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ORIGINAL ARTICLE

Correlation between root surface strain and apical micro-cracks produced during canal preparation with thermally treated single or multi-file NiTi systems

ABSTRACT

Aim: To determine the apical root surface strain (RSS) generated during shaping with thermally treated file NiTi systems, and its association with the development of apical microcracks.
Methodology: Twenty extracted human mandibular molars with severely curved mesial roots having two separate canals were prepared using XP-Endo Shaper files (Group A: XPS in mesio-buccal canals) and Hyflex CM files (Group B: HCM in mesio-lingual canals). Pre-instrumentation images of apical surface of each root were obtained with Environmental Scanning Electron Microscope (ESEM). Root surface strain (RSS) generated during canal preparation was measured as micro-strain (̂istrain) using electrical strain gauges fixed on apical third. Strain output was digitally recorded to analyze both instantaneous RSS and the maximum RSS. Mean maximum RSS values produced during canal preparation with both systems were tested for statistical significance using independent t-test. Post-instrumentation images were acquired to evaluate the presence/absence of apical microcracks. Examination was performed twice by three blinded examiners at 2-week intervals. Inter- and intra-evaluator reliability was analyzed using the Kappa statistic test. Association between the mean maximum RSS and development of apical microcracks was evaluated by linear regression.
Results: Increased baseline RSS from strain accumulation during canal shaping was observed in both groups. The mean ± SD maximum RSS recorded with XPS and HCM were 165.71 ± 86.57, and 132.14 ± 97.26 respectively with no statistical difference between them ($p>0.05$). Post-instrumentation microcracks were observed in only two canals prepared by XPS (10%) versus one canal prepared by HCM (5%), and this difference was also statistically non-significant ($P>0.05$). The inter-evaluator reliability for microcrack detection using ESEM had a Kappa value of 0.98 ($p<0.001$), while the intra-evaluator reliability had a Kappa value of 0.99 ($p<0.001$). The maximum RSS obtained during canal shaping was poorly correlated with the number of microcracks found (R2=0.090).
Conclusions: Within the limitations of this study, canal shaping by the two systems was confirmed to strain the tooth structure. However, the measured RSS was poorly correlated with the development of apical microcracks. Hence, from the clinical context, both systems can be safely used to prepare severely curved root canals.

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Received 2020, March 3
Accepted 2020, March 20

KEYWORDS *multi-file system, root canal shaping, root surface strain, single file system, thermally treated NiTi*

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Peer review under responsibility of Società Italiana di Endodonzia
10.32067/GIE.2020.34.02.03

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Introduction

Biomechanical preparation of root canals is the most essential step in achieving endodontic success due to enabling bacterial elimination, removal of debris, and facilitating obturation (1, 2). The use of Nickel-Titanium (NiTi) engine-driven instruments in the preparation of the root canal space reduces operator fatigue, the time required for shaping, and the risk of procedural preparation errors (3). NiTi was firstly introduced in Endodontics in 1988, over 30 years of research and clinical use have led to advancements in NiTi rotary instruments including various design concepts and new techniques for root canal preparation. Firstly and foremost, NiTi endodontic instruments were found to be more flexible with an increased torsional fracture resistance when compared to stainless steel instruments (4). These enhanced characteristics allowed a major improvement in engine driven endodontic instruments (5). NiTi endodontic instruments contain approximately 56 wt% nickel and 44 wt% titanium resulting in a nearly one-to-one atomic ratio. This equiatomic NiTi alloy can exist in two different temperature-dependent crystal structures named austenite (high-temperature or parent phase, with a cubic B2 crystal structure) and martensite phase (low-temperature phase, with a monoclinic B19‘crystal structure) and possesses two major characteristics which are superelasticity and shape memory effect (6).
The use of recently introduced martensitic alloys result in improvement of the mechanical properties, leading to more flexible instruments, with an increased cyclic fatigue resistance when compared to austenitic alloys (7). Because of these variations in the properties of the NiTi instruments, manufacturers have introduced several proprietary manufacturing procedures including thermal, mechanical and surface treatments. A change in the transformation temperatures (Ms, Mf, As, Af) of the utilized NiTi alloy, is the most important tool for manufacturers to alter the phase composition and consequently themomechanical properties of the NiTi alloy (7). Differently from austenitic NiTi files, martensitic instruments do not straighten during the preparation of curved root canals, thus resulting in more centered preparations (7).
Over time, advancements in NiTi instruments have introduced new generations of NiTi files with different working motions and design features such as the NiTi core diameter, cross-sectional shape, flute depth, and rake angle (1). During canal shaping, the development of forces at or near the tip of the instrument is inevitable and the file design is one of the features that can affect apical stress and strain concentrations during root canal instrumentation (8). The induced strain on the canal wall may lead to the development of dentinal microcracks that can originate apically and propagate coronally (9), mainly in the buccolingual direction (10), ultimately resulting in vertical root fractures (VRF). Vertical root fracture is one of the most frustrating complications of root canal treatment, often resulting in tooth extraction.
Attempts have been made to modify and improve the metallurgical and mechanical characteristics of NiTi instruments. Currently, there are many instruments with innovative metallurgical properties including XP-Endo Shaper files (XPS; FKG Dentaire, La Chaux-de-Fonds, Switzerland), which is a single-file system made with MaxWire (Martensite-Austenite-electropolish-fileX) alloy, instruments acquire higher flexibility, super elasticity, and the ability to progress within the canals, expanding or contracting according to the canal morphology.
HyFlex CM rotary instruments (Coltene-Whaledent, Allstetten, Switzerland) are made from CM wire, a thermally treated NiTi wire with controlled memory. CM-wire is a nearly equiatomic alloy produced by a peculiar thermomechanical process consisting in a specific sequence of heating and cooling methods during their grinding manufacturing process and leading to extremely flexible instruments (11, 12). These instruments are characterized by a symmetrical cross-sectional

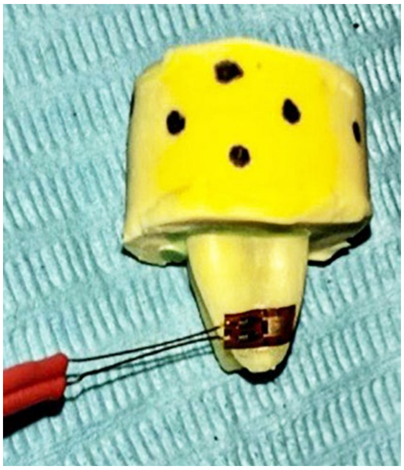
design showing three cutting edges, with the exception of the instruments with size 25, .04 taper, which have a square cross section with four flutes.
Many studies have been performed on root surface strain development during canal shaping (8, 10, 13, 14). However, whether single-file or multi-file instruments may produce similar apical strain has not been examined yet. Therefore, observing the apical root surface strain generated during root canal preparation with XP-Endo Shaper and HyFlex CM instruments would provide relevant data to be utilized clinically. The null hypothesis was that there is no difference between XP-Endo Shaper and HyFlex CM in terms of strain generated development during canal instrumentation.

Materials and Methods

Selection of the teeth
The study design was reviewed and approved by the Ethics Committee and the University Institutional Review Board. Sound human mandibular first molars atraumatically extracted for periodontal reasons were collected from local clinics without demographic data. All superficial tissues were gently removed using a hand scaler, and the teeth were kept hydrated by immediate storage in distilled water. Teeth were examined under a digital microscope (OMS2350 Zumax, Suzhou New District, China) at a 6.9X magnification to confirm absence of cracks, fractures, resorptions or anatomic aberrations.
Coronal access was achieved using diamond burs, and the mesial canals were controlled for apical patency with a size 10 K-file (Mani, Tochigi, Japan). Teeth that did not allow the insertion of a size 10 K-file to the major foramen or the passive placement of a size 15 K-file to within 1 mm of the foramen were discarded. Slight occlusal reduction was done using diamond stone to standardize the working length of all mesial canals to 18.5 mm. This was done by measuring the length of the initial instrument (K-file #10) at the apical foramen minus 1 mm.
Digital radiographs (EzSensor classic, Vatech, Gyeonggi-do, Korea) with the files in place were obtained from the proximal view to identify mesial canals morphology. The acquired digital radiographs were transferred to AutoCAD 2008 (Autodesk, San Rafael, CA, USA), and the angle and radius of curvature of the mesio-buccal and mesio-lingual root canals were determined as described previously (15).
Finally, twenty molars with mesial roots having two separate canals from the orifice to the apex along the entire length, and whose radii of curvature ranged between 4 and 7 mm and whose angles of curvature ranged between 25° and 35° were selected for use in the study.

Preparation of the teeth
To simulate the periodontal ligament, each tooth was wrapped with a single layer of 0.3 mm aluminium foil (BMJ METAL, Zhejiang, China) and embedded in regular body addition silicon impression material (Zhermack silicone Elite HD, Badia Polesine, Italy) to set in an acrylic tube (12 mm tall and 20 mm in diameter), ensuring that each tooth was centrally positioned with the long axis of the roots aligned parallel to the sides of the tube. The tooth was then removed from the tube, and the aluminium foil peeled off, then super light body impression material (Zhermack silicone Elite HD, Badia Polesine, Italy) was injected in the socket and the tooth was immediately replaced. Finally, the apical end of the acrylic tube was cut to a level that exposed 4 mm of the root apex to allow strain gauge placement and intraoperative image recordings. The teeth were kept hydrated by immersion in distilled water until root canal instrumentation.

Pre-instrumentation imaging
Baseline pre-instrumentation images of the apical surface surrounding the apical foramen (AF) of each root canal were obtained with an Environmental Scanning Electron Microscope (ESEM) Model Quanta FEG-250 (ThermoFisher Scientific, Oregon, USA) under a magnification of 500X. Subsequently, the samples were kept hydrated by immersion in distilled water until root canal instrumentation.



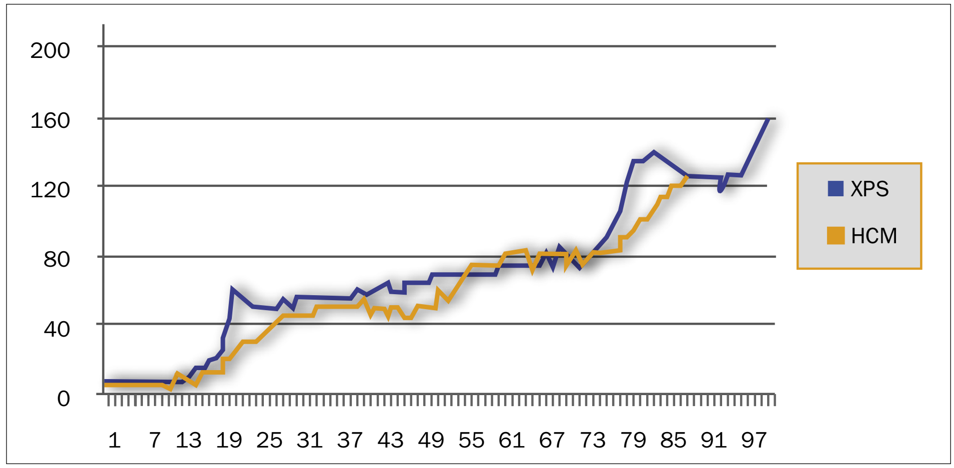


Figure 1.
Instantaneous RSS (μstrain) recorded over time (seconds) by the strain gauge attached to the apical third of the mesial root during instrumentation of MB and ML canals by XPS and HCM files respectively.

Strain gauge mounting

An electrical strain gauge (KFG02-120-C1-16, Kyowa, Tokyo, Japan) was fixed on the exposed apical third of the proximal root surface 1mm from the apex before instrumentation as described previously (Figure 1) (10).

The root surface was first cleaned with acetone in order to bond the strain gauge with a cyanoacrylate adhesive (Super glue, Ontario, Canada).

The strain gauge was connected to a strain amplifier (EDX-200A Universal Recorder, Kyowa, Tokyo, Japan) via a bridge box (JM3812; JingMing Technology, Hangzhou, China) to measure the root surface strain (RSS) values that were induced by canal instrumentation.

Root canal shaping

Before shaping, the canals were irrigated with distilled water and agitated with K-file #10, and a glide-path was established using the same file in watch-winding motion until stable RSS readings appeared, then the amplifier was adjusted to zero to start the procedure. During canal shaping, all samples were fixed.

For each molar (n=20); the mesio-buccal canal was prepared using XP-Endo Shaper files (Group A: XPS) while the mesio-lingual canal was prepared using HyFlex CM files (Group B: HCM).

For group A the XPS file was first placed in 35 °C water for 1 minute to allow for phase transformation followed by immediate placement in the root canal at 800 rpm and 1 Ncm torque. According to the manufacturer instructions, the Booster Tip permits the XPS instrument to begin shaping and to steadily increase its working field to achieve a size 30 with one instrument.

For group B the HCM instrumentation began with size 20/0.04, then size 25/0.04, and finally ended up by size 30/0.04. Hence, the final apical preparation was set to size 30 in both groups. All HCM instruments were used at a rotational speed of 500 rpm, and the torque of 2.5 Ncm according to the manufacturers' instructions.

All instruments were used to the full length of the canals (single-length technique). The rubber stoppers of the files were fixed by cyanoacrylate at 18.5 mm. Instrumentation was performed by a single operator in strict accordance with the manufacturers' recommendations. All instruments were advanced in the canal with a vertical amplitude of about 3 mm. The flutes of the instruments were cleaned after three in-and-out movements (pecks) and the root canal was flushed with 3 mL of a distilled water solution using a 30-gauge needle (NaviTip; Ultradent, South Jordan, UT, USA) that was inserted as deeply as possible into the canal without binding. Apical patency was maintained using a size 10 K-file. Once the rotary instrument had negotiated to the end of the canal and had rotated freely, it was removed. Each instrument was used to prepare four canals only and the same operator performed all the instrumentation procedures.

RSS recording
During canal shaping, the strain output of the amplifier was digitally recorded by a multi-input data logger (NR-1000, Keyence, Osaka, Japan) and saved as data files, which contained the strain values (in micro-strain) induced by the canal shaping on the external surface of the root and converted to Excel files (Excel, Microsoft Corp., Redmond, WA, USA). The instantaneous RSS induced by each instrument, and the maximum RSSs were determined.

Post-instrumentation imaging
Once the root canal shaping was completed, post-instrumentation images were acquired under the same parameters to evaluate the presence/absence of apical microcracks. Any microcrack that originated from the root canal was assumed to have been produced by the shaping procedure and was annotated (Figure 2).
Examination was done twice by three blinded examiners at 2-week intervals. Inter-evaluator and intra-evaluator reliability were analyzed using the Kappa statistic test. In the event of differences of opinions, a consensus was reached after discussion amongst the three evaluators. To avoid artifacts by dehydration, the teeth were kept in distilled water.

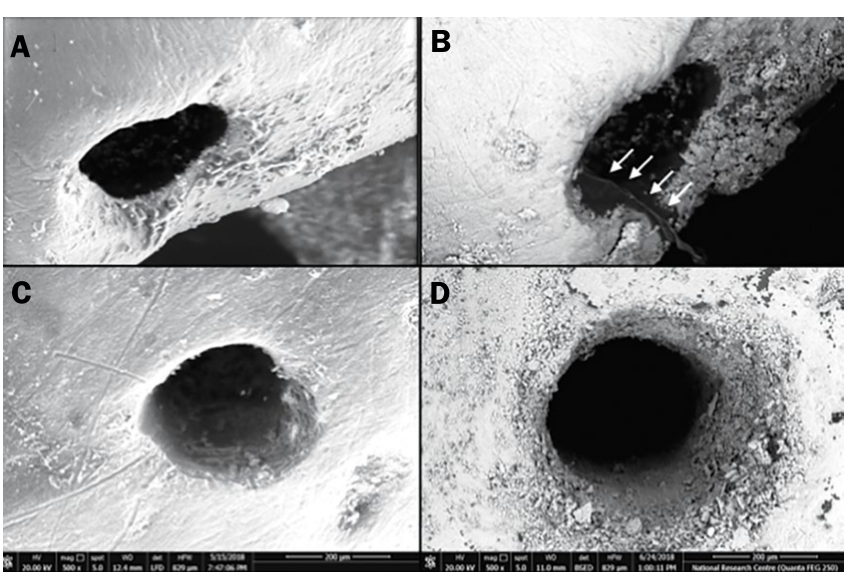


Figure 2.
Pre- **(A, C)** and post-instrumentation **(B, D)** ESEM micrographs for samples prepared with XPS showing presence (**B** white arrows) and absence **(D)** of post-instrumentation apical microcracks (magnification 500x).

Statistical analysis
RSS numerical data were explored for normality by checking the data distribution, calculating the mean and median values using Kolmogorov-Smirnov and Shapiro-Wilk tests. Data showed parametric distribution so; it was represented by mean and standard deviation (SD) values. Intergroup comparisons were done using independent t-test. The significance level was set at $P \leq 0.05$. Statistical analysis was performed with IBM® SPSS® Statistics Version 25 for Windows.

Results

None of the XPS OR HCM instruments fractured during canal shaping. The Mean±SD value of the maximum RSS recorded and number/percentage of apical microcracks in the experimental groups are presented in Table 1. Increased baseline RSS from strain accumulation during canal shaping was observed in both groups. The mean ± SD maximum RSS recorded with XPS and HCM were 165.71±86.57, and 132.14± 97.26 respectively with no statistical difference between them ($p>0.05$). Regarding the incidence of post-instrumentation microcracks; this was observed in only two canals prepared by XPS (10%) versus one canal prepared by HCM (5%), and this difference (Figure 3) was statistically non-significant ($P>0.05$). The inter-evaluator reliability for microcrack detection using ESEM had a kappa value of 0.98 ($p<0.001$), while the intra-evaluator reliability had a kappa value of 0.99 ($p<0.001$). The maximum RSS obtained during canal shaping was poorly correlated with the number of microcracks found ($R2=0.090$).

Discussion

New thermally treated NiTi alloys are characterized by the appearance of martensite under clinical conditions, leading to an enhanced resistance to cyclic fatigue and a higher flexibility (16). However, preparing highly tortuous or curved root canals with NiTi rotary files often results in inadequate debridement or asymmetric canal shaping, leading to many adverse effects such as generation of abnormal root

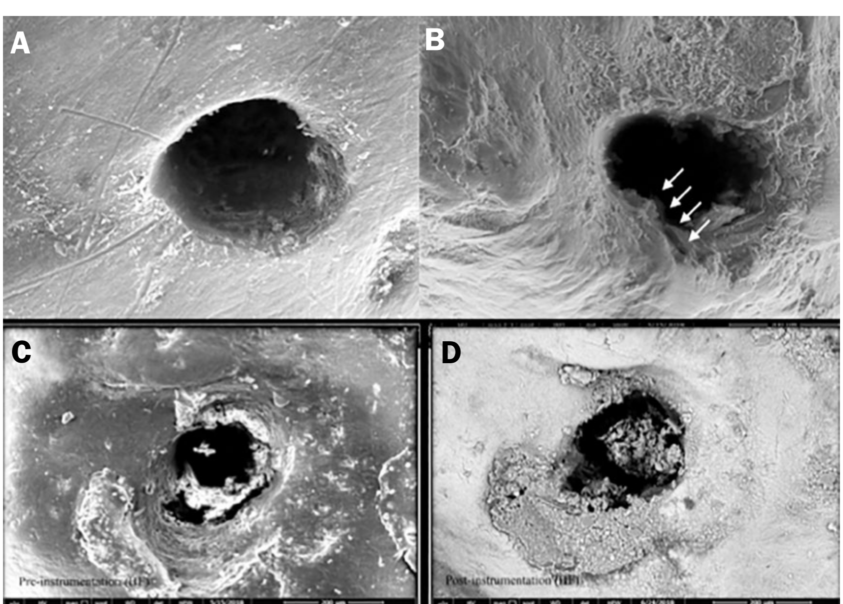
Table 1

	Maximum RSS (mstrain)	Number of apical microcracks (%)
XPS	165.71 ± 86.57	2/20 (10%)
HCM	132.14 ± 97.26	1/20 (5%)
P value	0.344 ns	0.225 ns

Table 1.
Mean ± SD maximum RSS recorded and number/percentage of apical microcracks in the experimental groups.

surface strain, due to the contact between instruments and dentin that creates many momentary stress concentrations in dentin (8). These stresses are transmitted through the root to the surface, where they might also overcome the bonds holding dentin together hence induce dentinal defects such as microcracks (3). Despite the Literature provides controversial results (17), these dentinal microcracks may have the potential to propagate into root fractures, which usually lead to tooth loss as microorganisms can proliferate in crack lines leading to secondary bacterial infections (18). These complications necessitate a better understanding of the factors that initiate microcracks (19).
This laboratory study was designed to measure the apical root surface strain (RSS) during canal shaping with new NiTi thermally treated single and multi-file NiTi systems.
In the present study XP-Endo Shaper, and HyFlex CM files were selected for root canal preparation. To the best of our knowledge, there are no current data concerning the measurement of the apical RSS with these instruments. XP-Endo Shaper is the first endodontic NiTi alloy single-file system manufactured in MaxWire that combines both shape memory effect and superelasticity in clinical application (7). HyFlex CM files, are manufactured using a unique process in which the crystallographic phase transitions from austenite to martensite at room temperature in contrast to conventional NiTi files, making the files extremely flexible and fracture resistant (12).
Root canal irrigation with sodium hypochlorite irrigating solution could significantly affect strain, elastic modulus and flexural strength of the dentin, potentially predisposing teeth to fracture (20). In the present research, distilled water was used in order to avoid the irrigant effect on RSS as previously recommended for investigations of human dentine because it causes the least amount of changes in dentine over time (21).
External reinforcement was avoided using a thin layer of silicone as a simulated periodontal ligament (19). Because an "exposed" apex is common in teeth with chronic apical periodontitis or periapical cysts, the apical 4 mm portion of the root was exposed to allow for intraoperative strain recordings (22). Therefore, present results may not be extrapolated in teeth completely surrounded by bone tissue or with periapical lesion smaller than those simulated.
Canal shaping was performed by a single experienced operator who attempted to maintain a consistent pressure on the instruments. However, it was difficult to standardize the vertical load during shaping. In addition, because the direction and magnitude of internal strain on the root canal wall surfaces could not be measured, the outer circumferential RSS values (10) were evaluated in this study. The present laboratory study was conducted at room temperature, and this is a bias of the research. Especially for thermally treated files in fact, it is well

Figure 3.
Pre- **(A, C)** and post-instrumentation **(B, D)** ESEM micrographs for samples prepared with HCM showing presence (**B** white arrows) and absence **(D)** of post-instrumentation apical microcracks



known that the body temperature significantly affects the mechanical behavior with a better arrangement of the crystal structure (23). Results of the present results showed that canal shaping strained the tooth structure as previously reported (10, 18, 24). Nevertheless, the mean maximum RSS of XPS was found not to be different from that of HCM. Conservation of the dentin adjacent to the apical root canal is crucial to maintain strength and fracture resistance of the tooth structure. Another factor is working length calibration, which was 1 mm short of the apical foramen, as previously reported (9). This agrees with Versluis et al. (24) who found that stresses resulting from canal preparation 1 mm short of the apical foramen were one-third of the stresses recorded at more coronal levels.
The instantaneous root surface strain reflects the amount of strain that each instrument generates during canal shaping and on the other hand, the maximum RSS reflects the total amount of strain applied after completion of canal shaping. The measured RSS was poorly correlated with the development of apical microcracks in the canal wall. Apical microcrack formation has been a very controversial topic in the past (25). Results of our study validates recent evidence that microckacks in in vitro studies are not related to instrumentation, nor other conditions but are mainly related to in vitro conditions. This suggests that microcracks are not a direct result of an increased maximum RSS, but might be caused by other factors, such as extraction process and/or the post-extraction storage conditions (17). Thus, the null hypothesis is accepted.

Conclusions

Within the limitations of this study, canal shaping by the two systems was confirmed to strain the tooth structure. However, the measured RSS was poorly correlated with the development of apical microcracks. Hence, from the clinical context, both systems can be safely used to prepare severely curved root canals.

Clinical Relevance

Apical microcracks are not a direct result of an increased maximum root surface strain exerted during root canal instrumentation.

Conflict of Interest

Authors deny any conflict of interest related to this research.

Acknowledgements

The present research was self-founded.

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