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"FINITE ELEMENT ANALYSIS OF A NOVEL ALGORITHM-BASED DUAL-CORE HYBRID NITI ENDODONTIC FILE MODEL"

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ABSTRACT

To evaluate the mechanical behavior of an innovative nickel–titanium rotary files incorporating dual-core hybrid architecture, combining a flexible controlled-memory (CM) external shell with an inner superelastic R-phase core, while preserving established eccentric cross-sectional geometries tested previously. The study assessed the influence of this new internal dual-core engineering on bending flexibility, torsional resistance, and stress redistribution. Materials and A rotary file prototype was developed: triangular-to-rhomboid eccentric cross-section. The design maintained identical external geometrical parameters of previously validated Finite Element model. Novel internal dual-core engineering was introduced by integrating a continuous CM-NiTi outer shell layer and a R-phase inner core. Finite element model was created using SolidWorks Package to simulate and analyze the stress propagation. Mechanical performance was tested using torsional fracture resistance, and bending stiffness testing according to ISO protocols. The Finite Element Analysis (FEA) revealed that the Peak Von Mises stresses were significantly reduced by the dual-core system depending on the tested design. The new dual-core rhomboid eccentric file model demonstrated high mechanical performance when contrasted with homogeneous monolithic NiTi designs due to a more robust effective core area. Stress-mapping revealed substantial redirection of critical stresses from flute edges into the energy-absorbing R-phase core that improved the mechanical performance of the novel dual-core file model. The dual-core hybrid configuration provides enhanced flexibility and improved torsional safety without altering external cutting geometry. This internal engineering offers a promising direction for next-generation endodontic

files by mitigating stress accumulation and extending fatigue life tube current.

KEYWORDS: Nickel–Titanium Rotary Files, Dual-Core Niti, Controlled Memory CM, R-Phase, Eccentric Cross-Section, Torsional Resistance, Bending, Flexibility, Finite Element Analysis.

1. INTRODUCTION

Nickel–titanium (NiTi) rotary files have undergone continuous advancements in surface treatment, thermomechanical modification, and geometric refinements (Almnea et al. 2024; Makanjuola et al. 2022; Galal et al 2025). Despite these developments, nearly all contemporary instruments still rely on a monolithic solid NiTi core, which inherently concentrates stresses during mechanical preparation of root canal that may result in file fracture (Hamdy et al 2023; Terauchi et al. 2021; Ismail et al 2020). The mechanical properties of NiTi rotary files are closely related to the phase composition of the alloy after thermal treatment (Kwak et al. 2021; Gambarini et al. 2020; Galal et al 2019; Ismail et al 2018). NiTi alloys exhibit two distinct crystalline phases structures: the low-temperature martensitic phase, which is flexible and ductile, and the higher-temperature austenite phase, which is rigid and hard. The martensitic phase allows the file to bend and conform to the root canal’s curvature without fracturing, while the austenite phase provides increased stiffness and strength, which is beneficial for cutting efficiency (Hussein et al 2025; Saber et al 2023). The transition between these phases, driven by temperature changes, plays a crucial role in determining the file’s overall performance during endodontic procedures (Kwak et al. 2021; Hamdy et al 2019; Zupanc et al. 2018; Chan et al. 2022).

In recent years, M-wire has been developed through specialized thermomechanical treatments (Tabassum et al. 2019; Hamdy et al 2024). At a specific temperature, M-wire exhibits three distinct phases: the micro-twinned and deformed martensite phase, the rhombohedral crystalline structure phase (R-phase), and the austenite phase. The R-phase, which lies between martensite and austenite, serves as an intermediate phase and is characterized by a lower modulus of elasticity compared to the martensite phase. This unique property contributes to its enhanced flexibility and resistance to cyclic fatigue (Kwak et al. 2021; Ği and Çetinkaya 2024).

Controlled Memory (CM) wire represents a major advancement in the thermomechanical optimization of nickel–titanium (NiTi) rotary instruments. CM wire is produced through proprietary heat-treatment protocols that alter the alloy’s transformation temperatures, resulting in a predominantly martensitic microstructure at room and intracanal temperatures (Ismail et al 2020). This martensitic state significantly enhances instrument flexibility and allows for greater elastic deformation without returning to the original shape, giving the alloy its characteristic “controlled memory” behavior. The thermomechanical treatment also reduces the internal stresses typically present in conventional superelastic NiTi, markedly improving resistance to cyclic fatigue and decreasing the likelihood of unexpected instrument separation during clinical use **(**Fayez et al 2025; Abdulkareem et 2025**)**. As a result, CM-wire instruments demonstrate superior performance when navigating severely curved or complex root canal anatomies, offering improved safety, efficiency, and preservation of canal curvature compared with traditional NiTi alloys.

The present study introduces an internally engineered architecture: Dual-Core Hybrid NiTi System, with an outer shell manufactured from controlled-memory NiTi (CM), an inner core with superelastic R-phase NiTi, and a transition zone of a gradual metallurgical shift to prevent shear discontinuity. This dual-core concept aims to emulate composite structures used in material engineering, where layered materials distribute forces and limit crack propagation.

The external geometry with a clinically relevant triangular apical design transitioning to a rhomboid eccentric cross-section was previously introduced and intentionally preserved (Galal M. et al 2025). This enables isolation of the internal metallurgical innovation as the primary source of mechanical improvement. The null hypothesis is no statistically significant difference in mechanical performance between dual-core NiTi and conventional monolithic NiTi as assessed by numerical testing.

2. MATERIALS AND METHODS

External File Design and Architecture: The file design was constructed using CAD-software, SolidWorks software package (SolidWorks Premium 2018 x64 Edition, USA) to create the 2-D model. The cross section of the file model was triangular at the tip then converted into rhomboid. The triangular apical cross-section transitioned into a rhomboid eccentric in the mid-coronal, the length of triangular cross section part was 5.5 mm, while the length of transformation zone from triangle to rhomboid was 5mm, and the length of rhomboidal cross section part was 5.5 mm. The Tip size #25, the taper 6%, Working length 16 mm, the number of threads 10, and Eccentricity was 0.15 mm offset. This geometrical design was previously introduced and validated (Galal M. et al 2025). (Fig.1)

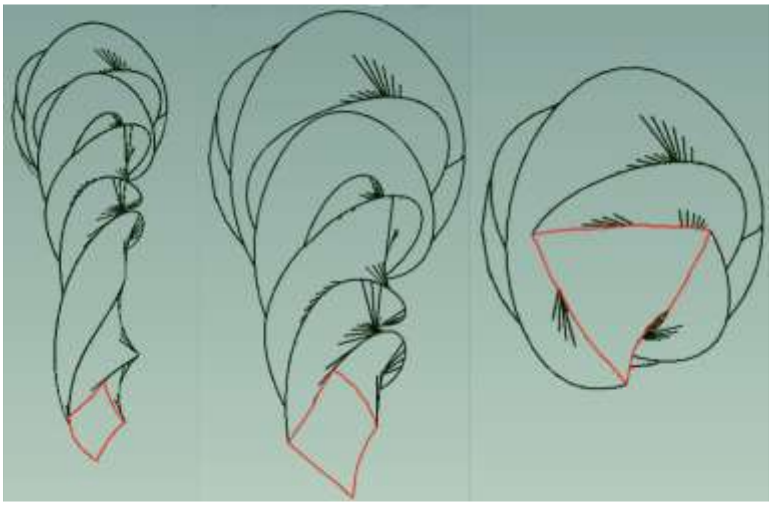

Fig. (1): External File Design and Architecture.

2.1. Internal Dual-Core Configuration

The dual core configuration consists of an outer shell layer (0.03-0.05 mm thickness) constructed from CM-NiTi to provide more flexibility and crack deflection, inner core constructed from R-phase NiTi to provide superelastic stress absorption, and a gradual transition zone for smoother load transfer. The inner core thickness increased coronally, consistent with increasing both the file taper and clinical stress distribution patterns.

2.2. Finite Element Modeling

2.2.1. 3-D Model Construction

3-D models were constructed by transforming the 2-D file with (prt) extension to stereolithographic (stl) extension using Solidworks software package and MATLAB software (MATLAB, R2014b software) (Galal et al. 2015). Sectional construction of the 3-D model was done utilizing this information: file taper, pitch change within the length, changes in cross section (Galal M. et al. 2025). (Fig. 2)

Fig. (2): The 3-D File Model.

2.3. Finite Element Model Construction

Using the computer-aided design program, and Solid-Works software package, the finite element model of the dual core proposed design was generated. Mesh work model was created by SolidWorks software package. The meshing of the rhomboidal C.S file model was created by (SolidWorks software package) using curved-based mesh. The final finite element rhomboidal C.S. model is composed of 2969 elements along with 5757 nodes.

2.4. Material Properties

The superelastic dual-core constitutive models were defined using nonlinear stress–strain curves incorporating two different material properties, (CM and R-phase). The required parameters describing each material were fed to the system. The data of the CM material was obtained based on the stress–strain relationship established by (Zhou et al. 2012) for the

48 cm wire analyzed at room temperature. Those variables used to give details for the R-phase material were extracted from the stress–strain curve presented by (Santos et al. 2016).

2.5. Mechanical testing of the newly dual-core designed files

2.5.1. Bending Test

Cantilever bending simulations for the finite element model involved applying a 1 N concentrated load at the file tip, with the shaft securely gripped in place. Vertical displacement was calculated, and the Von Mises stress distribution was assessed (Eskibağlar et al. 2023).

2.5.2. Torsional Test

The shaft of the file model was loaded with a clockwise shear moment of 2.5 N, where the last 4 mm of the file tip securely held in place. The distribution of stresses was analyzed (Eskibağlar et al. 2023).

3. RESULTS

The FEA indicated that the new dual core file model showed better mechanical performance than did the monolithic NiTi rhomboidal cross section file model tested in our previous study (Galal M. et al 2025). When bending test was performed the dual core file model showed maximum Von Misses reaching 131MPa with a displacement of 4.25 mm compared with the CM-monolithic NiTi file model that showed 158 MPa with displacement of 3.89 mm, while the R-phase monolithic NiTi file model showed 163 MPa with displacement of 3.45 mm. (Fig. 3,4)

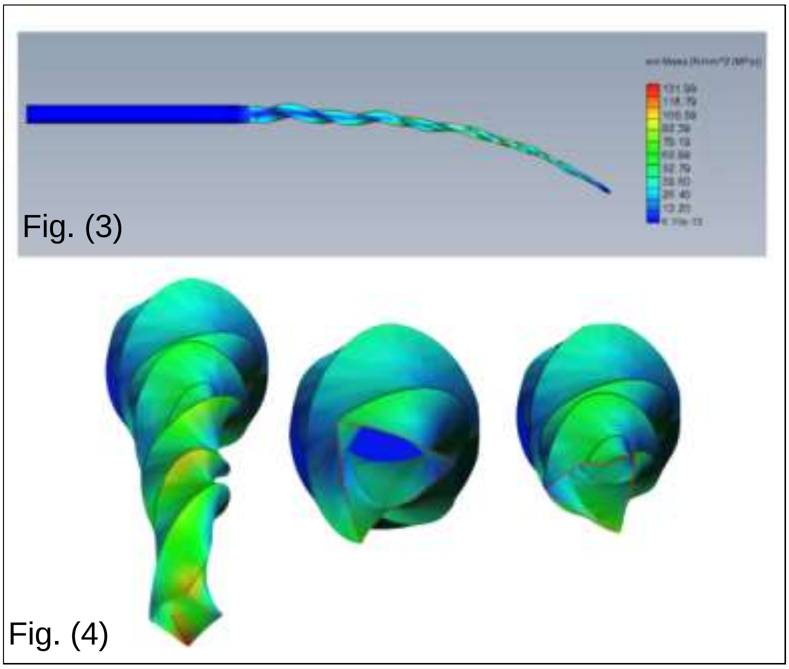

Fig. (3,4): Showing Stress Distribution in Dual-Core File Model During Bending Test.

The results of the torsional test indicated that the least stress value was associated with the dual core file model 135 MPa, while the CM-monolithic file model showed stress value 150 MPa, and the R-phase monolithic file model showed stress value 170 MPa. Stress analysis of the dual core file model showed clear migration of stress from the flute edges to the R-phase core, and from the cutting blades to the inner transition zone, this pattern was not present in monolithic NiTi model. (Fig. 5,6)

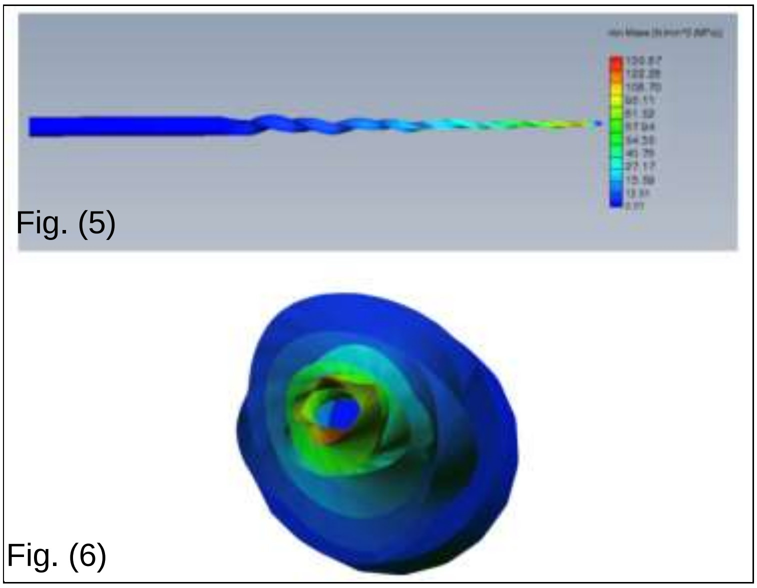

Fig. (5,6): Showing Stress Distribution in Dual-Core File Model During Torsional Test.

4. DISCUSSION

Rotary endodontic nickel-titanium (NiTi) instruments are widely used in root canal cleaning and shaping due to their superior flexibility, cutting efficiency, and ability for navigating the complex and curved anatomy of root canals, allowing for removal of debris and infected tissue (Galal M. et al 2025; Ismail et al 2025).

The present study evaluated the mechanical behavior of a newly engineered rotary file system that incorporates a dual-core hybrid NiTi architecture while maintaining unchanged external geometry previously tested (Galal M. et al 2025). This approach allowed the isolation of internal metallurgical influence on bending flexibility, torsional resistance, and stress redistribution. The results clearly demonstrated that layered internal engineering offers substantial improvements over conventional monolithic NiTi designs.

4.1. Biomechanical Significance of Dual-Core Engineering

The majority of modern NiTi innovations focus on heat treatment (CM-wire, M-wire, Blue, Gold), surface modifications, kinematic variations, or external geometry. Conventional NiTi rotary instruments are manufactured as solid, single-phase, monolithic structures. Thus, all stresses generated during canal shaping must be absorbed by the same homogenous material. The current novel hybrid-core concept introduced in this study fundamentally changed this stress pathway and differs from all commercially available heat-treated files because two metallurgical behaviors coexist in the same instrument. The dual-core file design as the CM-NiTi outer shell provided low stiffness, enabling the instrument to flex and conform to canal curvature with reduced bending fatigue, the R-phase inner core with its superior superelastic behavior, absorbed and redistributed the accumulated stress, while the transition zone prevented interfacial discontinuities that could lead to stress amplification and act as a smoother load transfer area. This multilayered configuration resembled composite materials used in engineering fields. This is a conceptual breakthrough that aligns more closely with biomaterials engineering principles where energy absorption is optimized by layering materials with different mechanical properties than did the traditional endodontic file manufacturing.

Computational modeling has emerged as a promising approach for assessing rotary instrument fatigue. Analytical methods based on stress– strain theory and elasticity principles can be applied to simulate and predict the mechanical behavior of rotary files under various stresses (Chien et al 2021; Gharechahi et al 2023). The finite element analysis (FEA) technique, in particular, has been shown to effectively replicate the results obtained from experimental tests on rotary instruments (Ismail et al 2020). Several studies have demonstrated the capability of FEA to model the performance of these files accurately, providing valuable insights into their behavior and potential points of failure under different loading conditions. This approach allows for a more efficient and cost-effective evaluation of rotary instruments compared to traditional physical testing (Faus-Llácer et al. 2021; Roda-Casanova et al. 2021; Omar et al. 2019; Rahmatian et al. 2023; Morales et al. 2024).

Finite element mapping revealed critical differences in stress analysis between monolithic and dual-core file designs. When bending test was performed the dual-core NiTi file model showed the least amount of Von Misess stresses than did the traditional single phase NiTi file models either with CM-NiTi or R-phase alloys. The stresses distribution in the monolithic models were concentrated at the cutting edges, the flute base, and the transition between apical and middle segments. These areas typically served as the origin of bending-related fatigue cracks. In contrast, dual-core file model exhibited reduced peak in the Von Mises stresses at cutting edges, smoother gradient transitions in the stresses between high- and low-stress regions, and migration of stress internally into the R-phase core.

Under torsional loading, conventional single layer file designs either with CM-NiTi or R-phase Niti experienced more Von Misses stresses values, higher shear concentration at the apical 3–4 mm, and abrupt failure when the elastic limit was exceeded. While in the dual-core file the R-phase core dissipated torsional stresses before they reached critical thresholds that cause torsional failure and fracture of the file. The CM-NiTi external shell absorb stresses under torsional strain, delaying the file failure and leading to less Von Misses Values. This produced an improvement in torsional resistance in the dual core file design.

The clinical relevance of these findings enhanced safety in severely curved canals as the greater flexibility allows safer negotiations of abrupt apical curvatures. Also, it improved the mechanical performance during torsional loading when the file tip binds in narrow or irregular canals, the R-phase core absorbs torsional load which reduces the likelihood of instrument separation especially in complex molar anatomy. The eccentric external design, combined with a compliant outer CM shell and a R-phase core, minimizes self-threading forces and enhances safety during root canal shaping.

The success of the new dual-core system suggests new avenues for next-generation endodontic instruments as the multi-layer cores with gradient thermal treatments could allow adaptive mechanical performance along the file length. It could be associated with more variable core geometry to adjust the internal core thickness segmentally to match expected stress zones. Also, the integration with reciprocating or adaptive motion could act as a shock-absorbing property may synergize with new metallurgical patterns. Thus, the present design represents a foundational step toward a new class of endodontic instruments defined more by internal engineering than by external geometry alone.

5. CONCLUSION

Within the limitations of this study, the dual-core hybrid NiTi rotary file model demonstrated substantial mechanical advantages compared to traditional monolithic designs. This internal engineering transforms the file into a self-protective structure, capable of redistributing, dissipating, and delaying mechanical failure. This differs from all commercially available designs, which rely exclusively on external geometry or heat-treatments but remain structurally monolithic. This concept represents a promising advancement for safer and more durable endodontic rotary instruments. No currently available commercial file incorporates internal dual-phase metallurgical engineering. Therefore, this study represents a novel technological direction for next-generation rotary instruments.

5.1. Future Directions

The findings of this study support a major conceptual shift from geometry-driven design toward material-driven architecture. Future rotary files may incorporate triphasic cores, multi-directional reinforcement, and AI-optimized internal stress-routing designs. The dual-core hybrid model introduced here lays the foundational scientific rationale for this new generation. Several areas require deeper exploration as creating advanced metallurgical architectures require advanced fabrication techniques. Incorporation of dynamic kinematic modifications required further studies that should incorporate adaptive rotary motion or torque-controlled reciprocation.

Declarations: Ethics Approval: Not applicable **Conflict of Interest:** None declared **Funding:** No external funding **Data Availability:** Available upon request

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