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DENTINAL CRACK FORMATION ASSOCIATED WITH FOUR NICKEL-TITANIUM SYSTEMS: INFLUENCE OF ALLOY SURFACE TREATMENT, MOTION TYPE, AND NUMBER OF INSTRUMENTS

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ABSTRACT

Objective: This in vitro investigation used different nickel-titanium (NiTi) rotational and reciprocating systems to evaluate the development of dentinal microcracks after root canal preparation. Additionally assessed were the effects of file metallurgy, motion type and the number of instruments used.

Materials and Methods: ProTaper Universal (PTU), ProTaper Gold (PTG), OneCurve (OC), WaveOne Gold (WOG), and Control (unprepared) were the five groups (n=10) of fifty extracted single-rooted human teeth with straight canals. The size of every prepared canal was enlarged to #25. Samples were sectioned at 3, 6, and 9 mm from the apex, and the presence of cracks was checked using a stereomicroscope set to 25× magnification. Both the Mann-Whitney and Kruskal-Wallis tests ($p \leq 0.05$) were used in the statistical analyses.

Results: No cracks were observed in the control group. All experimental groups exhibited varying levels of microcracks, with the highest incidence in PTU and WOG groups, especially in middle and apical thirds. PTG and OC caused significantly fewer cracks, indicating the beneficial effects of heat treatment and increased file flexibility. Motion type influenced crack formation; WOG (reciprocating) induced more cracks than OC (rotating). However, the number of instruments used (single vs. multiple) showed no significant impact.

Conclusion: Root canal instrumentation with NiTi systems may lead to dentinal crack formation. Heat-treated rotating systems; PTG (M-Wire) and OC (C-Wire) demonstrated lower crack incidence compared to the conventional NiTi rotating PTU system and the heat-treated reciprocating system WOG (Gold-Wire). Crack formation appears to be influenced by alloy properties, motion kinematics and file design rather than the number of instruments used.

KEYWORDS: Nickel-Titanium Instrument, Rotary Endodontics, Dentinal Microcracks, Instrument Kinematics, Thermomechanical Treatment.

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INTRODUCTION

Root canal debridement involves the use of mechanical instruments to eliminate infected or inflamed pulp tissue along with microbial biofilms adhering to the dentinal walls, thereby preparing the canal for obturation Nickel-titanium (NiTi) instruments are widely preferred for canal cleaning due to their exceptional flexibility and shape memory characteristics(1).

These instruments simplify the procedure, shorten the preparation time(2), and minimize the likelihood of canal transportation due to their pliability(3).

Nevertheless, current NiTi systems present certain drawbacks despite their advantages. Extensive contact between the files and dentinal walls during instrumentation is thought to generate transient stress, which may result in microcracks or craze lines within the root structure(1,4).

These possible defects have the potential to extend into vertical root fractures under repeated functional or procedural loading, including restorative interventions and masticatory stress(5).

Ongoing research aims to evaluate crack formation linked to different endodontic instruments, although findings remain inconsistent.

The ProTaper Universal (PTU, Dentsply Maillefer, Switzerland) system utilizes traditional superelastic austenitic NiTi alloy and features a convex triangular cross-section with a progressively variable taper along its cutting edge. ProTaper Gold (PTG, Dentsply, Maillefer, Switzerland), introduced as a counterpart to PTU due to its similar sequence and design, differs primarily in its metallurgical properties, notably a two-phase transformation behavior and higher austenite finish temperature, which contribute to enhanced flexibility.

While both PTU and PTG employ a full-sequence rotary motion, newer single-file NiTi systems have emerged, utilizing either continuous rotation or reciprocation to complete canal shaping with a single instrument(6).

OneCurve Endodontic File system (OC, Micro Mega) was launched in 2018 as a further development of the OneShape instrument. The OneCurve file is fabricated from heat-treated NiTi alloy (C-wire technology), endowing it with shape memory properties and enabling pre-curvature for canal adaptation. The OC file has a triangular shape at the tip and variable cross section of s-shape near the shaft allowing effective cutting and a cantered trajectory(7).

WaveOne Gold File system (WOG, Dentsply, Maillefer) uses the same reciprocal kinematics as WaveOne instrument. The WOG file features an eccentric parallelogram-shaped cross-section and a variable taper, enhanced through successive cycles of heat treatment that not only impart its signature golden hue but also augment its flexibility and fatigue resistance(8).

Despite extensive studies on the role of NiTi instruments in dentinal crack formation, it remains debated whether enhancements such as thermomechanical modifications, motion kinematics, or instrument count effectively reduce defect incidence.

This in vitro research aimed to evaluate dentinal microcrack formation following canal preparation with various NiTi systems, employing a sectioning method and microscopic assessment.

The null hypothesis was that there is no quantitative difference in dentin microcrack formation between the tested groups; PTU, PTG, OC, WOG and control at the same section level, and between different section levels within the same system. In addition, there are neither difference in effect of surface treatment on incidence of cracks between PTU and PTG groups, difference in effect of type of motion on incidence of cracks between OC and WO groups nor difference in effect of number of instruments on incidence of cracks between single and multiple file systems groups.

MATERIALS AND METHODS

Sample size calculation

The required sample size was determined based on the study of *Pedulla et al.2017* [9], who evaluated dentinal defects associated with different rotary systems. Using G*Power software (version 3.1.9.2) and Fisher's exact test, with a 5% margin of error and 80% power, a total of 50 teeth (10 per group) was considered adequate to detect statistically significant differences among the five groups.

Sample selection and preparation

Ethical approval for the study was granted by the Research Ethics Committee, Faculty of Dentistry, Cairo University (Approval No. 29-7-21).

Fifty extracted human permanent single-rooted teeth exhibiting fully developed apices and straight canals (< 5^0 inclination according to Schneider's) were selected. Canal curvature was assessed using initial radiographs captured with a VistaScan 3 system (Dürr Dental, Germany).

The crowns were sectioned using a low-speed saw (Isomet 1000, Buehler, Lake Bluff, IL) under water cooling, leaving roots with a standardized length of 12 mm from the apex. A glide path was established in all samples using a #10 K-file. Canal length was determined by inserting the file until its tip became visible at the apical foramen. Working length was established 1 mm short of this measurement.

To mimic the periodontal ligament's cushioning effect, each root was wrapped in a single layer of aluminum foil prior to embedding in auto-polymerizing acrylic resin blocks. After polymerization, the foil was removed and replaced with a thin coat of light-body silicone material (Speedex, Coltene Whaledent, Switzerland) before reinserting the root into its mold(10).

Cleaning and shaping

The specimens were randomly divided into five groups (n=10); Gp1: Control where specimens were left unprepared, and four treatment groups named by the instrument used for preparation: Gp2: ProTaper Universal (PTU; Dentsply Tulsa Dental Specialties, Tulsa, OK), Gp3: ProTaper Gold (PT; Dentsply Maillefer, Ballaigues, Switzerland), Gp4: OneCurve (OC; Micro Mega, Besancon, France), Gp5: WaveOne Gold (WOG; Dentsply Maillefer, Ballaigues, Switzerland).

To ensure uniform apical shaping, canals across all groups were enlarged to a final size of #25 with a taper 0.07 or as close to taper 0.07 as possible, following the respective full file sequences recommended by each system's manufacturer irrespective of the number of files.

Instrumentation was performed using the X-smart Plus (Dentsply Maillefer, Ballaigues, Switzerland), with torque and speed settings adjusted according to manufacturer specifications. The sequences, torque and speed settings used for each system are given in **Table (1).**

TABLE (1) Sequences, torque and speed settings used for each system.

System name	Sequence	Movement
Gp2: PTU	S1, S2, F1, F2(#25/08)	Continuous rotation, 300 rpm, 1.5 Ncm
Gp3: PTG	S1, S2, F1, F2(#25/08)	Continuous rotation, 300 rpm, 1.5 Ncm
Gp4: OC	#25/06	Continuous rotation, 300 rpm, 2.5 Ncm
Gp5: WOG	#25/07	Reciprocation, 350 rpm

Using a 27-gauge needle, 3 mL of 5.25% sodium hypochlorite was irrigated after each rotary file use or, after every three pecking motions for reciprocating instruments. Following instrumentation, canals were flushed using 5 mL of sterile saline. Each instrument was used in four canals before being discarded.

Sectioning and stereomicroscopic examination

A low-speed precision saw (Isomet) with continuous water cooling was used to cut each specimen transversely at 3, 6, and 9 mm from the apex, perpendicular to the long axis.

This process yielded 150 sections (3 per root), which were analyzed under a digital stereomicroscope (SZTP, Olympus, Japan) at 25× magnification.

Evaluation of dentinal microcracks

Microcrack formation was evaluated using the criteria specified by *Shemesh et al. 2009* (11), and *Priya et al. 2014* (12), categorizing findings as either "no crack" or "crack" based on observed features.

- **No Crack:** Dentin free of any visible lines or fractures on both internal canal walls and external root surfaces.
- **Crack:** Presence of lines extending either from the canal lumen outward or from the external root surface into the dentin.

Statistical Analysis

For every group, descriptive statistics including means and standard deviations, were calculated. The Shapiro-Wilk and Kolmogorov-Smirnov tests were used to evaluate the data distribution, and the results confirmed that it was non-parametric.

The Kruskal-Wallis test was used for comparisons between groups, and the Mann-Whitney U test was used for comparisons between two independent samples. Statistical significance was set at $P \leq 0.05$. All analyses were conducted using IBM® SPSS® Statistics for Windows, Version 20.

RESULTS

Total percentage of cracks:

The percentage of cracks of different groups in each third after root canal preparation with rotary systems is presented in **Figure (1).**

Coronal:

There was no significant difference between all groups (Gp1/Control), (Gp2/PTU), (Gp3/PTG), (Gp4/OC) and (Gp5/WO) where (p=0.172).

Middle:

There was a significant difference between (Gp1/Control), (Gp2/PTU), (Gp3/PTG), (Gp4/OC) and (Gp5/WO) where (p<0.001).

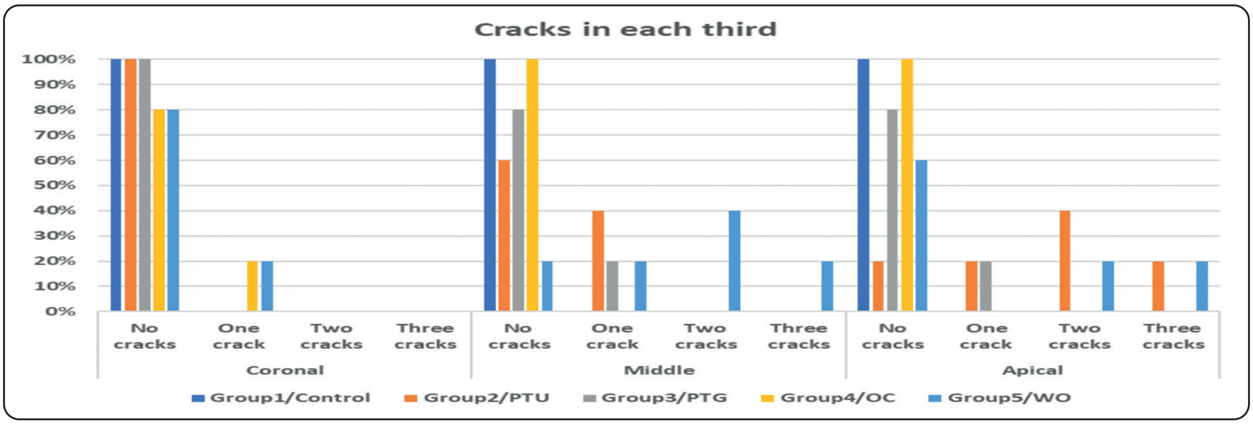


Fig. (1) Bar chart representing percentage of cracks of different groups in each third.

A significant difference was found between (Gp1/Control) and each of (Gp2/PTU) and (Gp5/WO) where (p=0.029) and (p=0.001), respectively. While no significant difference was found between (Gp 1/Control) and each of (Gp3/PTG) and (Gp4/OC) where (p=0.146) and (p=1), respectively.

No significant difference was found between (Gp 2/PTU) and (Gp 3/PTG) where (p=0.342), while a significant difference was found between (Gp2/PTU) and each of (Gp4/OC) and (Gp5/WO) where (p=0.029) and (p=0.011), respectively.

No significant difference between (Gp3/PTG) and (Gp4/OC) where (p=0.146), while a significant difference between (Gp3/PTG) and (Gp5/WO) where (p=0.003).

A significant difference between (Gp4/OC) and (Gp5/WO) where (p=0.001).

Apical:

There was a significant difference (p<0.001) between (Gp1/Control), (Gp2/PTU), (Gp3/PTG), (Gp4/OC) and (Gp5/WO).

A significant difference was found between (Gp1/Control) and each of (Gp2/PTU) and (Gp5/WO) where (p=0.001) and (p=0.030), respectively. While no significant difference was found between (Gp1/Control) and each of (Gp3/PTG) and (Gp4/OC) where (p=0.146) and (p=1), respectively.

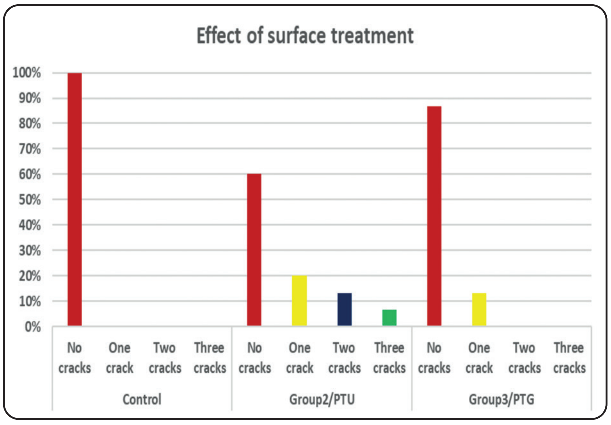


Fig. (2) Bar chart representing effect of surface treatment.

A significant difference was found between (Gp2/PTU) and each of (Gp3/PTG) and (Gp4/OC) where (p=0.003) and (p=0.001), respectively, while no significant difference was found between (Gp2/PTU) and (Gp5/WO) where (p=0.265).

No significant difference between (Gp3/PTG) and each of (Gp4/OC) and (Gp5/WO) where (p=0.146) and (p=0.191), respectively.

A significant difference between (Gp4/OC) and (Gp5/WO) where (p=0.030).

Effect of surface treatment:

The comparison of incidence of cracks between PTU and PTG groups is presented in **Figure (2).**

A significant difference was found between (Gp2/PTU) and (Gp3/PTG) where (p=0.012), with the higher incidence of cracks in the PTU group in the apical third of the roots.

In addition, there was a significant difference between (Gp1/Control), (Gp2/PTU) and (Gp3/PTG) where (p<0.001).

And between (Gp1/Control) and each of (Gp2/PTU) and (Gp3/PTG) where (p<0.001) and (p=0.040).

Effect of type of motion:

The comparison of incidence of cracks between OC and WO groups is presented in **Figure (3).**

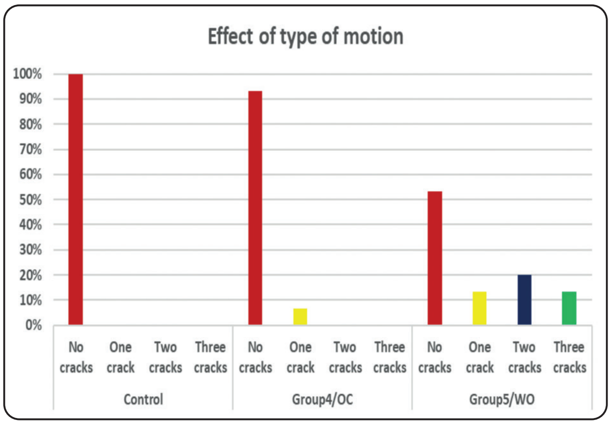


Fig. (3) Bar chart representing effect of type of motion.

A significant difference was found between WOG and OC, where OC generally caused less cracks especially in the middle and apical thirds.

There was a significant difference between (Gp1/Control), (Gp4/OC) and (Gp5/WO) where ($p<0.001$).

However, no significant difference was found between (Gp1/Control) and (Gp4/OC) where ($p=0.154$).

Effect of number of instruments:

The comparison of incidence of cracks between single and multiple file systems groups is presented in **Figure (4).**

There was no significant difference between (Single file) and (Multiple files) where ($p=0.818$), where least number of cracks was found in OC and PTG respectively.

Finally, the frequencies of percentage of cracks of different groups and images of dentinal cracks using different rotary file systems are summarized in **Table (2)** and presented in **Figure (5).**

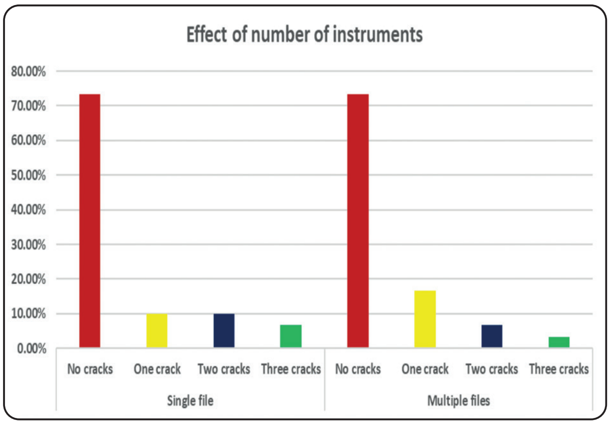
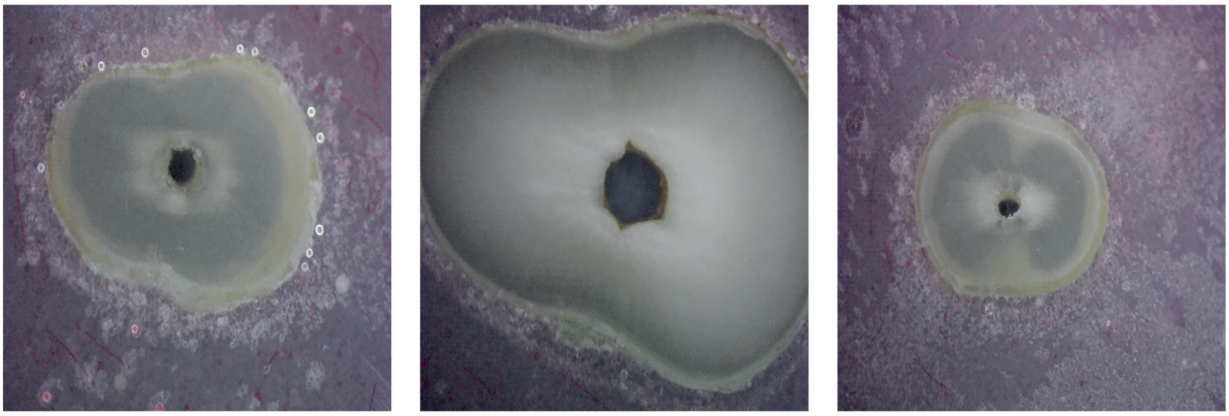


Fig. (4) Bar chart representing effect of number of instruments.

TABLE (2) Frequencies of percentage of cracks of different groups:

Variables		Percentage of cracks n	%
Group1/Control	No cracks	30	100%
	One crack	0	0%
	Two cracks	0	0%
	Three cracks	0	0%
Group2/PTU	No cracks	18	60%
	One crack	6	20%
	Two cracks	4	13.3%
	Three cracks	2	6.7%
Group3/PTG	No cracks	26	86.7%
	One crack	4	13.3%
	Two cracks	0	0%
	Three cracks	0	0%
Group4/OC	No cracks	28	93.3%
	One crack	2	6.7%
	Two cracks	0	0%
	Three cracks	0	0%
Group5/WO	No cracks	16	53.3%
	One crack	4	13.3%
	Two cracks	6	20%
	Three cracks	4	13.3%
p-value		<0.001*	

; significant ($p<0.05$) ns; non-significant ($p>0.05$)



One crack seen after the use of rotary files. Two cracks seen after the use of rotary files. Three cracks seen after the use of rotary files.

Fig. (5) Images of dentinal cracks using different rotary file systems.

DISCUSSION

Root canal instrumentation using various rotary NiTi systems can exert stress on dentin, potentially initiating microcracks or craze lines[13].

In the present study, straight, single-rooted teeth with curvature less than 5° were selected. This selection was based on the fact that if cracks are induced in relatively uncomplicated anatomies, they are even more likely to occur in curved canals. To replicate the periodontal ligament's mechanical cushioning, it was simulated during sample preparation. The periodontal ligament plays a critical role in absorbing mechanical stresses and preventing external forces from being directly transferred to the root structure.

For evaluating dentinal defects, a digital stereo-microscope was utilized, offering magnification and clarity in assessing microcrack formation. Some previous studies, such as those by *Dedeus et al.* [14,15] and *PradeepKumar et al.* [16], found no correlation between instrumentation and cracking when analyzed via CT imaging. In contrast, findings from *Aksoy et al.*[17] and *Bayram et al.*[4] suggested that rotary instrumentation could induce such defects.

Microscopic methods tend to reveal more defects than CT, likely due to differences in detection sensitivity and the possibility that the sectioning method itself contributes to crack initiation [18,19].

Nonetheless, in this study, the control group (Gp1) did not exhibit any defects, supporting the validity of the sectioning process and that the cracks induced were the result of the different instrumentation procedures used[20].

Effect of surface treatment

Several approaches, such as electropolishing, surface coatings, and thermal treatments, have been introduced to enhance the mechanical properties of NiTi instruments[21].

Though PTU and PTG share similar design features such as taper, size, and cross-section, they differ in their metallurgical properties. PTU is composed of conventional superelastic NiTi, while PTG incorporates a gold heat-treated NiTi alloy, which is believed to enhance flexibility and resistance to fatigue due to its two-stage transformation behavior. Therefore, the different results of the two systems could be based on their metallurgical properties[22].

After additional heat treatment, NiTi alloys typically go through a one-stage transformation from austenitic to martensitic and Austenitic-R-Martensitic. During the production process, PTG's two-stage transformation behavior adds advantages to the instruments by showing the alloy's reverse transformation as it passes through the intermediate R-phase[23].

The gold heat treatment also forms a rigid titanium oxide surface layer ranging from 100-140 nm in thickness, giving the instruments their characteristic gold color and potentially improving its cutting ability and durability[24].

Our results showed that the PTU group exhibited significantly more apical cracks than the PTG group. The same results were obtained in other studies; *karatas E et al. 2016*[25]*, Nishad and Shivamurthy 2018*(10)*, Chole et al. 2019*[26]*, and Scarlatescu SA et al 2020*[27]. This difference is likely due to the increased stiffness of PTU instruments, which may transmit greater stress to root dentin. According to *Cohen S et al. 2006*[28] stiffer files can concentrate more stress in the apical region, predisposing dentin to cracks.

The enhanced flexibility of PTG instruments, resulting from their metallurgical modifications, may allow for a more centered canal preparation and reduced mechanical stress[29]. Furthermore, the presence of the titanium oxide surface layer could enhance cutting efficiency and reduce friction, contributing to the lower crack incidence observed[30].

Effect of type of motion

The development of single-file systems using reciprocating motion has aimed to simplify canal preparation and minimize instrument stress.

Continuous rotary instruments are subjected to constant torsional and bending forces, increasing the risk of breakage and dentinal damage. Reciprocating motion, with its alternating cutting (counter-clockwise) and releasing (clockwise) action, is claimed to reduce these stresses and shorten instrumentation time[30, 32, 33].

Additionally, reciprocation may reduce cyclic fatigue and canal transportation compared to continuous rotation[32, 34, 35]. However, some studies have noted a potential decrease in cutting efficiency in reciprocating instruments, which may make canal negotiation more difficult[36].

In our study, we compared the OneCurve (OC) system (continuous rotary) and WaveOne Gold (WOG) system (reciprocating). WOG features an offset parallelogram cross-section and with a progressive taper while OC has a variable cross-section; triangular in apical third and almost S-shaped in coronal third, with heat-treated C-wire alloy.

The type of motion of instruments has been reported as an important factor in crack formation[37]. Previous literature suggested that reciprocating motion may be associated with fewer dentinal cracks than continuous rotation, potentially because it reduces the cumulative torsional forces applied to canal walls[6, 24, 38].

However, our findings indicated that OC caused fewer cracks than WOG, especially in the apical and middle thirds. These results suggest that factors beyond motion kinematics such as file design, alloy type, and taper, play a significant role in crack formation[39, 40].

Interestingly, *Burklein and Schafer 2012*[41] reported that reciprocation might cause increased apical debris accumulation, leading to higher torsional stress, while *Versluis et al 2006*[42], noted that stress concentration is lower at 1 mm short of the apex compared to more coronal levels, possibly contributing to the higher incidence of cracks in the WOG group.

Effect of number of instruments

The concept of using a single file for complete canal preparation has become more popular due to its time efficiency and reduced instrument fatigue thus, minimizing the possibility of its fracture[22,43].

While some studies suggested that single-file systems may generate more stress and thus more cracks due to the lack of a pre-enlarged glide path[11, 40, 44]. others have found that full-sequence systems with multiple files can also increase crack formation, possibly due to repeated instrumentation[39, 45].

In this study, no significant difference was observed between single- and multiple-file systems regarding dentinal crack formation. The lowest incidence of cracks was observed in the OC and PTG groups respectively.

These results support the view that dentinal damage is multifactorial, influenced by the combination of design, taper, kinematics, manufacturing method, and number of instruments used [46].

Thus, the null hypothesis was partially rejected, as significant differences were found based on surface treatment and motion type, but not the number of instruments used.

CONCLUSION

Within the limitations of this in vitro study, the following conclusions can be made:

1. All tested rotary NiTi systems were associated with the formation of dentinal microcracks, with the most pronounced defects observed in the middle and apical thirds of the roots.
2. Thermally treated full-sequence instruments (PTG) and the single-file system (OC) used in continuous rotation produced significantly fewer dentinal cracks compared to PTU and WOG systems, which operate using rotating and reciprocating motion, respectively.
3. The number of instruments used during canal preparation did not have a significant impact on the incidence of dentinal defect formation.

Recommendations

1. Further Investigations: Future studies should incorporate more advanced imaging techniques such as micro-CT to assess dentinal microcrack formation without the potential artifacts introduced by sectioning.
2. Clinical Correlation: In vivo studies are recommended to validate these findings under physiological conditions, including masticatory load and periodontal ligament response.
3. Extended Sample Variety: Expanding the study to include teeth with different canal curvatures, root morphologies, and varying degrees of calcification could provide a more comprehensive understanding of crack formation patterns.
4. Long-term Outcome Studies: Longitudinal clinical research is needed to determine whether the presence of instrumentation-induced cracks has a significant effect on the long-term prognosis of endodontically treated teeth.
5. Instrument Design Consideration: Manufacturers should continue to refine the design, metallurgy, and motion kinematics of NiTi rotary and reciprocating systems to minimize crack formation and enhance dentin preservation.

REFERENCES

1. Algarni AF, Elshinawy MI, Nahi ZA, Algarni AS, Alghamdi NS. Comparative evaluation of root dentin integrity after root canal preparation with rotary file systems of different Ni-Ti alloys. Ann Med Health Sci Res. 2019;9:614–20.
2. Özyürek T, Tek V, Yılmaz K, Uslu G. Incidence of apical crack formation and propagation during removal of root canal filling materials with different engine driven nickel-titanium instruments. Restor Dent Endod. 2017;42(4):332.
3. Portenier, Lutz, Barbakow. Preparation of the apical part of the root canal by the Lightspeed and step–back techniques. Int Endodontic J. 1998 Mar;31(2):103–11.
4. Capar ID, Arslan H, Akcay M, Uysal B. Effects of ProTaper Universal, ProTaper Next, and HyFlex Instruments on Crack Formation in Dentin. Journal of Endodontics. 2014 Sep;40(9):1482–4.
5. Bier CAS, Shemesh H, Tanomaru-Filho M, Wesselink PR, Wu MK. The Ability of Different Nickel-Titanium Rotary Instruments To Induce Dentinal Damage During Canal Preparation. Journal of Endodontics. 2009 Feb;35(2):236–8.
6. Liu R, Hou BX, Wesselink PR, Wu MK, Shemesh H. The Incidence of Root Microcracks Caused by 3 Different Single-file Systems versus the ProTaper System. Journal of Endodontics. 2013 Aug;39(8):1054–6.

7. Serafin M, De Biasi M, Franco V, Angerame D. In vitro comparison of cyclic fatigue resistance of two rotary single-file endodontic systems: OneCurve versus OneShape. Odontology. 2019 Apr;107(2):196–201.

8. Karataş E, Ersoy İ, Gündüz HA, Uygun AD, Kol E, Çakıcı F. Influence of Instruments Used in Root Canal Preparation on Amount of Apically Extruded Debris. Artificial Organs. 2016 Aug;40(8):774–7.

9. Pedullà E, Genovesi F, Rapisarda S, La Rosa GRM, Grande NM, Plotino G, et al. Effects of 6 Single-File Systems on Dentinal Crack Formation. Journal of Endodontics. 2017 Mar;43(3):456–61.

10. Nishad S, Shivamurthy G. Comparative analysis of apical root crack propagation after root canal preparation at different instrumentation lengths using protaper universal, protaper next and protaper gold rotary files: An In vitro study. Contemp Clin Dent. 2018;9(5):34.

11. Shemesh H, Bier CAS, Wu M -K., Tanomaru–Filho M, Wesselink PR. The effects of canal preparation and filling on the incidence of dentinal defects. Int Endodontic J. 2009 Mar;42(3):208–13.

12. Priya NT. "Dentinal Microcracks After Root Canal Preparation" A Comparative Evaluation with Hand, Rotary and Reciprocating Instrumentation. JCDR [Internet]. 2014 [cited 2025 Jun 23]; Available from: http://www.jcdr.net/article_fulltext.asp?issn=0973-709x&year=2014&volume=8&issue=12&page=ZC70&issn=0973-709x&id=5349

13. Blum J-Y, Machtou P, Esber S, Micallef JP. Analysis of forces developed during root canal preparation with the balanced force technique. Int Endodontic J. 1997 Nov;30(6):386–96.

14. De-Deus G, Silva EJNL, Marins J, Souza E, Neves ADA, Gonçalves Belladonna F, et al. Lack of Causal Relationship between Dentinal Microcracks and Root Canal Preparation with Reciprocation Systems. Journal of Endodontics. 2014 Sep;40(9):1447–50.

15. De-Deus G, César De Azevedo Carvalhal J, Belladonna FG, Silva EJNL, Lopes RT, Moreira Filho RE, et al. Dentinal Microcrack Development after Canal Preparation: A Longitudinal in Situ Micro–computed Tomography Study Using a Cadaver Model. Journal of Endodontics. 2017 Sep;43(9):1553–8.

16. PradeepKumar AR, Shemesh H, Archana D, Versiani MA, Sousa-Neto MD, Leoni GB, et al. Root Canal Preparation Does Not Induce Dentinal Microcracks In Vivo. Journal of Endodontics. 2019 Oct;45(10):1258–64.

17. Aksoy Ç, Keriş EY, Yaman SD, Ocak M, Geneci F, Çelik HH. Evaluation of XP-endo Shaper, Reciproc Blue, and ProTaper Universal NiTi Systems on Dentinal Microcrack Formation Using Micro–Computed Tomography. Journal of Endodontics. 2019 Mar;45(3):338–42.

18. Parashos P, Messer HH. Rotary NiTi Instrument Fracture and its Consequences. Journal of Endodontics. 2006 Nov;32(11):1031–43.

19. Pawar AM, Thakur B, Kfir A, Kim HC. Dentinal defects induced by 6 different endodontic files when used for oval root canals: an *in vitro* comparative study. Restor Dent Endod. 2019;44(3):e31.

20. Okitsu M, Takahashi H, Yoshioka T, Iwasaki N, Suda H. Effective Factors Including Periodontal Ligament on Vertical Root Fractures. Dental Materials Journal. 2005;24(1):66–9.

21. Shen Y, Zhou H min, Zheng Y feng, Campbell L, Peng B, Haapasalo M. Metallurgical Characterization of Controlled Memory Wire Nickel-Titanium Rotary Instruments. Journal of Endodontics. 2011 Nov;37(11):1566–71.

22. Gavini G, Santos MD, Caldeira CL, Machado MEDL, Freire LG, Iglecias EF, et al. Nickel–titanium instruments in endodontics: a concise review of the state of the art. Braz oral res [Internet]. 2018 Oct 18 [cited 2025 Jun 23];32(suppl 1). Available from: http://www.scielo.br/scielo.php?script=sci_arttext&pid=S1806-83242018000500602&lng=en&tlng=en

23. Uygun AD, Kol E, Topcu MKC, Seckin F, Ersoy I, Tanriver M. Variations in cyclic fatigue resistance among ProTaper Gold, ProTaper Next and ProTaper Universal instruments at different levels. Int Endodontic J. 2016 May;49(5):494–9.

24. Shen Y, Hieawy A, Huang X, Wang Z jun, Maezono H, Haapasalo M. Fatigue Resistance of a 3-dimensional Conforming Nickel-Titanium Rotary Instrument in Double Curvatures. Journal of Endodontics. 2016 Jun;42(6):961–4.

25. Karataş E, Gündüz HA, Kırıcı DÖ, Arslan H. Incidence of dentinal cracks after root canal preparation with ProTaper Gold, Profile Vortex, F360, Reciproc and ProTaper Universal instruments. Int Endodontic J. 2016 Sep;49(9):905–10.

26. Chole D, Kamble S, Bakle S, Gandhi N, Hatte N, Bawa P. Effects of 3 single-file system (ProTaper Universal, ProTaper Next, Protaper Gold) on crack formation in dentin after root canal preparation: an in vitro study. IOSR-JDMS. 2019;18(11):47–50.

27. Scarlatescu SA, Preoteasa C, Suciu I, Gheorghiu IM, Perlea P. Evaluation of three different rotary systems on dentinal defects formation in curved canals. Rom Biotechnol lett. 2020;4:1716–23.

28. Cohen S, Berman L, Blanco L, Bakland L, Kim J. A Demographic Analysis of Vertical Root Fractures. Journal of Endodontics. 2006 Dec;32(12):1160–3.

29. Gagliardi J, Versiani MA, De Sousa-Neto MD, Plazas-Garzon A, Basrani B. Evaluation of the Shaping Characteristics of ProTaper Gold, ProTaper NEXT, and ProTaper Universal in Curved Canals. Journal of Endodontics. 2015 Oct;41(10):1718–24.

30. Gao Y, Gutmann JL, Wilkinson K, Maxwell R, Ammon D. Evaluation of the Impact of Raw Materials on the Fatigue and Mechanical Properties of ProFile Vortex Rotary Instruments. Journal of Endodontics. 2012 Mar;38(3):398–401.

31. Varela-Patiño P, Ibañez-Párraga A, Rivas-Mundiña B, Cantatore G, Otero XL, Martin-Biedma B. Alternating versus Continuous Rotation: A Comparative Study of the Effect on Instrument Life. Journal of Endodontics. 2010 Jan;36(1):157–9.

32. De-Deus G, Brandão MC, Barino B, Di Giorgi K, Fidel RAS, Luna AS. Assessment of apically extruded debris produced by the single-file ProTaper F2 technique under reciprocating movement. Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology, and Endodontology. 2010 Sep;110(3):390–4.

33. Bürklein S, Hinschitza K, Dammaschke T, Schäfer E. Shaping ability and cleaning effectiveness of two single–file systems in severely curved root canals of extracted teeth: Reciproc and WaveOne versus Mtwo and ProTaper. Int Endodontic J. 2012 May;45(5):449–61.

34. Plotino G, Grande NM, Testarelli L, Gambarini G. Cyclic fatigue of Reciproc and WaveOne reciprocating instruments. Int Endodontic J. 2012 Jul;45(7):614–8.

35. Ahn SY, Kim HC, Kim E. Kinematic Effects of Nickel-Titanium Instruments with Reciprocating or Continuous Rotation Motion: A Systematic Review of In Vitro Studies. Journal of Endodontics. 2016 Jul;42(7):1009–17.

36. Ruddle C.J.,. Endodontic canal preparation: WaveOne single- file technique, Dent. Today (2012)1–7January. Dent Today. 2012;1–7.

37. Aydin U, Aksoy F, Karataslioglu E, Yildirim C. Effect of ethylenediaminetetraacetic acid gel on the incidence of dentinal cracks caused by three novel nickel–titanium systems. Aust Endodontic J. 2015 Dec;41(3):104–10.

38. Kansal R, Rajput A, Talwar S, Roongta R, Verma M. Assessment of Dentinal Damage during Canal Preparation Using Reciprocating and Rotary Files. Journal of Endodontics. 2014 Sep;40(9):1443–6.

39. Kesim B, Sagsen B, Aslan T. Evaluation of dentinal defects during root canal preparation using thermomechanically processed nickel-titanium files. Eur J Dent. 2017 Apr;11(02):157–61.

40. Bürklein S, Tsotsis P, Schäfer E. Incidence of Dentinal Defects after Root Canal Preparation: Reciprocating versus Rotary Instrumentation. Journal of Endodontics. 2013 Apr;39(4):501–4.

41. Bürklein S, Schäfer E. Apically Extruded Debris with Reciprocating Single-File and Full-sequence Rotary Instrumentation Systems. Journal of Endodontics. 2012 Jun;38(6):850–2.

42. Versluis A, Messer HH, Pintado MR. Changes in compaction stress distributions in roots resulting from canal preparation. Int Endodontic J. 2006 Dec;39(12):931–9.

43. Sharma P, Goel M, Verma S, Sachdeva GS, Sharma N, Kumar V. Entering a new era in endodontics with revolutionary single file systems. A comprehensive review. EC Dent Sci. 2016;5(3):1100–22.

44. Shantiaee Y, Dianat O, Mosayebi G, Namdari M, Tordik P. Effect of Root Canal Preparation Techniques on Crack Formation in Root Dentin. Journal of Endodontics. 2019 Apr;45(4):447–52.

45. Monga P, Bajaj N, Mahajan P, Garg S. Comparison of incidence of dentinal defects after root canal preparation with continuous rotation and reciprocating instrumentation. Singapore Dental Journal. 2015 Dec;36:29–33.

46. Yoldas O, Yilmaz S, Atakan G, Kuden C, Kasan Z. Dentinal Microcrack Formation during Root Canal Preparations by Different NiTi Rotary Instruments and the Self-Adjusting File. Journal of Endodontics. 2012 Feb;38(2):232–5.