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Original Article

# Evaluation of apical root defects during canal instrumentation with two different nickel-titanium (NiTi) systems by optical coherence tomography (OCT) scan

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**KEYWORDS**
Optical coherence tomography;
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Root defect

**Abstract** *Background/purpose:* Canal instrumentation with rotary nickel-titanium (NiTi) instruments might weaken the dentinal wall. This study aims to investigate the apical root defects during canal instrumentation with two NiTi rotary systems by using optical coherence tomography (OCT) scans.
*Materials and methods:* Twenty mandibular incisors were selected and divided into two groups instrumented using HyFlex CM (HCM) and ProTaper Universal (PTU) systems. OCT scans were taken immediately after canal instrumentation with file #25, #30 and #40. Each cross-sectional reconstructed image of 1, 2 and 3 mm from the apex was examined, root cracks were scored, and dentin thickness was measured at 12 sites. The risk sites with dentin thickness less than 0.30 mm were recorded.
*Results:* In HCM group, no cracks were observed after instrumentation with file #30/.06, while in PTU group, root cracks were found in 6 teeth with a total score of 9 after using F3 (#30/.09) ($P < 0.05$). After file #40, 8 teeth with cracks had a score of 14 in PTU group, while one tooth was observed crack with a score of 1 in HCM group ($P < 0.05$). The number of risk sites in PTU group was 49 (13.16%), which was significantly more than the 28 (7.78%) in HCM group ($P < 0.05$) when canals were instrumented with file #30.

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*Conclusion:* Within the limitations of this study, when the canals of mandibular incisors were instrumented with size #30 and #40 files, OCT scans showed less root defects in HCM group.


## Introduction

The thorough instrumentation of the apical region is recognized as the critical factor for canal instrumentation.[1] But there is no consensus about the optimal apical size of instrumentation. A larger apical size is beneficial in the elimination of debris and bacteria in the root canal system.[2–4] However, as reported in recently published studies, instrumentation with rotary nickel-titanium instruments with larger file sizes might weaken the dentinal wall and cause more root cracks.[5–7]

Advances in rotary NiTi instruments have led to new designs and techniques for root canal preparation. ProTaper Universal (Dentsply Maillefer, Ballaigues, Switzerland) and HyFlex CM (Coltene-Whaledent, Allstetten, Switzerland) are both the main continuous engine-driven rotary systems in the current world panorama. ProTaper Universal (Dentsply Maillefer) system was invented based on a unique concept: having multiple tapers of increasing and decreasing size on a single file.[8] This design is supposed to reduce torsional loads and potential breakage.[9] Unlike PTU system, each file of HyFlex CM system (Coltene-Whaledent) has a constant taper, and HCM files were made from a new controlled memory (CM) wire. This CM wire was manufactured using a special thermomechanical treatment that controls the memory of the material, making the files extremely flexible but without the shape memory.[10–12] As suggested in previous studies, design features may affect the behavior of the NiTi file and, therefore, may influence the risk of root defects when canals were instrumented to the same apical size.[10,13,14]

Stereomicroscopy was commonly used to observe dentin defects in root sections after canal instrumentation.[5,6,14] However, it cannot provide dynamic information about dentin changes caused by the use of each file during the process of root canal instrumentation. Pertinently, optical coherence tomography (OCT) is a new diagnostic method for creating high-resolution cross-sectional imaging of the internal biological structures based on depth-resolved optical reflectivity.[15] In dentistry, OCT has been proven to be a reliable method for observing pulp–dentin complex,[16] root perforations,[17] intracanal anatomy cleanliness of the root canal after preparation,[17] and detecting root cracks of extracted human teeth.[18–20]

The aim of this study was to compare the incidence of apical root defects during canal instrumentation by using two different types of NiTi instruments with the help of OCT scan.

## Materials and methods

Twenty extracted mandibular incisors were selected according to the inclusion criteria: Radiographs were taken from bucco-lingual and mesio-distal angles to verify the presence of a single canal with curvature less than 10°. All the roots were observed under 20 × magnification in a stereomicroscope (Image Measure, CF-2000C, Shanghai Changfang Optical Instrument Co., Ltd, Shanghai, China) to exclude root with cracks. The included teeth were decoronated under water cooling with a low-speed saw (Leica sp1600, Wetzlar, Germany), leaving roots approximately 16 mm in length. Canal patency was established with a size #15/.02 K-file (Dentsply Maillefer, Ballaigues, Switzerland). The roots were mounted in resin blocks with simulated periodontal ligaments as suggested previously.[6] A hydrophilic vinyl polysiloxane impression material (Variotime, Heraeus Kulzer GmbH, Hanau, Germany) was used to simulate the periodontal ligaments. The apical 3 mm of the root was exposed and immersed in purified filtered water (Fig. 1).

### Sample preparation

The roots were divided into 2 experimental groups (n = 10) with comparable bucco-lingual and mesio-distal widths at 3 mm from the apex. To balance the influence of a deviated apical foramen (AF) on the development of root cracks, each group contained 5 teeth with a centered AF and 5 teeth with a deviated AF. The mean distances from the anatomical apex to the most occlusal point of the major foramen was 0.41 mm and 0.40 mm in the two groups. Then, canals were instrumented with a low-torque motor (TCM Endo III, Nouvag AG, Goldach, Switzerland) using HyFlex CM (HCM) or ProTaper Universal (PTU) system. One

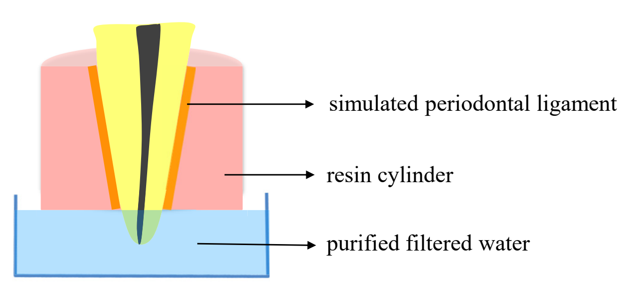


**Figure 1** Schematic representation of the experimental setup.

endodontist with 5 years of experience performed the canal instrumentation. Each file was discarded after preparing 5 canals. The same irrigation protocol was used for the two groups. Each canal was irrigated with 2 mL of a freshly prepared 1% sodium hypochlorite solution between the use of each instrument and administered with a syringe and a 27-G needle which was performed at 1 mm short of the working length from size #25 file.

In HCM group, the HyFlex CM rotary files (Coltene-Whaledent) of sizes #20 to #40 were performed with a constant speed of 500 rpm and 200 g/cm torque. The file #25/.08 was used to enlarge the coronal portion of the canal, and files: #15/.02, #20/.04, #20/.06, #25/.06, #30/.06, and #40/.06 were used sequentially to instrument the canal that terminated at the apical foramen.

In PTU group, for each ProTaper rotary file (Dentsply Maillefer), the individual rotational speed (250 rpm) and the torque limit programmed in the file library of the motor were used. Sx was used to prepare the coronal half of the canal; thereafter, S1, S2, F1, F2, and F3 files were used to reach the working length. The last file used was F4, which corresponds to file #40 with a taper of 0.06.

## OCT scanning and image reconstruction

After instrumentation using file #25, #30 and #40, the apical roots of the 2 groups were scanned from the root surface by OCT (Dental-OCT 2015, Tsinghua University Department of Physics, China) with a light source that repetitively sweeps the wavelengths from 1300 to 1310 nm at a 20 kHz sweep rate (Fig. 2). The axial and transverse image resolutions were 16 and 25 μm, respectively.

Images were reconstructed by using three-dimensional (3D) image processing software (Multireference optical path image registration program 2015, Tsinghua University Department of Physics, China). The images were inspected with this software on a liquid crystal display (BL2410PT, BenQ, Taiwan) at a resolution of 1024 × 1024 pixels. The flow chart was shown in Fig. 3.

## Evaluation of apical root defects

Two observers evaluated the cross-sectional scanning images from the two groups taken 1, 2 and 3 mm from the apex after each file was used.

On OCT scans, a root crack was defined as a bright line extending from the canal or 2 bright lines with a void between them separating the dentin (Fig. 4). The presence of root carcks was noted by two observers. Then, the observers reviewed the same scans again after an interval of 2 weeks. In case of disagreement in detection of cracks, the image was discussed until consensus was obtained. The crack degree of each tooth was scored based on the number of cross-sectional scanning images with cracks. The scores were defined as explained below.

Score 0: no root crack;

Score 1: one cross-sectional image showing cracks;

Score 2: two cross-sectional images showing cracks;

Score 3: all three cross-sectional images showing cracks.

The dentinal wall with thickness less than 0.30 mm was defined as risk site. For each cross-sectional image, dentin thickness was measured twice at 12 sites (Fig. 5) with a two weeks interval, and the mean measurement was used. The risk sites of each tooth were recorded.

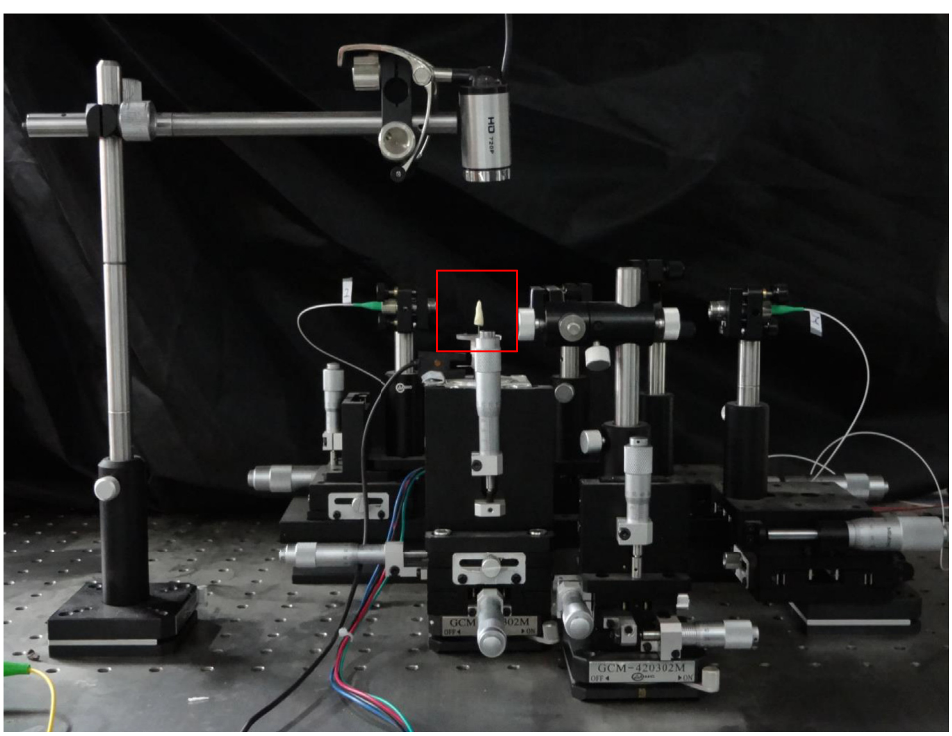

**Figure 2** Schematic representation of OCT system. A root sample was shown in the red box.

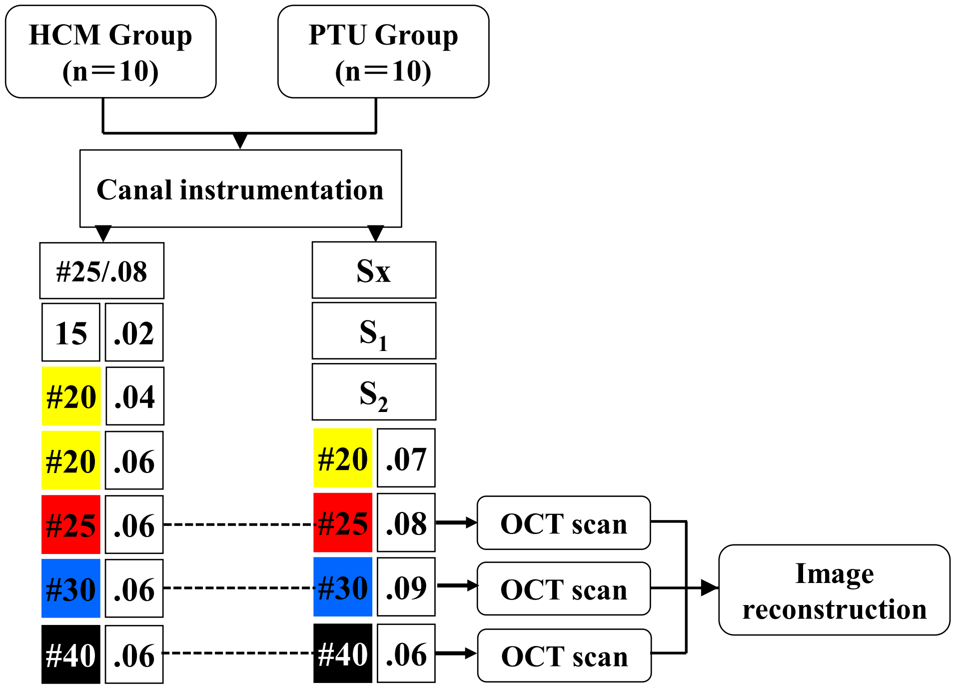


**Figure 3** Work flow chart of this experiment. HCM, HyFlex CM; PTU, ProTaper Universal.

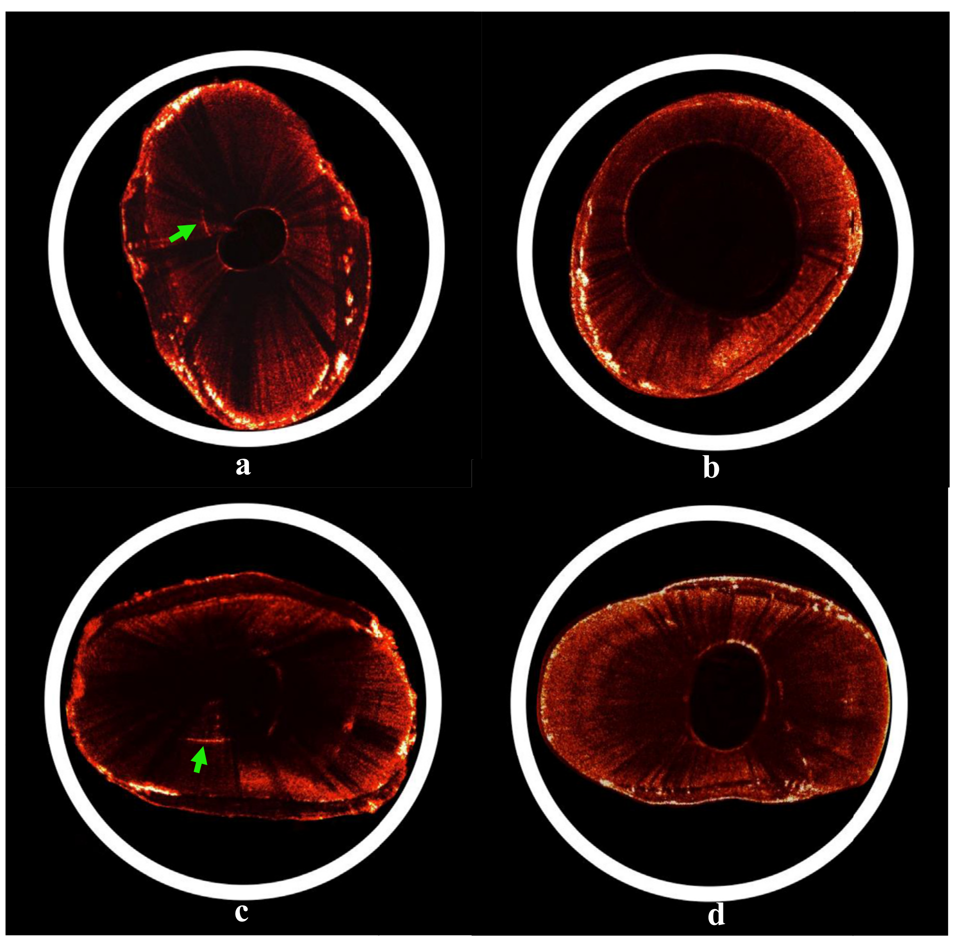


**Figure 4** OCT scan showed a root crack (green arrow) (a) (c) and an intact wall (b) (d).

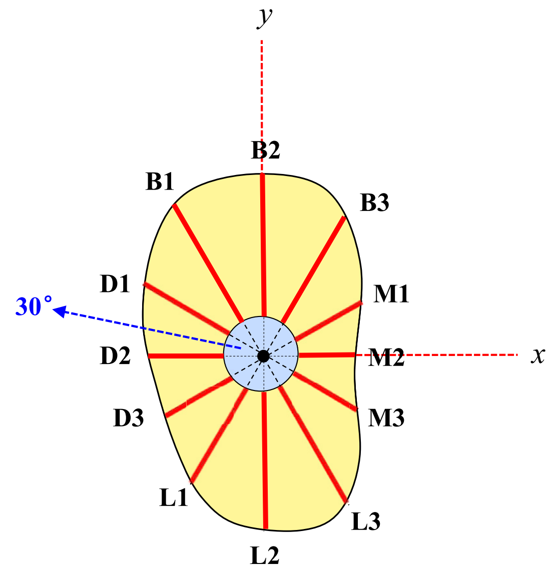


**Figure 5** Established the abscissa and ordinate (×, y) with the shortest diameter of root cross-sectional image as the reference, and measured the dentin thickness every 30°. Dentinal thickness (distance between the canal wall and outer surface of the root) (red line) was measured at 12 sites in each cross-sectional image. B1, B2, B3: buccal sites; L1, L2, L3: lingual sites; M1, M2, M3: mesial sites; D1, D2, D3: distal sites.

### Statistical analysis

The data was evaluated using SPSS ver. 20.0 (SPSS Inc., Chicago, IL). The Cohen kappa was used to compare the inter-observer and intra-observer consistency in detecting root cracks. The Mann–Whitney U test was used to analyze the different root crack scores in HCM and PTU groups after each file was used. The chi-square test was performed to compare the risk sites. The level of significance was set at $\alpha = 0.05$.

## Results

For intra-observer agreement in detecting root crack, the kappa values were 0.80 and 1.00 for the two observers. For inter-observer agreement, the kappa value was 0.90, showing high reproducibility.

Table 1 showes the distribution of teeth with different root crack scores in the two groups after each file was used. When apical canals were instrumented with file #25/.06 and #30/.06 in HCM group, the score was 0. In PTU group, the crack scores were 3 and 9, respectively, after using F2 (#25/.08) and F3 (#30/.09). After file #40 was used, one tooth was observed crack with a score of 1 in HCM group, while root cracks were found in 8 teeth with a total score of 14 in PTU group. When the apical canals were instrumented with files #30 and #40, more cracks were shown in PTU group than in HCM group ($P < 0.05$).

Dentinal thickness was measured on OCT scans at 36 sites in 3 cross-sections of each tooth after each file was used. The dentinal wall with thickness thinner than 0.30 mm was defined as risk site. All risk sites were located in the mesio-distal canal walls. After file #30 was used, the number of risk sites was 49 (13.61%) in PTU group and 28 (7.78%) in HCM group ($P < 0.05$). However, there was no significant difference in risk sites between the two groups after using file #40 ($P > 0.05$). In HCM group, after file #40/.06 was used, the appearance of risk sites increased significantly, while in PTU group, the number of risk sites increased after using F3 (#30/.09) ($P < 0.05$) (Fig. 6).

**Table 1** The number of teeth in the two groups with different root crack scores after each file was used (n = 10).

| Group | File | Root crack score | | | |
|---|---|---|---|---|---|
| | | 0 | 1 | 2 | 3 |
| PTU | F2 (#25/.08) | 7 | 3 | 0 | 0 |
| | F3 (#30/.09) | 4 | 4 | 1 | 1 |
| | F4 (#40/.06) | 2 | 3 | 4 | 1 |
| HCM | #25/.06 | 10 | 0 | 0 | 0 |
| | #30/.06 | 10 | 0 | 0 | 0 |
| | #40/.06 | 9 | 1 | 0 | 0 |

PTU, ProTaper Universal; HCM, HyFlex CM.
**0**: no scan image showed cracks.
**1**: one scan image showed cracks.
**2**: two scan images showed cracks.
**3**: all three scan images showed cracks.
Ex: In PTU group, after using F2, 7 teeth were scored 0, 3 teeth were scored 1 and no teeth was scored 2 or 3.

## Discussion

To the best of our knowledge, the present in vitro study was the first to use OCT scans to compare the incidence of root defects during the process of canal instrumentation by using HCM or PTU NiTi instruments. In our previous studies, OCT was validated as an effective tool for accurate diagnosis of root cracks.[21,22]

Under the conditions in this study, PTU could produce significantly more dentinal defects than HCM when the canals were instrumented with files #30 and #40. HCM and PTU systems are both continuous rotary nickel-titanium instruments but have different features in apical tapers and metallic wires. In agreement with previous findings, design features may affect the behavior and clinical performance of the NiTi files.[10,13,14]

As reported in recent studies, instrumentation with rotary NiTi instruments could potentially cause localized dentinal cracks;[5–7] these cracks might have the potential to develop into root fractures.[23] In PTU group, there were 3, 6 and 8 teeth with varying root crack scores when apical canals were instrumented with F2 (#25/.08), F3 (#30/.09) and F4 (#40/.06) files, respectively. ProTaper Universal system has multiple tapers of increasing and decreasing size on a single file. This design is supposed to reduce torsional loads and potential breakage. Whereas, when transitioning from file S2 to F3, the apical taper increases from 0.04 to 0.09. It has been reported that the torque of PTU system increases for each instrument with increasing tip size and taper.[9] PTU system caused more root cracks than other instruments in all the studies by Bier, Liu and

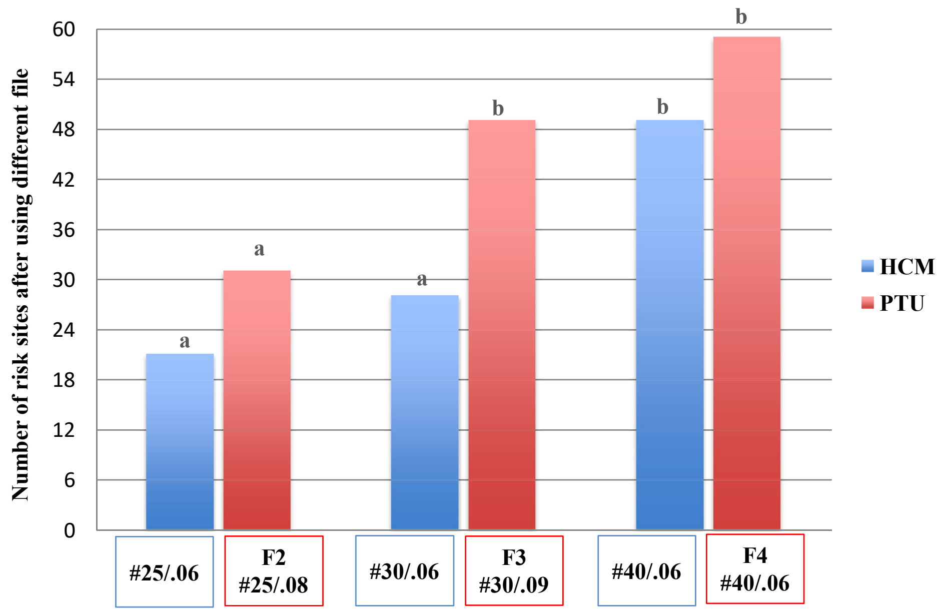


**Figure 6** The risk sites after instrumentation. Different letters denote statistical significance. HCM, HyFlex CM; PTU, ProTaper Universal.

Capar.[13,14,24] Notably, Liu reported that 50% of the mandibular incisors were found cracks after canal preparation with F2 in the PTU system.[14]

In the present study, no cracks were observed in HCM group when canals were instrumented with files #25/.06 and #30/.04. When the #40/.06 file was used, one tooth received a scored of 1. This suggests that the superior flexibility of HCM files might reduce the risk of dentin cracks during root canal instrumentation.

HyFlex CM is a NiTi rotary system made from specific NiTi alloy that has a lower percent in weight of nickel (52.1 wt%) than conventional NiTi alloys composed of 54.5—57 wt% Ni.[11] Moreover, a unique sequence of thermal treatments was used during the manufacturing process, which improved the mechanical properties of the alloy.[25] The austenite/martensite transition temperature of HCM system is approximately 50 °C; thus, a stable martensitic microstructure is present at room temperature.[26] Previous studies have shown that HCM instruments provide superior flexibility and higher fatigue resistance during instrumentation than other conventional NiTi instruments that are purely austenitic.[11,27]

Mandibular incisors with a single canal were used in this study. Wolf et al. reported that more than 50% of the physiological foramen of lower incisors are oval.[28] The difficulty in instrumenting oval canals lies in the possibility of creating strip perforations. Weller et al. observed that the minimum thickness of dentinal wall at 1, 2, and 3 mm from the apex was 0.52 mm, 0.67 mm, 0.76 mm, respectively, in mandibular incisors.[29] These thinnest areas were all present in mesio-distal wall. In Katz's study, the minimum dentin thicknesss of mesial and distal walls in the apical 1/3 region were 0.82 and 0.74 mm, respectively. After instrumentation with a size #40/.02 K-file, the thicknesses of the mesial and distal walls were reduced to 0.70 mm and 0.62 mm, respectively.[30] During canal instrumentation, excessive removal of dentin contributes to weakening the tooth structure. Lim proposed that the thickness of dentinal wall should retain at least 0.3 mm after root canal preparation to resist canal filling pressure and functional load during chewing.[31] In the present study, "risk site" was defined as dentinal wall thinner than 0.3 mm. All the risk sites were located in the mesio-distal canal walls. F3 (#30/.09) with 0.09 taper caused significantly more risk sites than the HCM file with an apical size of #30/.06 ($P < 0.05$). Moreover, it has been reported that the taper of root canal in the mesio-distal direction was only 0.02—0.04 in the apical area of mandibular incisors.[32] Thus, the present result suggests that using a file with a taper that is too large to instrument mandibular incisor canals may lead to overpreparation in the mesio-distal wall, thus weakening the fracture resistance of the root.

Two studies suggested that final apical files on preparation of mandibular incisors were #35 and #40 based on 3D analysis of root canal morphology.[28,33] In the present study, when the apical canals were instrumented with file #30, PTU produced significantly more cracks and risk sites than HCM ($P < 0.05$). After using file #40, the root crack score in PTU group was more than that in HCM group ($P < 0.05$). Thus, an appropriate instrumentation plan should be devised in which different root canal anatomies and different features of rotary instrument systems are considered and the balance of cleaning canals and maintaining the root structure is weighed.

In dentistry, OCT has previously been shown to be a valuable tool in assessing intracanal anatomy,[17,34] measuring remaining dentin thickness (RDT)[34] and detecting root cracks of extracted human teeth.[18—20] Rashed[34] reported that OCT could accurately measured RDT compared with CBCT and micro-CT. In the studies of Yoshioka[19] and Lee,[35] the ability of OCT for detecting the presence of cracks was comparable to that with micro-CT. In this in vitro study, the OCT which provided a high-resolution images with resolutions of 16 μm and 25 μm in axial and transverse images, respectively, was first used to evaluate root defects during canal instrumentation. Although OCT is a high-resolution, noninvasive, real-time display and nonradiative technique for tooth scanning, its use is limited due to its shallow penetrating depth. The penetration depth is dependent on optical attenuation from tissue scattering and absorption, which is about 2—3 mm in dental hard tissue.[34—36]

Within the limitations of this in vitro study, when the canals of mandibular incisors were instrumented with apical size #30 and #40 files, the HCM system could create less root defects in the apical dentin wall than the PTU system.

## Declaration of competing interest

The authors have no conflicts of interest relevant to this article.

## Acknowledgments

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## References

1. Peters OA. Current challenges and concepts in the preparation of root canal systems: a review. *J Endod* 2004;30:559—67.
2. McGurkin-Smith R, Trope M, Caplan D, Sigurdsson A. Reduction of intracanal bacteria using GT rotary instrumentation, 5.25% NaOCl, EDTA, and $Ca(OH)_2$. *J Endod* 2005;31:359—63.
3. Siqueira Jr JF, Araújo MC, Garcia PF, Fraga RC, Dantas CJ. Histological evaluation of the effectiveness of five instrumentation techniques for cleaning the apical third of root canals. *J Endod* 1997;23:499—502.
4. Wu MK, Wesselink PR. Efficacy of three techniques in cleaning the apical portion of curved root canals. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 1995;79:492—6.
5. Shemesh H, Bier CAS, Wu MK, Tanomaru M, Wesselink PR. The effects of canal preparation and filling on the incidence of dentinal defects. *Int Endod J* 2009;42:208—13.
6. Liu R, Kaiwar A, Shemesh H, Wesselink PR, Hou B, Wu MK. Incidence of apical root cracks and apical dentinal detachments after canal preparation with hand and rotary files at different instrumentation lengths. *J Endod* 2013;39:129—32.
7. 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;37:522—5.
8. Haapasalo M, Shen Y. Evolution of nickel-titanium instruments: from past to future. *Endod Top* 2013;29:3—17.
9. Peters OA, Peters CI, Schönenberger K, Barbakow F. ProTaper rotary root canal preparation: assessment of torque and force in relation to canal anatomy. *Int Endod J* 2003;36:93—9.
10. Thompson SA. An overview of nickel-titanium alloys used in dentistry. *Int Endod J* 2000;33:297—310.
11. Shen Y, Zhou H, Zheng Y, Campbell L, Peng B, Haapasalo M. Metallurgical characterization of controlled memory wire nickel-titanium rotary instruments. *J Endod* 2011;37:1566—71.
12. Gavini G, dos Santos M, Caldeira CL, et al. Nickel—titanium instruments in endodontics: a concise review of the state of the art. *Braz Oral Res* 2018;32:e67.
13. 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.
14. 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;39:1054—6.
15. Fercher AF, Drexler W, Hitzenberger CK, Lasser T. Optical coherence tomography-principles and applications. *Rep Prog Phys* 2003;66:239—303.
16. Braz A, Kyotoku B, Gomes A. In vitro tomographic image of human pulp-dentin complex: optical coherence tomography and histology. *J Endod* 2009;35:1218—21.
17. Shemesh H, Van Soest G, Wu MK, van der Sluis LWM, Wesselink PR. The ability of optical coherence tomography to characterize the root canal walls. *J Endod* 2007;33:1369—73.
18. Shemesh H, Van Soest G, Wu MK, Wesselink PR. Diagnosis of vertical root fractures with optical coherence tomography. *J Endod* 2008;34:739—42.
19. Yoshioka T, Sakaue H, Ishimura H, Ebihara A, Suda H, Sumi Y. Detection of root surface fractures with swept-source optical coherence tomography (SS-OCT). *Photomed Laser Surg* 2012;31:23—7.
20. Rashed B, Iino Y, Ebihara A, Okiji T. Evaluation of crack formation and propagation with ultrasonic root-end preparation and obturation using a digital microscope and optical coherence tomography. *Scanning* 2019;2019:5240430—6.
21. Chen C, Zhang WX, Qi LY, Gao XJ, Liang YH. Detection of root cracks after root canal preparation using rotary NiTi systems by optical coherence tomography (OCT) scan. *J Peking Univ Health Sci* 2018;50:547—52 [In Chinese, English abstract].
22. Qi LY, Chen C, Jiang L, Li JN, Liang YH. Construction of swept source optical coherence tomography imaging system for root canal endoscopy and application in diagnosis of root fractures. *J Peking Univ Health Sci* 2019;51:753—7 [In Chinese, English abstract].
23. 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.
24. 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;40:1482—4.
25. Shen Y, Zhou HM, Wang Z, Campbell L, Zheng YF, Haapasalo M. Phase transformation behavior and mechanical properties of thermomechanically treated K3XF nickel-titanium instruments. *J Endod* 2013;39:919—23.
26. Santos LA, Bahia MG, de Las Casas EB, Buono VT. Comparison of the mechanical behavior between controlled memory and superelastic nickel-titanium files via finite element analysis. *J Endod* 2013;39:1444—7.
27. Testarelli L, Plotino G, Al-Sudani D, et al. Bending properties of a new nickel-titanium alloy with a lower percent by weight of nickel. *J Endod* 2011;37:1293—5.
28. Wolf TG, Stiebritz M, Boemke N, et al. 3-dimensional analysis and literature review of the root canal morphology and physiological foramen geometry of 125 mandibular incisors by means of micro—computed tomography in a German population. *J Endod* 2020;46:184—91.
29. Weller PJ, Svec TA, Powers JM, Ludington Jr JR, Suchina JA. Remaining dentin thickness in the apical 4 mm following four cleaning and shaping techniques. *J Endod* 2005;31:464—7.
30. Katz A, Tamse A. A combined radiographic and computerized scanning method to evaluate remaining dentine thickness in mandibular incisors after various intracanal procedures. *Int Endod J* 2003;36:682—6.
31. Lim SS, Stock CJR. The risk of perforation in the curved canal: anticurvature filing compared with the stepback technique. *Int Endod J* 1987;20:33—9.

32. Leoni GB, Versiani MA, Pécora JD, Damião de SM. Micro—computed tomographic analysis of the root canal morphology of mandibular incisors. *J Endod* 2014;40:710—6.
33. Miyashita M, Kasahara E, Yasuda E, Yamamoto A, Sekizawa T. Root canal system of the mandibular incisor. *J Endod* 1997;23:479—84.
34. Rashed B, Iino Y, Komatsu K, et al. Evaluation of root canal anatomy of maxillary premolars using swept-source optical coherence tomography in comparison with dental operating microscope and cone beam computed tomography. *Photomed Laser Surg* 2018;36:487—92.
35. Lee S, Lee J, Chung H, Park J, Kim H. Dental optical coherence tomography: new potential diagnostic system for cracked-tooth syndrome. *Surg Radiol Anat* 2016;38:49—54.
36. Fujimoto JG, Pitris C, Boppart SA, Brezinski ME. Optical coherence tomography: an emerging technology for biomedical imaging and optical biopsy. *Neoplasia* 2000;2:9—25.