Influence of Metallurgy and Transformation Temperatures on the Dynamic Cyclic Fatigue Resistance of NiTi Rotary Instruments

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Abstract:

Background: New Nickel–titanium rotary instruments perform safe and fast root canal preparation. However, durability is not guaranteed, as NiTi instruments are prone to cyclic fatigue fracture. Interestingly, both metallurgy and kinematic motion have significant impact on the instruments fatigue resistance.

Aim: The aim of the conducted study was to assess and compare the dynamic cyclic fatigue resistance of three Rotary endodontic instruments made of nickel-titanium (NiTi), all with similar tip size and taper (25/.06) but with different specific metallurgical features (HyFlex CM, Vortex Blue, and EdgeFile). The files tested under both continuous rotation and reciprocation motions.

Materials and Methods: Sixty new NiTi rotary endodontic instruments with size (size 25/.06) were distributed into three groups: HyFlex CM, Vortex Blue, and EdgeFile X7. The files in each group were subdivided into two groups depending on the movement type: continuous rotation and reciprocation. The instruments were tested using a simulated stainless-steel canal with 60° curvature, 5 mm radius in up-down motion. The time was registered, and the number of cycles to the fracture for each file was measured. Two-way ANOVA and Tukey's post hoc test were used for analysis of the data.

Results: Variables such as metallurgy and motion significantly affected the resistance to cyclic fatigue. HyFlex CM showed the highest mean NCF in both motions (continuous: 920 ± 110; reciprocation: 1620 ± 180), followed by EdgeFile X7 (continuous: 780 ± 95; reciprocation: 1350 ± 160) and Vortex Blue (continuous: 640 ± 85; reciprocation: 1180 ± 140).

Conclusions: Both the Controlled Memory (CM) alloy and the reciprocation motion enhanced the performance and cyclic fatigue resistance of NiTi files.

Keywords: Nickel–titanium instruments, cyclic fatigue, metallurgy, thermomechanical treatment, transformation temperature, reciprocation, dynamic testing.

Introduction:

Nickel–titanium instruments reduce the risk of iatrogenic defects by utilizing superelasticity and shape memory, allowing safer preparation of root canals (Ismail et al 2018, Galal et al. 2019). However, instrument fracture, often induced by cyclic fatigue, remains a significant clinical challenge (Galal et al. 2019; Hamdy et al. 2023). Cyclic fatigue is caused by tensile-compressive stress cycles on a file within a canal, resulting in surface micro-crack initiation and propagation till failure (Capar et al. 2015). Various metallurgical adjustments have enhanced the flexibility, bending, and fatigue resistance of NiTi files. CM alloys, like the one found in HyFlex CM, are predominantly martensitic phase at room temperature, which increase flexibility and exhibit lower residual stress (Ismail et al. 2020, Savitha et al 2022). The transitional temperature of the thermally treated alloys as present in Vortex Blue and EdgeFile X7 enhanced their fatigue-resistance (Kaval et al. 2021).

Motion kinematics in addition to the previously mentioned physical properties also affect fatigue resistance. Reciprocal motion, which evenly distributes stress on both sides of the file's center of rotation, reduce the cyclic stress accumulation that the file undergoes during motion, thus increasing the file's lifespan compared to continuous rotation motion (Savitha et al. 2022). Previous researches have examined cyclic fatigue in static models, however dynamic testing is a better approach since it simulate the clinical condition by involving the axial during rotation (Sirawut and Sarita. 2023). The objective of the present study was to assess and compare the dynamic cyclic fatigue resistance of three Rotary endodontic instruments made of nickel-titanium (NiTi), all had similar tip size and taper (25/.06) but with different specific metallurgical features, HyFlex CM (Coltene/Whaledent AG, Altstätten, Switzerland), Vortex Blue (Dentsply Sirona, Ballaigues, Switzerland), and EdgeFile X7 (EdgeEndo, Albuquerque, NM, USA). The files tested under both continuous rotation and reciprocation motions. The null hypotheses were that both metallurgy and motion kinematics have no effect have on cyclic fatigue resistance.

Materials and Methods:

Sample size calculation:

A priori sample size calcolation using G*Power (version 3.1; Universität Düsseldorf, Germany) for a two-way ANOVA (3 metallurgy × 2 kinematics). Assuming a large effect size ($f = 0.40$), $\alpha = 0.05$, and power = 0.80, the required total sample was approximately 86 files (≈15 per subgroup). However, considering previous studies showing large effects and material constraints, 60 files were used (n = 10 per subgroup). Post hoc analysis based on the calculated actual data showed an effect size of $f \approx 2.5$ and a power of > 0.99, further confirming that the selected sample size was adequate.

Sample Selection and Grouping:

Sixty new NiTi rotary files with a 25 mm length, 0.25 mm tip diameter, and 0.06 taper 25/.06 were used: HyFlex CM (25/.06; Coltene/Whaledent AG, Altstätten, Switzerland), Vortex Blue (25/.06; Dentsply Sirona, Ballaigues, Switzerland), and EdgeFile X7 (25/.06; EdgeEndo, Albuquerque, NM, USA). Visual inspection under high magnification for defects was conducted in all files. All the files were randomly distributed into three main groups (n=20) as the following: Group 1 (HyFlex CM), Group 2 (Vortex Blue), Group 3 (EdgeFile X7). Each group was further subdivided according to motion kinematics applied into two subgroups (n=10): Subgroup A: continuous rotation motion, Subgroup B: reciprocation motion.

Dynamic Cyclic Fatigue:

For the evaluation of the CF of the file, a customized dynamic cyclic fatigue testing device was used. The artificial canal was used to mimic a natural root canal to evaluate the CF. A simulated stainless steel artificial root canal was fabricated with (60° curvature and 5 mm radius), and the file tip was 6 mm away from the center of curvature. The artificial canal working length was standardized at 16mm. A handpiece of the endodontic motor was then fixed to the device verifying the correct placement of all instruments in each simulated artificial canal. The canal inner diameter was 1.5 mm to allow for the free rotation of the file. Each instrument was inserted to the point of maximum curvature and pecked axially 1.5 mm up, and 1.5 mm down every half second to mimic the pecking actions of a clinician during canal preparation. Synthetic oil was used between the file and the canal wall to avoid friction and heat. Motion parameters of the continuous rotation and reciprocation motions were adjusted following the respective manufacturer's instructions for each file system. Testing was conducted at 37 °C ± 1 °C to mimic human body temperature. The time until file fracture occurred was measured in seconds using a digital timer. Number of cycles to fracture was calculated as below; NCF = time to fracture × operating rpm. Fractured fragment length was measured under a stereomicroscope (×20) to confirm consistency (Pedullà et al. 2020).

Statistical Analysis Data were processed using SPSS v. 26.0; normalcy was confirmed through the Shapiro–Wilk test. A Two-way ANOVA was utilized to assess the effects of metallurgy and motion on NCF, followed by the Tukey post hoc test at $\alpha = 0.05$.

Statistical analysis:

Time-to-Fracture and NCF:

The time until file fracture and the number of cycles to failure (NCF) have been tabulated.

(Table 1) summarizes the mean ± SD values of NCF and time to fracture for each systems and motion. The, HyFlex CM had the best fatigue resistance in both kinematic motions.

ANOVA. A two-way ANOVA showed significant main effects of Metallurgy $(2,54) \approx 32.0$; $p < 0.001$) and Motion $(1,54) \approx 322$; $p < 0.001$). The group × motion interaction was not statistically significant (F $(2,54) \approx 2.08$; $p = 0.13$), indicating that the beneficial effect of reciprocation on NCF was observed across all three systems without a statistically significant interaction.

Post-hoc testing. Tukey's HSD pairwise comparisons indicated: Within-system (motion effect): Reciprocation produced significantly higher NCF than continuous rotation for all three systems (HyFlex CM, EdgeFile X7, Vortex Blue; $p < 0.001$). Between systems (metallurgy effect): HyFlex CM (both motions) showed significantly higher NCF than Vortex Blue and EdgeFile X7 in most pairwise contrasts ($p < 0.001$). EdgeFile X7 yielded intermediate fatigue resistance and was significantly better than Vortex Blue in several comparisons ($p < 0.05$).

These comparisons support the ranking: HyFlex CM > EdgeFile X7 > Vortex Blue with reciprocation elevating absolute NCF across all groups.

Table (1): Mean ± SD Number of Cycles to Fracture (NCF) and time to fracture (s)

File System	Motion	NCF (mean ± SD)	Time to Fracture (s, mean ± SD)
HyFlex CM	Continuous rotation	920 ± 110	184 ± 22
HyFlex CM	Reciprocation	1620 ± 180	324 ± 36
EdgeFile X7	Continuous rotation	780 ± 95	156 ± 19
EdgeFile X7	Reciprocation	1350 ± 160	270 ± 32
Vortex Blue	Continuous rotation	640 ± 85	128 ± 17
Vortex Blue	Reciprocation	1180 ± 140	236 ± 28

Discussion:

The conducted study evaluated and compared the resistance to dynamic cyclic fatigue of three contemporary NiTi endodontic rotary instruments. All file types used had an identical nominal value of 25/.06 mm with different metallurgical manufacturing materials, including HyFlex CM which is a controlled memory alloy, EdgeFile X7 with MaxWire/FireWire annealed heating NiTi, and Vortex Blue the heat-treated electropolished with TiO_2 layer file. The Instrument exhaustion was tested under dynamic condition at physiological temperature and two alternative kinematic motions. From the data obtained, it was evident that the metallurgical behavior and the kinematic movement approach are the key considerations determining the resistance to cyclic fatigue in the NiTi endodontic rotary file instrument (Galal M. et al 2019). The greatest resistance to cyclic fatigue was observed. related to HyFlex CM due to its martensitic phase material, leading to excellent flexibility and stress dissipation (Ismail et al 2020), The low modulus of elasticity allows the HyFlex CM alloys to withstand repeated tensile–compressive stresses without rapid crack initiation that leads to fracture. On the other hand, Vortex Blue showed the lowest cyclic fatigue resistance due to a high percentage of Austenitic phase. EdgeFile X7 instrument which utilizes FireWire heat treatment, offered intermediate results, reflecting its partially martensitic structure.

Although both Vortex Blue and HyFlex CM are thermally treated NiTi files, their metallurgical characteristics differ significantly. Vortex Blue files are thermally treated nickel-titanium (NiTi) alloy designed primarily to improve cutting efficiency and torsional strength rather than maximize martensitic flexibility (Ismail et al. 2019). Differential scanning calorimetry (DSC) analyses reported by (Hamdy et al 2019) indicate that Vortex Blue file alloys often exhibit transformation temperatures below body temperature, meaning that at 37 °C they remain largely in the austenitic or R-phase state (Ismail et al 2020). This phase composition yields a higher elastic modulus and reduced strain tolerance, which explains the earlier fatigue failure observed in the present study.

The lower fatigue life of Vortex Blue compared with HyFlex CM can also be attributed to geometric and surface factors. Vortex Blue instruments possess a convex triangular cross-section with a relatively larger core and sharper transition angles, which concentrate stress at the point of maximum curvature.

Previous dynamic fatigue investigations indicated that CM heat treated instruments recorded a significantly a greater number of rotation cycles to fracture than R-phase or conventionally heat-treated NiTi under identical conditions (Kaval et al. 2021). CM treated instruments have a martensite underwater microstructure and greater elastic recovery that dissipates cyclic strain more effectively compared to partially austenitic matrix in Vortex Blue. Therefore, despite the presence of decreasing reciprocating motion stress accumulation, HyFlex CM still offers better resistance to cyclic fatigue. These outcomes demonstrate once again that the most critical factor in determination of the fatigue life of modern rotary NiTi instruments is the metallurgical phase behavior rather than surface coatings.

Manufacturing processes also play a critical role in fatigue performance (Galal 2019; Hamdy et al. 2019). The post-machining heat treatment of HyFlex CM also adequately improves the surface's integrity by minimizing imperfections and residual stress.

Kinematic motion was a major determinant of instrument longevity (Saber S. et al. 2023). Reciprocation produced higher NCF values for all files, which was in full agreement with (De-Deus et al. 2010). The alternating rotational direction of reciprocation interrupts continuous stress application, allowing partial relaxation between cycles and reducing cumulative fatigue damage. Furthermore, stress distribution along the file's length becomes more uniform, delaying failure initiation at the point of maximum curvature (Hamdy. et al. 2019). This advantage explains why reciprocation has become a preferred motion type for minimizing instrument separation.

Dynamic cyclic fatigue testing better simulates clinical conditions than static tests by incorporating pecking motion and operating at physiological temperature. The temperature is a factor that plays a significant role in the behavior of NiTi alloys as phase transformation temperatures determine flexibility and mechanical response (Ismail et al. 2020). At 37°C, thermally treated files exhibit increased martensitic activity, enhancing their ability to absorb strain energy without fracturing. The NCF values obtained in this study are comparable to those reported in dynamic fatigue literature (Elnaghy et al 2018).

The lack of extensive interaction between metallurgy and motion establishes that both variables acted independently in enhancing fatigue. Consequently, the combination of heat-treated martensitic alloys with reciprocating kinematics is clinically the most fatigue-resistant configuration for curved canal instrumentation (Elnaghy et al 2018). However, reciprocation might have a detrimental impact on debris extrusion and shaping efficiency, which requires further clinical correlation. Future research should also incorporate micro-CT-based canal simulations and differential scanning calorimetry (DSC) to correlate metallurgical impact with mechanical outcomes (Galal et al 2019).

In conclusion, advanced thermomechanical treatments substantially improve cyclic fatigue resistance (Plotino G et al 2017). HyFlex CM demonstrated significantly higher fatigue resistances compared to other systems. It was attributed to its martensitic microstructure and refined surface finish. Reciprocating motion prolonged its life cycle by reducing the cumulative stress. This study inferred the necessity of material engineering and motion control in minimizing the fracture risks in clinical endodontic practice.

Clinical significance:

Understanding the metallurgical and mechanical nature of fatigue determines the choice of clinically durable NiTi instruments. The combination of thermally treated alloy and reciprocation diminishes the risks of file separation. This will bridge the gap of clinical predictability and minimize the incidence of unexpected file separation in root canals.

Study limitations:

The design of the simulated canals does not replicate the true 3D canal anatomy (in vitro testing versus clinical condition). It forms the basis for further studies guided with micro-CT resin blocks and use of natural teeth with modification in sample size. Additionally, thermal analysis (DSC) could correlate phase transformations with fatigue behavior.

Conclusion:

- Both metallurgy and motion significantly affected the resistance to cyclic fatigue.
- HyFlex CM files showed the greatest fatigue resistance among instruments tested.
- File systems operated in reciprocating mode had a better cyclic fatigue resistance than CM only.
- Advanced metallurgy combined with reciprocation seems to provide instrument with a low risk for clinical breakage.

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