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COMPARATIVE EVALUATION OF METALLURGY, MECHANICAL PERFORMANCE, AND FRACTURE RESISTANCE IN HEAT-TREATED NITI ENDODONTIC INSTRUMENTS

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ABSTRACT
Background: Nickel–titanium (NiTi) endodontic instruments have undergone significant metallurgical advancements through proprietary heat-treatment protocols aimed at improving mechanical performance and clinical safety. However, variations in phase transformation behavior and mechanical properties among different heat-treated NiTi systems remain incompletely understood.
Aim: This study aimed to comparatively evaluate the metallurgical characteristics and mechanical performance of four heat-treated NiTi endodontic instrument systems— Martenistic (M)-Wire, Controlled Memory (CM) Wire, Blue, and Gold—with respect to austenite finish (Af) temperature, cyclic fatigue resistance, flexibility, torsional resistance, and angular deflection before fracture.
Materials and Methods: Sixty NiTi instruments (n = 15 per group) were evaluated. Af temperature was assessed using differential scanning calorimetry. Mechanical tests included cyclic fatigue resistance (number of cycles to failure), flexibility (force required for 45° deflection), maximum torsional resistance, and angular deflection before fracture, performed under standardized laboratory conditions. Data were analyzed using one-way Analysis of Variance (ANOVA) followed by Tukey post hoc testing ($p < 0.05$).
Results:
Statistically significant differences were observed among all groups for Af temperature, cyclic fatigue resistance, flexibility, torsional resistance, and angular deflection before fracture ($p < 0.05$). CM Wire instruments exhibited the highest Af temperature, greatest cyclic fatigue resistance, highest flexibility, and maximum angular deflection before fracture. Blue instruments demonstrated the highest torsional resistance. M-Wire instruments consistently showed inferior performance across most parameters.
Conclusion:
Heat-treatment protocols significantly influence the metallurgical and mechanical behavior of NiTi endodontic instruments. CM Wire instruments demonstrated superior flexibility, fatigue resistance, and deformation capacity, suggesting enhanced clinical safety, particularly in curved canals.

KEYWORDS: Cyclic fatigue, Endodontic instrumentation, Fracture resistance, Heat-treated NiTi, Metallurgical properties, Root canal preparation, Torsional resistance

INTRODUCTION
Nickel–titanium (NiTi) endodontic instruments have revolutionized modern endodontic practice because of their superior flexibility, shape-memory characteristics, and enhanced resistance to torsional stresses compared with traditional stainless-steel instruments [1]. The advent of rotary and reciprocating NiTi systems has significantly

improved the efficiency, safety, and predictability of root canal preparation, particularly in curved and anatomically complex canals [2]. Despite these advancements, instrument separation remains a clinically significant complication, most frequently resulting from cyclic fatigue and torsional overload during instrumentation [3].

To address these limitations, ongoing research has focused on improving the metallurgical and mechanical properties of NiTi instruments [4]. A major breakthrough in this regard has been the incorporation of proprietary heat-treatment processes, which have been shown to markedly influence the phase transformation behavior and mechanical performance of NiTi alloys [5]. Heat treatment modifies transformation temperatures, phase distribution, and microstructural characteristics of NiTi, resulting in variations in the relative proportions of austenite (A), martensite (M), and intermediate rhombohedral (R)-phase at clinical temperatures [6]. These metallurgical alterations play a crucial role in enhancing flexibility, fatigue resistance, and controlled memory behavior of endodontic instruments [7].

Heat-treated NiTi instruments demonstrate improved resistance to cyclic fatigue and greater adaptability to canal curvatures, which collectively contribute to a reduced risk of fracture during clinical use [8]. Several commercially available heat-treated NiTi systems—including M-Wire, Controlled Memory (CM) Wire, Blue, and Gold alloys—have been introduced, each employing distinct thermal processing protocols that produce unique mechanical and metallurgical profiles [9]. Variations in heat treatment influence critical properties such as austenite finish (Af) temperature, surface oxide layer characteristics, and phase transformation behavior, which subsequently affect mechanical performance parameters including flexibility, cyclic fatigue resistance, torsional resistance, and deformation behavior prior to fracture [10, 11].

In light of these considerations and the variability observed among heat-treated NiTi systems, the present study aimed to comparatively evaluate the metallurgical characteristics, mechanical performance, and fracture resistance of selected heat-treated NiTi endodontic instruments. By correlating phase transformation behavior with mechanical outcomes, this investigation seeks to provide clinically relevant evidence to support informed, evidence-based instrument selection and enhance procedural safety in endodontic practice.

MATERIALS & METHODS

Study Design and Sample Selection

This in vitro experimental study evaluated four commercially available heat-treated NiTi endodontic instrument systems: M-Wire, CM Wire, Blue, and Gold. A total of 60 instruments were included, with 15 instruments allocated to each group. All instruments were standardized for size and taper 20/.06 to minimize geometric variability.

Assessment of Af Temperature

Differential scanning calorimetry (DSC) was used to determine the phase transformation behavior of each instrument system. Specimens were subjected to controlled heating and cooling cycles, and the Af temperature was recorded for each sample.

Cyclic Fatigue Resistance Testing

Cyclic fatigue resistance was evaluated using a standardized artificial canal with a fixed curvature and radius. Instruments were rotated until fracture occurred, and the number of cycles to failure (NCF) was calculated based on rotational speed and time to separation.

Flexibility Testing

Flexibility was assessed by measuring the force required to produce a 45° deflection using a universal testing machine. Lower force values were interpreted as greater flexibility.

Torsional Resistance and Angular Deflection

Torsional resistance testing was conducted according to International Organization for Standardization (ISO) standards. Instruments were clamped at the tip and rotated until fracture, recording maximum torsional load (N·cm) and angular deflection (degrees) prior to failure.

Statistical Analysis

The collected data were entered into Microsoft Excel and analyzed using IBM SPSS Statistics for Windows (Version 29.0, IBM Corp., Armonk, NY, USA). Descriptive statistics were computed for all continuous variables, including mean, standard deviation (SD), standard error (SE), and 95% confidence intervals (95% CI). The normality of the data

distribution was assessed using the Shapiro–Wilk test, while the assumption of homogeneity of variances was evaluated using Levene's test before performing parametric analyses.
Comparisons among the four heat-treated NiTi instrument groups (M-Wire, CM Wire, Blue, and Gold) were performed using one-way analysis of variance (ANOVA) for all quantitative outcome variables, including Af temperature, cyclic fatigue resistance (number of cycles to failure), flexibility (force required for 45° deflection), maximum torsional resistance, and angular deflection before fracture. When the ANOVA demonstrated statistically significant differences, Tukey's Honestly Significant Difference (HSD)/Least Significant Difference (LSD) post hoc multiple comparison test was employed to identify significant pairwise differences between the instrument groups. Mean differences, standard errors, 95% CI, and adjusted p-values were reported for all post hoc comparisons.
Metallurgical and qualitative characteristics obtained from differential scanning calorimetry (DSC) and scanning electron microscopy (SEM), including phase transformation behavior, surface morphology, oxide layer characteristics, machining defects, cyclic fatigue striations, crack initiation zones, torsional abrasion marks, and fibrous dimple patterns, were analyzed descriptively and presented as qualitative observations without inferential statistical testing.
All statistical tests were two-tailed, and a p-value < 0.05 was considered statistically significant. The results are presented as Mean ± SD, along with SE, 95% CI, F values, p-values, and post hoc multiple comparison statistics wherever applicable to facilitate comprehensive comparison of the metallurgical characteristics, mechanical performance, and fracture resistance of the evaluated heat-treated NiTi endodontic instruments.

RESULTS
Table 1, Table 2 & Figure 1 present the comparison of Af temperatures among the four heat-treated NiTi instrument groups demonstrated statistically significant differences (F = 185.67, p = 0.001). The CM Wire instruments exhibited the highest mean Af temperature (47.20 ± 1.50°C), followed by Blue (39.40 ± 1.20°C), Gold (34.80 ± 1.40°C), and M-Wire instruments, which showed the lowest mean Af temperature (27.80 ± 1.30°C). The standard errors were low, ranging from 0.31 to 0.39°C, indicating minimal variability within each group. Similarly, the 95% CI were narrow, suggesting good precision of the estimated mean values.
Post hoc Tukey Least Significant Difference (LSD) analysis revealed statistically significant pairwise differences between all instrument groups (p < 0.001). The Af temperature of CM Wire was significantly higher than that of M-Wire (mean difference = 19.40°C), Blue (mean difference = 7.80°C), and Gold (mean difference = 12.40°C). Likewise, Blue instruments exhibited significantly higher Af temperatures than M-Wire (mean difference = 11.60°C) and Gold (mean difference = 4.60°C), while Gold instruments also demonstrated significantly higher Af temperatures than M-Wire (mean difference = 7.00°C). Overall, CM Wire instruments showed the greatest phase transformation temperature, indicating a higher proportion of M phase at clinical temperatures, whereas M-Wire instruments exhibited the lowest Af temperature, reflecting a predominantly austenitic microstructure. These findings confirm that proprietary heat-treatment protocols significantly influence the metallurgical characteristics of NiTi endodontic instruments.

Table 1: Comparison of Af Temperature Among Heat-treated NiTi Instruments

Instrument Group	**N**	**Mean (°C)**	**SD**	**SE**	**95% CI Lower**	**95% CI Upper**	**F Value**	**P Value**
Group I (M-Wire)	15	27.80	1.30	0.34	27.08	28.52	185.67	0.001
Group II (CM Wire)	15	47.20	1.50	0.39	46.37	48.03		
Group III (Blue)	15	39.40	1.20	0.31	38.74	40.06		
Group IV (Gold)	15	34.80	1.40	0.36	34.02	35.58		

Table 2: Tukey Post Hoc LSD Test

Comparison	**Mean Difference**	**SE**	**95% CI**	**P value**
M-Wire vs CM Wire	-19.40	0.53	-20.85 to -17.95	<0.001
M-Wire vs Blue	-11.60	0.53	-13.05 to -10.15	<0.001
M-Wire vs Gold	-7.00	0.53	-8.45 to -5.55	<0.001
CM Wire vs Blue	7.80	0.53	6.35 to 9.25	<0.001
CM Wire vs Gold	12.40	0.53	10.95 to 13.85	<0.001

Blue vs Gold	4.60	0.53	3.15 to 6.05	<0.001

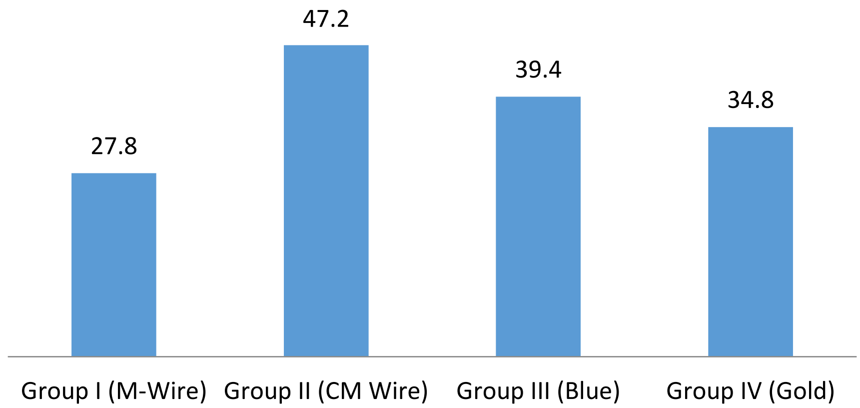

Figure 1: Comparison of Af temperatures among heat-treated NiTi endodontic instrument groups (CM Wire, Blue, Gold, and M-Wire).

Table 3, Table 4 & Figure 2 present the comparison of cyclic fatigue resistance among the four heat-treated NiTi instrument groups demonstrated highly statistically significant differences ($F = 214.76$, $p < 0.001$). CM Wire instruments exhibited the highest mean NCF (1328 ± 88), followed by Blue (1192 ± 79), Gold (1095 ± 73), and M-Wire instruments, which showed the lowest cyclic fatigue resistance (765 ± 62). The standard errors ranged from 16.01 to 22.72, while the 95% CI were relatively narrow for all groups, indicating good precision and consistency of the measurements.

Post hoc Tukey LSD analysis revealed statistically significant pairwise differences between all instrument groups. CM Wire instruments demonstrated significantly greater cyclic fatigue resistance than M-Wire (mean difference = 563 cycles, $p < 0.001$), Blue (mean difference = 136 cycles, $p < 0.001$), and Gold instruments (mean difference = 233 cycles, $p < 0.001$). Similarly, Blue instruments exhibited significantly higher fatigue resistance than M-Wire (mean difference = 427 cycles, $p < 0.001$) and Gold instruments (mean difference = 97 cycles, $p = 0.009$). Gold instruments also showed significantly greater cyclic fatigue resistance than M-Wire (mean difference = 330 cycles, $p < 0.001$). Overall, CM Wire instruments demonstrated the greatest resistance to cyclic fatigue, followed by Blue and Gold instruments, whereas M-Wire instruments exhibited the lowest fatigue resistance. These findings indicate that heat-treatment protocols substantially enhance the fatigue resistance of NiTi endodontic instruments, with CM Wire providing the highest resistance to cyclic loading and consequently the lowest susceptibility to fatigue-related fracture.

Table 3: Comparison of Cyclic Fatigue Resistance (Number of Cycles to Failure)

Instrument Group	**N**	**Mean (°C)**	**SD**	**SE**	**95% CI Lower**	**95% CI Upper**	**F value**	**P value**
Group I (M-Wire)	15	765	62	16.01	730.66	799.34	214.76	<0.001
Group II (CM Wire)	15	1328	88	22.72	1279.27	1376.73		
Group III (Blue)	15	1192	79	20.40	1148.24	1235.76		
Group IV (Gold)	15	1095	73	18.85	1054.56	1135.44		

Table 4: Tukey Post Hoc LSD Test

Comparison	**Mean Difference**	**SE**	**95% CI**	**P value**
M-Wire vs CM Wire	-563	28.5	-640.8 to -485.2	<0.001
M-Wire vs Blue	-427	28.5	-504.8 to -349.2	<0.001
M-Wire vs Gold	-330	28.5	-407.8 to -252.2	<0.001
CM Wire vs Blue	136	28.5	58.2 to 213.8	<0.001
CM Wire vs Gold	233	28.5	155.2 to 310.8	<0.001
Blue vs Gold	97	28.5	19.2 to174.8	0.009

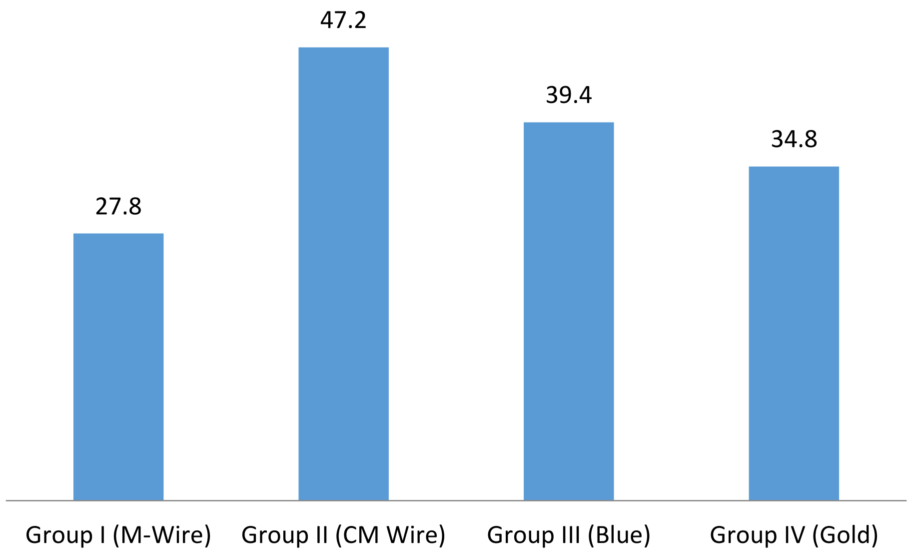

Figure 2: Comparison of cyclic fatigue resistance (number of cycles to failure) among heat-treated NiTi endodontic instrument groups (CM Wire, Blue, Gold, and M-Wire).

Table 5, Table 6 & Figure 3 present the comparison of flexibility among the four heat-treated NiTi instrument groups demonstrated highly statistically significant differences ($F = 169.33$, $p < 0.001$). Flexibility was assessed by measuring the force required to produce a 45° deflection, with lower force values indicating greater flexibility. CM Wire instruments required the lowest force for deflection (2.78 ± 0.24 N), indicating the greatest flexibility, followed by Blue (3.05 ± 0.26 N), Gold (3.31 ± 0.29 N), and M-Wire instruments, which required the highest force (4.62 ± 0.31 N), indicating the least flexibility. The standard errors ranged from 0.06 to 0.08 N, and the narrow 95% CI reflected the precision and consistency of the measurements across all groups.

Post hoc Tukey LSD analysis demonstrated statistically significant pairwise differences between all instrument groups. M-Wire instruments required significantly greater bending force than CM Wire (mean difference = 1.84 N, $p < 0.001$), Blue (mean difference = 1.57 N, $p < 0.001$), and Gold instruments (mean difference = 1.31 N, $p < 0.001$). Furthermore, CM Wire instruments were significantly more flexible than Blue (mean difference = −0.27 N, $p = 0.024$) and Gold instruments (mean difference = −0.53 N, $p < 0.001$). Blue instruments also demonstrated significantly greater flexibility than Gold instruments (mean difference = −0.26 N, $p = 0.031$). Overall, CM Wire instruments exhibited the highest flexibility, followed by Blue and Gold instruments, whereas M-Wire instruments showed the lowest flexibility. These findings indicate that proprietary heat-treatment protocols significantly improve the flexibility of NiTi endodontic instruments, thereby enhancing their ability to negotiate curved root canals while reducing internal stresses during instrumentation.

Table 5: Comparison of Flexibility (Force Required for 45° Deflection)

Instrument Group	**N**	**Mean (°C)**	**SD**	**SE**	**95% CI Lower**	**95% CI Upper**	**F value**	**P value**
Group I (M-Wire)	15	4.62	0.31	0.08	4.45	4.79	169.33	<0.001
Group II (CM Wire)	15	2.78	0.24	0.06	2.65	2.91		
Group III (Blue)	15	3.05	0.26	0.07	2.91	3.19		
Group IV (Gold)	15	3.31	0.29	0.07	3.15	3.47		

Table 6: Tukey Post Hoc LSD Test

Comparison	**Mean Difference**	**SE**	**95% CI**	**P value**
M-Wire vs CM Wire	1.84	0.09	1.60–2.08	<0.001
M-Wire vs Blue	1.57	0.09	1.33–1.81	<0.001
M-Wire vs Gold	1.31	0.09	1.07–1.55	<0.001
CM Wire vs Blue	-0.27	0.09	-0.51 to -0.03	0.024
CM Wire vs Gold	-0.53	0.09	-0.77 to -0.29	<0.001
Blue vs Gold	-0.26	0.09	-0.50 to -0.02	0.031

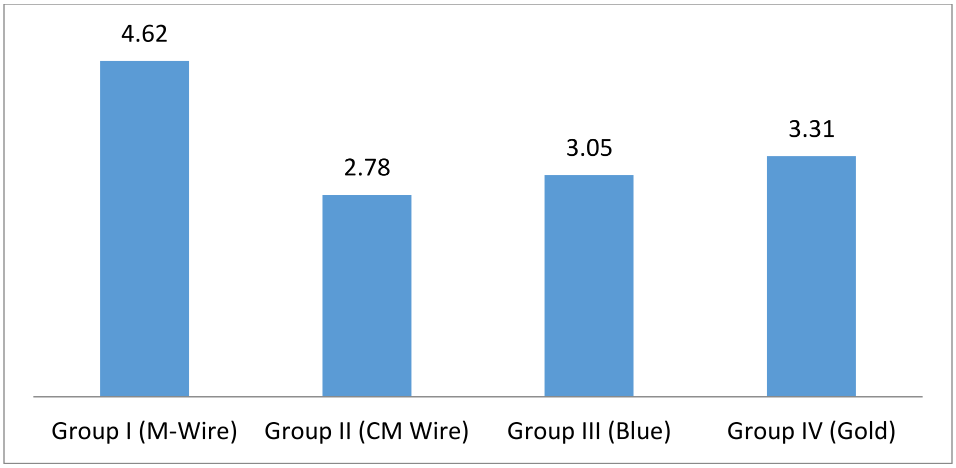

Figure 3: Comparison of flexibility among heat-treated NiTi endodontic instrument groups, expressed as the force (N) required to produce a 45° deflection (lower force values indicate greater flexibility)

Table 7, Table 8 & Figure 4 present the comparison of maximum torsional resistance among the four heat-treated NiTi instrument groups demonstrated a statistically significant difference ($F = 6.48$, $p = 0.002$). Blue instruments exhibited the highest mean maximum torsional resistance (1.42 ± 0.10 N•cm), followed by Gold (1.38 ± 0.09 N•cm), M-Wire (1.36 ± 0.09 N•cm), and CM Wire instruments, which demonstrated the lowest torsional resistance (1.28 ± 0.08 N•cm). The standard errors ranged from 0.021 to 0.026 N•cm, while the 95% CI were narrow for all groups, indicating good precision and low variability in the measurements.

Post hoc Tukey LSD analysis revealed selective statistically significant pairwise differences between the instrument groups. CM Wire instruments exhibited significantly lower torsional resistance than M-Wire (mean difference = 0.08 N•cm, $p = 0.041$), Blue (mean difference = −0.14 N•cm, $p = 0.001$), and Gold instruments (mean difference = −0.10 N•cm, $p = 0.014$). However, no statistically significant differences were observed between M-Wire and Blue instruments (mean difference = −0.06 N•cm, $p = 0.118$), M-Wire and Gold instruments (mean difference = −0.02 N•cm, $p = 0.842$), or Blue and Gold instruments (mean difference = 0.04 N•cm, $p = 0.318$). Overall, Blue instruments demonstrated the greatest torsional resistance, whereas CM Wire instruments exhibited the lowest resistance. These findings suggest that although heat treatment improves flexibility and cyclic fatigue resistance, torsional resistance is also influenced by instrument design and cross-sectional geometry, resulting in comparatively smaller differences among certain heat-treated NiTi systems.

Table 7: Comparison of Maximum Torsional Resistance

Instrument Group	n	Mean (°C)	SD	SE	95% CI Lower	95% CI Upper	F value	P value
Group I (M-Wire)	15	1.36	0.09	0.023	1.31	1.41	6.48	0.002
Group II (CM Wire)	15	1.28	0.08	0.021	1.24	1.32		
Group III (Blue)	15	1.42	0.10	0.026	1.36	1.48		
Group IV (Gold)	15	1.38	0.09	0.023	1.33	1.43		

Table 8: Tukey Post Hoc LSD Test

Comparison	Mean Difference	SE	95% CI Lower	95% CI Upper	P value
M-Wire vs CM Wire	0.08	0.036	0.01	0.15	0.041
M-Wire vs Blue	-0.06	0.036	-0.13	0.01	0.118
M-Wire vs Gold	-0.02	0.036	-0.09	0.05	0.842
CM Wire vs Blue	-0.14	0.036	-0.21	-0.07	0.001
CM Wire vs Gold	-0.10	0.036	-0.17	-0.03	0.014
Blue vs Gold	0.04	0.036	-0.03	0.11	0.318

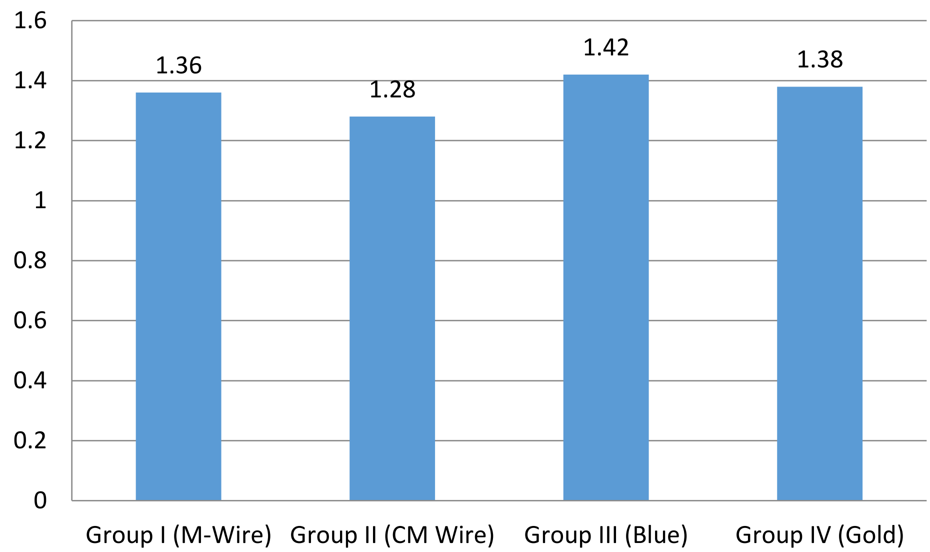

Figure 4: Comparison of maximum torsional resistance (N·cm) among heat-treated NiTi endodontic instrument groups (M-Wire, CM Wire, Blue, and Gold)

Table 9, Table 10 & Figure 5 present the comparison of angular deflection before fracture among the four heat-treated NiTi instrument groups demonstrated statistically significant differences ($F = 6.48$, $p = 0.002$). CM Wire instruments exhibited the highest mean angular deflection before fracture (566 ± 28°), followed by Blue (531 ± 24°), Gold (497 ± 25°), and M-Wire instruments, which demonstrated the lowest angular deflection (392 ± 22°). The standard errors ranged from 5.68° to 7.23°, while the 95% CI were narrow across all groups, indicating high precision and consistency of the measured values.

Post hoc Tukey LSD analysis revealed significant pairwise differences between all instrument groups. CM Wire instruments exhibited significantly greater angular deflection before fracture than M-Wire (mean difference = 174°, $p < 0.001$), Blue (mean difference = 35°, $p = 0.003$), and Gold instruments (mean difference = 69°, $p < 0.001$). Similarly, Blue instruments demonstrated significantly higher angular deflection than M-Wire (mean difference = 139°, $p < 0.001$) and Gold instruments (mean difference = 34°, $p = 0.005$). Gold instruments also exhibited significantly greater angular deflection than M-Wire (mean difference = 105°, $p < 0.001$). Overall, CM Wire instruments showed the greatest angular deflection before fracture, followed by Blue and Gold instruments, whereas M-Wire instruments demonstrated the lowest angular deflection. These findings indicate that heat-treated NiTi instruments, particularly CM Wire, possess superior plastic deformation capacity before fracture, which may provide a greater clinical safety margin by allowing visible deformation prior to instrument separation.

Table 9: Comparison of Angular Deflection Before Fracture

Instrument Group	**n**	**Mean (°C)**	**SD**	**SE**	**95% CI Lower**	**95% CI Upper**	**F value**	**P value**
Group I (M-Wire)	15	392	22	5.68	379.82	404.18	6.48	0.002
Group II (CM Wire)	15	566	28	7.23	550.49	581.51		
Group III (Blue)	15	531	24	6.20	517.70	544.30		
Group IV (Gold)	15	497	25	6.45	483.16	510.84		

Table 10: Tukey Post Hoc LSD Test

Comparison	**Mean Difference**	**SE**	**95% CI**	**P value**
M-Wire vs CM Wire	-174	9.1	-198.8 to -149.2	<0.001
M-Wire vs Blue	-139	9.1	-163.8 to -114.2	<0.001
M-Wire vs Gold	-105	9.1	-129.8 to -80.2	<0.001
CM Wire vs Blue	35	9.1	10.2 to59.8	0.003
CM Wire vs Gold	69	9.1	44.2 to93.8	<0.001
Blue vs Gold	34	9.1	9.2 to58.8	0.005

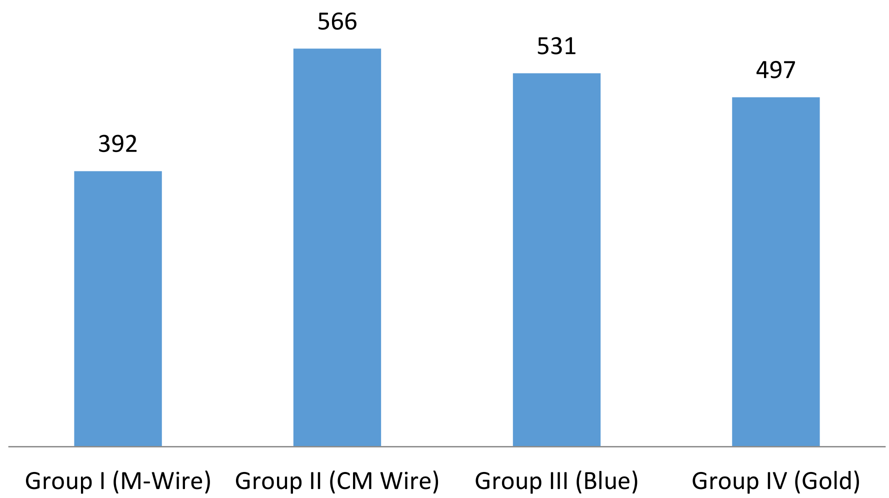

Figure 5: Comparison of angular deflection before fracture (degrees) among heat-treated NiTi endodontic instrument groups (M-Wire, CM Wire, Blue, and Gold)

DISCUSSION

The present study demonstrates that heat treatment plays a pivotal role in determining the metallurgical configuration and mechanical behavior of NiTi endodontic instruments, leading to measurable improvements in clinically relevant performance parameters. In agreement with the findings of Kimura et al. (2024) [12], the evaluated heat-treated instruments exhibited altered phase-transformation behavior, characterized by increased proportions of M and R phases at temperatures approximating clinical conditions. This phase predominance contributes to enhanced flexibility and reduced restoring forces when compared with predominantly austenitic (A) conventional NiTi instruments, thereby facilitating improved negotiation of curved and anatomically complex root canal systems while limiting internal stress accumulation during instrumentation.

A key outcome of the present investigation was the significantly higher cyclic fatigue resistance observed in heat-treated NiTi instruments, particularly those with elevated martensitic content. The presence of M-phase enables more efficient stress accommodation and redistribution during repetitive tensile and compressive loading, which delays crack initiation and reduces the rate of crack propagation. These observations are consistent with those reported by Li et al. (2002) [14], who demonstrated that cyclic fatigue resistance is closely related to metallurgical characteristics and testing conditions, especially in curved canals where cyclic fatigue represents the primary mechanism of instrument failure. The superior fatigue performance observed in this study further underscores the clinical advantage of heat-treated NiTi systems in minimizing unexpected instrument separation.

Variations in torsional resistance among the tested instruments were comparatively less pronounced and appeared to be influenced by both heat-treatment protocols and instrument design features, including cross-sectional configuration, taper, and core mass. This finding aligns with the conclusions of Khasnis et al. (2018) [17], who emphasized that torsional failure is multifactorial and dependent on the interaction between metallurgical properties and geometric design. Although instruments with greater flexibility may exhibit slightly reduced maximum torsional strength, the present study demonstrated that these instruments often displayed greater angular deflection before fracture. This behavior is clinically advantageous, as it allows visible plastic deformation prior to separation, providing an early warning sign to the clinician. Similar observations were reported by Jamleh (2022) [13] in his assessment of force generation and deformation behavior in heat-treated endodontic instruments.

Heat treatment was also associated with modifications in surface characteristics, particularly through the formation of titanium oxide layers, which may influence corrosion resistance and surface integrity. These findings correspond with the work of MacDonald et al. (2011) [16], who reported that thermal processing alters oxide layer composition and surface chemistry in titanium alloys, thereby affecting their physicochemical behavior. In addition, fracture mechanics concepts described by Maruschak and Maruschak (2024) [15] provide a framework for understanding how microstructural and surface alterations can influence crack initiation sites, propagation pathways, and overall fatigue behavior in polycrystalline materials such as NiTi alloys.

Despite the demonstrated benefits of heat treatment, the clinical performance of NiTi instruments cannot be attributed solely to metallurgical enhancements. Factors such as instrument design, kinematics of motion, canal morphology, and adherence to manufacturer-recommended usage protocols remain critical determinants of clinical outcomes. This multifactorial perspective is supported by Arias and Peters (2022) [18], who highlighted the complex interplay between instrument properties and clinical variables during root canal shaping. Furthermore, comprehensive reviews by Zanza et al. (2021) [19] and Silva et al. (2025) [20] emphasized that advancements in endodontic instrument technology must be complemented by evidence-based clinical strategies to optimize procedural safety and treatment success.

Overall, the findings of the present study reinforce existing evidence that heat-treated NiTi instruments provide superior flexibility, enhanced resistance to cyclic fatigue, and more favorable deformation behavior prior to fracture. A comprehensive understanding of the interaction between metallurgical properties, instrument design, and clinical application is essential for maximizing the benefits of these advanced systems, reducing fracture risk, and improving the predictability and long-term success of endodontic treatment.

Limitations

Despite providing valuable insights into the metallurgical and mechanical behavior of heat-treated NiTi endodontic instruments, the present study has certain limitations. The investigation was conducted under in vitro conditions, which cannot fully replicate the complex clinical environment of the root canal system, including variations in canal anatomy, temperature, presence of irrigants, and operator-related factors. Only a limited number of commercially available heat-treated NiTi instruments were evaluated; therefore, the findings may not be generalizable to all heat-treated NiTi systems currently in use.

The study focused primarily on laboratory-based mechanical tests such as cyclic fatigue, torsional resistance, and bending resistance, which, although standardized, may not completely reflect the multifactorial stresses encountered during clinical instrumentation. Additionally, proprietary heat-treatment protocols used by manufacturers are not fully disclosed, limiting precise correlation between specific thermal processes and observed metallurgical characteristics.

Furthermore, the effects of repeated clinical use, sterilization cycles, and long-term aging on the mechanical properties of the instruments were not assessed. Future studies incorporating dynamic clinical simulations, a broader range of instrument systems, and evaluation of clinical performance over time are recommended to validate and extend the present findings.

Limitations

This in vitro study may not fully reproduce the complex clinical conditions encountered during root canal instrumentation. Only a single size and taper from each instrument system were evaluated, which may limit the generalizability of the findings across other instrument dimensions. Dynamic intracanal factors such as variations in canal anatomy, irrigant temperature, and operator-related techniques were not simulated. In addition, metallurgical findings obtained from SEM and differential scanning calorimetry was analyzed descriptively without quantitative statistical validation. Furthermore, the long-term clinical performance and fracture behavior of the instruments under repeated clinical use were not assessed.

CONCLUSION

Within the constraints of this in vitro investigation, distinct variations in metallurgical behavior and mechanical performance were observed among heat-treated NiTi endodontic instruments, reflecting the influence of proprietary thermal processing techniques. CM Wire instruments demonstrated the most favorable overall performance, characterized by the highest AF temperature, enhanced resistance to cyclic fatigue, superior flexibility, and greater angular deflection prior to fracture, collectively suggesting a reduced risk of instrument separation and improved clinical reliability. Blue instruments exhibited the greatest resistance to torsional stress, whereas M-Wire instruments consistently showed comparatively lower mechanical performance across most tested parameters. These results highlight the importance of heat-treatment strategies in tailoring the functional properties of NiTi instruments and provide valuable guidance for clinicians when selecting instruments for the management of complex and curved root canal systems.

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