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Comparative cyclic fatigue resistance of heat-Treated rotary nickel–Titanium systems in curved canals: An *in vitro* study

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Abstract:
Cyclic fatigue–related instrument separation remains a major concern during rotary nickel–titanium instrumentation of curved canals, prompting advances in alloy processing and heat treatment to improve fatigue resistance. Therefore, it is of interest to compare the cyclic fatigue resistance of Flexicon X3, Hyflex CM and Mtwo instruments in simulated canals with 60° and 90° curvatures. Hence, sixty instruments (ISO size 25, 0.06 taper, 25 mm length) were divided into three groups of 20 and tested using a dynamic fatigue model in stainless-steel canals at manufacturer-recommended speed and torque; time to fracture was recorded, the number of cycles to failure was calculated and data were analysed using two-way ANOVA followed by Tukey post-hoc tests at a significance level of $p < 0.05$. Flexicon X3 presented the highest cyclic fatigue resistance in both curvatures, followed by Hyflex CM and Mtwo. Significant differences were found between the groups ($p < 0.05$), but no significant effect of canal curvature was found. Thus, the Flexicon X3 showed higher cyclic fatigue resistance, indicating that the annealed heat treatment and metallurgical properties may improve the performance of this instrument in curved canals.

Keywords: Cyclic fatigue, resistance, instrument separation, endodontic instrumentation, nickel–titanium rotary instruments

Background:
Over the decades, the field of endodontics has witnessed substantial breakthroughs due to advancements in root canal instrumentation. Procedural errors such as ledging and canal transportation had been the major drawbacks of rigid stainless steel instruments which were used initially **[1]**. To counter this, NiTi instruments were introduced which improved the efficiency and predictability of root canal instrumentation by providing greater flexibility, improved canal centering and reduced iatrogenic damage **[2]**. Apart from these advantages, particularly in curved canals, NiTi rotary instruments were prone to fracture, primarily due to cyclic and torsional fatigue that occurred when instruments were subjected to repeated tension–compression cycles at the point of maximum canal curvature **[3]**. These limitations were addressed by advancements in alloy processing and heat treatment. Instruments such as Mtwo, Hyflex CM and Flexicon X3 differed not only in metallurgical properties but also in manufacturing techniques. These factors influence their clinical performance in root canal instrumentation **[4]**. Therefore, it is of interest to compare the cyclic fatigue resistance of Flexicon X3, Hyflex CM and Mtwo rotary NiTi instruments in simulated canals with 60° and 90° curvatures.

Materials and Methodology:
Sample size and study design:
Sixty rotary nickel–titanium instruments categorized into 3 groups were included in this study: Group-1: HyFlex CM (Coltene, Altstatten, Switzerland), Group 2: Mtwo (VDW, Munich, Germany) and Group 3: Flexicon X3 (EdgeEndo, Canada). Each group consisted of 20 rotary instruments standardized to ISO size 25, a 0.06 taper and a length of 25 mm. Based on canal curvature (60° and 90°); each group was further subdivided into two subgroups. To exclude manufacturing defects, all instruments were examined prior to testing under a dental operating microscope. The study protocol was approved from the Institutional Ethics Committee with protocol number. Pr.84/IEC/SIBAR/2016. Artificial stainless-steel canals with a 5-mm radius of curvature, fabricated according to Schneider's method were used for cyclic fatigue testing. An endodontic motor (X-Smart, Dentsply Maillefer) was used at manufacturer-recommended speed and torque for each file system. To reduce friction, synthetic oil was used. Each instrument was allowed to rotate freely till instrument separation and a video camera was used to record time of fracture. From the recorded time and rotational speed, the number of cycles for fracture (NCF) was calculated.

Statistical analysis:
Data were tabulated in Microsoft Excel and analysed using SPSS version 20.0. Overall group differences were assessed by analysis

of variance (ANOVA), followed by Tukey post hoc comparisons for pairwise testing. Statistical significance was set at $p < 0.05$.

Results:

Under the present *in vitro* conditions, Flexicon X3 showed the highest mean time to fracture at both 60° and 90° canal curvatures, followed by HyFlex CM and Mtwo **(Table 1).** The overall analysis indicated a significant instrument-group effect ($p < 0.05$), whereas canal curvature did not show a significant main effect. Tukey-adjusted pairwise comparisons of mean time to fracture did not reach the conventional $p < 0.05$ threshold **(Table 2),** although the comparison between Mtwo and Flexicon X3 was closest to significance in the reported analysis. The results therefore consistently favoured Flexicon X3 numerically, but individual pairwise differences should be interpreted cautiously. **Table 1** interpretation: Ten instruments from each system were tested per curvature. At 60°, mean fracture time was 40.71 s for HyFlex CM (Group 1), 49.28 s for Mtwo (Group 2) and 68.58 s for Flexicon X3 (Group 3); at 90°, the corresponding values were 46.82, 50.10 and 70.34 s. Thus, Flexicon X3 had the longest mean fracture time under both conditions, with Mtwo intermediate and HyFlex CM lowest. Variability was substantial, particularly for HyFlex CM at 90° (SD 31.02 s; CV 66.3%), so the numerical ranking should not be interpreted as statistically significant for every pairwise comparison. Standard errors and coefficients of variation describe precision and relative variability, respectively, rather than independently demonstrating group differences. **Table 2** interpretation: Tukey-adjusted comparisons across the six system-by-curvature subgroups did not demonstrate a statistically significant difference for any displayed pair (all adjusted p values exceeded 0.05). The smallest listed p value was 0.0864 for HyFlex CM at 60° versus Flexicon X3 at 90°, which was still above the prespecified threshold. The within-system comparisons between 60° and 90° also had high adjusted p values, indicating no statistically detectable change in fracture time in this dataset. These post hoc findings should be distinguished from the manuscript's reported omnibus group effect, for which the original ANOVA output should be verified.

Table 1: Mean, standard deviation, standard error and coefficient of variation of time to fracture (seconds) at 60° and 90° canal curvatures for Groups 1, 2 and 3

Groups with degree	N	Mean	SD	SE	CV
60° with Group 1	10	40.71	16	5.1	39.4
60° with Group 2	10	49.28	16.8	5.3	34
60° with Group 3	10	68.58	30.4	9.6	44.3
90° with Group 1	10	46.82	31	9.8	66.3
90° with Group 2	10	50.1	19.8	6.3	39.5
90° with Group 3	10	70.34	27	8.5	38.3

Table 2: Pairwise comparisons of time to fracture (seconds) at 60° and 90° canal curvatures using Tukey's multiple-comparison procedure

Groups with degree	60° with Group 1	60° with Group 2	60° with Group 3	90° with Group 1	90° with Group 2	90° with Group 3
Mean	40.71	49.28	68.58	46.82	50.1	70.34
SD	16.04	16.76	30.4	31.02	19.76	26.96
60° with Group 1 Group 1	-					
60° with Group 2 Group 2	p=0.9682	-				
60° with Group 3 Group 3	p=0.1239	p=0.4894	-			
90° with Group 1 Group 1	p=0.9931	p=0.9999	p=0.3542	-		
90° with Group 2 Group 2	p=0.9534	p=0.9990	p=0.5371	p=0.9997	-	
90° with Group 3 Group 3	p=0.0864	p=0.3911	p=0.9999	p=0.2710	p=0.4356	-

Discussion:

Nickel–titanium rotary instruments may separate because of torsional overload, cyclic fatigue, or a combination of both mechanisms **[5, 6]**. Although clinical separation is uncommon, fracture can occur with limited visible warning and the

probability of deformation or fracture is influenced by instrument design, alloy treatment, canal anatomy and frequency of use **[7]**. Cyclic fatigue develops when a rotating file is repeatedly subjected to alternating tensile and compressive stresses at the point of maximum curvature **[8, 9]**. Dynamic fatigue models, which incorporate axial movement during rotation, more closely approximate the pecking motion used clinically than static models **[10]**; accordingly, the present study used a dynamic model in simulated canals with 60° and 90° curvatures. Across both curvatures, Flexicon X3 showed the longest mean time to fracture, HyFlex CM was intermediate and Mtwo had the shortest mean time. The direction of these findings is biologically plausible because thermomechanical processing modifies the phase transformation behaviour, flexibility and fatigue resistance of NiTi alloys **[3–6]**. Flexicon X3 is an annealed heat-treated system, whereas HyFlex CM uses controlled-memory processing and Mtwo represents a more conventional NiTi design. Heat-treated instruments commonly show improved cyclic fatigue resistance compared with conventional austenitic instruments under standardized laboratory conditions **[11, 12]**. The present results also support the broader observation that the cross-sectional metal mass at the point of maximum curvature and the local instrument diameter influence fatigue life: larger metal volume increases the tensile-compressive strain generated during each rotational cycle **[13, 14]**. The overall group effect was statistically significant, but Tukey-adjusted pairwise comparisons of mean time to fracture were not individually significant at $p < 0.05$. Consequently, the ranking Flexicon X3 > Mtwo > HyFlex CM should be interpreted as a consistent numerical pattern rather than proof that every pair of systems differs under all conditions. The absence of a significant curvature main effect also does not imply that curvature is clinically unimportant; fatigue life generally decreases as curvature becomes more severe, but the magnitude of that effect depends on radius, instrument dimensions, kinematics, speed, torque and the dynamic amplitude of the test. Laboratory fatigue resistance should not be equated directly with clinical separation risk. In clinical use, torsional loading, dentinal engagement, irrigants, sterilization, glide-path preparation, reuse, operator technique and canal anatomy interact with cyclic fatigue. Clinical studies of used NiTi instruments have documented measurable deformation and fracture rates that vary with the number of uses and instrument type **[7]**. Therefore, the present study is most useful for comparing the tested systems under a controlled dynamic-fatigue protocol. Additional studies should use standardized artificial canals, report radius and centre of curvature, evaluate fragment length and metallurgical phase and include clinical or clinically simulated loading before definitive recommendations are made. Comparable laboratory investigations have likewise shown that heat treatment and design can materially affect cyclic-fatigue behavior **[15]**. Recent comparisons strengthen the rationale for carefully controlled fatigue protocols. Ubaed and Bakr demonstrated that simulated clinical reuse may reduce the fatigue resistance of some NiTi systems but not others, reinforcing the instrument-specific character of cyclic failure **[16].** A systematic review by Fule and colleagues identified heat treatment, test temperature, curvature geometry and motion type as important sources of heterogeneity **[17].** In a single-curvature comparison, Altabatabiee reported significant differences in cycles to fracture among four NiTi systems, but those brands and conditions were not identical to the present experiment **[18].** Peters and colleagues proposed a standardized testing fixture and minimum-quality approach based on material properties and canal geometry, underscoring the importance of transparent reporting before extrapolating across studies **[19].**

Conclusion:

Among the three rotary nickel–titanium systems tested, Flexicon X3 showed the greatest cyclic fatigue resistance, followed by HyFlex CM and Mtwo. Thus, data support the influence of heat treatment and alloy phase on fatigue behaviour in curved canals; however, laboratory fatigue performance should not be interpreted as a direct substitute for clinical separation risk. Further standardized dynamic-fatigue and clinical studies are warranted before broad recommendations are made for instrument selection.

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