NARRATIVE REVIEW

How heat treatments and design influence the mechanical properties of NiTi endodontic instruments: a comprehensive review

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ABSTRACT

The evolution of nickel-titanium metallurgy has significantly changed endodontic instrumentation, with thermomechanical treatments fundamentally altering the phase transformation behavior and mechanical properties of endodontic files. This review comprehensively examines the relationship between phase transformation temperatures, particularly the austenite finish (Af) temperature, and the heat treatments and cross-section design of the NiTi alloys, including conventional superelastic alloys, M-Wire, R-phase, CM Wire, and Blue and Gold systems. The position of the Af temperature relative to body temperature (37°C) is the primary determinant of the crystallographic structure, directly governing the balance among flexibility, cyclic fatigue resistance, and torsional strength. Conventional austenitic alloys, characterized by Af below 37°C, provide superior cutting efficiency and torsional resistance but are compromised by lower flexibility and reduced cyclic fatigue life, particularly in curved canals. In contrast, martensitic and mixed-phase alloys prioritize flexibility and cyclic fatigue resistance at the expense of torsional strength. Furthermore, taper, cross-sectional geometry, and central core diameter modulate these mechanical properties, with triangular and double S-shaped designs maximizing fatigue life and flexibility, whereas square cross-sections confer greater stiffness and buckling resistance. The clinical selection of endodontic files must be guided by the integration of alloy composition, phase transformation behavior, cross-sectional design, tailored to the specific anatomical demands of each case.

KEY WORDS

Nickel titanium; endodontic instruments; heat treatment; cyclic fatigue; torsional resistance.

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INTRODUCTION

Developed in the early 1960s by the metallurgical engineer William F. Buehler and Frederick Wang in Silver Spring, Maryland, the metallic alloy Nitinol derives its name from an acronym formed by the chemical symbols of its primary constituents, nickel (Ni) and titanium (Ti), combined with the abbreviation of the laboratory where it was conceived, the Naval Ordnance Laboratory (1). Characterized by an equiatomic stoichiometry, this alloy exhibits a remarkable combination of mechanical properties, corrosion resistance, fatigue resistance, and biocompatibility. Owing to this distinctive set of attributes, Nitinol has become a benchmark material in the biomedical field, with widespread use in prostheses, stents, and a variety of surgical instruments, including catheters, needles, capillaries, and guide tubes, as well as in dental applications (2–5).

The NiTi alloy employed in endodontic instruments has a near-equiatomic composition, comprising approximately 56 wt% nickel and 44 wt% titanium, corresponding to an atomic ratio of nearly 1:1. The NiTi alloy is characterized by two primary temperature-dependent crystallographic phases: austenite, the high-temperature parent phase with a cubic B2 structure, and martensite, the low-temperature phase exhibiting a monoclinic B19 lattice. The essential basis for both superelasticity and the shape memory effect is the reversible transformation between the austenite and martensite phases (6–9).

Nickel-titanium (NiTi) endodontic files offer significant advantages over traditional stainless-steel instruments, making them essential tools in modern endodontics. Mechanized NiTi instruments offers superior flexibility, reduced procedural errors, faster preparation times, and improved clinical outcomes compared to stainless-steel hand files in endodontic treatment (10–12). However, despite these remarkable attributes, instrument fracture remains a persistent clinical concern, occurring primarily through two distinct mechanisms. Cyclic fatigue arises when the file rotates in a curved canal, subjecting the metal to alternating tensile and compressive stresses at the point of maximum flexure; over time, this repeated loading leads to cumulative microstructural damage and eventual separation, often without prior visible distortion. In contrast, torsional failure occurs when the instrument tip binds firmly within the root canal while the shaft continues to rotate, generating torque that exceeds the alloy's ultimate strength, resulting in plastic deformation and abrupt fracture (13,14). These failure modes underscore the inherent limitations of NiTi alloys. Consequently, manufacturers continuously invest in strategic modifications to enhance instrument safety and durability. These advancements include innovative fabrication techniques, thermomechanical heat, and refined cross-sectional designs and optimized taper geometries aimed at reducing stress concentrations and improving flexibility in challenging anatomies (15).

PROPERTIES OF NITI ALLOY

Superelasticity

Superelasticity or pseudoelasticity occurs when the NiTi alloy is in the austenitic state, above its austenite-finish temperature. Under these conditions, mechanical stress induces a stress-driven martensitic transformation, enabling the material to sustain remarkably large elastic deformations, typically up to 8–10% strain. Upon unloading, the stress field falls below the critical threshold, prompting the spontaneous reversion of stress-induced martensite to the parent austenite and resulting in an immediate, complete recovery of the macroscopic shape. This capacity far exceeds that of conventional metallic materials, which are generally limited to elastic strains of only 0.2–0.8% (6,8,16).

Shape memory effect

The shape memory effect is the ability of the NiTi alloy to recover a predetermined macroscopic configuration upon heating above a critical transformation temperature, after being mechanically deformed at a lower temperature. This behavior is driven by a thermally induced, reversible phase transformation between the low-temperature martensite and the high-temperature austenite, conferring upon the material a "crystallographic memory" of its original shape (16–18).

The martensitic and reverse transformations occur over specific temperature intervals, dictated by four parameters: the martensite start (Ms) and martensite finish (Mf) temperatures, which govern the forward transition during cooling; and the austenite start (As) and austenite finish (Af) temperatures, which define the reverse transition during heating (15,19,20). At the atomic level, the shape memory effect proceeds through a well-defined sequence. Initially, at temperatures above Af, the alloy resides in the stable austenitic phase, retaining its pre-set shape. As the temperature drops below Ms, a shear-type transformation converts the austenite into a twinned martensitic structure composed of multiple self-accommodating crystallographic variants, arranged to minimize internal strain. When a mechanical load is subsequently applied to this martensitic state, deformation is accommodated not by dislocation slip, but by the detwinning and reorientation of these variants along the direction of the applied stress. Upon reheating above As, the deformed martensite undergoes the reverse transformation back to the parent austenite lattice, thereby restoring the material to its original macroscopic geometry and completing the memory cycle (21–23).

Thermomechanical treatment and phase transformation temperatures

Thermal treatment fundamentally alters the phase transformation behavior of NiTi endodontic files by modifying the Af temperature and the proportions of austenite, martensite, and R-phase at body temperature, thereby directly impacting cyclic and torsional fatigue

resistance (24–29). These alloys undergo temperature-dependent phase transformations characterized by specific critical temperatures. The relationship between these transformation temperatures and body temperature (37°C) may determine which phase(s) predominate during clinical use (30,31).

The position of the Af temperature relative to body temperature is a primary determinant of mechanical behavior. Files with an Af above 37°C tend to exhibit a predominantly martensitic phase at body temperature; however, this behavior and the resulting mechanical benefits depend on the specific fraction of martensite present – Figure 1. Consequently, they may provide greater flexibility, deformation capacity under low stress, enhanced cyclic fatigue resistance, and a reduced risk of canal transportation. Conversely, heat-treated files with an Af below 37°C remain predominantly austenitic, exhibiting higher stiffness and elastic modulus, as well as superelastic shape-memory behavior, though they generally exhibit lower cyclic fatigue resistance than their heat-treated counterparts(17,32,33).

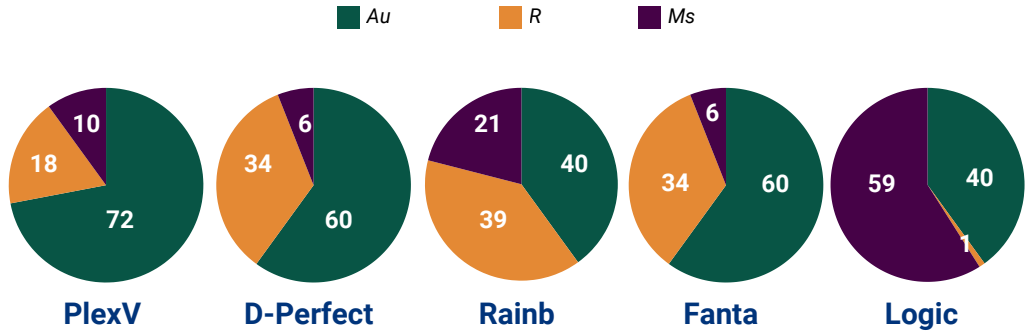

Figure 1. Graphical representation of the Austenite (Au), R-Phase (R), and Martensite (Ms) percentages (%) of heat-treated NiTi files.

Types of NiTi thermomechanical treatments

Conventional NiTi alloy

Conventional NiTi instruments are fabricated through machining processes that may produce surface defects. These defects are expected to adversely affect fracture strength, cutting efficiency, and corroxion resistance. Conventional NiTi alloys typically exhibit an Af temperature well below body temperature, generally ranging from 15,9°C to 34°C, which results in a predominantly austenitic structure at 37°C and confers superelastic behavior (19,30,35–37). Examples of conventional superelastic (SE) NiTi endodontic files include ProFile (Dentsply Tulsa Dental Specialties, Tulsa, OK, USA), K3 (SybronEndo, Orange, California), One Shape (Micro-Mega, Besançon, France), ProTaper (original- Dentsply Maillefer, Ballaigues, Switzerland), FlexMaster (VDW, Munich, Germany), and Hero 642 (Micro-Mega).

M-Wire

Developed by Sportswire LLC (Langley, Oklahoma, USA) in 2007, the alloy was named M-Wire (17). M-Wire is classified as an austenitic alloy with an R-phase, distinguishing it from fully martensitic alloys while offering advantages over conventional austenitic NiTi. M-Wire files contain martensite and R-phase at body temperature, providing enhanced flexibility and cyclic fatigue resistance compared to conventional austenitic NiTi files. Several endodontic file systems are manufactured using this M-Wire technology, including ProTaper Next (Dentsply), Reciproc (VDW), the original WaveOne (Dentsply), and Profile GT Series X (Dentsply). The alloy exhibits an Af temperature of approximately 50°C (19). M-Wire files demonstrate significantly higher cyclic fatigue resistance than conventional NiTi instruments (16,38).

NiTi Phase R

It was developed by SybronEndo (Orange, California, USA) in 2008 using a different manufacturing process to create new torsion-fabricated NiTi files (Twisted-File - SybronEndo, Amersfoort, The Netherlands). The manufacturing process includes three new methods: R-phase heat treatment, twisting of the metal wire, and specific surface conditioning. The twisting process transforms a raw NiTi wire in the austenitic state into a wire with a higher percentage of phase R (15,17,39). The R phase has a lower shear modulus; consequently, less stress is required to cause plastic deformation in the R phase. After twisting, the instrument is converted back to austenite by additional thermal treatments while retaining its new shape (8,40). Twisted-File instruments have Af temperatures that typically range from 20°C to 23.6°C (41,42). This intermediate Af temperature range is a defining characteristic that determines the crystallographic structure and mechanical behavior of R-phase files at clinical temperatures. The principal advantage of R-phase files is their non-machined fabrication, which reduces surface defects and structural mass loss, thereby decreasing instrument weakening. Consequently, regarding cyclic fatigue resistance, R-phase files tend to exhibit markedly superior performance compared to conventional austenitic alloys, as demonstrated by significantly higher fracture cycles (38,39). Additionally, R-phase instruments demonstrate substantially greater angular deflection at failure, with R-phase files reaching nearly 800 to 1000 degrees, a value far exceeding that of

conventional NiTi and M-Wire instruments (43). In terms of maximum torque, R-phase files exhibit lower values than conventional NiTi files (44).

NiTi controlled memory (CM) alloy

The NiTi CM wire was introduced in 2010. Because of their modified phase composition, CM Wire instruments can undergo deformation through the reorientation of martensite variants. Thus, unlike NiTi austenitic files, CM Wire instruments do not tend to fully rectify during the preparation of curved canals (17,45). This alloy is among those with the greatest overall flexibility, which is directly attributed to its elevated transformation temperatures (with Af exceeding 50 °C), as well as to the high fractions of R-phase and martensite provided at clinical temperatures – Figure 2. Accordingly, it exhibits distinctive differential scanning calorimetry (DSC) characteristics, with Af temperatures well above body temperature and unique dual-peak exothermic patterns on cooling curves, confirming a predominantly martensitic structure at clinical temperatures (16,31,46–48). CM wire endodontic files, when compared to M-wire and conventional NiTi instruments, exhibit markedly superior flexibility and enhanced cyclic fatigue resistance (16,49,50**).** However, this improved flexibility comes at the cost of reduced torsional strength and torsional resistance compared with conventional superelastic files, highlighting an intrinsic trade-off between flexibility and torsional durability in these instruments (51,52). Examples of CM wire files include HyFlex CM (Coltène/Whaledent, Cuyahoga Falls, Ohio, USA), One Curve (Micro-Mega), ZenFlex (Kerr, Brea, California, USA), Logic (Easy-Bassi Equipamentos Odontológicos, Minas Gerais, Brasil), and S2 (Easy-Bassi Equipamentos Odontológicos).

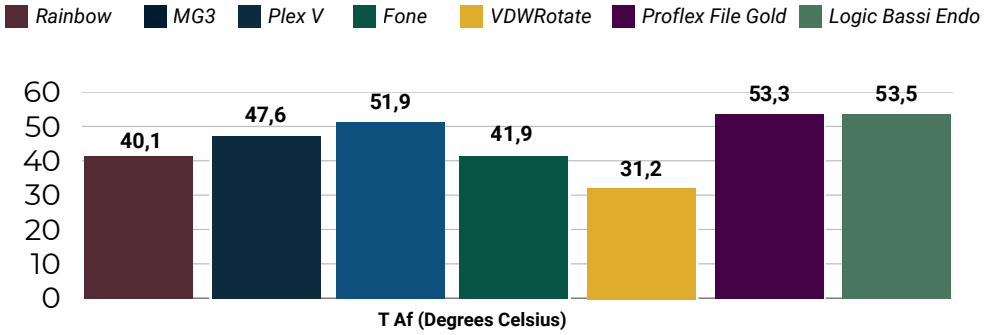

Figure 2. Graphical representation of the final austenite transformation temperature (Af) of some mechanized instruments.

Blue and Gold heat treatments

Currently, the market offers a wide array of NiTi systems subjected to blue or gold thermal treatments, such as Only One File Blue (Shenzhen Denco Medical Co., Shenzhen, China), Reciproc Blue (VDW), CC One Blue (Bondent, Shanghai, China), ProTaper Gold (Dentsply), ProFile Vortex Blue (Dentsply), TruNatomy (Dentsply), and WaveOne Gold (Dentsply). These instruments also exhibit a controlled memory effect and can be deformed (53). Blue heat-treated NiTi systems exhibit variable Af temperatures depending on the specific instrument, with Reciproc Blue at 37.16°C, Vortex Blue at 38.5°C, and Only One File Blue significantly above 37°C. For Reciproc Blue specifically, an Af of 37.16°C, coupled with an As of 28.42°C, dictates that at body temperature (37°C) the instrument is predominantly austenitic, conferring greater rigidity and high torsional strength (maximum torque of 1.62 N·cm), although this results in lower cyclic fatigue resistance compared to systems with higher Af values. X-ray diffraction (XRD) analysis reveals sharp peaks corresponding to austenite as the major phase, with minor peaks for martensite and the R-phase, while DSC confirms a two-stage transformation and metallurgical stability after clinical use, with similar patterns between new and used instruments (20,54). Conversely, ProFile Vortex Blue, with an Af of 38.5°C, presents a mixed austenite-martensite-R-phase structure at body temperature, as 37°C lies slightly below its Af, distinguishing it from conventional ProFile Vortex, which exhibits an Af above 50°C and a single-stage transformation. Moreover, Only One File Blue stands out by exhibiting the highest As and Af temperatures among the tested blue reciprocating systems, resulting in a predominantly martensite-austenite mixture at body temperature; its diffractograms show more intense peaks for martensite and R-phase than those of other blue files, with distinct peaks around 40 (19,55). Gold heat-treated NiTi systems exhibit variable transformation temperatures that differ significantly from those of their conventional counterparts, with ProTaper Gold demonstrating an austenite finish (Af) of 50.1°C ± 1.7°C and WaveOne Gold exhibiting an Af below body temperature (37°C), resulting in distinct mechanical behaviors (30,56).

Regarding cyclic fatigue resistance, the results are consistently superior for both thermally treated alloys in comparison to conventional alloys, with Reciproc Blue exhibiting greater longevity than M-Wire Reciproc in both 60° curved canals and artificial S-shaped canals (57), and ProTaper Gold significantly outperforming ProTaper Universal and ProTaper Next in the number of cycles to fracture (58). However, when directly compared against each other, the Gold treatment appears to offer advantages in certain parameters, as observed in the study with the Flat 25.04 instrument, in which the Gold version (Af of 42.8°C) exhibited superior cyclic fatigue resistance to the Blue version (Af of 32.2°C), suggesting that higher Af values, associated with the presence of R-phase and austenite at body temperature, may confer greater cyclic resilience. With respect to torsional properties, the Flat Gold again stood out by presenting lower maximum torque and greater angular deflection to fracture than the Flat Blue, indicating higher ductility and greater energy absorption capacity prior to failure (59), whereas Reciproc Blue revealed reduced microhardness compared to M-Wire, which accounts for its enhanced flexibility, although this may imply lower absolute torsional strength (28).

Max-Wire

Developed by FKG Dentaire (La Chaux-de-Fonds, Switzerland), the MaxWire alloy, commercially designated as Martensite-Austenite Electropolish Flex, was the first NiTi material to synergistically combine shape memory and superelasticity for clinical endodontics. This alloy exhibits a near-equiatomic composition (approximately 50.8% Ni and 49.2% Ti), and its proprietary heat treatment establishes a finely tuned phase balance among austenite, martensite, and R-phase, ensuring a predominantly martensitic crystallographic structure at body temperature (37 °C) while preserving adequate strength and flexibility (60,61).

The XP-Endo Finisher (FKG Dentaire) was initially launched in 2015 as an adjunctive tool for post-instrumentation finishing, followed in 2016 by the XP-Endo Shaper (FKG Dentaire), a single-use, disposable file indicated for primary canal shaping. A dedicated retreatment lineage emerged in 2017 with the XP-Endo Retreatment (FKG Dentaire) set, which includes both the Shaper and Finisher R for non-surgical retreatment procedures. The most recent developments, unveiled in 2022, are the XP-Endo Rise and its retreatment variant (XPE-Rise-R - FKG Dentaire), both featuring a redesigned apical tip (60).

Among these, the XP-Endo Shaper (FKG Dentaire) has been extensively investigated. Its superior cyclic fatigue resistance has been consistently demonstrated against most other NiTi systems. At intracanal temperature (35 °C), it exhibits significantly higher cycles to fracture than ProTaper Gold (Dentsply) and K3XF (SybronEndo) (62), and at body temperature (37 °C), it outperforms TRUShape (Dentsply), HyFlex CM (Coltène/Whaledent), Vortex Blue (Dentsply), and iRace files (FKG Dentaire) (63). In a 60° angle curvature with a 5-mm radius, the XP-Endo Shaper (FKG Dentaire) shows significantly longer time to failure and higher fracture cycles compared to TRUShape (Dentsply)(61). This outstanding fatigue performance is primarily attributed to the unique phase composition of the MaxWire alloy, the electropolished surface finish, which minimizes microcracks and surface defects, and the file's minimal taper design (0.01 taper). Additionally, its capacity to expand from 0.01 to a larger effective size when rotated at body temperature considerably reduces mechanical stress during canal preparation (60). Regarding torsional behavior, the XP-Endo Shaper (FKG Dentaire) demonstrates a lower maximum torque load than TRUShape (Dentsply) (61); however, it affords a substantially greater angular rotation to fracture, indicating superior flexibility before torsional failure.

EDM (Electrical Discharge Machining)

EDM (Electrical Discharge Machining) NiTi endodontic files represent an advanced manufacturing technology that produces files with exceptional fatigue resistance through a unique spark-machining process. The primary commercial example is HyFlex EDM (Coltène/Whaledent), which combines EDM manufacturing with CM heat treatment. The spark-machining process imparts a characteristic surface topography to the file, marked by micro-craters and a distinctive erosion-induced texture that contrasts sharply with conventional grinding (64). Metallurgically, EDM files exhibit a homogeneous microstructure composed largely of lenticular martensite with interspersed residual austenite, a phase constitution that remains stable even after clinical use(65), and although specific Af values are not extensively documented, the predominantly martensitic nature of the alloy confirms that the Af temperature exceeds body temperature (37 °C), aligning it with other controlled-memory alloys that prioritize flexibility over superelasticity(17). In terms of cyclic fatigue resistance, this alloy system ranks among the most durable tested to date: HyFlex EDM (Coltène/Whaledent) delivers up to a 700% improvement over its HyFlex CM (Coltène/Whaledent) predecessor from the same manufacturer (64), and it demonstrates significantly higher cycles to fracture than ProTaper Gold (Dentsply), ProTaper Universal (Dentsply), Reciproc R25 (VDW), WaveOne Primary (Dentsply), OneShape (Micro-Mega), Reciproc Blue (VDW), and WaveOne Gold (Dentsply) (65–67). Regarding torsional performance, HyFlex EDM exhibits a lower maximum torque load than Reciproc R25 (VDW), WaveOne Primary (Dentsply), and ProTaper Gold files (Dentsply); nevertheless, it affords a significantly greater angular rotation to fracture compared to both reciprocating instruments and ProTaper systems, with the highest angular deflection among all tested groups (66,67).

Cross-sectional design and central core volume: critical determinants of mechanical behavior

Cross-sectional design and central core size are critical determinants of the mechanical performance of NiTi endodontic files, affecting flexibility, torsional and cyclic fatigue resistances (14,31,68–72). Regarding cross-sections, there are triangular, quadrangular, parallelogram, and S-cross-sections – Table 1. The cross-section influences the volume of the central metal core – Figure 3 (73).

Files with square cross-sections demonstrate approximately double the stiffness of triangular cross-sections in both bending and torsion, but this increased rigidity comes at a cost. Triangular cross-section files can undergo 20% more deformation in bending and 40% more in torsion before failure and exhibit up to 300% higher fatigue life than square designs, particularly when combined with smaller pitch values (74). Among triangular designs, specific variations show distinct performance characteristics. Double S-shaped cross-sections demonstrate superior cyclic fatigue resistance compared to rectangular, convex triangular, and standard triangular designs (70).

The central core diameter directly impacts the balance between strength and flexibility. Files with larger apical cores demonstrate greater buckling strength and torsional resistance, particularly when combined with austenitic-phase dominance. This increased core size provides superior resistance to torsional failure when the instrument binds within the canal (75). However, larger cores reduce flexibility. The relationship between core size and flexibility is inversely proportional: instruments with smaller cores and reduced tapers (such as conservative shaping designs) exhibit greater bending adaptability and can navigate curved canals with lower pressure. Files with reduced taper (e.g., 25/0.07 vs 25/0.08) and smaller cores require less compressive force to navigate canals and demonstrate improved flexibility (69).

Table 1. Overview of NiTi endodontic file systems, wire technology, and corresponding cross-section shapes.

NiTi Endodontic File System		Cross-Section Design
Conventional NiTi	ProFile	Triangular
	U-Files	Variable
	Protaper Universal	Convex Triangular
	Biorace	Triangular
	BT Race	Triangular
	MTwo	S-shaped
M-Wire	Reciproc	S-shaped
	WaveOne	parallelogram (offset)
	Protaper Next	Off-centered rectangular cross-section (except for the X1 file, which is square at its apical end)
	Profile GT Series	U-shaped (modified triangular)
Phase-R	Twisted File Adaptive	Triangular
	K3XF	Asymmetrical triple-fluted
Controlled-memory (CM)	HyFlex CM	Convex Triangular
	HyFlex EDM	Progressive variable cross-section design (Apical features a rectangular cross-section; middle transitions into a trapezoidal cross-section; coronal changes into an almost triangular cross-section)
	One Curve	Off-centered rectangular cross-section
	Logic	Double helix section (tapers .03, .05, and .06); triple helix section (taper .04); quadruple helix section (taper .01); quadrangular helix section (files #.15/05 and #.15/03)
	S2	Orifice Shaper with quadruple helix; glide path with quadrangular helix; shaper with double helix
	ZenFlex	Triangular
Blue	Vortex Blue	Triangular
	Only One File Blue	S-shaped
	Reciproc Blue	S-shaped
	CC One Blue	S-shaped
Gold	ProTaper Gold	Convex Triangular
	WaveOne Gold	Parallelogram
	Flat File	Asymmetrical cross-section (one side of the cross-section is flattened and features no cutting blades)
Max-Wire	XP-endo Shaper	triangular cross-section
	XP-endo Finisher	triangular cross-section
EDM	Hyflex EDM	Progressive variable cross-section design (Apical features a rectangular cross-section; middle transitions into a trapezoidal cross-section; coronal changes into an almost triangular cross-section)

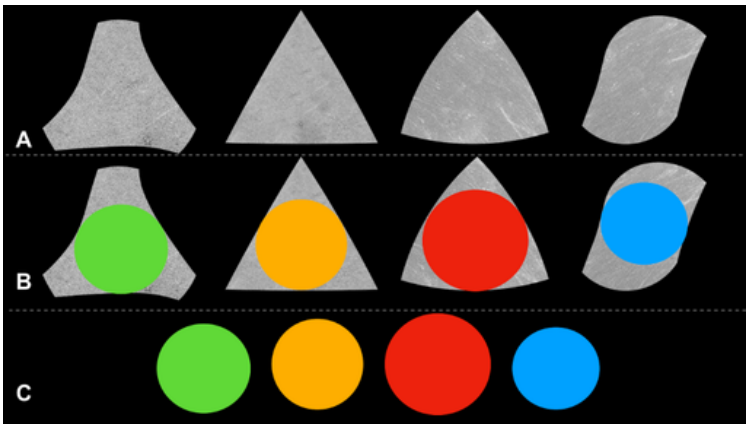

Figure 3. Relationship between cross-sectional geometry and the central core. (A) Representative images of different cross-section designs;(B) Colored circles in the center of the cross-section to represent the core mass; (C) Colored circles to represent the different core masses among the cross-sections.

A critical consideration is that the effects of cross-sectional geometry and core mass cannot be evaluated in isolation from material properties. Heat treatment effects dominate over cross-sectional area and core geometry in determining flexibility and fatigue resistance. Studies comparing identical geometric designs with different heat treatments demonstrate that the effect of heat treatment on flexibility is more significant than that of cross-sectional area alone (32,73). The synergistic optimization of advanced alloys with conservative geometry yields maximum performance: instruments combining thermomechanically treated alloys (such as Gold or Blue) with reduced taper and optimized cross-sections consistently outperform those with only one factor optimized. For instance, WaveOne Gold (Dentsply) instruments with reduced taper 0.07, and square cross-section outperformed WaveOne Gold (Dentsply) instruments with variable taper 0.08, and dual convex triangular cross-section in flexibility, cyclic fatigue resistance, and canal tracking, demonstrating that the outstanding performance results from both the enhanced phase transformation behavior of the Gold alloy and the reduced taper/square cross-section geometry that lowers stress concentration during reciprocating motion (76).

The taper can significantly influence the mechanical properties of NiTi endodontic instruments. A reduction in taper generally enhances cyclic fatigue resistance, as lower taper diminishes the cross-sectional mass and bending stiffness along the working length, thereby lowering stress concentration and reducing the tensile and compressive forces generated during rotation in curved anatomies (76,77). Furthermore, increased taper confers greater torsional strength by providing a larger cross-sectional area at the apical region capable of withstanding higher torque loads; however, this advantage comes at the expense of reduced angular deflection and substantially greater bending stiffness, which translate clinically into increased canal transportation, higher apical forces, and an elevated risk of procedural errors such as ledging or zipping (77,78).

Importantly, the influence of taper is not exerted in isolation but is closely modulated by cross-sectional geometry and alloy composition. Square cross-sections combined with reduced taper enhance flexibility and reduce tracking pressure, whereas triangular designs with higher taper may increase cutting efficiency at the cost of greater stress concentration; simultaneously, heat-treated alloys, such as M-Wire, Gold wire, or CM wire, magnify the benefits of reduced taper, while conventional superelastic alloys exhibit inferior fatigue performance regardless of taper (76). To address these competing mechanical demands, contemporary systems such as ProTaper Next (Dentsply) employ variable taper designs that optimize flexibility in the apical region while preserving coronal rigidity (79).

CLINICAL IMPLICATIONS

The clinical selection of NiTi endodontic files must be guided by a thorough understanding of how the design (cross-sectional geometry, taper, and core) and thermal treatment interact to determine mechanical behavior, with specific anatomic configurations. In straight or atretic canals, where the risk of deviation is minimal and cyclic fatigue is not the primary concern, conventional superelastic NiTi alloys or M-Wire/R-phase instruments may be safely employed, as taper exerts a comparatively limited influence on mechanical performance in these less demanding geometries. For moderately curved canals, heat-treated alloys in general become advantageous, as their enhanced flexibility provides adequate adaptation to the curvature while still allowing the use of 0.06 or 0.08 tapers (whether fixed or regressive), which offer sufficient torsional strength without substantially compromising fatigue life. In severely curved anatomies, however, the preferred strategy shifts toward alloys with high transformation temperatures, such as Gold, Blue, CM, and EDM, combined with low taper designs, because this triad: high-Af alloy + low taper + optimized design maximizes flexibility and safety (70,73,74).

Additionally, double S-shaped designs combined with CM, Blue or Gold thermal treatments confer superior cyclic fatigue resistance and reduced fracture risk, while conservative shaping protocols favor small core instruments with martensitic alloys to enhance flexibility and minimize stress transmitted to the root canal walls (33,57,80,81). Notably, the effect of heat treatment on flexibility can be more significant than that of cross-sectional area alone (75), establishing alloy treatment as the primary consideration when selecting instruments for curved canals.

CONCLUSIONS

- Phase transformation temperatures serve as the primary determinants of the crystallographic structure present at body temperature, directly governing the balance between flexibility, cyclic fatigue resistance, and torsional strength.
- Conventional austenitic alloys, characterized by Af temperatures below 37°C, provide superior cutting efficiency and torsional resistance but are compromised by lower flexibility and reduced cyclic fatigue life, particularly in curved canals. In contrast, martensitic and mixed-phase alloys, including M-Wire (Af ≈ 50°C), CM Wire, and heat-treated blue and gold systems, prioritize flexibility and cyclic fatigue resistance at the expense of torsional strength, reflecting an intrinsic clinical trade-off that must be carefully considered.
- Cross-sectional design, core diameter, and taper are closely related to the mechanical properties of the instruments. A greater metal volume tends to yield less flexible instruments, and the converse is equally true.
- No single file system or alloy type universally addresses all clinical situations; optimal outcomes depend on the synergistic integration of alloy composition, phase transformation behavior, cross-sectional design, and motion kinematics, tailored to the specific anatomical demands.
- The triad of high-Af alloy, low taper, and optimized design maximizes the flexibility and safety of NiTi mechanized endodontic files for severely curved root canals.

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