsional strength of endodontic instruments [17, 29, 30]. The reciprocating kinematics, characterized by avoiding instruments locked inside the root canal, enhance the clinical applicability of an instrument by minimizing exposure to high torques. Instruments with higher torque values are recommended for use in challenging treatment scenarios, such as anatomical cases involving calcifications or retreatments, where greater cutting or force is required for the advancement of the instrument [31].

Although ISO 3630-1 was originally developed for stainless steel endodontic instruments, it remains one of the most widely adopted methods for comparative laboratory evaluation of NiTi systems. Standardized testing protocols improve reproducibility and allow direct comparison among instruments with different geometric and metallurgical characteristics. Recent studies have also highlighted the importance of standardized mechanical testing when investigating the influence of phase transformation behavior on the mechanical performance of contemporary heat-treated NiTi instruments [32]. A limitation of the present study is the absence of cyclic fatigue evaluation, which represents one of the main failure mechanisms of reciprocating NiTi instruments during clinical use, especially in curved canals. Therefore, the findings of the present investigation should be interpreted based on static bending and torsional properties, without direct extrapolation to cyclic fatigue resistance. Further studies evaluating the dynamic cyclic fatigue behavior of these systems are recommended.

Conclusion

This multimethod study evaluated the Reciproc Blue system and four replica-type instruments, revealing critical insights into their structural and mechanical properties. While all systems shared an S-shaped cross-sectional design, notable disparities in cross-section size (assessed 3 mm from the apical tip) and geometric parameters such as tip configuration and taper were observed.

Metallurgical analysis identified R-phase as the dominant crystalline structure across most instruments, with the exception of Univy One. This system exhibited a dual-phase microstructure combining martensite and R-phase, a feature metallurgically associated with enhanced flexibility in NiTi devices. Bending tests further demonstrated that flexibility was associated with sectional geometry, emphasizing the role of design in mechanical performance. Univy One, however, deviated from this trend, as its behavior appeared to be more strongly influenced by phase interactions than by dimensional factors. Notably, Reciproc Blue and V File displayed superior torsional resistance, suggesting that instrument durability depends on synergistic optimization of shape and material properties. Collectively, these findings contribute to the understanding of how geometry and metallurgical characteristics influence the static mechanical behavior of reciprocating NiTi instruments.

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Conflict of interest

None.

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Authors' contributions

Conceptualization: ACDV; Methodology: LAS/ACDV; Formal Analysis and Investigation: GOC/JDS/IFCP/ACDV; Writing-Original Draft Preparation: GOC; Writing-Review and Editing: LAS/ACDV; Supervision: VTLB/LAS/IFCP/ACDV. All authors read and approved the final manuscript.

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