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Cyclic Fatigue and Fracture Resistance in Contemporary Rotary File Systems: An Evidence-Based Review

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ABSTRACT

Nickel-titanium (NiTi) rotary endodontic instruments have revolutionized root canal treatment. However, their clinical performance can be influenced by various factors, including material properties, design modifications, and sterilization techniques. The review explores the impact of material science innovations, such as the development of R-phase NiTi alloys and gold-wire NiTi instruments, on improving flexibility, fatigue resistance, and torsional resistance. Additionally, the significance of design modifications, including triangular cross-sections, variable tapers, S-shaped cross-sections, and modified tip designs, is discussed.The clinical implications of these advancements are highlighted, with a particular focus on cyclic fatigue resistance in curved canals Cyclic fatigue and fracture resistance are critical factors influencing the clinical success of rotary file systems in endodontics. Recent advancements, including heat-treated NiTi alloys, innovative designs, and surface modifications, have significantly improved these properties. This review provides an evidence-based analysis of these advancements and their implications for clinical practice.

INTRODUCTION

Root canal therapy aims to remove infected pulp and prevent reinfection by sealing the root canal space. Chemo-mechanical preparation significantly reduces microorganisms in the root canal, but despite good treatment, microorganisms can still survive in lateral canals and apical branches, leading to endodontic failure. Rotary endodontic files are indispensable tools in modern dentistry, enabling predictable root canal shaping[1,2]. However, their fracture during use, primarily due to cyclic fatigue, poses a significant challenge. . Nickel-titanium (NiTi) endodontic rotary instruments have improved mechanical preparation, allowing for more effective cleaning and shaping of

the root canal system. Despite their effectiveness in promoting postendodontic healing, both groups have similar favorable outcomes and survival rates after an extended 5-year monitoring period[3,4].
Advancements in recent years include thermal treatment of NiTi alloys, new NiTi alloys, new movements to instrumentation systems, and innovations in instrument design. Changes in the martensitic phase of NiTi alloy and reduced tendency of the file to straighten during use result in a more flexible file with greater resistance to torsional fracture and cyclic fatigue. Cyclic fatigue occurs when repeated flexural stress leads to crack initiation and propagation. This review examines material advancements, design innovations, and clinical outcomes to address these challenges [5,6].
Fracturing instruments in the canal system remains a major concern and complications during endodontics. The constant evolution of mechanical instrumentation systems requires continuous evaluation to determine improvements. File fractures are an unwanted factor that negatively affects root canal treatment and are difficult to solve. The polar moment of inertia is a crucial factor in determining torsional resistance of rotary instruments over metal mass and cross-sectional area[7,8].

Advancements in material science and design modifications

The advancements in material science and design modifications that have significantly improved the performance of NiTi rotary endodontic instruments. Conventional NiTi alloys, while flexible and shape memory, have limitations in terms of fatigue resistance. Newer NiTi alloys with enhanced phase transformation properties have improved durability and resistance to cyclic fatigue. Additionally, R-phase NiTi alloys offer better flexibility in complex canal anatomies.[9] Gold-wire NiTi instruments further enhance flexibility and reduce the risk of instrument separation.**(Table1)**In terms of design modifications, triangular cross-sections reduce core mass and increase flexibility, leading to improved maneuverability. Variable tapers ensure even stress distribution and enhanced durability. S-shaped cross-sections increase cutting efficiency, resulting in faster preparation times. Finally, modified tip designs reduce canal wall engagement and torsional stress, minimizing the risk of instrument fracture.[10-12]

Table1 The advancements in material science and design modifications[6,8,10,12]

Material Science Innovation	**Design Modification**	**Clinical Implications**
NiTi Materials		
Conventional NiTi	- Martensitic and austenitic phases	- Flexibility, shape memory
NiTi with Enhanced Phase Transformation	- Increased cyclic fatigue resistance	- Improved durability
R-phase NiTi	- Martensitic transformation at lower temperatures	- Better flexibility in complex canals
Gold-wire NiTi	- Enhanced flexibility and fatigue resistance	- Lower risk of instrument separation
Design Modifications		
Triangular Cross-section	- Reduced core mass, increased flexibility	- Improved maneuverability
Variable Taper	- Even stress distribution	- Improved durability
S-shaped Cross-section	- Increased cutting efficiency	- Faster preparation
Modified Tip Design	- Reduced canal wall engagement, less torsional stress	- Reduced risk of instrument fracture

Cyclic fatigue resistance

The cyclic fatigue resistance of four different rotary endodontic instrument systems: WaveOne Gold, ProTaper Next, Reciproc Blue, and TruNatomy depicted in **(Table2)** Cyclic fatigue resistance is a crucial factor in determining the longevity and reliability of endodontic instruments, especially in curved canals.
As shown in the **Table2** , TruNatomy demonstrated the highest cyclic fatigue resistance with 1300 cycles to failure. This suggests that TruNatomy instruments are more resistant to fracture in curved canals, potentially reducing the risk of instrument separation and increasing clinical efficiency[9,10,11]. WaveOne Gold exhibited the second-highest resistance with 1200 cycles, followed by Reciproc Blue with 1100 cycles. ProTaper Next showed the lowest resistance among the four systems, with 950 cycles to failure. Cyclic fatigue resistance, a critical factor in determining instrument longevity and clinical success, has been extensively studied[12,13].

Table2 Cyclic fatigue resistance of four different rotary endodontic instrument systems

WaveOne Gold	1200 cycles	Higher resistance to fracture
ProTaper Next	950 cycles	Lower resistance to fracture compared to WaveOne Gold
Reciproc Blue	1100 cycles	Moderate resistance to fracture
TruNatomy	1300 cycles	Highest resistance to fracture

Case studies & Discussion

Micro-computed tomography (μCT) is widely used for evaluating shaped root canals in two- and three-dimensional (2D, 3D) formats due to its noninvasiveness, repeatability, and high accuracy. Scanning electron microscopy (SEM) is commonly used for assessing fracture resistance and topographic profiles.
Al-Amidi AH et al[7] aimed to compare the cyclic fatigue resistance of EdgeFile X7, 2Shape, and F-One files in a curved simulated canal before and after autoclave sterilization. The results showed that EdgeFile X7 was the most fatigue-resistant file, while autoclaving significantly decreased its resistance. The study also found that the number of cycles to fracture (NCF) of the tested files was higher in nonsterilized instruments, and the NCF of 2Shape was lower in sterilized and nonsterilized groups.
Drukteinis S[8] et al investigates the shaping and centering ability of HyFlex CM, HyFlex EDM, and EdgeFile thermally treated nickel-titanium endodontic instrument systems. Sixty curved root canals were shaped using these systems, and μCT scanning was performed. The instruments were subjected to cyclic fatigue resistance tests at 37°C until fractures occurred. Fractured fragments were not significantly different between the groups, and fractographic analysis by SEM detected typical topographic features of separated thermally treated NiTi

instrument surfaces. Understanding these clinically important behavioral features is crucial for clinical endodontics.

The study done by Sobral TKM [9]compared the fatigue resistance of heat-treated reciprocating instruments in a dynamic cyclic fatigue model. The instruments were divided into 12 groups: X1 Blue, Pro-R, Reciproc, and Reciproc Blue. The results showed that Pro-R and Reciproc Blue instruments had the highest fatigue resistance, while Reciproc had intermediate results. The fractographic analysis showed typical cyclic fatigue features for all instruments.

In addition to the methodology used to perform the cyclic fatigue tests, the resistance of NiTi endodontic instruments can be influenced by several factors such as diameter, kinematics, taper, cross-section, and type of alloy.The studies reviewed(**Table 3)** provide valuable insights into the factors affecting the cyclic fatigue resistance of NiTi rotary instruments[14-23]. Several key findings emerge:

- **Material and Design:** The material composition and design of NiTi instruments significantly influence their fatigue resistance. Newer generations of NiTi alloys, such as those used in HyFlex EDM and WaveOne Gold, often exhibit enhanced flexibility and fatigue resistance compared to older generations.
- **Sterilization:** Autoclave sterilization can have a positive impact on the fatigue resistance of some instruments, particularly those with newer alloy compositions.
- **Disinfectant Solutions:** Immersion in certain disinfectants, such as NaOCl, can negatively affect the fatigue resistance of NiTi instruments.
- **Temperature:** Elevated temperatures, such as body temperature, can reduce the fatigue resistance of NiTi instruments.
- **Irrigation Solutions:** The type of irrigation solution used during endodontic procedures may also influence the fatigue resistance of instruments.
- **Canal Curvature:** The degree of canal curvature and the radius of curvature can significantly impact the fatigue resistance of instruments. Instruments with greater flexibility and resistance to torsional stress tend to perform better in curved canals.

Dentists should consider factors such as the specific clinical scenario, patient anatomy, and instrument design when selecting rotary instruments to optimize treatment outcomes and minimize the risk of instrument fracture.

Table 3 Cyclic Fatigue Resistance of Nickel-Titanium Rotary Instruments: A Summary of Research[14-23]

Study Author(s)	Year	Sample Size	Instruments Tested	Testing Conditions	Primary Outcome	Key Findings
Gündoğar et al.[14]	2019	180	Reciproc Blue, HyFlex EDM, WaveOne Gold, Twisted File Adaptive	Room temperature (20°C) vs. body temperature (35°C) in air and water	Cyclic fatigue resistance	Fatigue resistance decreased with increasing temperature and in air compared to water.
Oh et al.[15]	2020	120	WaveOne Gold, Reciproc Blue, HyFlex EDM	Bending resistance and cyclic fatigue at room temperature and body temperature	Bending resistance and cyclic fatigue resistance	HyFlex EDM showed superior flexibility and fatigue resistance at body temperature.
Nino-Barrera et al.[16]	2021	40	Conventional NiTi files	Shot peening vs. no treatment	Cyclic fatigue resistance	Shot peening increased resistance to fatigue fracture.
Furlan et al.[17]	2021	140	GN, TS, LOG, VB, PTG, HCM, EDM	Cyclic and torsional fatigue testing	Cyclic and torsional fatigue resistance	EDM had highest cyclic fatigue resistance, PTG had highest torsional strength.
Al-Obaida et al.[18]	2022	40	WaveOne, Reciproc, Protaper F2, Unicone	Cyclic flexural fatigue testing	Cyclic flexural fatigue resistance	WaveOne had highest fatigue resistance, Unicone had lowest.
Alasvand Javadi et al.[19]	2023	90	M3 Pro Gold, SP1	Immersion in NaOCl, Deconex, or no immersion	Cyclic fatigue resistance	Disinfectant solution and file type significantly affect fatigue resistance.
Stošić et al.[20]	2023	384	ProTaper Universal, BioRace, ProTaper Next, Twisted File, HyFlex CM	Autoclave sterilization cycles (0, 1, 3, 5)	Cyclic fatigue resistance (NCF)	Newer instruments showed increased fatigue resistance after sterilization.
Alsunboli et al.[21]	2024	42	Edge File, Fanta File	Irrigation with NaOCl, Glycine, EDTA	Cyclic fatigue resistance	Irrigation solution affects fatigue resistance.
Singh et al.[22]	2024	100	2Shape, Trunatomy, ProTaper Gold, Hyflex CM, Hyflex EDM	Cone beam CT analysis	Canal shaping ability	Trunatomy showed better centering ability, less canal transportation, and less dentin removal.
Youssef et al.[23]	2024	90	OneShape, WaveOne, WaveOne Gold	Body temperature (37°C) vs. room temperature (20°C)	Cyclic fatigue resistance	All files showed lower fatigue resistance at body temperature.

Cyclic fatigue resistance is a critical factor in the performance of endodontic instruments, with rotary instruments being more susceptible to fractures. Factors such as file dimensions, root canal curvature angle, operator experience, torque, and rotation speed also influence this resistance. Cyclic fatigue is a significant cause of fractures in postgraduate students and is more common in larger sizes. The speed of rotation during reciprocating motion is not constant, resulting in less tension on the instrument, providing greater cyclic fatigue resistance[24,25].

The influence of file design on cyclic fatigue resistance is controversial, with some authors suggesting that the file cross-section affects its half-life and strength. However, the single use of reciprocating files reduces the risk of accumulating fatigue in the metal. The number of cycles to fracture (NCF) is a measure of the degeneration process in endodontic files when subjected to cyclical loads within the tooth root canal. The number of cycles performed is related to the tension generated by compression and traction forces in the curved part of the instrument during instrumentation [23,26]. To calculate the number of cycles to fracture, multiply the time (in seconds) to failure by the number of rotations, regardless of the direction of rotation [27] Reciproc files have better cyclic fatigue resistance than rotary files, with a statistically significant difference when measured in NCF. This is due to the use of reciprocating motion, which increases fatigue resistance compared to continuous rotation and extends the life of the NiTi instrument. Martensitic NiTi files are more resistant to cyclic fatigue at body and room temperature [28].

Heat treatments of NiTi alloys influence martensitic/austenitic transformation behavior, increasing cyclic fatigue resistance and durability. New generation files have higher austenitic finish temperatures than traditional NiTi rotary files, with Reciproc Blue and Wave One Gold having higher Af temperatures at body and above. Differential scanning calorimetry analysis supports the idea that heat-treated files have higher cyclic fatigue resistance than traditional NiTi rotary files[29,30].

Selventhra et al. [31] analysed the effect of body temperature on the cyclic fatigue strength of Ni-Ti alloy instruments. Twenty-one studies were included, six of which underwent a meta-analysis with comparative study parameters analysing the distortion effect of heat-treated Ni-Ti files at room and body temperatures with continuous and reciprocating motion. The conclusions showed that the cyclic fatigue strength of heat-treated instruments decreases at body temperature compared to room temperature. Therefore, tests on these instruments should be performed at a temperature simulating the endodontic space, The study by plotino et al [32]compared the cyclic fatigue resistance of blue heat-treated RACE EVO files with heat-treated files like Vortex Blue, ProTaper gold, and HyFlex EDM. The results showed that HyFlex EDM had the highest resistance, followed by Vortex Blue, PTG, and RACE EVO. RACE EVO, an improved generation of RaCe, showed greater resistance to cyclic fatigue compared to traditional RaCe. This enhanced resistance can be attributed to the thermal heating-cooling treatment process, which created a Blue titanium oxide layer on the file's surface, resulting in improved flexibility. This process also influenced the crystallographic state by high austenite transformation finish temperature, ensuring the file remained in the martensitic phase at body temperature. Khandagale et al.[33] demonstrated greater cyclic fatigue resistance of HyFlex EDM compared to PTG. Uygun et al.[34] showed Hyfelx EDM performed better than PTG, but not significantly different from PTG and Vortex Blue. Vortex Blue showed significantly higher NCF compared to One Curve, 2shape, Profile Vortex, and RaCe rotary instruments.

A study by Srikumar GPV et al [35]aimed to evaluate the cyclic fatigue resistance (CFR) of rotary and reciprocating file systems in simulated canals with 45°, 60°, and 90° angles of curvature. Sixty nickel-titanium files were divided into four groups: Neoendo Flex, ProTaper Next, WaveOne Gold (WOG), and Reciproc Blue (RPB). Each file was tested for CFR using a torque-controlled reduction handpiece and repeated until the fracture occurred. The results showed a statistically significant difference between the four groups, with WOG and RPB reciprocating file systems showing superior CFR, especially in canals with abrupt 90° angles. Neoendo Flex showed greater CFR than ProTaper Next among the tested rotary file systems.

The systematic review of 25 in vitro studies[36] on cyclic fatigue resistance of rotary glide path files in endodontic applications found that continuous rotation resulted in significantly higher resistance. The study also found that the cyclic fatigue resistance of rotary GP files may be influenced by intrinsic factors like taper, cross-sectional design, alloy properties, kinematics, and external factors like the curvature and radius of the file, irrigation or lubricant used, and temperature.

CONCLUSION

The advancements in NiTi rotary instrument technology have significantly improved endodontic treatment outcomes. However, there is still a need for further research to optimize their performance and minimize the risk of instrument fracture.

Future Directions

Novel Material Development: Research into innovative NiTi alloys with enhanced mechanical properties and resistance to fatigue could lead to the development of even more durable instruments.

Advanced Manufacturing Techniques: Exploring advanced manufacturing techniques, such as selective laser melting, could allow for the creation of instruments with complex geometries and optimized properties.

In Vivo Studies: Conducting clinical trials to assess the long-term performance of NiTi instruments under real-world conditions is crucial.

Real-Time Monitoring: Developing real-time monitoring systems to track instrument performance during root canal treatment could help identify potential issues early on.

Artificial Intelligence: Utilizing AI to analyze large datasets of clinical and laboratory data could provide valuable insights into instrument performance and optimize treatment protocols.

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