

# Influence of Optimum Torque Reverse Motion on Dentinal Cracks after Root Canal Preparation with Two Nickel-Titanium Rotary Systems

## Abstract

**Objectives:** This study was aimed to evaluate the cause-effect relationship between canal preparation with ProTaper Next (PTN) and ProTaper Gold (PTG) using optimum torque reverse (OTR) motion or continuous rotation and dentinal crack formation. **Materials and Methods:** Fifty distobuccal roots of human maxillary first molars were divided into five groups; Group I: PTG Full rotation, Group II: PTG in OTR, Group III: PTN Full rotation, Group IV: PTN in OTR, Group V: unprepared (control group). After mechanical preparation, the distobuccal roots were sectioned horizontally at 3, 6, and 9 mm from the apex. Images were captured using a stereomicroscope at 25X to determine the presence or absence of dentinal cracks. Friedman test was used to compare between root sections followed by Wilcoxon signed-rank test for pairwise comparison. Kruskal–Wallis test was used to compare between tested rotary systems followed by pairwise comparison with Dunn Bonferroni correction ( $\alpha = 0.05$ ). **Results:** Crack development was significantly higher in PTG using OTR motion 36.7% followed by PTN using OTR 33.3%, while the control group showed no cracks. PTG and PTN with full rotation showed crack development with 23.3% and 13.3%, respectively. **Conclusions:** The type of motion kinematics used during mechanical preparation have an impact on dentinal crack formation. Nickel-titanium instruments with larger taper tend to induce more cracks.

**Keywords:** *Dentinal cracks, optimum torque reverse, ProTaper gold, ProTaper next, Vertical root fracture*

## Introduction

Vertical root fracture (VRF) is one of the most frustrating complications of root canal treatment. The principal factor that causes endodontically treated teeth to fracture is coronal and radicular tooth structure loss due to prior pathology or endodontic and/or restorative treatment procedures.<sup>[1]</sup> Endodontic treatment procedures may also cause structural changes<sup>[2]</sup> or loss of tooth substance due to chemo-mechanical preparation which may have harmful effect on the tooth itself.<sup>[3-5]</sup> Chemomechanical preparation of the root canals involves, contact between the instrument and canal walls that could exert stresses on the dentin that may cause micro-cracks and craze lines.<sup>[2]</sup> Those micro-cracks could propagate under occlusal forces and cause VRF.<sup>[2,3]</sup> Studies have linked between the amount of dentin removed and consequent crack formation with excessive dentin removal. How much dentin is required to be removed to ensure complete eradication of

microorganisms without causing excessive damage to the sound dentin is still not completely known.<sup>[6,7]</sup> In addition, stresses applied during the obturation phase may also lead to the development of VRFs.<sup>[3]</sup>

The use of nickel titanium (NiTi) rotary instruments produces rotational force that can create microcracks or craze lines in root dentin. The formation as well as the extension of such defect may be related to different geometrical features of the file, such as the tip design, cross-section geometry, constant or progressive taper type, constant or variable pitch, and flute form.<sup>[8,9]</sup> Additional factor that may influence the incidence of dentinal defects is the motion kinematics (continuous rotation, reciprocation with different angles, or adaptive motion) used during root canal instrumentation.

Root ZX II Low Speed Handpiece offers an optimum torque reverse (OTR) function. A new kinematics developed specifically as studies have reported that a reciprocating motion might increase NiTi

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instruments' resistance to fatigue, and thus extend its life span, with respect to continuous rotation.<sup>[10-12]</sup> However, the reciprocating motion has also the disadvantage that debris are carried towards the apex.<sup>[13]</sup> Subsequently, continuous innovations are being developed to exploit reciprocation's benefits and reduce its disadvantages. In OTR motion, automatic measurement of the torque is done, as long as the torque is below the set value, clockwise (CW) rotation of the file continues, but when the torque is above the set value, rotation of the file is reversed in a counter CW (CCW) direction by 90° and then continues in the cutting direction (CW) for 180° until the torque decreases again below the set value, with maximum torque level in OTR mode of 1.0 Ncm.<sup>[10]</sup> According to the manufacturer, OTR decreases file fatigue, and the incidence of file separation.<sup>[10]</sup> It is reasonable to assume that the new motion might affect the stresses applied into the root canal dentin during instrumentation.

ProTaper Gold (PTG; Dentsply Tulsa Dental Specialties) instruments have a file design features that matches ProTaper Universal (PTU); however, it is developed through an advanced metallurgy, according to the manufacturer, these instruments are more flexible and have fatigue resistance superior to PTU.<sup>[11]</sup>

ProTaper Next (PTN; Dentsply Maillefer, Ballaigues, Switzerland) are made of M-wire, a distinctive NiTi alloy that increases flexibility and resistance to cyclic fatigue due to thermal treatment process.<sup>[12]</sup> According to the manufacturer, PTN has a design of variable regressive taper and rectangular cross section, this design helps to decrease points of contact with the canal walls thus creating less fatigue in the instrument during use.

There is only limited information about OTR motion. In particular, the effect of root canal instrumentation with OTR motion on the dentinal crack formation. Therefore, the purpose of the present study was to assess the effect of root canal instrumentation using PTN and PTG instruments with different kinematics (continuous rotation and OTR motion) on dentinal crack formation. The null hypothesis tested was that using the OTR motion has no influence on the incidence of dentinal defects.

## Materials and Methods

### Sample selection

After the approval of the ethical committee at the National Research Centre (no. 16/344), 50 human maxillary first molars with completely separated roots extracted for periodontal reasons from the department of Oral Surgery, Minia University were selected for the current study. All roots were initially inspected with a stereomicroscope (Olympus BX43; Olympus Co., Tokyo, Japan) under ×12 to detect and exclude teeth with any visible preexisting craze lines or cracks. Preoperative periapical radiographs were taken to inspect the distobuccal

root and to determine the angle of root curvature. The inclusion criteria included complete root formation, no internal root calcification, no internal or external root resorption, canal curvatures between 20° and 35° according to Schneider's method.<sup>[14]</sup> Teeth were stored in 0.1% thymol until the beginning of the experiment, but no longer than 2 weeks after extraction.

### Preparation of the samples

The crowns were sectioned using a water-cooled safe sided diamond disc leaving 3 mm above the cemento-enamel junction. The distobuccal roots were separated by using a low-speed saw (Isomet; Buhler Ltd, Lake Bluff, NY) with water-cooling. Patency was checked and the working length was determined by subtracting 1 mm from the apical foramen.

### Root canal preparation

A #15 K-file (Maillefer, Ballaigues, Switzerland) was used to establish a glide path. The samples were randomly divided using (<https://www.randomizer.org>) into five equal groups ( $n = 10$  canals per group) as follows:

- Group I: PTG full rotation
- Group II: PTG OTR mode
- Group III: PTN full rotation
- Group IV: PTN OTR mode
- Group V: Control group left unprepared.

Before instrumentation, the roots of all teeth were covered with a thin layer of polyvinylsiloxane impression material (Elite HD, Zhermack, Italy) to simulate the periodontal ligament, then mounted vertically in copper rings and filled with self-curing acrylic resin (Acrostone dental factory, Industrial Zone, Salam City, Egypt).

The instrument sequence in the PTG groups was S1 (17/02), S2 (20/04), F1 (20/07), and F2 (25/08), the Shaping Files were used with a brushing action on the withdrawal stroke, at 300 RPM and a torque of 5 Ncm for S1 and SX, 1.50 Ncm for S2 and F1, and 3 Ncm for F2 according to the manufacturer instructions.

In the PTN groups, the sequence used was X1 (17/04) and X2 (25/06), at 300 RPM and a torque of 4 Ncm according to the manufacturer instructions. After 3 gentle in-and-out strokes in an apical direction, the instrument was removed from the canal and cleaned. This was repeated until the WL was reached, then the instrument was discarded.

Root canal preparation was performed using X-smart plus endodontic motor (Dentsply, Tulsa Dental, Tulsa, OK) in the full rotation groups, and with the Root ZX II Low-Speed Handpiece (J. Morita Corp., Osaka, and Tokyo, Japan) which was set to its specific OTR mode. Freshly prepared 2.5% sodium hypochlorite solution (NaOCl; Clorox, HC Egyptian company, Cairo, Egypt) was used as an irrigant during instrumentation with 30 G needle tips (NaviTip, Ultradent, South Jordan, UT, USA) 1 mm

short from the working length, followed by a 5-mL rinse with distilled water. Canals were dried with paper points (Dentsply Sirona, York, Pennsylvania).

### Sectioning and microscopic examination

All roots were sectioned perpendicular to the long axis at 3, 6, and 9 mm from the apex using a low-speed saw (Isomet, Buehler Ltd, Lake Bluff, IL, USA) under water cooling. Digital images of each section were captured at  $\times 25$  magnification using a digital camera attached to a stereomicroscope (Olympus BX43; Olympus Co., Tokyo, Japan). To avoid any artifacts induced by sample dehydration, all teeth were kept moist in purified filtered water throughout all experimental procedures.

In each group, the coronal surface of a total of 30 slices was blindly examined for cracks. To define crack formation, two different categories were made as no cracks and cracked. To avoid the confusing description of root cracks, a crack was defined if only defects were originating from the inner root canal space [Figure 1]. All other defects that did not originate from the canal wall as craze lines were not considered as cracks.<sup>[9]</sup> All root canal preparations were performed by the same operator (RH) and the assessments of the cross-sections for determining the frequency of cracks were performed by another calibrated examiner (MK) who were blinded to all experimental groups.

### Statistical analysis

Data were explored for normality using Kolmogorov–Smirnov and Shapiro–Wilk tests, data showed nonparametric distribution. Friedman was used to compare between root section followed by Wilcoxon signed-rank test for pairwise comparison. Kruskal–Wallis was used to compare between

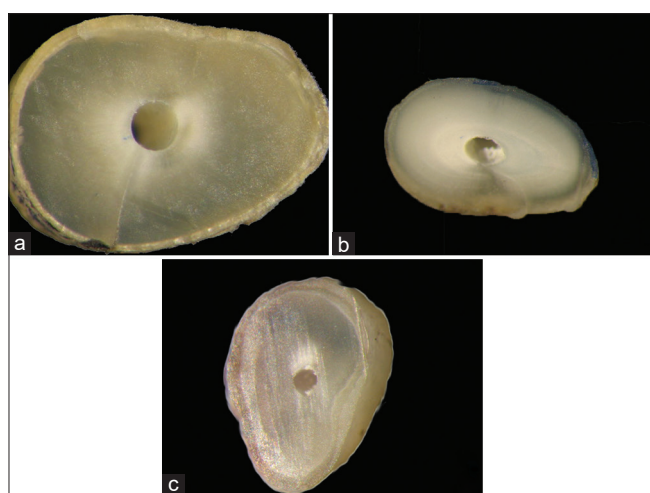


Figure 1: Stereomicroscope cross-sectional images (X25) of distobuccal roots of first maxillary molars. (a and b): Coronal and middle thirds respectively showing the presence of complete cracks extending from the root canal wall to the outer surface of the root after preparation with ProTaper Gold using optimum torque reverse motion, (c) middle cross section with no cracks after preparation with ProTaper Next using optimum torque reverse motion

tested rotary system followed by pairwise comparison with Dunn Bonferroni correction ( $\alpha = 0.05$ ) (IBM SPSS Statistics for Windows, Version 20.0. Armonk, NY: IBM Corp.).

### Results

During mechanical preparation, neither instrument fracture nor loss of working length was encountered in any of the samples. PTG OTR showed the greater potential for crack development with 36.7% followed by PTN OTR with 33.3% with no significant difference. PTG and PTN with full rotation showed crack development with 23.3% and 13.3%, respectively [Table 1].

The four tested groups showed significantly higher mean values compared to the control which showed no cracks development ( $P < 0.003$ ). Comparing the cracks developed in the three sections, For the PTN full rotation group, no difference was found between all sections. On the other hand, PTN using the OTR motion showed a significant higher cracked root percentage at the coronal section at 9 mm with 4 cracked roots. The same result was found in the PTG with Full rotation group; with 5 cracked roots at the coronal section [Figure 2].

### Discussion

VRF has been identified as a leading cause of the extraction of endodontically treated teeth.<sup>[15]</sup> Although the occurrence of VRF in teeth is unpredictable and is considered to be a multifactorial disease, concerns are raised on the effect of the root canal treatment procedures as a predisposing factor for VRF incidence. Root canal instrumentation is considered to be one of these risk factors that leads to the formation of incomplete root dentinal cracks.<sup>[4,5,16]</sup> These incomplete cracks may act as concentration areas; where the crack might propagate to the root canal surface causing fractures during retreatment or after long-term functional stresses like chewing.<sup>[3,17]</sup> In the present work, the incidence of crack formation on the distobuccal canal of maxillary first molars prepared with two NiTi systems (PTG and PTN) using either Full rotation or OTR motion were tested.

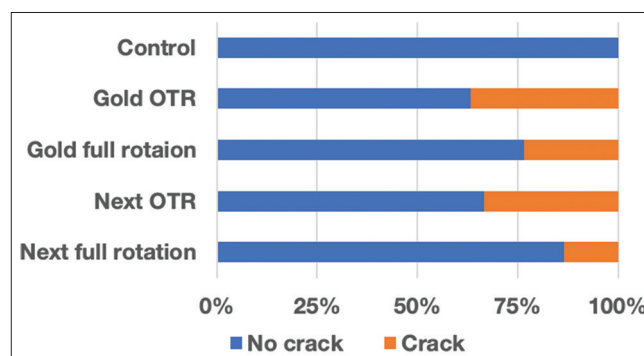


Figure 2: Bar chart showing crack formation in different cross-sectional levels of different tested groups

**Table 1: Number of cracked and noncracked samples in both ProTaper next and ProTaper gold groups with full rotation or optimum torque reverse**

Variables	Cracks, n (%)
PTN/full rotation	
Cracked	4 <sup>a,b</sup> (13.30)
No cracks	26 (86.70)
PTN/OTR	
Cracked	10 <sup>b</sup> (33.30)
No cracks	20 (66.70)
PTG/full rotation	
Cracked	7 <sup>a,b</sup> (23.30)
No cracks	23 (76.70)
PTG/OTR	
Cracked	11 <sup>b</sup> (36.70)
No cracks	19 (63.30)
Control	
Cracked	0 <sup>a</sup> (0)
No cracks	30 (100)
<i>P</i>	0.003*

Superscripts with different small letters in the same column indicate statistically significance difference. \*Significant ( $P < 0.05$ ). OTR: Optimum torque reverse, PTN: ProTaper next, PTG: ProTaper gold

Different methods for the assessment of the development of dentinal microcracks after root canal treatment procedures have been suggested previously, starting from simple methodologies like stereomicroscopy<sup>[3,4]</sup> to overly complicated technologies such as magnetic resonance imaging<sup>[18]</sup> and micro-computed tomographic (micro-CT) imaging,<sup>[19,20]</sup> nonetheless lots of controversies exist about each method. An ongoing search is required for the best method for the evaluation of the presence of dentinal defects. Micro-CT imaging is a noninvasive method for dentinal crack assessment. It allows three-dimensional visualization and measurements of the internal microstructure of opaque objects without requiring and damage, cutting or preparation of the sample or even chemical fixation with the advantage of examining the specimen before and after instrumentation. While De-Deus *et al.*,<sup>[21]</sup> found that Micro-CT was as reliable as stereomicroscopy in detecting dentinal defects, however, the risk of temperature rise due to the use of high-resolution micro-CT scan was found to cause dehydration of the samples which could initiate new cracks or augment already existing microcracks.<sup>[22,23]</sup>

In the current study, stereomicroscopy attached to digital camera was used to assess the presence of dentinal defects after root canal preparation with the tested NiTi systems. A low-speed saw (Isomet, Buehler Ltd, Lake Bluff, IL, USA) was used to slice the roots under water coolant to prevent sample dehydration at 3, 6, and 9 mm from the apex. The control group in this study showed no defects, confirming that any dentinal defects detected consequently happened during the instrumentation procedures,<sup>[4,5,24]</sup>

Previous studies evaluated the possible effect of the force applied during tooth extraction,<sup>[19]</sup> thus the inclusion criteria for teeth selected in this study was limited to those extracted for periodontal reasons which require only minimal force to extract.

The results of the present study revealed that dentinal cracks occurred independently of the type of instrument or the motion used during root canal instrumentation [Figure 1]. Several studies had similar results to ours, where they found that root canal instrumentation with NiTi systems might cause cracks in root dentin, this could be attributed to the high taper of rotary NiTi instruments and the higher number of rotations in the canal required to complete a preparation.<sup>[4,24,25]</sup>

PTG OTR showed higher potential for crack formation with 36.7% followed by PTN OTR with 33.3% with a significantly higher value compared to the control group which showed no cracks developed [Table 1]. PTG and PTN with full rotation showed crack development with 23.3% and 13.3% respectively with no significant difference between each other. The varying degree of taper of root canal shaping instruments as well as the difference in the cross-section geometry are the most common contributing factor for crack formation in root dentin.<sup>[24,26]</sup> The PTG has a triangular cross-section geometry while the PTN instruments have an offset rectangular cross-sectional design combined with the asymmetrical rotary motion, where the file only contacts the wall at 2 points. This results in the reduced contact area between the instruments' cutting edges and the canal wall which limits the undesirable taper lock, and provides more cross-sectional space for enhanced cutting and loading of debris, this lowers the frictional forces to the canal wall, leading to fewer dentinal defects.<sup>[22]</sup>

PTN files were used namely X1, X2, with corresponding taper 17/04, 25/06, while PTG F1, F2 with corresponding taper 20/7%, 25/8%. The larger taper of the PTG system used could be one of the reasons contributing to the higher cracks percentage. These results come in accordance with Capar *et al.*<sup>[27]</sup> who concluded that the swaggering motion and less taper of the PTN instruments produce lesser dentinal defects. Not only the M-wire alloy requires less pressure on the instrument during instrumentation but also less pressure is exerted on the root canal walls, thus inducing less stresses on the root canal walls, moreover, the flexibility of PTN rotary files offered by the M-Wire technology may have contributed to the less number of dentinal defects formation.<sup>[28]</sup> In the current study, the torque settings for the chosen NiTi instruments followed the manufacturer instruction, however, Dane *et al.* 2016<sup>[29]</sup> correlated between the increase in the torque setting with increased crack formation due to greater stress on the dentinal surface which could explain the results of this study.

The recently developed OTR kinematic is considered a torque-sensitive reciprocal rotation<sup>[30,31]</sup> or a partial

reciprocation with CW rotational effect, thus, it can be used with instruments that cut in a CW direction such as the PTN and PTG. Data for direct comparison between the OTR motion and full rotation used in this investigation on the crack formation are currently unavailable. As to the best of our knowledge, neither the use of PTN and PTG using the OTR motion nor the effect of OTR on crack formation was previously reported.

It's theoretically presumed that the reciprocating motion can decrease the torsional stresses and decreases the screwing effect of the instrument,<sup>[32]</sup> based on the balanced forced technique, CW and CCW rotations allow the instrument to cut and then disengage dentin. It also creates less invasive root canal preparations by increasing canal centering. In a study by Pedullà *et al.*,<sup>[33]</sup> the reciprocating OTR motion were found to improve the time to fracture of all instruments used and improved significantly cyclic fatigue resistance of all instruments, PTN, Revo-S (MicroMega, Besançon, France), Mtwo (VDW, Munich, Germany), Twisted Files (SybronEndo, Orange, CA) and EndoWave (FKG Dentaire, La Chaux-de-Fonds, Switzerland) as compared to continuous rotation. Unfortunately, the effect of this motion on the dentin and the crack formation were not inspected in their study to correlate between the improved cyclic fatigue resistance with the effect of the OTR on root canal dentin.

According to Bürklein *et al.*,<sup>[22]</sup> reciprocating instruments are more linked with the development or propagation of dentin microcracks than conventional full-sequence rotary systems. As most of the reciprocating instruments available are based on the single file system which during mechanical preparation cuts substantial amounts of dentin in a short time, which tends to create or aggravate more dentinal defects. Previously published study by Gergi *et al.*,<sup>[34]</sup> reported that reciprocating instrument; Reciproc (VDW, Munich, Germany) and WaveOne (Dentsply Maillefer, Ballaigues, Switzerland) were accompanied with more complete cracks compared with rotary instruments; twisted files adaptive (SybronEndo, Orange, CA). Again, a study by Priya *et al.*<sup>[35]</sup> found that the crack formation with PTN using full rotation was less compared to using the same file system in reciprocation motion with no significant difference. In the current study, both NiTi files caused more crack formation when used in OTR motion than in continuous rotation with no significant difference, thus the null hypothesis was rejected [Table 1]. The reciprocal component of the OTR motion could be responsible for the increased tendency for crack formation, it could be assumed that the reciprocation motion decreases the stresses on the rotary files and increases the stresses on the canal wall. Future studies which focus on the stresses created by OTR motion during cutting in the root canal dentin are therefore required.

## Conclusions

The results of the present study revealed that canal preparation using the OTR motion did not reduce the

incidence of dentinal crack formation. Both tested NiTi rotary systems can create dentinal cracks. NiTi instruments with larger taper tend to induce higher degrees of dentinal damages during root canal preparation.

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## Conflicts of interest

There are no conflicts of interest.

## References

1. Haueisen H, Gärtner K, Kaiser L, Trohorsch D, Heidemann D. Vertical root fracture: Prevalence, etiology, and diagnosis. *Quintessence Int* 2013;44:467-74.
2. Kishen A. Mechanisms and risk factors for fracture predilection in endodontically treated teeth. *Endod Topics* 2006;13:57-83.
3. Wilcox LR, Roskelley C, Sutton T. The relationship of root canal enlargement to finger-spreader induced vertical root fracture. *J Endod* 1997;23:533-4.
4. Shemesh H, Bier CA, Wu MK, Tanomaru-Filho M, Wesselink PR. The effects of canal preparation and filling on the incidence of dentinal defects. *Int Endod J* 2009;42:208-13.
5. Adorno CG, Yoshioka T, Suda H. The effect of working length and root canal preparation technique on crack development in the apical root canal wall. *Int Endod J* 2010;43:321-7.
6. Mickel AK, Chogle S, Liddle J, Huffaker K, Jones JJ. The role of apical size determination and enlargement in the reduction of intracanal bacteria. *J Endod* 2007;33:21-3.
7. Plotino G, Özyürek T, Grande NM, Gündoğar M. Influence of size and taper of basic root canal preparation on root canal cleanliness: A scanning electron microscopy study. *Int Endod J* 2019;52:343-51.
8. 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. *J Endod* 2012;38:232-5.
9. Hin ES, Wu MK, Wesselink PR, Shemesh H. Effects of self-adjusting file, Mtwo, and ProTaper on the root canal wall. *J Endod* 2013;39:262-4.
10. J Morita CORP; 2021. Available from: <https://www.morita.com/group/en/products/endodontic-systems/apex-location-and-canal-preparation-systems/tri-auto-zx2/>. [Last accessed on 2020 Oct 09].
11. Arias A, Singh R, Peters OA. Torque and force induced by ProTaper universal and ProTaper next during shaping of large and small root canals in extracted teeth. *J Endod* 2014;40:973-6.
12. Ye J, Gao Y. Metallurgical characterization of M-Wire nickel-titanium shape memory alloy used for endodontic rotary instruments during low-cycle fatigue. *J Endod* 2012;38:105-7.
13. Li SH, Lu Y, Song D, Zhou X, Zheng QH, Gao Y, *et al.* Occurrence of dentinal microcracks in severely curved root canals with ProTaper universal, WaveOne, and ProTaper next file systems. *J Endod* 2015;41:1875-9.
14. Schneider SW. A comparison of canal preparations in straight and curved root canals. *Oral Surg Oral Med Oral Pathol*

- 1971;32:271-5.
15. Landys Borén D, Jonasson P, Kvist T. Long-term survival of endodontically treated teeth at a public dental specialist clinic. *J Endod* 2015;41:176-81.
  16. White JD, Lacefield WR, Chavers LS, Eleazer PD. The effect of three commonly used endodontic materials on the strength and hardness of root dentin. *J Endod* 2002;28:828-30.
  17. Lertchirakarn V, Palamara JE, Messer HH. Load and strain during lateral condensation and vertical root fracture. *J Endod* 1999;25:99-104.
  18. Idiyatullin D, Garwood M, Gaalaas L, Nixdorf DR. Role of MRI for detecting micro cracks in teeth. *Dentomaxillofac Radiol* 2016;45:20160150.
  19. De-Deus G, Silva EJ, Marins J, Souza E, Neves Ade A, Gonçalves Belladonna F, *et al.* Lack of causal relationship between dentinal microcracks and root canal preparation with reciprocation systems. *J Endod* 2014;40:1447-50.
  20. De-Deus G, Belladonna FG, Souza EM, Silva EJ, Neves Ade A, Alves H, *et al.* Micro-computed tomographic assessment on the effect of ProTaper next and twisted file adaptive systems on dentinal cracks. *J Endod* 2015;41:1116-9.
  21. De-Deus G, Belladonna FG, Marins JR, Silva EJ, Neves AA, Souza EM, *et al.* On the causality between dentinal defects and root canal preparation: A Micro-CT assessment. *Braz Dent J* 2016;27:664-9.
  22. Bürklein S, Werneke M, Schäfer E. Impact of glide path preparation on the incidence of dentinal defects after preparation of severely curved root canals. *Quintessence Int* 2018;49:607-13.
  23. Shantiaee Y, Dianat O, Mosayebi G, Namdari M, Tordik P. Effect of root canal preparation techniques on crack formation in root dentin. *J Endod* 2019;45:447-52.
  24. 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;35:236-8.
  25. Pasqualini D, Scotti N, Tamagnone L, Ellena F, Berutti E. Hand-operated and rotary ProTaper instruments: A comparison of working time and number of rotations in simulated root canals. *J Endod* 2008;34:314-7.
  26. 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;36:1195-9.
  27. Capar ID, Arslan H, Akçay M, Uysal B. Effects of ProTaper Universal, ProTaper Next, and HyFlex instruments on crack formation in dentin. *J Endod* 2014;40:1482-4.
  28. 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;9:41-6.
  29. Dane A, Capar ID, Arslan H, Akçay M, Uysal B. Effect of different torque settings on crack formation in root dentin. *J Endod* 2016;42:304-6.
  30. Pedullà E, Corsentino G, Ambu E, Rovai F, Campedelli F, Rapisarda S, *et al.* Influence of continuous rotation or reciprocation of Optimum Torque Reverse motion on cyclic fatigue resistance of nickel-titanium rotary instruments. *Int Endod J* 2018;51:522-8.
  31. Kimura S, Ebihara A, Maki K, Nishijo M, Tokita D, Okiji T. Effect of optimum torque reverse motion on torque and force generation during root canal instrumentation with crown-down and single-length techniques. *J Endod* 2020;46:232-7.
  32. Plotino G, Grande NM, Testarelli L, Gambarini G. Cyclic fatigue of Reciproc and WaveOne reciprocating instruments. *Int Endod J* 2012;45:614-8.
  33. Pedullà E, Grande NM, Plotino G, Gambarini G, Rapisarda E. Influence of continuous or reciprocating motion on cyclic fatigue resistance of 4 different nickel-titanium rotary instruments. *J Endod* 2013;39:258-61.
  34. Gergi RM, Osta NE, Naaman AS. Dentinal crack formation during root canal preparations by the twisted file adaptive, Reciproc and WaveOne instruments. *Eur J Dent* 2015;9:508-12.
  35. Priya NT, Chandrasekhar V, Anita S, Tummala M, Raj TB, Badami V, *et al.* Dentinal microcracks after root canal preparation a comparative evaluation with hand, rotary and reciprocating instrumentation. *JCDR* 2018;8:ZC70-2.