

The effects of heat treatment files and taper lock depth on the torsional fatigue resistance of rotary NiTi instruments

Pengaruh Heat Treatment File pada Kedalaman Taper Lock terhadap Torsional Fatigue Rotari NiTi

Viola Shelvannia Haryanto¹, Rosita Stefani^{1*}, Eddy², Bernard Ongkie Iskandar¹

¹Departemen Konservasi Gigi, Fakultas Kedokteran Gigi, Universitas Trisakti, Jakarta, Indonesia

²Departemen Bahan Kedokteran Gigi, Fakultas Kedokteran Gigi, Universitas Trisakti, Jakarta, Indonesia

*Email: rosita@trisakti.ac.id

ABSTRACT

Background: A file fracture is a significant complication in endodontic treatment, particularly when it obstructs access to the apical root canal. The primary cause is torsional fatigue, occurring when applied force exceeds the elastic limit of NiTi alloys. Heat-treated rotary files have been developed to improve torsional resistance.

Objective: To compare the time to fracture due to torsional fatigue between gold and blue heat-treated rotary files under taper lock conditions.

Methods: A total of 48 heat-treated rotary files (#25.04) were embedded in bulk-fill composite resin blocks to simulate taper lock. Samples were randomly divided into eight groups (n=6): E-Flex Gold (3 mm, 5 mm), EndoArt Smart Gold (3 mm, 5 mm), E-Flex Blue (3 mm, 5 mm), and EndoArt Smart Blue (3 mm, 5 mm). Torsional fatigue time was recorded from the start of rotation using an endomotor until fracture occurred.

Results: One-way ANOVA revealed a statistically significant difference in torsional fatigue time among groups (p<0.05).

Conclusion: Blue heat-treated rotary files showed longer fracture times and may be safer in high taper lock conditions, although results are limited by the in vitro resin model.

Keywords: blue heat treatment, gold heat treatment, taper lock, torsional fatigue

ABSTRAK

Latar Belakang: Fraktur file merupakan komplikasi penting dalam perawatan endodontik, terutama jika menghambat akses ke saluran akar bagian apikal. Penyebab utamanya adalah kelelahan torsional akibat gaya yang melebihi batas elastis paduan NiTi. File rotari dengan perlakuan panas dikembangkan untuk meningkatkan ketahanan torsional.

Tujuan: Membandingkan waktu fraktur akibat torsional *fatigue* antara file dengan perlakuan panas *gold* dan *blue* pada kondisi taper lock.

Metode: Sebanyak 48 file rotari (#25.04) ditanam dalam blok resin komposit bulk-fill untuk mensimulasikan taper lock, kemudian dibagi acak menjadi delapan kelompok (n=6): E-Flex Gold (3 mm, 5 mm), EndoArt Smart Gold (3 mm, 5 mm), E-Flex Blue (3 mm, 5 mm), dan EndoArt Smart Blue (3 mm, 5 mm). Waktu torsional *fatigue* dicatat sejak rotasi dimulai dengan endomotor hingga terjadi fraktur.

Hasil: Uji ANOVA satu arah menunjukkan perbedaan signifikan antar kelompok (p<0,05).

Kesimpulan: File dengan perlakuan panas blue memiliki waktu fraktur lebih lama dan berpotensi lebih aman, dengan keterbatasan pada model in vitro berbasis resin.

Kata kunci: *blue heat treatment, gold heat treatment, taper lock, torsional fatigue.*

INTRODUCTION

The ideal root canal treatment results in a continuous tapered mechanical preparation along the entire length of the root canal, from the coronal to the apical third, while respecting the anatomical shape and keeping the apical foramen as small as possible. Root canal preparation becomes more difficult for clinicians in narrow and curved root canals[1].

File Nickel-titanium (NiTi) rotary tools have been widely used for root canal preparation due to their advantages in reducing iatrogenic errors and minimizing treatment time while maintaining the original root canal anatomy[2], [3]. File NiTi rotary files are more elastic and have better cutting qualities and allow the operator to obtain anatomical root canal tapers with minimal canal transportation due to the superelastic properties of NiTi compared to conventional stainless steel files[1]. NiTi's superelasticity is useful in root canal preparation due to its flexibility and ability to provide elastic deformation in tooth root canals, which is obtained from the physical transformation properties of the austenite and martensite phases[4], [5].

Intracanal file fracture is one of the most common procedural errors during root canal treatment and can involve a variety of endodontic instruments. The prevalence of NiTi rotary file fractures ranges from 1.04–13.54%[6]. Patnana's study reported that the most frequently found instrument fragment lengths were <2 mm (38%), followed by 2–4 mm (29%), 4–6 mm (21%), and >6 mm (12%)[7]. In line with these findings, Terauchi reported that the prevalence of instrument fractures was significantly higher in the apical third of the root canal (52.5%) compared to the middle third (27.5%) and coronal third (12.5%), and most of the fractured instruments were NiTi instruments with an average fragment length of approximately 3 mm, which confirms the high risk of instrument fractures in the apical area of the root canal[7], [8].

The performance of endodontic files has improved over time, but file fracture is the biggest challenge for clinicians[4]. The main causes of rotary file fracture are torsional fatigue and cyclic fatigue, which occur when the force exceeds the plastic limit of the NiTi alloy[9]. Cyclic fatigue occurs when the file is rotated freely, causing repeated compressive and tensile stress on the curved root canal until fracture occurs.[10]. Torsional fatigue occurs when the tip or other component of the file becomes locked in a narrow root canal while the file is still rotating (taper lock). Excessive torque will occur and cause the file to fracture[11]. Torsional resistance is one of the mechanical properties of NiTi files that can affect clinical performance in narrow root canals[3].

Various geometric and dimensional design modifications have been developed into the instrument design to reduce the incidence of fracture due to excessive torsional loading[12]. In addition, heat treatment was developed to increase the torsional resistance of NiTi instruments with the aim of improving safety during root canal preparation. Heat treatment changes the crystal disposition of nickel and titanium atoms, which undergo a major shift from cubic (austenite phase) to tetragonal (martensite phase) molecular arrangement, which induces different mechanical properties[13]. Heat treatment aims to influence the transition temperature of the NiTi alloy and then modify the resistance, both cyclic fatigue and torsional fatigue[14], [15].

Thermomechanical treatment after grinding produces a blue or gold titanium oxide layer on the surface of the file, thus developing various gold heat treatment and blue heat treatment file systems[16]. Heat treatment aims to change the crystal phase structure of NiTi alloy to increase the flexibility and mechanical resistance of the instrument, with a titanium oxide layer thickness of around 60–80 nm in blue heat treatment and 100–140 nm in gold heat treatment[15], [17].

Blue heat treatment file has a higher proportion of stable martensite, resulting in a more flexible NiTi alloy and resulting in improved performance compared to conventional NiTi files[18]. Heat-treated NiTi gold files exhibit increased flexibility and superior cyclic fatigue resistance compared to conventional files. The final austenite temperature of heat-treated NiTi gold files is 49-52°C[19]. This difference affects the crystal phase transformation of NiTi, where blue heat-treated files have a higher fraction of the martensite phase at clinical temperatures, making them more flexible and resistant to fatigue, while gold heat-treated files tend to have a balance of austenite–martensite phases that provide good flexibility but with relatively lower torsional resistance[17].

Both types of heat-treated files show superior flexibility and cyclic fatigue resistance compared to conventional NiTi, but comparative evidence regarding torsional fatigue resistance between the two types of heat-treated rotary files is still limited, especially at different taper lock depths. The taper lock condition in narrow and curved root canals contributes to increased torsional loads that are difficult to control clinically and is the main mechanism for sudden instrument fracture. This study aims to compare the torsional fatigue resistance of NiTi rotary files with blue and gold heat treatments at different taper lock depths, with similar file design characteristics, based on the time of fracture at different taper lock depths, and analyze the difference in fracture time due to torsional fatigue in rotary files with the same heat treatment at 3 mm and 5 mm taper lock depths.

METHODS

Study Design

This study was conducted from April to May 2025 at the Dental Material & Testing Center of Research and Education (DMT Core), Faculty of Dentistry, Universitas Trisakti. This research was a laboratory experimental study using a post-test only control group design.

Data Source and Sampling Procedure

The sample population consisted of NiTi rotary files, including E-Flex Gold (Eighteenth, Changzhou, China), E-Flex Blue (Eighteenth, Changzhou, China), EndoArt Smart Gold (Inci Dental, Istanbul, Turkey), and EndoArt Smart Blue (Inci Dental, Istanbul, Turkey), with two different taper lock depths.

A total of 48 files were included, determined using the Lemeshow formula, then selected through simple random sampling and equally divided into eight groups ($n = 6$ per group) based on heat treatment type, instrument brand, and taper lock depth. The taper lock simulation was performed by embedding the files into bulk-fill composite resin blocks, and all tests were conducted at room temperature.

Before testing, the endomotor and time-measuring instruments were calibrated according to the manufacturer's standards. Initial function testing was also performed to ensure the stability of rotational speed and torque, thereby maintaining the validity and reliability of the measurements.

Variables of the Study

This study included two independent variables, namely rotary file heat treatment and taper lock depth. The heat treatment variable consisted of NiTi gold heat-treated rotary files (E-Flex Gold and EndoArt Smart Gold) and NiTi blue heat-treated rotary files (E-Flex Blue and EndoArt Smart Blue). The taper lock depths used in this study were 3 mm and 5 mm.

Data Collection

The torsional fatigue test was performed by rotating NiTi rotary files (#25.04) using an endodontic endomotor. E-Flex Gold and E-Flex Blue files were rotated at 350 rpm with

a torque of 2.5 N-cm, while EndoArt Smart Gold files were rotated at 300 rpm with a torque of 2 N-cm, and EndoArt Smart Blue files at 300 rpm with a torque of 1.6 N-cm.

Torsional fatigue was identified when file fracture occurred, without the addition of external loads other than resistance from the simulated taper lock condition. The duration of testing was recorded as the time until file fracture.

Measurement and Instruments

Sample Preparation

Forty-eight #25.04 rotary files were divided into E-Flex Gold with taper lock depths of 3 mm ($n = 6$) and 5 mm ($n = 6$), EndoArt Smart Gold with taper lock depths of 3 mm ($n = 6$) and 5 mm ($n = 6$), E-Flex Blue with taper lock depths of 3 mm ($n = 6$) and 5 mm ($n = 6$), and EndoArt Smart Blue with taper lock depths of 3 mm ($n = 6$) and 5 mm ($n = 6$).

Composite Resin Block Preparation

A total of 24 files were embedded perpendicularly in composite resin blocks using metal molds at a depth of 3 mm, and another 24 files were embedded in bulk-fill composite resin (Xtra Base; VOCO, USA) at a depth of 5 mm. The composite resin was polymerized using a light-curing unit (Bluephase; Ivoclar Vivadent, Schaan, Liechtenstein) for 10 seconds per 4 mm layer at an intensity of 1000 mW/cm².

Sample Treatment

All files in the torsional fatigue test were rotated using an endomotor (X-Smart Plus; Dentsply Maillefer, Ballaigues, Switzerland), which was securely mounted on a handpiece holder, in a clockwise motion until fracture occurred. Time measurement was recorded from the start of rotation until file fracture using a stopwatch.

Data Analysis

Data were analyzed using SPSS version 26. Normality was assessed using the Shapiro–Wilk test ($n \leq 50$), and homogeneity was evaluated using Levene's test ($p > 0.05$). Differences in torsional fatigue time were analyzed using one-way ANOVA, followed by Tukey's post hoc test ($p < 0.05$).

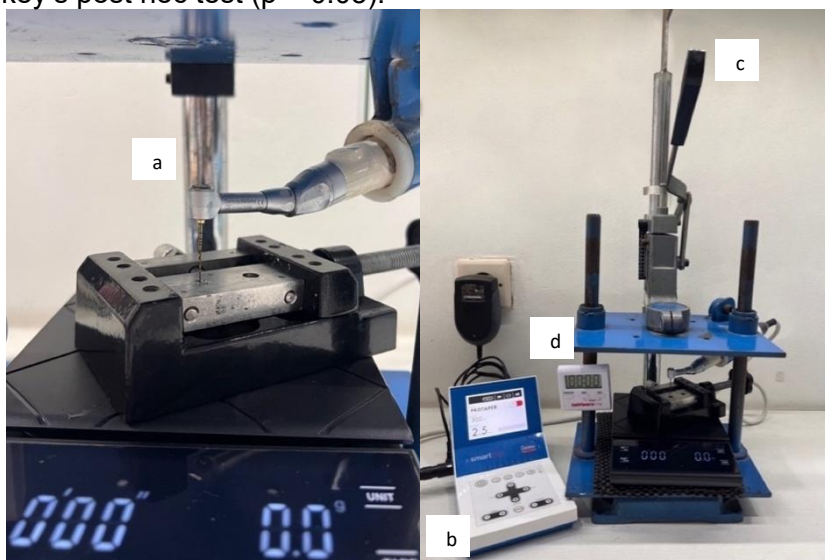


Figure 1. Arrangement of tools and materials during the torsional fatigue test.

- (a) The condition of the 3 mm and 5 mm taper lock simulated by embedding the file in bulk-fill composite resin polymerized in a mold;
- (b) Endomotor settings according to the manufacturer's recommendations;
- (c) A lever used to press the handpiece with equal pressure weight for all samples, measured using a scale;
- (d) A stopwatch used to calculate the time at which the file fracture occurs.

The results of the normality and homogeneity tests showed that each data set was normally distributed and homogeneous ($p > 0.05$). The one-way ANOVA test showed a significant difference in the average torsional fatigue time for each file type in the 8 groups, with a significance value of $p < 0.05$.

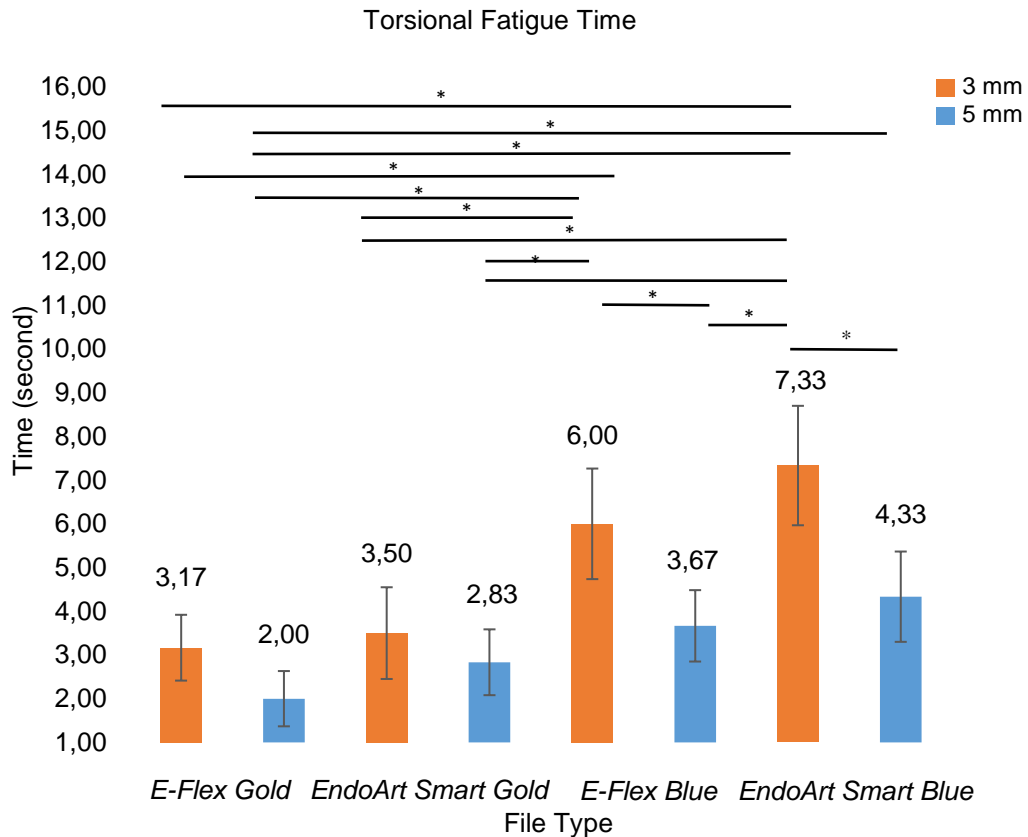


Figure 2. Average torsional fatigue time of 8 test groups in the study

Post-hoc test results showed that there were significant differences between gold heat-treated and blue heat-treated files at various taper lock depths ($p < 0.05$). In general, blue heat-treated files, especially those with a 3 mm taper lock, showed significant differences compared to all gold heat-treated files at both 3 mm and 5 mm depths. In addition, increasing the taper lock depth from 3 mm to 5 mm also affected the differences between groups, especially in blue heat-treated files. However, no significant differences were found between E-Flex Blue and EndoArt Smart Blue files at a 3 mm taper lock depth ($p > 0.05$), indicating relatively similar torsional resistance characteristics between blue files under these conditions.

The test results showed a significant difference between the blue heat treatment file with a 3 mm taper lock compared to the gold heat treatment file at a 3 mm or 5 mm taper lock, as well as a significant difference between the gold heat treatment file and the blue heat treatment at a 5 mm taper lock depth.

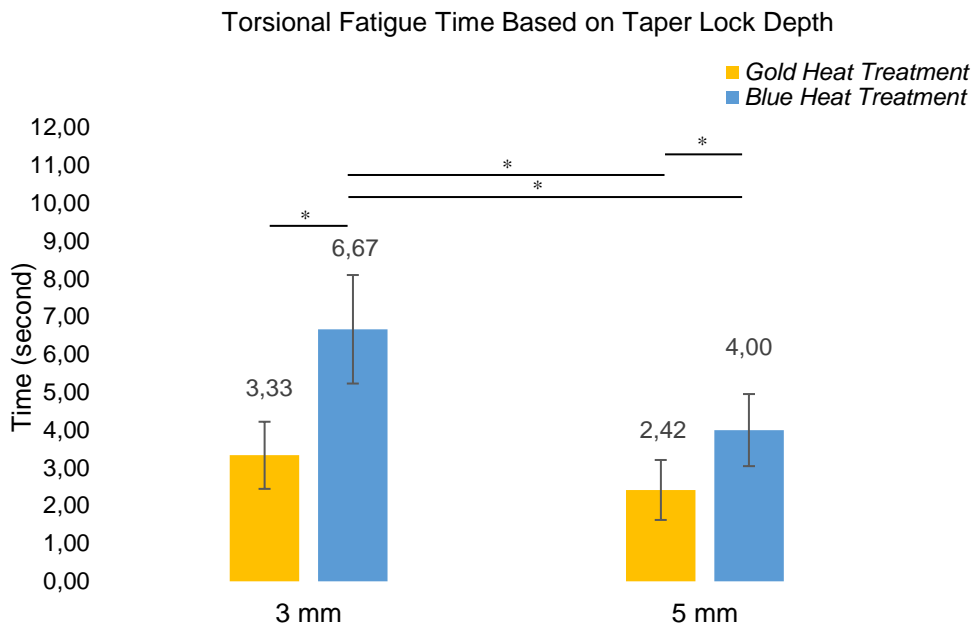


Figure 3. Torsional fatigue time based on taper lock depth

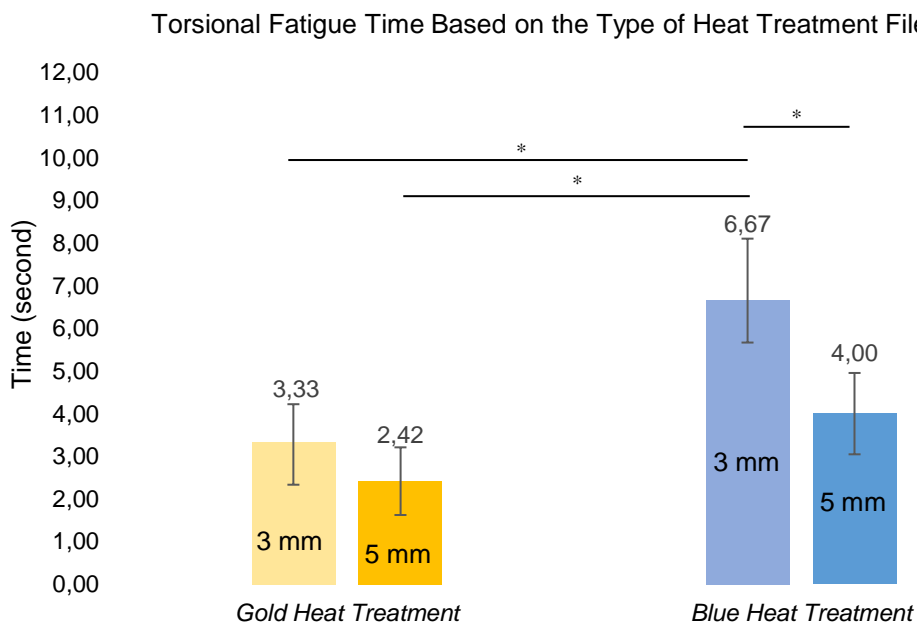


Figure 4. Torsional fatigue time based on the type of heat treatment file with different taper lock depths.

Significant differences were found in blue heat treatment files with a taper lock depth of 3 mm compared to blue heat treatment files with a depth of 5 mm and gold heat treatment files with a taper lock depth of 3 mm and 5 mm.

DISCUSSION

Effective root canal preparation is essential for achieving adequate root canal treatment results. Various instruments and techniques have been developed to achieve adequate treatment results, including the development of gold heat treatment and blue

heat treatment instruments[17]. There are causes of root canal treatment failure due to file fractures that occur due to torsional fatigue[7]. This study evaluates the time to torsional fatigue in NiTi rotary files with identical designs but manufactured using different heat treatment technologies, so that other variables can be eliminated.

The E-Flex and EndoArt Smart rotary files were used because they both have a convex triangular cross-sectional design with a 4% taper and a #25 size, which is known to provide optimal stress distribution and flexibility. Convex triangular cross sectional design have minimal contact points between the root canal surface wall and the instrument, which will increase the flexibility of the instrument[20], [21]. In accordance with the research of Kilic et al., final preparation using size and taper #25.04 will significantly increase fracture resistance, which minimizes dentinal stress[22]. Taper lock depths of 3 mm and 5 mm were simulated using composite resin bulkfill with a similar elastic modulus to dentin to represent narrow root canal conditions[23], [24].

The results showed significant differences between the four file types. The blue heat treatment provided longer torsional fatigue times than the gold heat treatment at the same taper lock depth. Furthermore, the 3 mm taper lock depth produced higher torsional resistance than the 5 mm, which can be attributed to the increase in torque with increasing working diameter, which causes reduced flexibility of the file [25], [26]. This is not similar to the research of Pedulla et al., which showed that file diameter did not provide a significant difference in terms of maximum torque or rotation angle until file fracture occurred[27].

The difference in the time of torsional fatigue is caused by variations in the crystalline structure resulting from heat treatment. Blue heat treatment and gold heat treatment do not differ in alloy composition, but the color difference is the color of the titanium oxide layer resulting from the thermal treatment applied to the same NiTi base alloy. This heat treatment changes the phase transformation behavior and mechanical properties of the file, and the resulting color is a visual byproduct of the specific titanium oxide layer formed during the process[20]. Heat treatment file have different fatigue resistance due to the variation in martensite composition associated with the high phase transformation temperatures of gold heat-treated and blue heat-treated files. At the same applied force, files with higher flexibility will experience lower stresses, allowing for higher fatigue resistance when other factors are held identical[29].

Gold heat treatment maintains the superelastic properties of NiTi, while blue heat treatment produces a greater proportion of the martensite phase, which increases flexibility and fatigue resistance[30]. Martensitic alloys have a lower modulus of elasticity, so they are capable of undergoing greater elastic deformation before fracture. Similar to the research of Alcalde et al. and Klymus et al.[19]. Higher flexibility is related to the austenite and martensite transformation temperatures; the final austenite transformation temperature (A_f) of the blue heat treatment file ranges from 34.42–38.5°C, while the gold heat treatment file ranges from 50.1°C. The difference in temperature A_f in the blue heat treatment file causes a lower percentage of the martensite phase at body temperature and a higher proportion of stable martensite, which is influenced by the heat treatment of the metal alloy, which increases the flexibility of the instrument and increases the elastic deformation capacity of NiTi[22], [23], [24].

EndoArt Smart Blue showed the longest fracture time, followed by E-Flex Blue, EndoArt Smart Gold, and E-Flex Gold. These results are consistent with other studies that have shown that blue heat-treated files have higher torsional resistance and flexibility than gold heat-treated files. Variations in torque and endomotor speed between brands can also influence the time to torsional fatigue, as higher rotational speeds increase file strain and temperature, accelerating the austenite-martensite transition and

the risk of fatigue. Overall, increasing the proportion of martensite and decreasing the taper lock depth have been shown to increase resistance to torsional fatigue in NiTi rotary files[24], [25].

The significant differences between file types in this study were also influenced by variations in torque and rotational speed according to manufacturer recommendations. Operative torque is dynamic and influenced by root canal conditions, where narrower canals increase the torque stress on the file[33]. In this study, the endomotor was set at a constant speed to maintain a safe torque and assessed torsional resistance through a single rotational load until fracture. Literature suggests that high speeds can increase stress, temperature, and the risk of taper lock, thus accelerating fatigue, although several other studies have reported different results, indicating that the effect of speed and torque on file fracture still depends on the testing conditions[32].

This study has the advantage of using NiTi rotary files with identical geometric designs, so that the observed differences in torsional fatigue resistance are only influenced by heat treatment. In addition, the simulation of taper lock conditions in this study uses materials with elastic modulus similar to dentin, and the taper lock evaluation increases the relevance to the clinical conditions of narrow root canals. However, the limitation of this study lies in the in vitro design that does not fully represent actual clinical conditions, including variations in root canal anatomy and the influence of intraoral temperature. The implications of this study indicate that the use of blue heat-treated files has the potential to improve clinical safety by reducing the risk of instrument fracture in narrow root canals.

CONCLUSION

Blue heat-treated rotary files showed higher torsional resistance than gold heat-treated files, characterized by longer fracture times at all taper lock depths, while increasing taper lock depth accelerated fracture due to increased torsional load. However, the results of this study have limitations, such as the use of a resin-based in vitro model and test conditions that do not fully represent the clinical situation. Clinically, blue heat-treated files are recommended for root canals with a high risk of taper lock, while further research is recommended, including SEM fractography analysis and varying test temperatures to assess the effect of the intraoral environment on torsional fatigue.

REFERENCES

- [1] A. S. Boscornea-Puşcu *et al.*, “Experimental study of the effects of torsional loading on three types of nickel-titanium endodontic instruments,” *Applied Sciences (Switzerland)*, vol. 11, no. 16, Aug. 2021, doi: 10.3390/app11167224.
- [2] E. Pedullà *et al.*, “Torsional, Static, and Dynamic Cyclic Fatigue Resistance of Reciprocating and Continuous Rotating Nickel-Titanium Instruments,” *J Endod*, vol. 48, no. 11, pp. 1421–1427, Nov. 2022, doi: 10.1016/j.joen.2022.08.005.
- [3] A. Alqedairi, H. Alfawaz, B. Abualjadayel, M. Alanazi, A. Alkhalifah, and A. Jamleh, “Torsional resistance of three ProTaper rotary systems,” *BMC Oral Health*, vol. 19, no. 1, Jun. 2019, doi: 10.1186/s12903-019-0820-7.
- [4] C. Ribeiro Camargo, T. Bittencourt, A. Hasna, R. Palo, C. Talge Carvalho, and M. Valera, “Cyclic fatigue, torsional failure, and flexural resistance of rotary and reciprocating instruments,” *Journal of Conservative Dentistry*, vol. 23, no. 4, pp. 364–369, Jul. 2020, doi: 10.4103/JCD.JCD_409_20.

- [5] P. Sánchez, B. Vidi, J. Mena-Alvarez, J. Gil, C. Rico, and J. M. Aragonese, "Effect of Stabilized Martensite on the Long-Term Performance of Superelastic NiTi Endodontic Files," *Materials*, vol. 16, no. 11, Jun. 2023, doi: 10.3390/ma16114089.
- [6] A. P. Kharkar, K. S. Reddy, S. Banerjee, and Z. Maheshwari, "Coping with complexity: Navigating severe curve canals in endodontic root canal treatment: A clinical case series," *Journal of Conservative Dentistry and Endodontics*, vol. 27, no. 7, pp. 785–788, Jul. 2024, doi: 10.4103/JCDE.JCDE_208_24.
- [7] A. K. Patnana, A. Chugh, V. K. Chugh, and P. Kumar, "The incidence of nickel-titanium endodontic hand file fractures: A 7-year retrospective study in a tertiary care hospital," *Journal of Conservative Dentistry*, vol. 23, no. 1, pp. 21–25, Jan. 2020, doi: 10.4103/JCD.JCD_254_20.
- [8] Y. Terauchi, W. T. Ali, and M. M. Abielhassan, "Present status and future directions: Removal of fractured instruments," May 01, 2022, *John Wiley and Sons Inc.* doi: 10.1111/iej.13743.
- [9] D. Di Nardo, A. Zanza, M. Seracchiani, O. Donfrancesco, G. Gambarini, and L. Testarelli, "Angle of insertion and torsional resistance of nickel–titanium rotary instruments," *Materials*, vol. 14, no. 13, Jul. 2021, doi: 10.3390/ma14133744.
- [10] H. R. Ubaed and D. K. Bakr, "Cyclic Fatigue Resistance of Nickel-Titanium Rotary Instruments after Simulated Clinical Use," *Appl Bionics Biomech*, vol. 2022, 2022, doi: 10.1155/2022/1716008.
- [11] T. Weissheimer *et al.*, "Evaluation of cyclic and torsional fatigue resistance of several heat-treated reciprocating nickel–titanium instruments," *Australian Endodontic Journal*, vol. 49, no. 3, pp. 524–529, Dec. 2023, doi: 10.1111/aej.12774.
- [12] P. Mangat, A. Ajaz Raina, S. Vaidya, A. Bhattacharya, A. Dhingra, and V. Sharma, Torque and Speed in Endodontics: A Review. *Int J Oral Care Res.* 2018;6(2):97-100.
- [13] D Furlan, MP Alcalde, MAH Duarte, et al. Cyclic and Torsional Fatigue Resistance of Seven Rotary Systems. *Iran Endod J.* 2021;16(2):78–84. doi: 10.22037/iej.v16i2.23760
- [14] M. Pillay, M. Vorster, and P. J. Van der Vyver, "Fracture of endodontic instruments - Part 1: Literature review on factors that influence instrument breakage," *South African Dental Journal*, vol. 75, no. 10, pp. 553–563, Nov. 2020, doi: 10.17159/2519-0105/2020/v75no10a4.
- [15] S. Tabassum, K. Zafar, and F. Umer, "Nickel-titanium rotary file systems: What's new?" 2019, *Kare Publishing.* doi: 10.14744/eej.2019.80664.
- [16] S. W. Kwak, Y. Shen, H. Liu, Z. Wang, H. C. Kim, and M. Haapasalo, "Heat Treatment and Surface Treatment of Nickel–Titanium Endodontic Instruments," 2021, *Frontiers Media S.A.* doi: 10.3389/fdmed.2021.769977.
- [17] A. B. Dablanca-blanco, P. Castelo-baz, R. Miguéns-vila, P. Álvarez-novoa, and B. Martín-biedma, "Endodontic Rotary Files, What Should an Endodontist Know?," Jun. 01, 2022, *MDPI.* doi: 10.3390/medicina58060719.
- [18] R. M. Barakat *et al.*, "Comprehensive Characterization of Blue Wire NiTi File Failure: A Comparative Analysis of Cyclic Fatigue and Torsional Resistance Properties," *Coatings*, vol. 14, no. 3, Mar. 2024, doi: 10.3390/coatings14030361.
- [19] S. Oh, T. H. Kim, and S. W. Chang, "Mechanical Properties of NiTi Rotary Files Fabricated through Gold-Wire, CM-Wire, T-Wire, and R-Phase Heat Treatment," *Applied Sciences (Switzerland)*, vol. 13, no. 6, Mar. 2023, doi: 10.3390/app13063604.
- [20] N. Nanthapraphip, S. Morakul, S. Hiran-Us, and P. Singhatanadgid, "Effect of Cross-sectional Designs on Torsional Resistance of Endodontic Nickel-Titanium Files: A Finite

- Element Study,” *Eur J Dent*, vol. 19, no. 2, pp. 513–522, Nov. 2024, doi: 10.1055/s-0044-1791785.
- [21] W. Hadriyanto *et al.*, “Influence of nickel-titanium rotary systems with varying cross-sectional, pitch, and rotational speed on deflection and cyclic fatigue: a finite element analysis study,” in *BIO Web of Conferences*, EDP Sciences, Dec. 2021. doi: 10.1051/bioconf/20214105005.
- [22] Y. Kılıç, E. Karataşlıoğlu, and M. E. Kaval, “The Effect of Root Canal Preparation Size and Taper of Middle Mesial Canals on Fracture Resistance of the Mandibular Molar Teeth: An In Vitro Study,” *J Endod*, vol. 47, no. 9, pp. 1467–1471, Sep. 2021, doi: 10.1016/j.joen.2021.06.002.
- [23] E. Pedullà *et al.*, “Cyclic fatigue resistance, torsional resistance, and metallurgical characteristics of M3 Rotary and M3 Pro Gold NiTi files,” *Restor Dent Endod*, vol. 43, no. 2, 2018, doi: 10.5395/rde.2018.43.e25.
- [24] S. Oh *et al.*, “Torsional and Bending Properties of v Taper 2H, ProTaper NEXT, NRT, and One Shape,” *Biomed Res Int*, vol. 2019, 2019, doi: 10.1155/2019/6368958.
- [25] J. Zupanc, N. Vahdat-Pajouh, and E. Schäfer, “New thermomechanically treated NiTi alloys – a review,” Oct. 01, 2018, *Blackwell Publishing Ltd*. doi: 10.1111/iej.12924.
- [26] G. Uslu, M. Gündoğar, T. Özyürek, and G. Plotino, “Cyclic fatigue resistance of reduced-taper nickel-titanium (NiTi) instruments in doubled-curved (S-shaped) canals at body temperature,” *J Dent Res Dent Clin Dent Prospects*, vol. 14, no. 2, pp. 111–115, Jun. 2020, doi: 10.34172/joddd.2020.024.
- [27] E. Pedullà *et al.*, “Influence of NiTi Wire Diameter on Cyclic and Torsional Fatigue Resistance of Different Heat-Treated Endodontic Instruments,” *Materials*, vol. 15, no. 19, Oct. 2022, doi: 10.3390/ma15196568.
- [28] J. A. Aparicio *et al.*, “Multimodal Evaluation of Three NiTi Rotary Systems: Clinical Simulation, Mechanical Testing, and Finite Element Analysis,” *Dent J (Basel)*, vol. 13, no. 8, Aug. 2025, doi: 10.3390/dj13080368.
- [29] X. M. Hou, Y. J. Yang, and J. Qian, “Phase transformation behaviors and mechanical properties of NiTi endodontic files after gold heat treatment and blue heat treatment,” *J Oral Sci*, vol. 63, no. 1, pp. 8–13, 2021, doi: 10.2334/josnusd.19-0331.
- [30] R. M. Barakat *et al.*, “Comprehensive Characterization of Blue Wire NiTi File Failure: A Comparative Analysis of Cyclic Fatigue and Torsional Resistance Properties,” *Coatings*, vol. 14, no. 3, Mar. 2024, doi: 10.3390/coatings14030361.
- [31] S. Khasnis, P. Kar, A. Kamal, and J. Patil, “Rotary science and its impact on instrument separation: A focused review,” *Journal of Conservative Dentistry*, vol. 21, no. 2, p. 116, 2018, doi: 10.4103/jcd.jcd_240_17.
- [32] M. S. Kyaw *et al.*, “Influence of rotational speed on torque/force generation and shaping ability during root canal instrumentation of extracted teeth with continuous rotation and optimum torque reverse motion,” *Int Endod J*, vol. 54, no. 9, pp. 1614–1622, Sep. 2021, doi: 10.1111/iej.13485.
- [33] G. Gambarini *et al.*, “The relevance of operative torque and torsional resistance of nickel-titanium rotary instruments: A preliminary clinical investigation,” *Saudi Endodontic Journal*, vol. 10, no. 3, pp. 260–264, Sep. 2020, doi: 10.4103/sej.sej_157_19.