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# Comparative Evaluation of the Bending Flexibility of Heat-Treated Nickel–Titanium Endodontic Rotary Files: An In Vitro Study

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**Abstract**

**Objective:** Nickel–titanium (NiTi) rotary instruments exhibit superior flexibility and fatigue resistance compared with stainless steel files due to their superelasticity and shape memory effect. This study compared the bending flexibility of three NiTi rotary endodontic files of identical size (#25/.06) manufactured using different thermal treatments: ProTaper Next (M-Wire), M3 Pro Gold (CM Wire with gold heat treatment), and E Flex Blue (Blue heat-treated NiTi). The null hypothesis was that there would be no difference in bending flexibility among the tested instruments.

**Methods:** Bending resistance was measured using a standardized cantilever bending test according to ISO 3630-1, a method widely employed for evaluating NiTi instrument flexibility. Forty-five files ($n = 15$ per group) were tested. Statistical analysis was performed using one-way ANOVA and Tukey's post hoc test with significance set at $P < 0.05$, consistent with previous mechanical studies on NiTi instruments.

**Results:** E Flex Blue demonstrated significantly lower bending resistance (higher flexibility) compared with M3 Pro Gold CM and ProTaper Next ($P < 0.001$). M3 Pro Gold CM exhibited intermediate flexibility, while ProTaper Next showed the highest bending stiffness.

**Conclusions:** Within the limitations of this in vitro study, Blue heat-treated NiTi files demonstrated superior bending flexibility, supporting their potential clinical advantage in negotiating curved root canals, as previously suggested in recent metallurgical and mechanical investigations.

**Keywords:** NiTi instruments, Bending flexibility, Thermomechanical treatment, Blue wire, CM wire, M-Wire, Rotary endodontic files, Cantilever bending test, ISO 3630-1.

## Introduction

NiTi rotary instruments have transformed endodontic treatment by enabling safer and more efficient shaping of curved root canals while reducing procedural errors such as canal transportation, ledging, and zipping (Gergi et al., 2010; Peters, 2004; Schäfer et al., 2004). Their unique mechanical behavior is derived from reversible phase transformations between austenite and martensite, which confer superelasticity and shape memory (Thompson, 2000). However, conventional NiTi instruments still present risks of fracture due to cyclic fatigue and torsional stress, especially in complex canal anatomies (Sattapan et al., 2000).

To address these limitations, manufacturers have introduced various thermomechanical processing techniques to optimize the microstructure and mechanical behavior of NiTi alloys (De-Deus et al., 2017; Pereira et al., 2015). M-Wire was developed to enhance cyclic fatigue resistance and flexibility compared with conventional NiTi by modifying the phase composition to include martensite and R-phase (Johnson et al., 2008). Controlled Memory (CM) Wire further increases martensitic content, resulting in lower bending resistance and greater flexibility, while also allowing pre-bending of instruments (Elnaghy & Elsaka, 2016; Plotino et al., 2014).

More recently, Blue heat-treated NiTi instruments have been introduced. This treatment involves precise thermal processing and surface oxidation, producing a characteristic blue titanium oxide layer and altering phase transformation temperatures (De-Deus et al., 2017; Pedullà et al., 2020). Studies have shown that Blue heat-treated instruments exhibit higher austenite finish (Af) temperatures, allowing them to remain predominantly martensitic at body temperature, which enhances flexibility and fatigue resistance (Shen et al., 2013; Zupanc et al., 2018).

Although numerous studies have investigated cyclic fatigue, torsional resistance, and fracture behavior of heat-treated NiTi files (Elnaghy & Elsaka, 2016; Özyürek, 2020; Sattapan et al., 2000), fewer studies have focused specifically on bending flexibility, a property directly related to an instrument's ability to follow curved canals safely (Oh et al., 2023; Plotino et al., 2007). Moreover, direct comparisons among M-Wire, CM Wire, and Blue heat-treated files of identical size and taper remain limited (Versiani et al., 2015).

Therefore, this study aimed to compare the bending flexibility of three NiTi rotary systems manufactured using different thermal treatments ProTaper Next (M-Wire), M3 Pro Gold (CM Wire), and E Flex Blue (Blue heat-treated NiTi) all standardized to ISO size 25/.06. The hypothesis was that E Flex Blue would demonstrate superior flexibility due to its advanced heat treatment and metallurgical characteristics.

**Materials and Methods**

**Experimental Design**

A total of 45 new NiTi rotary instruments were evaluated (n = 15 per group). All instruments were standardized to ISO size 25, 6% taper, and 25-mm length to minimize confounding variables related to geometry, as recommended in mechanical testing studies (Chaniotis et al., 2021; Oh et al., 2023; Versiani et al., 2015).
The tested groups were ProTaper Next, M3 Pro Gold, and E Flex Blue (Table 1). Standardization of size and taper is essential because instrument geometry significantly influences bending behavior and stiffness (Kim et al., 2009; Versiani et al., 2015).

Table 1 The Ni Ti rotary instruments tested

| Brand Name | Alloy/Heat Treatment | Manufacturer | Length |
|---|---|---|---|
| Protaper Next | M-wire | Dentsply Sirona | 25 |
| M3 Pro Gold | CM wire gold heat treatment | United Dental, China | 25 |
| E Flex Blue | CM wire Blue heat treatment | Eighteeth, China | 25 |

**Bending Test Protocol**

Bending resistance was measured using a cantilever bending test performed with a Universal Testing Machine (Model 3345; Instron, Norwood, MA, USA), following ISO 3630-1 guidelines and previously validated protocols (ISO, 2019; Plotino et al., 2007). Each instrument was clamped horizontally, and a mono-beveled chisel applied a load at 3 mm from the tip at a crosshead speed of 0.5 mm/min until a 45° deflection was achieved. Figure 1

The maximum load required to bend the instrument was recorded in gram-force (gf). Lower bending force values indicate higher flexibility, a parameter closely associated with improved clinical performance in curved canals (Pedullà et al., 2020; Plotino et al., 2007).

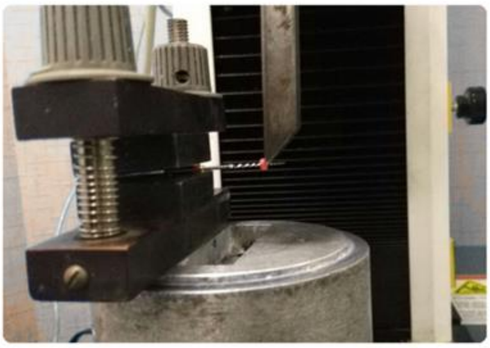

Fig.1 Laboratory Cantilever bending Test of NiTi instrument

**Statistical Analysis**

Statistical analysis was performed using IBM® SPSS® Statistics Version 20. Data normality was confirmed, and one-way ANOVA was used to detect differences among groups, followed by Tukey's HSD test for pairwise comparisons. The significance level was set at $P < 0.05$, consistent with previous studies evaluating NiTi mechanical properties (Chaniotis et al., 2021; Elnaghy & Elsaka, 2016).

**Results**

**Bending Resistance**

One-way ANOVA revealed statistically significant differences among the three instrument systems ($P < 0.001$), consistent with prior comparative studies on heat-treated NiTi files

E Flex Blue demonstrated the lowest bending resistance (495 ± 38 gf), indicating the highest flexibility. M3 Pro Gold CM exhibited intermediate bending resistance (662 ± 42 gf), while ProTaper Next showed the highest bending resistance (845 ± 48 gf), reflecting the lowest flexibility.

Post hoc Tukey analysis revealed significant differences between all groups ($P < 0.05$), confirming the influence of heat treatment and alloy type on bending behavior, as reported in previous investigations

**Discussion**

This in vitro study demonstrated that NiTi rotary instruments manufactured using different thermal treatments exhibit significantly different bending behaviors, even when standardized for size and taper. The superior flexibility of E Flex Blue instruments aligns with recent findings that Blue heat-treated NiTi files possess enhanced martensitic characteristics at clinical temperatures (De-Deus et al., 2017; Pedullà et al., 2020; Shen et al., 2013).

**Effect of Metallurgical Processing**

Blue heat treatment increases Af temperature and stabilizes the martensitic phase, resulting in lower elastic modulus and greater ductility under bending loads (Shen, Y., et al. 2013; Zupanc, J., et al. (2018).). Similar behavior has been reported for other Blue-treated systems such as Reciproc Blue and Vortex Blue, which show reduced bending stiffness compared with M-Wire and Gold-treated instruments (De-Deus et al., 2017; Pedullà et al., 2020; Özyürek, 2020).

M3 Pro Gold instruments exhibited intermediate flexibility, consistent with the properties of CM Wire alloys, which allow controlled deformation and pre-bending due to their predominantly martensitic structure (Elnaghy & Elsaka, 2016; Plotino et al., 2014). In contrast, M-Wire instruments such as ProTaper Next retain a higher proportion of austenite at body temperature, resulting in increased stiffness and higher bending resistance (Johnson et al., 2008).

**Influence of Phase Transformation Temperatures**

Phase transformation temperatures play a crucial role in determining NiTi mechanical behavior (Thompson, 2000; Zupanc et al., 2018). Instruments with austenite finish (Af) temperatures near or above body temperature remain martensitic during clinical use, enhancing flexibility. Blue heat-treated instruments typically exhibit the highest Af values, followed by gold-treated and M-Wire instruments, explaining the graded flexibility observed in this study (Shen et al., 2013; Zupanc et al., 2018).

**Influence of Instrument Design**

Although metallurgy was the primary variable, instrument geometry also influences flexibility. Cross-sectional design, core mass, and taper affect stress distribution and stiffness (Kim et al., 2009; Versiani et al., 2015). E Flex Blue instruments combine advanced metallurgy with a slimmer core design, which likely contributes to their superior bending ability (Kim et al., 2009).

**Clinical Implications**

Greater bending flexibility allows instruments to better follow canal curvature, reducing stress concentration and minimizing the risk of canal transportation and instrument separation (Gergi et al., 2010; Sattapan et al., 2000). Enhanced flexibility is also associated with improved cyclic fatigue resistance, indirectly contributing to safer instrumentation in curved canals (Pedullà et al., 2020; Özyürek, 2020).

**Limitations of the Study**

This study has several limitations that should be considered when interpreting the results. The bending test was conducted under static laboratory conditions, which may not fully replicate the dynamic stresses experienced by instruments during clinical use (ISO, 2019; Plotino et al., 2022). Only one instrument size and taper were evaluated, and the findings may not be directly applicable to instruments with different geometries. Additionally, other mechanical properties, such as torsional resistance, cutting efficiency, and cyclic fatigue under dynamic conditions, were not assessed (Sattapan et al., 2000).

**Future Research Directions**

Future studies should incorporate dynamic fatigue testing, multiple instrument sizes, and comprehensive metallurgical analyses such as differential scanning calorimetry and scanning electron microscopy to further elucidate the relationship between heat treatment, phase transformation behavior, and mechanical performance (De-Deus et al., 2017; Elnaghy & Elsaka, 2016; Plotino et al., 2022). Clinical studies are also needed to confirm whether the enhanced bending flexibility observed in vitro translates into improved treatment outcomes

**Conclusion**

Blue heat-treated NiTi rotary files (E Flex Blue) demonstrated superior bending flexibility compared with CM Wire (M3 Pro Gold) and M-Wire (ProTaper Next) instruments of identical size and taper. These findings highlight the critical influence of thermal treatment, phase composition, and instrument design on mechanical behavior. Enhanced bending flexibility may translate into safer and more effective root canal shaping, particularly in curved canals.

**References**

2. Chaniotis, A., De-Deus, G., Silva, E. J. N. L., & Lopes, H. P. (2021). Bending resistance of heat-treated nickel–titanium endodontic instruments. *Applied Sciences, 11*(13), 5956. https://doi.org/10.3390/app11135956
3. De-Deus, G., Silva, E. J. N. L., Vieira, V. T. L., Belladonna, F. G., Elias, C. N., & Lopes, H. P. (2017). Blue thermomechanical treatment optimizes fatigue resistance and flexibility of rotary nickel–titanium instruments. *Journal of Endodontics, 43*(6), 1020–1024. https://doi.org/10.1016/j.joen.2017.02.003
4. Elnaghy, A. M., & Elsaka, S. E. (2016). Mechanical properties of controlled memory wire nickel–titanium rotary instruments. *International Endodontic Journal, 49*(8), 776–783. https://doi.org/10.1111/iej.12512

5. Gergi, R., Rjeily, J. A., Sader, J., & Naaman, A. (2010). Comparison of canal transportation and centering ability of twisted files, Pathfile-ProTaper system, and stainless steel hand K-files by using computed tomography. *Journal of Endodontics, 36*(3), 495–499. https://doi.org/10.1016/j.joen.2009.11.003

6. ISO. (2019). *Dentistry—Root canal instruments—Part 1: General requirements and test methods* (ISO 3630-1:2019). International Organization for Standardization.

7. Johnson, E., Lloyd, A., Kuttler, S., & Namerow, K. (2008). Comparison between a novel nickel–titanium alloy and 508 nitinol on the cyclic fatigue life of ProFile 25/.04 rotary instruments. *Journal of Endodontics, 34*(7), 1016–1019. https://doi.org/10.1016/j.joen.2008.03.014

8. Kim, H. C., Kim, H. J., Lee, C. J., Kim, B. M., Park, J. K., & Versluis, A. (2009). Mechanical response of nickel–titanium instruments with different cross-sectional designs during shaping of simulated curved canals. *International Endodontic Journal, 42*(9), 843–851. https://doi.org/10.1111/j.1365-2591.2009.01585.x

9. Oh, S., Kim, H., & Chang, S. W. (2023). Mechanical properties of heat-treated nickel–titanium endodontic instruments. *Applied Sciences, 13*(3), 1820. https://doi.org/10.3390/app13031820

10. Özyürek, T. (2020). Cyclic fatigue resistance of reciprocating and rotary nickel–titanium instruments manufactured with different heat treatments. *International Endodontic Journal, 53*(1), 128–136. https://doi.org/10.1111/iej.13238

11. Pedullà, E., Lo Savio, F., Boninelli, S., Plotino, G., Grande, N. M., & Rapisarda, E. (2020). Influence of different heat treatments on cyclic fatigue resistance and bending properties of nickel–titanium rotary instruments. *Journal of Endodontics, 46*(9), 1305–1310. https://doi.org/10.1016/j.joen.2020.05.005

12. Pereira, E. S., Peixoto, I. F. C., Viana, A. C. D., Oliveira, I. I., Gonzalez, B. M., & Buono, V. T. L. (2015). Physical and mechanical properties of a thermomechanically treated NiTi wire used in the manufacture of rotary endodontic instruments. *Journal of Endodontics, 41*(12), 2079–2083. https://doi.org/10.1016/j.joen.2015.08.020

13. Peters, O. A. (2004). Current challenges and concepts in the preparation of root canal systems: A review. *International Endodontic Journal, 37*(8), 501–514. https://doi.org/10.1111/j.1365-2591.2004.00811.x

14. Plotino, G., Grande, N. M., Cordaro, M., Testarelli, L., & Gambarini, G. (2007). A review of cyclic fatigue testing of nickel–titanium rotary instruments. *Journal of Endodontics, 33*(4), 474–477. https://doi.org/10.1016/j.joen.2006.11.017

15. Plotino, G., Grande, N. M., Testarelli, L., & Gambarini, G. (2014). Cyclic fatigue of Reciproc and WaveOne reciprocating instruments. *Journal of Endodontics, 40*(1), 123–126. https://doi.org/10.1016/j.joen.2013.08.013

16. Plotino, G., Grande, N. M., Isufi, A., Ioppolo, P., Pedullà, E., Bedini, R., & Gambarini, G. (2022). Mechanical testing of nickel–titanium endodontic instruments: A methodological review. *Clinical Oral Investigations, 26*(5), 4583–4592. https://doi.org/10.1007/s00784-022-04487-y

17. Schäfer, E., Erler, M., & Dammaschke, T. (2004). Shaping ability and cleaning effectiveness of rotary nickel–titanium instruments. *International Endodontic Journal, 37*(3), 161–168. https://doi.org/10.1111/j.1365-2591.2004.00761.x

18. Sattapan, B., Nervo, G. J., Palamara, J. E. A., & Messer, H. H. (2000). Defects in rotary nickel–titanium files after clinical use. *Journal of Endodontics, 26*(2), 113–125. https://doi.org/10.1016/S0099-2399(99)00231-X

19. Shen, Y., Zhou, H., Zheng, Y., Peng, B., & Haapasalo, M. (2013). Metallurgical characterization of controlled memory wire nickel–titanium rotary instruments. *International Endodontic Journal, 46*(10), 910–917. https://doi.org/10.1111/iej.12090

20. Thompson, S. A. (2000). An overview of nickel–titanium alloys used in dentistry. *International Endodontic Journal, 33*(4), 297–310. https://doi.org/10.1046/j.1365-2591.2000.00352.x

21. Versiani, M. A., Pécora, J. D., & Sousa-Neto, M. D. (2015). Influence of instrument design on the mechanical behavior of nickel–titanium rotary instruments. *International Endodontic Journal, 48*(6), 817–825. https://doi.org/10.1111/iej.12378

22. Zupanc, J., Vahdat-Pajouh, N., & Schäfer, E. (2018). New thermomechanically treated NiTi alloys—A review. *International Endodontic Journal, 51*(2), 165–174. https://doi.org/10.1111/iej.12812