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Original Article

A comparative evaluation of dentinal defects after root canal preparation with different rotary and reciprocal systems

Farklı rotary ve resiprokal sistemlerle kök kanal preparasyonu sonrasında dentinal defektlerin karşılaştırmalı değerlendirilmesi

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ABSTRACT

Aim: This study aimed to compare dentinal defects after root canal preparation with various reciprocating and continuous rotary files.
Methods: 90 extracted human mandibular incisor teeth were used. 15 teeth left unprepared and the remaning teeth were randomly divided into 5 experimental groups (n=15). Root canals were prepared with WaveOne (Dentsply Maillefer, Ballaigues, Switzerland), WaveOne Gold (Dentsply Maillefer, Ballaigues, Switzerland), Hyflex EDM OneFile (Coltene/Whaledent, Altstätten, Switzerland), ProTaper Next (Dentsply Maillefer, Ballaigues, Switzerland), and ProTaper Universal (Dentsply Maillefer, Ballaigues, Switzerland) rotary files. Then roots were sectioned at 3, 6 and 9 mm from the apex and evaluated with a stereomicroscope. Statistical analysis was performed with chi-square and Fischer's Exact test. The significance level was set at 5%.
Results: No defects were observed in the unprepared control group. Dentin defect were observed in all the experimental groups, especially in the apical region (3 mm). WaveOne and Hyflex EDM showed more dentinal defects than the control group ($p<0.05$); however, no significant difference was found between them ($p>0.05$). WaveOne caused significantly more dentinal defects than the ProTaper Universal, ProTaper Next, and WaveOne Gold groups ($p<0.05$). Hyflex EDM caused more defects than ProTaper Next ($p<0.05$). There was no difference between the other experimental groups ($p>0.05$).
Conclusion: All the rotary file systems used in this study caused dentinal defects regardless of the motion kinematics.

Keywords: Dentinal defect, rotary instrumentation, stereomicroscope

ÖZ

Giriş: Bu çalışmanın amacı resiprokasyon ve sürekli rotasyonla kullanılan çeşitli eğelerle kök kanal preparasyonu sonrası oluşan dentin defektlerini karşılaştırmaktır.
Yöntem: 90 adet çekilmiş insan alt kesici diş kullanıldı. 15 diş prepare edilmeden bırakıldı ve kalan dişler rastgele 5 deney grubuna (n=15) ayrıldı. Kök kanalları WaveOne (Dentsply Maillefer, Ballaigues, Switzerland), WaveOne Gold (Dentsply Maillefer, Ballaigues, Switzerland), Hyflex EDM OneFile (Coltene/Whaledent, Altstätten, Switzerland), ProTaper Next (Dentsply Maillefer, Ballaigues, Switzerland) ve ProTaper Universal (Dentsply Maillefer, Ballaigues, Switzerland) döner eğeleri ile prepare edildi. Daha sonra köklerden apeksten itibaren 3, 6 ve 9 mm'de kesit alındı ve stereomikroskopla değerlendirildi. İstatistiksel analiz ki-kare ve Fischer's Exact testi ile gerçekleştirildi. Anlamlılık düzeyi %5 olarak belirlendi.
Bulgular: Preparasyon yapılmayan kontrol grubunda defekt gözlenmedi. Tüm deney gruplarında özellikle apikal bölgede (3 mm) dentinal defekt gözlendi. WaveOne ve Hyflex EDM, kontrol grubuna göre daha fazla dentin defekti gösterdi ($p<0.05$); ancak aralarında anlamlı bir fark bulunmadı ($p>0.05$). WaveOne; ProTaper Universal, ProTaper Next ve WaveOne Gold gruplarından daha fazla dentin defektine neden oldu ($p<0.05$). Hyflex EDM, ProTaper Next'den daha fazla defekte neden oldu ($p<0.05$). Diğer deney grupları arasında fark yoktu ($p>0.05$).
Sonuç: Bu çalışmada kullanılan tüm döner eğe sistemleri, hareket kinematiklerinden bağımsız olarak dentin defektine neden oldu.

Anahtar kelimeler: Döner enstrümantasyon, dentin defekti, stereomikroskop

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INTRODUCTION

Disinfection, shaping and filling of the root canal system are essential factors in the success of root canal treatment. Root canal preparation provides both the cleaning of the root canal system by removing the infected tissue from the root canal and the necessary space for an ideal root canal filling (1). However, the root canal preparation may also cause some dentinal defects such as micro-cracks in the root canal wall (2). Premature occlusal contact, chewing forces, and dental treatments may lead to the progression of these micro-cracks and even the formation of vertical root fractures (VRF) (3), which are one of the most undesirable complications of endodontic treatment and often require tooth extraction (4).

The use of nickel-titanium (NiTi) instruments may cause defects in the root canal dentin (5-7). The incidence of dentin defects after root canal preparation with rotary instruments varies depending on the amount of dentin removed from the root canal and the dimensions of the canal enlargement (8,9). Increasing the sizes of preparation poses a risk for VRFs (10). In the root dentin, the crack development increases with the increase in stress. It has been reported that the canal shaping procedure weakens the root and the alloy used in the instrument, the cross-section shape, taper diameter, and operator's usage style have an effect on the incidence of dentin defects (11).

There are conflicting results that the use of NiTi instruments causes defects in dentin. Also, there is no consensus on whether rotation or reciprocation movements make a difference in the incidence of defects in root canal dentin (12-14). The aim of our study is to compare the incidences of dentin defects detected by stereomicroscope following the completion of root canal preparation using the ProTaper Universal (PTU, Dentsply-Maillefer, Ballaigues, Switzerland), ProTaper Next (PTN, Dentsply Maillefer, Ballaigues, Switzerland), Hyflex EDM (HEDM, Coltene/Whaledent, Altstätten, Switzerland), WaveOne (WO, Dentsply-Maillefer, Ballaigues, Switzerland), and WaveOne Gold (WOG, Dentsply-Maillefer, Ballaigues, Switzerland) rotary systems. The null hypothesis of this study was that there would be no difference between the instrument systems, the type of instrument movement, and the third of the root canals in terms of creating dentinal defect.

MATERIALS AND METHODS

Sample size calculation

To evaluate the incidence of dentin defects between any two groups, a difference of at least 8.5% is required in order to test the statistical significance at 85% power and 5% error level. The sample size calculated to be at least 12, and it was decided to have 15 samples in each group to increase the reliability of the data (n=15). The sample size calculated using the G * Power 3.0.10. (Franz Faul, Universität Kiel, Germany) package program.

Ethical approval

This study was conducted in accordance with the Declaration of Helsinki, with the approval of the ethics committee of Ankara University Faculty of Dentistry (numbered 36290600/51).

Selection and Preparation of Teeth

Human mandibular incisors extracted for periodontal reasons were used in this study. The teeth were kept in 0.5% sodium hypochlorite (NaOCl) solution for 24 hours after extraction and the attachments on them were removed with a periodontal curette. The presence of any cracks or defects in the roots was examined with a stereomicroscope (Carl Zeiss Microscopy GmbH, Munich, Germany) at x12 magnification.

Teeth without restoration, abrasion, crack, root fracture, calcification, resorption, open apices, and with an inclination angle <5°, apical opening accessible with a #10 K-file were used in the study. Radiographs of each tooth were taken from the buccolingual and mesiodistal aspects. Then, the teeth with more than one root canal and internal resorption were excluded. In order to ensure standardization between the groups, the diameters of the canals at a distance of 9 mm from the apex on the radiographs taken from the teeth were measured in the buccolingual and mesiodistal directions. The measurements obtained were evaluated by analysis of variance ($p=1.000$). 90 mandibular incisors meeting these criteria were selected. The teeth were kept in distilled water until the experiment began.

To ensure root length standardization, the teeth were cut with a diamond fissure bur (ISO 806314, 014, Meisinger, Germany) at a distance of 13 mm of the apex under water coolant. The working length was determined 1 mm away from the apical foramen with a #15 K-file (Dentsply Maillefer, Ballaigues, Switzerland). The roots were wrapped in a single layer of aluminum foil and embedded perpendicularly in acrylic resin (Meliodent, Bayer Dental, Leverkusen, Germany) using plastic moulds. After polymerization, the samples were taken out and the aluminum foils were removed. After the silicone-based impression material was applied to the acrylic resin mold, the samples were placed again and randomly divided into 6 groups according to the file system to be used ($n=15$).

Group 1: Negative Control No root canal preparation was performed.

Group 2: ProTaper Universal PTU files were used at 250 rpm and torque values specified by the manufacturer for each file. First, the coronal part of the root was prepared using the SX file at 250 rpm and 3.0 Ncm torque setting. Subsequently, 2/3 of the root was prepared using the S1 file at 3.0 Ncm and the S2 file at 1.0 Ncm torque setting, respectively. The preparation was then completed using F1 (20 / .07) and F2 (25 / .08) files at 1.5 and 2.0 Ncm torque settings, respectively.

Group 3: ProTaper Next First, the coronal part of the root was prepared using the SX file at 250 rpm and 3.0 Ncm torque setting. Then, the root canal system was prepared using X1 (17 / .04) and X2 (25 / .06) PTN files at 300 rpm speed and 2.0 Ncm torque setting, respectively.

Group 4: Hyflex EDM The HEDM (25 / .08) single file system is used with continuous rotation movement at 500 rpm and 2.5 Ncm torque setting with a forward-backward movement.

Group 5: WaveOne Primary The WO (25 / .08) single file system was used by selecting the WO mode of the endodontic motor.

Group 6: WaveOne Gold The WOG (25 / .07) single file system was used in the WOG mode of the endodontic motor.

In each group, the rotary instrument system was used with the endodontic motor (X-Smart Plus, Dentsply-Maillefer, Ballaigues, Switzerland) in accordance with the manufacturer's instructions. Each file was discarded after 5 uses. Irrigation was applied after every 3 back and forth movements in single file systems and after every file change in multiple file systems. 2 mL 2.5% NaOCl (Werax; İzmir, Turkey) and a 30-gauge irrigation needle (Cerkamed, Poland) were used for irrigation. When resistance was felt while using the file, the file was removed from the canal and re-irrigated with NaOCl. A total of 10 mL NaOCl was used to irrigate each root. Preparation was completed when the working length was reached. All roots were kept in distilled water during the experiment. All stages were carried out by a single operator.

Sectioning from roots

The distances of 3, 6 and 9 mm from the apex of all roots were measured with an electronic caliper and marked with a permanent marker. From the marked points, sections were taken perpendicular to the long axis of the teeth on the Micracut device (Mikracut 201; Metkon, Bursa, Türkiye), under water cooling, with a diamond-coated disc (Exakt 300 CL; Norderstad, Germany).

Examination of Sections by Stereomicroscope

Photographs of all sections were taken at x16 and x25 magnification with a digital camera (Olympus, Tokyo, Japan) connected to a stereomicroscope. A total of 270 digital images, 45 in each group, were examined by two independent endodontists. The sections that were interpreted differently were reevaluated and a consensus was reached. If there was no line in relation to the internal/external surface of the root in the sections, it was evaluated as "no defect", if found it was evaluated as "there is a defect". Incomplete cracks, complete cracks, or crazy lines were considered microcracks (6).

Statistical analysis

The SPSS program (Statistical Package for Social Sciences) Windows 17.0 version was used for the statistical analysis of the data. Chi-square and Fischer's exact tests were used to compare the obtained parameters. Significance was set at the $p<0.05$ level.

RESULTS

Representative stereomicroscope images of samples after root canal preparation according to the experimental groups are shown in Figures 1, 2, and 3. No defects were observed in the control group. The incidence of defects was highest at 3, 6, and 9 mm, respectively. The difference between the control and experimental groups was significant in sections of 3 and 6 mm ($p<0.05$). While the WO and HEDM groups at 3 mm showed a higher incidence of defects than the control group ($p=0.0005$), there is no difference between them ($p>0.05$). WO created more defects than PTN, WOG, and control groups ($p<0.001$). However there was no difference between the other groups ($p>0.05$) (Table 1). While there were significantly more cracks at the 3 mm level in the WO group ($p=0.027$), there was no difference between the sections in the other groups (Table 2).

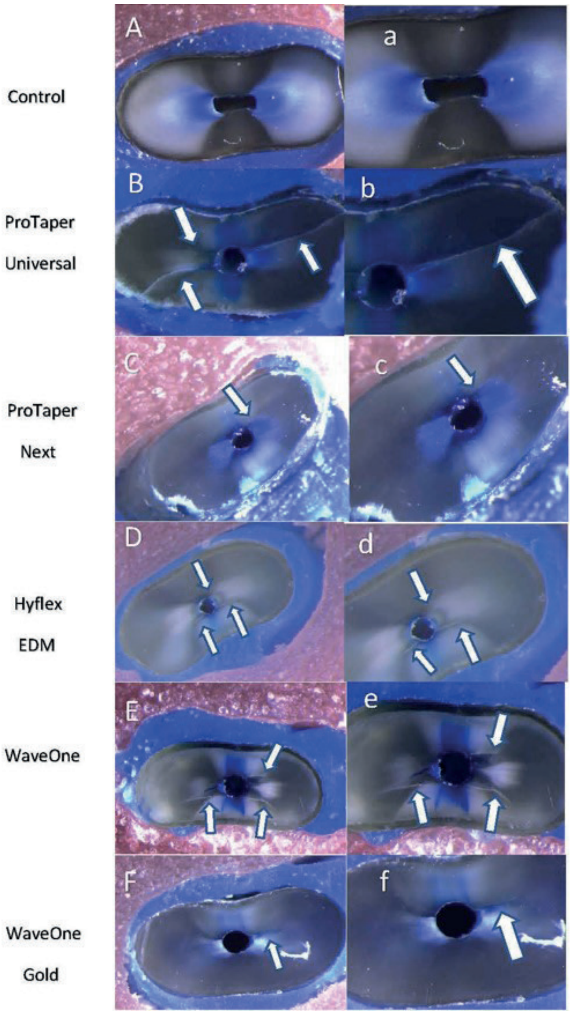

Figure 1. Images of horizontal sections taken at 3 mm from the apex at x16 (A, B, C, D, E, F) and x25 (a, b, c, d, e, f) magnifications according to the experimental groups. No cracks or defects were observed in the control group (A and a). Arrows indicate cracks and defects observed in the samples.

Table 1. Total number and percentage of sections with defects in different groups. Values with identical lowercase superscript letters indicate no significant difference (p < 0.05).

Groups	Number and percentage of cracked sections (%)			Total
	3 mm (χ^2:21,950)	6 mm (χ^2:17,504)	9 mm (χ^2:6,141)	
Control	0^{a} (0)	0^{a} (0)	0 (0)	0^{a} (0)
ProTaper Universal	$2^{a,b}$(13,3)	$1^{a,b}$ (6,7)	1 (6,7)	$4^{a,b}$ (8,8)
ProTaper Next	$1^{a,b}$ (6,7)	0^{a} (0)	0 (0)	1^{a} (2,2)
Hyflex EDM	$5^{b,c}$ (33,3)	$1^{a,b}$ (0)	2 (13,3)	$8^{b,c}$ (17,7)
WaveOne	9^{c} (60)	5^{b} (33,3)	2 (13,3)	16^{c} (35,5)
WaveOne Gold	$2^{a,b}$ (13,3)	0^{a} (0)	0 (0)	$2^{a,b}$ (4,4)
p value	0.0005	0.0036	0.2927	0.000013

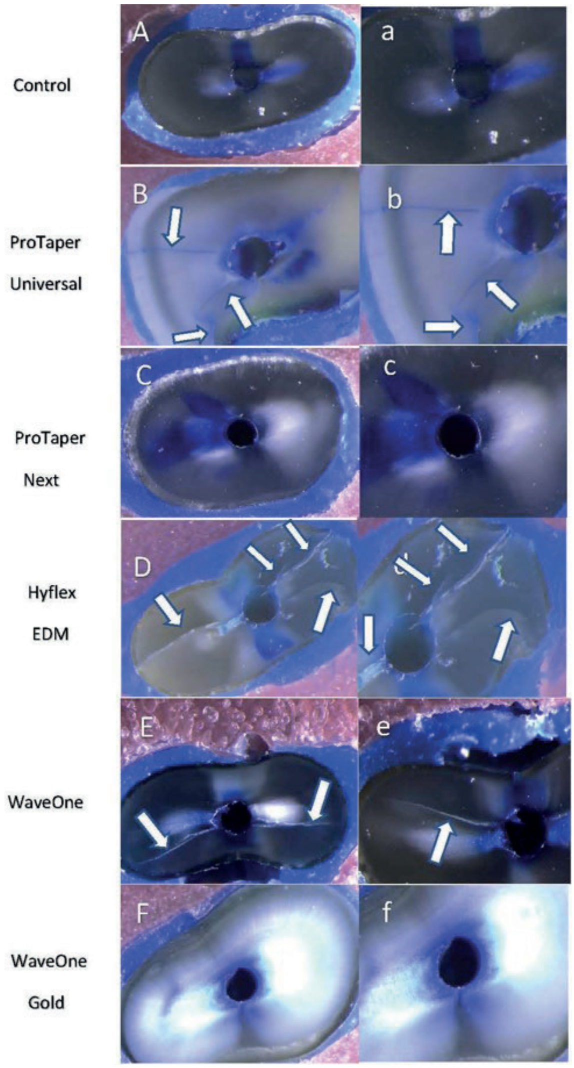

Figure 2. Images of horizontal sections taken at 6 mm from the apex at x16 (A, B, C, D, E, F) and x25 (a, b, c, d, e, f) magnifications according to the experimental groups. No cracks or defects were observed in the control group (A and a), ProTaper Next group (C and c), and WaveOne Gold group (F and f). Arrows indicate cracks and defects observed in the samples.

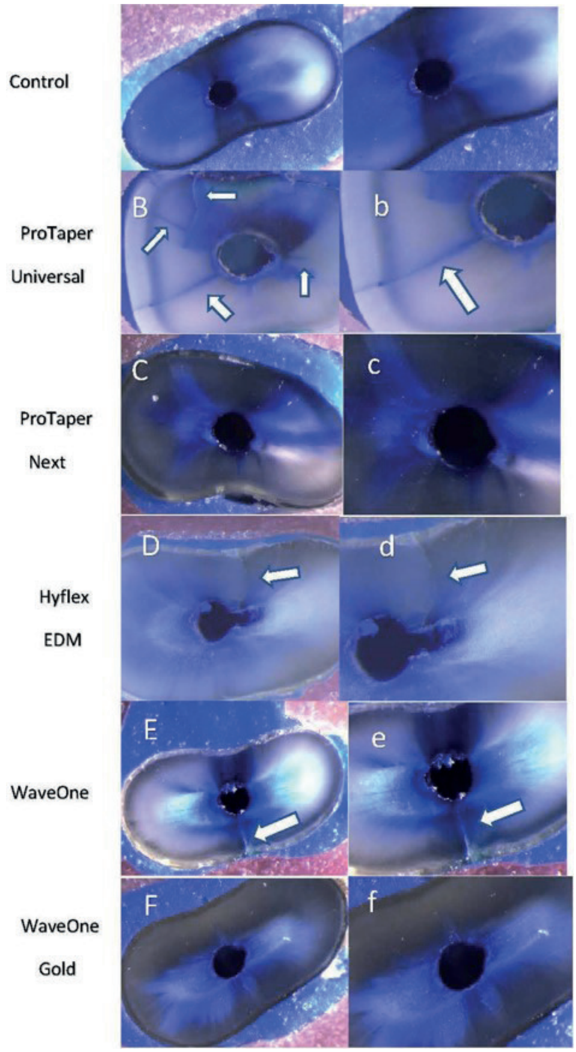

Figure 3. Images of horizontal sections taken at 9 mm from the apex at x16 (A, B, C, D, E, F) and x25 (a, b, c, d, e, f) magnifications according to the experimental groups. No cracks or defects were observed in the control group (A and a), ProTaper Next group (C and c), and WaveOne Gold group (F and f). Arrows indicate cracks and defects observed in the samples.

Table 2. The number and percentage (%) of sections with defects according to groups and levels. Within each group values with identical lowercase superscript letters indicate no significant difference ($p < 0.05$).

	Control	ProTaper Universal	ProTaper Next	Hyflex EDM	WaveOne	WaveOne Gold
3 mm	0	2 (13,3)	1 (6,7)	5 (33,3)	9^{a} (60)	2 (13,3)
6 mm	0	1 (6,7)	0 (0)	1 (6,7)	5^{b} (33,3)	0 (0)
9 mm	0	1 (6,7)	0 (0)	2 (13,3)	2^{b} (13,3)	0 (0)
p value		0.760		0.138	0.0276	

DISCUSSION

Mechanical preparation of root canals allows removal of infected dentin tissue, creation of a suitable form for hermetic canal filling, and prevention of reinfection (1). However, the rotary instrument systems used in mechanical preparation may cause micro-cracks in the dentin (2). Micro-cracks progress and often result in VRF which may require tooth extraction (4). In this study, we aimed to compare the incidence of defect formation in the root canal dentin after the use of PTU, PTN, HEDM, WO, and WOG NiTi instruments. The null hypothesis of this study was partially rejected. While a difference was observed between NiTi instruments and the third of the roots in terms of dentinal defects, motion kinematics did not cause a difference.

Mandibular incisors, which are more prone to microcrack development due to their narrow mesiodistal dimensions, were preferred in this study (5). In our study, dentin defects were formed in all samples except for the control group. Most defects were observed in 3 mm sections. The WO group showed statistically significantly higher incidence of defects in 3 and 6 mm sections, and no difference was observed among the groups at 9 mm. The incidence of defects decreased towards the coronal. In NiTi rotary files, stress is usually concentrated at the tip of the file and the apical region (11). Therefore, the files cause less stress in the coronal region compared to the apical region. The taper angle of the file is effective in the formation of defects in the root canal dentin (5). The taper angle at the apical end of the files is .08, .06, and .07 for WO, PTN X2, and WOG, respectively. This information may explain why more defects were observed in the WO group. Also, the total number of defects observed in all samples was significantly higher in the WO group compared to the PTU, PTN, and WOG groups.

The file design is also effective in increasing compressive and tensile forces in the apical region of the root (15). PTU and WO have a triangular and modified triangular cross-sectional geometry, while PTN has a rectangular cross sectional geometry. The different cross-sectional geometry of PTN may be accountable for less dentin defects in the apical region. In single file systems, more stress occurs after canal preparation. This may be the reason for more defects in the WO group compared to the PTU and PTN groups (1). At the same time, there were more defects in the single file system HEDM group than in the PTU and PTN groups in sections taken from 3 mm and 6 mm, but the difference was not significant. However, the single file system WOG produced significantly less dentin defects compared to the WO group. This may be because WOG is produced with a special heat-treated technology.

There is no consensus on the effect of motion kinematics on the formation of dentinal defects. It has been reported that rotary systems produce more [7] or less [1] dentin defects than reciprocal systems. On the other hand, some studies have not found any difference between motion kinematics (9) or claimed that reciprocal motion does not cause cracks regardless of the working length (16). In our study, there were significantly more defects in HEDM than in PTN in all sections. The higher conical angle of HEDM (.08) compared to PTN X2 (.06), using it at higher speed, and its crater-like surface feature due to the production method may have caused this result (17). Significantly less defects occurred in the WOG group compared to the WO group. This result was attributed to WOG (.07) having a lower taper and higher torsional tensile strength than the WO (.08) system. In the WO group, the most significant defect was observed in 3 mm sections, which is consistent with the study of Bürklein et al. (6). Cicek et al.[18] reported that there was no difference between the dentinal defects caused by PTU, PTN, WO and K-type hand files. The use of mandibular molar mesial roots and evaluating with scanning electron microscopy in this study may have caused the inconsistency in the results. Priya et al.[1] examined dentin defects occurring in both rotational and reciprocal motion kinematics of the PTU, PTN, OneShape, and Reciproc systems and found that PTN created less dentin defects in both movements compared to PTU. Similarly, in our study, PTN created less dentin defects than PTU group, but there was no difference. This may be due to the completion of root canal preparation with smaller size files in their study. Priya et al.[1] also reported that the rotational movement created more defects than the reciprocating movement. In our study, significantly more defects occurred in the WO group compared to PTU and PTN. Comparing WO and WOG both of which were used with reciprocal motion, more defects were observed in the WO group.

Karataş et al.[19] observed fewer defects in the PTN group in the apical regions compared to the PTU and WO groups. Üstün et al.[20] found no difference between the PTU and PTN groups. Ashraf et al.[21] reported that PTN produced fewer defects than the PTU group, but there was no difference between them. These results are consistent with our study. In line with our findings, Pedulla et al.[22] found no difference between the WOG and HEDM groups in their study, and they observed the most defects in the apical region. It was also observed that these two groups created less defects compared to the WO group. This may be due to the increased flexibility of the WOG and HEDM systems as a result of the heat treatments they are subjected to (2,19). Das et al.[23] reported in their study that there was no difference between PTN and HEDM groups. In our study, significantly more defects occurred in the HEDM group compared to the PTN group. In this study, methodological differences such as the use of mandibular premolar teeth, the creation of a glide path with a #15 K-type hand file, and coronal flaring with the Orifice Shaper before preparation may have caused inconsistencies in the results.

It has been reported that microcomputed tomography (micro-CT), which is a non-destructive method, is more reliable than stereomicroscopy because the sectioning procedure causes the dentinal microcrack development that did not present before the instrumentation (12). However, different results have been obtained in studies conducted with micro-CT. While no cracks were observed after the instrumentation (24-27), in some studies, on the contrary, cracks were observed (8,28-30). Recently, Chen et al.[31] reported that rotating NiTi systems cause dentinal microcracks in their study conducted with optical coherence tomography, which does not require sectioning procedure. Pradeep et al.[25] observed no microcracks in their in vivo study. These findings may be due to the use of young premolar teeth. However, in the current study we do not have any information about the age of the teeth used. This is also one of the limitations of our study. Another limitation of the current study is that microcracks may develop in the samples before instrumentation due to factors such as the force applied when extracting the teeth, the storage conditions(14,32), and the inability to control external factors while simulating clinical conditions(6), and the standardization of the force applied by the operator during preparation (2). De-Deus et al.[33] reported that the microcracks in the root dentin were caused by the extracted teeth, so the results of the studies reporting the presence of microcracks were flawed. Although it is not possible to exclude the possibility that these factors may also cause microcracks in root dentin(34), it is a strong evidence that no cracks were observed in the non-instrumented but sectioned control groups in several stereomicroscope studies (5-7,11,19,22,35-37). Hereby, the aforementioned factors are unlikely to affect the findings (34). In order to better evaluate the findings obtained from the stereomicroscope and micro-CT studies, future experiments are needed in which both methods are tested on the same samples (38).

CONCLUSION

All file systems used in this study created defects in dentin. HEDM used with rotational motion and WO used with reciprocal motion created more defects in dentin than the PTN, PTU and WOG groups. In the light of these findings obtained from this in vitro study, it is not possible to draw a definite conclusion about the effect of motion kinematics on the formation of dentinal defects, which is a multifactorial situation that depends not only on the type of movement but also on many different features such as the cross-section designs of the files, taper angles, and the structure of the alloy.

Ethics Committee Approval: The study protocol was approved by the Ankara University Faculty of Dentistry Clinical Research Ethics Committee (18.04.2018 / 07/04).

Conflict of Interest: The authors have declared that they have no conflict of interest.

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REFERENCES

1. Priya NT, Chandrasekhar V, Anita S, et al. “Dentinal microcracks after root canal preparation” a comparative evaluation with hand, rotary and reciprocating instrumentation. J Clin Diagn Res. 2014; 8(12): ZC70-2. https://doi.org/10.7860/JCDR/2014/11437.5349
2. Capar ID, Arslan H, Akcay M, Uysal B. Effects of ProTaper Universal, ProTaper Next, and HyFlex instruments on crack formation in dentin. J Endod. 2014; 40(9): 1482-4. https://doi.org/10.1016/j.joen.2014.02.026
3. Cohen S, Blanco L, Berman L. Vertical root fractures: clinical and radiographic diagnosis. J Am Dent Assoc. 2003; 134(4): 434-41. https://doi.org/10.14219/jada.archive.2003.0192
4. Tsesis I, Rosen E, Tamse A, Taschieri S, Kfir A. Diagnosis of vertical root fractures in endodontically treated teeth based on clinical and radiographic indices: a systematic review. J Endod. 2010; 36(9): 1455-8. https://doi.org/10.1016/j.joen.2010.05.003
5. Bier CA, Shemesh H, Tanomaru-Filho M, Wesselink PR, Wu MK. The ability of different nickel-titanium rotary instruments to induce dentinal damage during canal preparation. J Endod. 2009; 35(2): 236-8. https://doi.org/10.1016/j.joen.2008.10.021
6. Bürklein S, Tsotsis P, Schäfer E. Incidence of dentinal defects after root canal preparation: reciprocating versus rotary instrumentation. J Endod. 2013; 39(4): 501-4. https://doi.org/10.1016/j.joen.2012.11.045
7. 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. J Endod. 2013; 39(8): 1054-6. https://doi.org/10.1016/j.joen.2013.04.013
8. Ceyhanli KT, Erdilek N, Tatar I, Celik D. Comparison of ProTaper, RaCe and Safesider instruments in the induction of dentinal microcracks: a micro-CT study. Int Endod J. 2016; 49(7): 684-9. https://doi.org/10.1111/iej.12497
9. Arias A, Lee YH, Peters CI, Gluskin AH, Peters OA. Comparison of 2 canal preparation techniques in the induction of microcracks: a pilot study with cadaver mandibles. J Endod. 2014; 40(7): 982-5. https://doi.org/10.1016/j.joen.2013.12.003
10. Wilcox LR, Roskelley C, Sutton T. The relationship of root canal enlargement to finger-spreader induced vertical root fracture. J Endod. 1997; 23(8): 533-4. https://doi.org/10.1016/S0099-2399(97)80316-0
11. Adorno CG, Yoshioka T, Suda H. Crack initiation on the apical root surface caused by three different nickel-titanium rotary files at different working lengths. J Endod. 2011; 37(4): 522-5. https://doi.org/10.1016/j.joen.2010.12.002
12. De-Deus G, Silva EJ, Marins J, et al. Lack of causal relationship between dentinal microcracks and root canal preparation with reciprocation systems. J Endod. 2014; 40(9): 1447-50. https://doi.org/10.1016/j.joen.2014.02.019
13. 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 Dent J. 2015; 36: 29-33. https://doi.org/10.1016/j.sdj.2015.09.003
14. Coelho MS, Card SJ, Tawil PZ. Visualization Enhancement of Dentinal Defects by Using Light-Emitting Diode Transillumination. J Endod. 2016; 42(7): 1110-3. https://doi.org/10.1016/j.joen.2016.04.006
15. Kim HC, Lee MH, Yum J, Versluis A, Lee CJ, Kim BM. Potential relationship between design of nickel-titanium rotary instruments and vertical root fracture. J Endod. 2010; 36(7): 1195-9. https://doi.org/10.1016/j.joen.2010.02.010
16. Belladonna FG, Rodrigues LLC, Leal ASM, et al. Is canal overinstrumentation able to produce apical root dentinal microcracks in extracted teeth? Int Endod J. 2021; 54(9): 1647-52. https://doi.org/10.1111/iej.13540
17. Pirani C, Iacono F, Generali L, et al. HyFlex EDM: superficial features, metallurgical analysis and fatigue resistance of innovative electro discharge machined NiTi rotary instruments. Int Endod J. 2016; 49(5): 483-93. https://doi.org/10.1111/iej.12470
18. Çiçek E, Koçak MM, Sağlam BC, Koçak S. Evaluation of microcrack formation in root canals after instrumentation with different NiTi rotary file systems: a scanning electron microscopy study. Scanning. 2015; 37(1): 49-53. https://doi.org/10.1002/sca.21178

19. Karataş E, Gündüz HA, Kırıcı DÖ, Arslan H, Topçu MÇ, Yeter KY. Dentinal crack formation during root canal preparations by the twisted file adaptive, ProTaper Next, ProTaper Universal, and WaveOne instruments. J Endod. 2015; 41(2): 261-4. https://doi.org/10.1016/j.joen.2014.10.019
20. Ustun Y, Aslan T, Sagsen B, Kesim B. The effects of different nickel-titanium instruments on dentinal microcrack formations during root canal preparation. Eur J Dent. 2015; 9(1): 41-6. https://doi.org/10.4103/1305-7456.149638
21. Ashraf F, Shankarappa P, Misra A, Sawhney A, Sridevi N, Singh A. A Stereomicroscopic Evaluation of Dentinal Cracks at Different Instrumentation Lengths by Using Different Rotary Files (ProTaper Universal, ProTaper Next, and HyFlex CM): An Ex Vivo Study. Scientifica (Cairo). 2016; 2016: 8379865. https://doi.org/10.1155/2016/8379865
22. Pedullà E, Genovesi F, Rapisarda S, et al. Effects of 6 Single-File Systems on Dentinal Crack Formation. J Endod. 2017; 43(3): 456-61. https://doi.org/10.1016/j.joen.2016.10.038
23. Das S, Pradhan PK, Lata S, Sinha SP. Comparative evaluation of dentinal crack formation after root canal preparation using ProTaper Next, OneShape, and Hyflex EDM. J Conserv Dent. 2018; 21(2): 153-6. https://doi.org/10.4103/JCD.JCD_219_17
24. De-Deus G, César de Azevedo Carvalhal J, Belladonna FG, et al. Dentinal Microcrack Development after Canal Preparation: A Longitudinal in Situ Micro-computed Tomography Study Using a Cadaver Model. J Endod. 2017; 43(9): 1553-8. https://doi.org/10.1016/j.joen.2017.04.027
25. PradeepKumar AR, Shemesh H, Archana D, et al. Root Canal Preparation Does Not Induce Dentinal Microcracks In Vivo. J Endod. 2019; 45(10): 1258-64. https://doi.org/10.1016/j.joen.2019.06.010
26. Martins J, Oliveira BP, Duarte DA, Antonino ACD, Aguiar CM, Câmara AC. Micro-computed tomographic assessment of dentinal microcrack formation in straight and curved root canals in extracted teeth prepared with hand, rotary and reciprocating instruments. Int Endod J. 2021; 54(8): 1362-8. https://doi.org/10.1111/iej.13521
27. Miguéns-Vila R, Martín-Biedma B, De-Deus G, Belladonna FG, Peña-López A, Castelo-Baz P. Micro-computed Tomographic Evaluation of Dentinal Microcracks after Preparation of Curved Root Canals with ProTaper Gold, WaveOne Gold, and ProTaper Next Instruments. J Endod. 2021; 47(2): 309-14. https://doi.org/10.1016/j.joen.2020.10.014
28. Bayram HM, Bayram E, Ocak M, Uygun AD, Celik HH. Effect of ProTaper Gold, Self-Adjusting File, and XP-endo Shaper Instruments on Dentinal Microcrack Formation: A Micro-computed Tomographic Study. J Endod. 2017; 43(7): 1166-9. https://doi.org/10.1016/j.joen.2017.02.005
29. Aggarwal A, Nawal RR, Yadav S, Talwar S, Kunnoth S, Mahajan P. Comparative Evaluation of Dentinal Microcrack Formation before and after Root Canal Preparation Using Rotary, Reciprocating, and Adaptive Instruments at Different Working Lengths-A Micro-computed Tomographic Study. J Endod. 2021; 47(8): 1314-20. https://doi.org/10.1016/j.joen.2021.05.004
30. 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. J Endod. 2019; 45(3): 338-42. https://doi.org/10.1016/j.joen.2018.12.005
31. Chen C, Zhang W, Liang Y. Evaluation of apical root defects during canal instrumentation with two different nickel-titanium (NiTi) systems by optical coherence tomography (OCT) scan. J Dent Sci. 2022; 17(2): 763-70. https://doi.org/10.1016/j.jds.2021.10.009
32. Shemesh H, Lindtner T, Portoles CA, Zaslansky P. Dehydration Induces Cracking in Root Dentin Irrespective of Instrumentation: A Two-dimensional and Three-dimensional Study. J Endod. 2018; 44(1): 120-5. https://doi.org/10.1016/j.joen.2017.07.025
33. De-Deus G, Cavalcante DM, Belladonna FG, et al. Root dentinal microcracks: a post-extraction experimental phenomenon?. Int Endod J. 2019; 52(6): 857-65. https://doi.org/10.1111/iej.13058
34. Fráter M, Jakab A, Braunitzer G, Tóth Z, Nagy K. The potential effect of instrumentation with different nickel titanium rotary systems on dentinal crack formation-An in vitro study. PLoS One. 2020; 15(9): e0238790. https://doi.org/10.1371/journal.pone.0238790
35. Üstün Y, Topçuoğlu HS, Düzgün S, Kesim B. The effect of reciprocation versus rotational movement on the incidence of root defects during retreatment procedures. Int Endod J. 2015; 48(10): 952-8. https://doi.org/10.1111/iej.12387
36. 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. https://doi.org/10.5395/rde.2019.44.e31
37. Rahman H, Chandra A, Khangwal M, Goel A, Shakya VK. Stereomicroscopic Evaluation of Microcrack Formation in Dentin by ProTaper Next, Revo S, and WaveOne Gold File System. Contemp Clin Dent. 2021; 12(4): 439-43. https://doi.org/10.4103/ccd.ccd_760_20
38. Zaslansky P, Prates Soares A, Shemesh H. Root dentinal microcracks - absence of evidence is not evidence of absence. Int Endod J. 2020; 53(1): 135-6. https://doi.org/10.1111/iej.13207