Micro computed tomography evaluation of the Self-adjusting file and ProTaper Universal system on curved mandibular molars

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The aim of this investigation was to compare the cleaning and shaping efficiency of Self-adjusting file and Protaper, and to assess the correlation between root canal curvature and working time in mandibular molars using micro-computed tomography. Twenty extracted mandibular molars instrumented with Protaper and Self-adjusting file and the total working time was measured in mesial canals. The changes in canal volume, surface area and structure model index, transportation, uninstrumented area and the correlation between working-time and the curvature were analyzed. Although no statistically significant difference was observed between two systems in distal canals ($p>0.05$), a significantly higher amount of removed dentin volume and lower uninstrumented area were provided by Protaper in mesial canals ($p<0.0001$). A correlation between working-time and the canal-curvature was also observed in mesial canals for both groups ($\text{SAFr}^2=0.792$, $p<0.0004$, $\text{PTUr}^2=0.9098$, $p<0.0001$)

Keywords: MicroCT, ProTaper, Self-adjusting file, Transportation, Working time

INTRODUCTION

Cleaning and shaping of the root canals with chemo-mechanical preparation and hermetic obturation of the canals are the main purposes of the root canal therapy¹. Although there are multiple factors which influence the success rate of endodontic treatment²; preparation of the canals can be accepted as the key step because of the complex root canal anatomy³. Removing the infected dentine equally from the canal walls and shaping the canals to an adequate geometry are vital for optimal cleaning and filling, especially in oval and curved canals^{4,5}. From the past to date, there are many instruments manufactured with different cross-sectional architecture, alloys, diameters and designs to enhance the shaping quality⁶. It is reported that the root canal cross-sections became round after using the current rotary files which have different spiral blade and helical formation⁷. Therefore, due to the complex root canal anatomies, the buccal and lingual areas of flat and tear shaped root canals cannot be adequately prepared and untouched areas may be left by the current rotary files^{5,8}. In 2010, Metzger *et al.* introduced a new concept named as Self-adjusting file (SAF) system (ReDent-Nova, Ra'anana, Israel) which does not have a core structure and allows continuous irrigation and concurrent preparation⁹. Thanks to the hollow-file design, when SAF system is inserted into a root canal, it provides a three-dimensional adaptation to the canal's shape both longitudinally and along the cross-section and applies a constant pressure while the lattice threads produce an abrasive effect on the dentine. In the previous studies it was reported that preparing the root canals with SAF system removed uniform dentin from the inner layer of

the root canals and percentage of uninstrumented root canal walls decreased when compared with the rotary files¹⁰⁻¹².

Finishing the root canal preparation by using a single system is preferable in clinical practice; therefore, *in vitro* investigations shall include both canals of mandibular molars in order to simulate the actual clinical conditions. Unfortunately, as we searched on Scopus database on August 2015, there were no papers which evaluated the cleaning and shaping effect of SAF both on mesial and distal root canals of mandibular molar teeth together. For this purpose, the aim of our *in vitro* study was to evaluate the cleaning and shaping efficiency of SAF *versus* Protaper Universal (PTU) (Dentsply-Maillefer, Ballaigues, Switzerland) on both canals of mandibular molar teeth and to investigate the correlation between root canal curvature and working time. Because of the adaptation characteristic and in the light of previous studies¹⁰⁻¹² related to the uninstrumented area, our hypothesis was "SAF system provides better clinical efficacy than PTU multiple rotary files on mesial and distal root canals of mandibular molar teeth".

MATERIALS AND METHODS

In this study, 20 human mandibular first molar teeth with mature apices and which were extracted for periodontal disease/prosthetic indications were selected. The inclusion criteria were the presence of two separate mesial and one distal root canal, absence of apical resorption, and vertical or horizontal cracks. All included teeth were radiographed in buccolingual and mesiodistal projections in order to ensure that they have only two mesial and one distal root canal. In order to provide an initial standardization, a simple criterion

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was utilized: the teeth in which a 20 K file could not reach to the apex and 15 K file was tightly fitted at the apical foramen in distal root canals were selected. Similarly, in mesial root canals, the teeth in which a 15 K file could not reach to the apex and 10 K file was tightly fitted at the apical foramen were utilized.

Using the radiographic images, mesial root canal angle and radius were determined for each tooth with AutoCAD 2013 software (Autodesk, San Rafael, CA, USA) according to the method described by Pruett *et al.*¹³⁾. The teeth which have two separate mesial canals with an angle of curvature of 25°–35° and radius of 8–10 mm were included in this study. In order to provide similar pre-operative values in terms of volume, surface area, SMI in both groups, three dimensional analysis values obtained by pre-operative micro-computed tomography scanning were used (Table 1). Additionally, the teeth were sub-grouped according to the severity of their root canal curvature angles (25–30; 31–35, respectively). Then, teeth from each subgroup were randomly assigned to one of the preparation systems.

In the literature there was no accurate information about the apical diameter of the curved mesial canals of mandibular molar teeth after shaping with SAF for 4 min. Therefore, a pilot study was performed on three extracted mandibular molar teeth in order to establish the apical diameter after preparation of mesial and distal canals with SAF. The findings of this preliminary study showed that mesial canal diameter was #30 and that was #40 for the distal canals after instrumentation with 1.5 mm diameter SAF for 4 min. Accordingly, it was decided to prepare the mesial canals up to F3 file and the distal canals up to F4 file in the PTU group to standardize the apical diameter of the canals in both experimental groups.

The clinical crowns of teeth were removed at the cemento-enamel junction and roots were separated from the bifurcation of the teeth with a high speed diamond bur. Three grooves in different planes were created on the occlusal surface of all roots to allow the accurate superimposition of pre and post-instrumentation images. All samples were mounted on scanning electron microscope (SEM) stubs and were scanned in a desktop X-ray micro-focus CT scanner (SkyScan 1172, SkyScan, Kontich, Belgium) at an isotropic resolution of 21 µm.

The reference grooves on the occlusal surfaces of the roots were used in order to place each sample to the exactly the same position during the preparation of the canals. So, every instrument was inserted into the canals at the same position and whole shaping procedure was completed accordingly in both experimental groups. #10 K file was inserted into the canals until its tip was visible at the apex and working length was determined 0.5 mm shorter than this measurement. Because of the manufacturer's advice of the SAF system, glide path was confirmed to a size #20 K file for all samples. In group I ($n=30$); canals were instrumented up to #F3 file in mesial and #F4 in distal root canals. Two canals were prepared with a one set of PTU instrument to

Table 1 Pre-operative values and changes of the volume, surface area, SMI and the amount of transportation and percentage of the uninstrumented areas after preparation

		Volume (mm ³)			Surface area (mm ²)			Structure model index (SMI) (br)			Transportation (mm)			Uninstrumented root canal wall %
		Apical Third (Mean±SD)	Middle Third (Mean±SD)	Coronal Third (Mean±SD)	Apical Third (Mean±SD)	Middle Third (Mean±SD)	Coronal Third (Mean±SD)	Apical Third (Mean±SD)	Middle Third (Mean±SD)	Coronal Third (Mean±SD)	Apical Third (Mean±SD)	Middle Third (Mean±SD)	Coronal Third (Mean±SD)	
Distal canals	SAF													
	Pre-op	0.64 (±0.29)	1.61 (±1.00)	2.29 (±1.05)	7.28 (±2.32)	13.55 (±6.30)	16.41 (±5.05)	2.36 (±0.65)	1.80 (±0.60)	1.78 (±0.92)	—	—	—	—
	Δ	0.11 (±0.05)	0.26 (±0.21)	0.39 (±0.27)	0.13 (±0.89)	-1.53 (±2.61)	-1.50 (±2.50)	0.41 (±0.62)	0.53 (±0.76)	0.66 (±0.80)	0.43 (±0.27)	0.29 (±0.21)	0.56 (±0.25)	27.51 (±10.53)
	PTU													
Mesial Canals	Pre-op	0.78 (±0.34)	1.85 (±0.67)	2.84 (±0.87)	7.77 (±2.46)	15.05 (±4.97)	19.12 (±6.43)	2.32 (±0.52)	1.60 (±0.76)	1.63 (±0.88)	—	—	—	—
	Δ	0.18 (±0.13)	0.44 (±0.44)	0.60 (±0.38)	0.54 (±1.34)	-1.02 (±1.44)	-1.34 (±2.44)	0.47 (±0.44)	0.76 (±0.58)	1.04 (±1.07)	0.36 (±0.25)	0.43 (±0.21)	0.49 (±0.17)	27.59 (±6.40)
	Δp values	$p=0.1780$	$p=0.2577$	$p=0.1713$	$p=0.4346$	$p=0.5928$	$p=0.8905$	$p=0.7826$	$p=0.4523$	$p=0.3747$	$p=0.5366$	$p=0.1696$	$p=0.5025$	$p=0.9843$
	SAF													
Mesial Canals	Pre-op	0.22 (±0.10)	0.42 (±0.21)	0.71 (±0.30)	3.68 (±1.08)	5.48 (±7.55)	7.55 (±3.00)	2.56 (±0.17)	2.41 (±0.29)	2.43 (±0.44)	—	—	—	—
	Δ	0.11 (±0.58)	0.18 (±0.09)	0.31 (±0.10)	0.81 (±0.56)	0.87 (±0.78)	0.97 (±0.56)	0.31 (±0.24)	0.22 (±0.20)	0.34 (±0.23)	0.44 (±0.19)	0.42 (±0.15)	0.53 (±0.26)	27.83 (±8.62)
	PTU													
	Pre-op	0.25 (±0.13)	0.45 (±0.23)	0.83 (±0.34)	4.39 (±1.45)	6.47 (±3.27)	8.87 (±3.20)	2.38 (±0.43)	2.16 (±0.69)	2.28 (±0.38)	—	—	—	—
Mesial Canals	Δ	0.22 (±0.87)	0.63 (±0.17)	1.00 (±0.27)	1.26 (±0.80)	2.41 (±1.26)	2.45 (±2.17)	0.62 (±0.38)	0.63 (±0.62)	0.65 (±0.40)	0.49 (±0.19)	0.58 (±0.35)	0.60 (±0.37)	19.64 (±7.52)
	Δp values	$p<0.0001$	$p<0.0001$	$p<0.0001$	$p=0.0840$	$p=0.0005$	$p=0.0211$	$p=0.0152$	$p=0.0264$	$p=0.0192$	$p=0.5380$	$p=0.1338$	$p=0.5469$	$p=0.0108$

* Pre-op=Pre-operative values, ** Δ=Changes after preparation

prevent the instrument fracture. After each instrument, root canals were irrigated with 2 mL 2.5% NaOCl. In mesial root canals, to evaluate the correlation between working-time and the canal-curvature, total working times were managed with a digital chronometer, including irrigation and file changing times. In group II ($n=30$), NSK FC C873 Direct-drive (1:1) quick coupling adaptor was used between RDT3-NX head and X-smart endodontic motor. A 1.5 mm diameter SAF was operated with constant-irrigation in a light-pecking, trans-line motion and continuous irrigation with 2.5% NaOCl was applied at 3 mL/min by using special irrigation apparatus (Vatea; ReDent-Nova). We realised that the 1.5 mm SAF could not reach the working length after 4 min in some of the mesial root canals. Because of this, we continued the shaping with the SAF file up to the working length. Because of the manufacturer's advice, the SAF file was changed with a new one after shaping only one canal. In mesial canals, working times were established *via* Vatea irrigation apparatus' monitor.

After finishing the root canal instrumentation, all samples were remounted to the stubs and were rescanned with μ CT by applying the initial setting parameters. All images were reconstructed with NRecon software (v1.6.8, SkyScan) at full canal length, so approximately 600 slices were generated for one specimen, and axial cross-sections of all reconstructed pre-instrumentation images were created with Dataviewer software (v1.4.4, SkyScan). Before making further 3D analysis, post-operative scanning images were oriented with Data Viewer software to superimpose the outlines of these images with the pre-operative ones by taking three reference grooves at the coronal, axial and sagittal plane and all data were saved to a file. For each canal, slices were revisited to find the first cross-sectional slice where the apical foramen was visible. This was recorded as the reference image for that particular canal. Afterwards, moving coronally from this point for 3 mms, the apical third was assessed. Using the same methodology, 3 mms from the apical third was found and this area was recorded as the middle third. Finally, 3 mms from the middle third was established and this distance was considered as the coronal third. Our 3D analysis in all samples was performed from the apex to the 9 mm coronal portion of root canal for standardization.

3D measurements of the volume, the surface area and the structure model index (SMI) of the root canal were analyzed with CTAn software (v1.12.11.0, SkyScan) for each section of the root canals on both pre and post-instrumentation images. Changes in all parameters were calculated by subtracting the post-instrumented values from pre-instrumented counterparts.

For each canal, a whole volume of an each third of the root canal was analyzed three dimensionally and x, y and z coordinate values which pertain to particular volume were obtained from the 3D analysis. The transportation (vectorial displacement) of the each third of the canal was investigated by calculating the vectorial translocation of all sections with these x, y and

z coordinate values. The following formula was utilised for all thirds of the canals:

$$\sqrt{(Xa-Xb)^2+(Ya-Yb)^2+(Za-Zb)^2}$$

(X, Y, Z: coordinate values, a: after preparation, b: before preparation)

Mimics Software was used to analyze the percentage of uninstrumented surface areas at full canal length. For each specimen, 2D cross-sectional pre-instrumentation and post instrumentation images were transferred to the Mimics software for 3D modelling. Hounsfield Unit thresholds were stated for the tooth and then, the masks were created and uninstrumented root canal surface was calculated along the root canal length.

Data were analyzed using a statistical package software program (GraphPad Software, LA Jolla CA, USA). Shapiro Wilk test was used to evaluate the distribution of the variables in each group. In both groups, one-way repeated-measures ANOVA were applied to compare the changes in volume, surface area, SMI and transportation between each section of the root canals and Tukey's multiple comparison test was used for the pairwise comparisons. The differences between two groups for the same parameters were assessed with unpaired Welch's *t*-test. Likewise, the correlation between the angle of the root canal curvature and working time was examined with Pearson correlation test. The level of significance was set at $\alpha=0.05$.

RESULTS

Pre-operative values and changes that occurred after root canal shaping were seen in Table 1. Teeth which were selected for this study had statistically similar pre-operative values in terms of the volume, surface area, SMI in both groups ($p>0.05$) (Table 1). One instrument fracture was observed in one of the mesial canal which was shaped with PTU. Besides, 3D analyses of four samples revealed large isthmuses between mesio-buccal and mesio-lingual canals. Thus, these five samples were excluded from the study.

Evaluation of preparation

1. Localization

1) Distal canals

When each third of a canal was considered, the mean removed dentin (volume change) in apical, middle and coronal thirds of the distal canals both in SAF and PTU systems were 0.11 (± 0.05), 0.26 (± 0.21), 0.39 (± 0.27) mm³, and 0.18 (± 0.13), 0.44 (± 0.44), 0.60 (± 0.38) mm³, respectively. The differences between the apical and middle and the coronal and middle thirds of the canals were not significant in both systems ($p>0.05$), however, in individual distal canals, both systems revealed significantly higher volume change in coronal thirds than the apical ones (SAF $p=0.0168$, PTU $p=0.0109$) (Table 1).

With respect to the surface area, both PTU and SAF caused a decrease on the surface area of the middle and

coronal thirds in some of the distal canals. The surface area values varied from -6.21 to 0.22 mm² in middle and from -5.37 to 1.14 mm² in coronal thirds with SAF. On the other hand, these values ranged between -3.90 and 0.63 mm² in middle and between -6.67 and 0.81 mm² in coronal thirds with PTU. Besides, both systems perceived similar changes in terms of comparing surface area amongst each third of a distal canal ($p>0.05$) (Table 1).

Considering the preservation of the pre-operative/original root canal shape, SAF and PTU systems caused similar changes in each thirds of an individual distal canal (Table 1). The differences between the SMI values of both systems were not statistically significant ($p>0.05$).

Although both systems caused transportation in each thirds of the distal canal, the differences amongst apical, middle and coronal thirds were not statistically significant in PTU group ($p>0.05$) (Table 1). On the other hand, even though the differences between the transportation of the apical-middle and the apical-coronal thirds of the canals were not significant, there was a statistically substantial difference between the middle and coronal thirds in SAF group ($p=0.0110$).

2) Mesial canals

The maximum volume change was noticed in the coronal thirds of mesial canals, and this change ranged from 0.45 to 0.17 mm³ with SAF and from 1.34 to 0.50 mm³ with PTU. Besides, the volume of change in coronal, middle and apical thirds of the mesial canals differed significantly with SAF system (apical-middle $p=0.0040$, middle-coronal $p<0.0001$, apical-coronal $p<0.0001$). Likewise, with PTU system, the volume change differed significantly in different localization within the canal (apical-middle $p<0.0001$, middle-coronal $p<0.0001$, apical-coronal $p<0.0001$) (Table 1).

On the contrary to the distal canals, the surface area increased with both systems. The mean increase of the surface area ranged from 0.81 to 0.97 mm² with SAF and from 1.26 to 2.45 mm² with PTU. Within the coronal, middle and apical thirds of the mesial canals, the surface area variations were not statistically significant in SAF group ($p>0.05$). Nevertheless, in PTU group, the surface area changes was not different between apical-coronal and middle-coronal thirds (apical-coronal $p=0.0670$, middle-coronal $p=0.9932$), but it was significant between the apical and middle thirds ($p=0.0038$).

Likewise, both systems changed the canal shape amongst each third of the mesial canal similarly, as revealed by SMI values ($p>0.05$) (Table 1).

Similarly, transportation ranged between 0.19 – 0.85 mm in the apical, 0.15 – 0.69 mm in the middle and 0.20 – 1.66 mm in the coronal thirds of the mesial canals with SAF. With PTU, the transportation was 0.25 – 1.05 mm in the apical, 0.16 – 1.41 mm in the middle and 0.18 – 1.54 mm in the coronal thirds. However, transportation was similar within the apical, middle and coronal thirds with both systems ($p>0.05$).

Fig. 1 Representative 3D views of μ CT data of distal canals of mandibular molars shaped with SAF (a, b), and PTU (c, d) (green=preoperative, red=postoperative areas superimposed on 3D images of distal canals (a, b, c, d).

The same data for mesial canals of mandibular molars shaped with SAF (f, h), and PTU (e, g) (yellow=preoperative, purple=postoperative areas for SAF; green=preoperative, red=postoperative areas for PTU).

2. Preparation systems

1) Distal canals

In all thirds of the distal canals, both preparation systems revealed similar values for the change of the volume, surface area, SMI, and transportation ($p>0.05$) (Table 1).

When the uninstrumented area was measured for each system; maximum 42.53% of the distal canal walls remained unprepared with PTU (Fig. 1c, d), whereas this value was 39.66% for SAF (Fig. 1a, b) (Table 1). However, the amount of uninstrumented root canal walls was comparable in both systems ($p>0.05$).

2) Mesial canals

In the mesial root canals, the mean changes with PTU were significantly higher in all thirds than SAF in terms of volume ($p<0.0001$) (Table 1) (Fig. 2). Consequential to the increased volume change, the SMI values revealed that PTU altered the root canal cross-section more than SAF in all thirds of the mesial canals ($p<0.05$) (Table 1) (Fig. 2). Moreover, when compared to SAF, the PTU significantly increased the surface area only in the middle and coronal thirds ($p<0.05$) (Table 1) (Fig. 2). Both systems caused similar transportation in all thirds of the mesial canals ($p>0.05$) (Table 1). The percentage of the uninstrumented area ranged from 8.84–34.08% with PTU, and 10.54–40.62% with SAF (Fig. 1f, h); the uninstrumented area provided by PTU (Fig. 1e, g) was significantly lower than that of the SAF ($p=0.0108$) (Table 1).

The mean preparation time for SAF was 5.2 min and for PTU, it was 8.5 min, so the SAF system shaped all the mesial canals faster than PTU ($p=0.0323$). For both systems, in mesial root canals, statistically significant

Fig. 2 Changes of the volume (a), surface area (b) and (c) SMI values which were measured in each third of the mesial canals using SAF and PTU (each dot represents one specimen).

correlation was observed between the working time and root canal curvature ($\text{SAF}r^2=0.792$, $p<0.0004$, $\text{PTU}r^2=0.9098$, $p<0.0001$).

DISCUSSION

In the current study, we aimed to compare the cleaning and shaping effect of SAF and PTU systems both on curved and oval canals with a high-resolution micro-computed tomography. The results revealed that the

SAF system was not superior to PTU multiple rotary files on mesial and distal root canals of mandibular molar teeth, and our hypothesis was rejected.

Removing the pulp tissue remnants, infected dentin and bacterial biofilm from the inner layers of the root canal walls with NiTi files are crucial for proper mechanical preparation⁷. Moreover, persisting bacteria or bacterial cell wall remnants can negatively influence the outcome of the root canal therapy. The straight and large canals can be shaped easily; however, ledge formation, debris remaining and transportation can occur in narrow and curved canals¹⁴. Therefore, many NiTi files have been manufactured with different cross-sectional architecture, alloys and designs to enhance the shaping quality. But, with current rotary files uninstrumented residual areas might be still observed after root canal preparation, especially in oval, long oval and flattened canals^{5,15}.

Since the pre-operative root canal morphology might affect all evaluated parameters, all root canals in this study were similar in terms of the pre-operative volume, surface area, SMI, canal curvature and radius for both mesial and distal canals in both experimental groups ($p>0.05$). Although there is still no particular decision about apical enlargement size of a root canal¹⁶, it was reported in the earlier studies that the cleaning ability decreased in the apical third regardless of the instrumentation technique employed and the irrigant used^{4,17}. Thus, during the whole procedure, apical diameter size of the instruments used and glide path preparation were standardized for each group.

Recommended preparation time with the SAF instruments is 4 min. However, there was no accurate information in the literature about size of the final apical diameter of the each root canal type after shaping with SAF for 4 min. It is only written on the brochure of the SAF system that the final canal size and taper greatly depends on the pre-operative morphology of the canals. Thus, it is advised by the manufacturer to determine the final apical diameter with using a gutta-percha cone or a NiTi hand file after 4 min shaping. Although different tooth types with different root canal morphology were used in the previous studies, the final apical sizes of the root canals were not determined with a pilot study. Furthermore, when comparing the SAF system with PTU system, different finishing files like F2, F3, F4 were used in the literature^{7,18,19}. We assume that the amount of dentin removed can vary from F1 file to F5 file according to the degree of the rotary instrument's taper in PTU²⁰. Hence, these findings also reveal the requirement of standard study protocols in order to compare the results of the studies accurately. Using the findings of our preliminary study, the apical diameter size of the instruments was standardized in both experimental groups. Considering that different systems with different shapes and concepts would give different results in cutting amount and locations, it was not surprising to obtain different results for each instrument type. However, we wanted to compare the efficiency of the new SAF system in reducing the preparation and

irrigation time with that of PTU instrument.

The mean increase of the volume in mesial canals was significantly higher with PTU in all thirds of the mesial root canals ($p < 0.0001$). Even though SAF system enables to homogeneously shape the narrow mesial canals with an abrasive effect by conserving the pre-operative morphology, PTU instruments removed higher amount of dentin. This finding was also reported by previous studies^{10,15}. It is suggested that the cutting efficiency and multi-tapered design of PTU may have provided more dentin removal²¹. Our volume results in mesial canals were similar to other studies^{22,23}, because these researchers have also utilized F3 as their finishing file. Contrarily, other authors have used F2 file as the finishing file and have reported less volume increase^{24,25}.

In the SAF group, dentin was removed uniformly from the inner layer of the root canals compared with the PTU. Even though different tooth types were preferred in other investigations, similar results to our study were reported^{10,15,26} and it is stated that the ability of SAF to adapt to the root canal walls leads to higher performance and uniform removal of dentin within the root canal¹¹.

To the best of the authors' knowledge, the decrease in the surface area of root canal after root canal shaping has not been previously reported in the literature. In the present study, both instruments reduced the surface area in the middle and coronal thirds of the distal canals. We propose that SAF and PTU might have abraded only the irregularities on the inner layer of the dentin, and this might have caused these results. The ratio of the uninstrumented areas obtained with both shaping systems in distal canals seemed to support this assumption, because we know from the mathematics that the total area of the recessed field is greater than the smooth ones. Similarly, the slight changes of the SMI values after canal preparation indicated that the canal shapes have not been altered significantly.

Another factor that influences the efficiency of the root canal therapy is "transportation" which can be described as the vectorial displacement of the root canal. After determining the first cross-sectional slice where the apical foramen was visible, moving coronally from this point for 3, 6 and 9 mms the apical, middle and coronal thirds were assessed respectively. Using the x, y and z coordinate values obtained from 3D analysis, transportation was calculated along volume of each section of the canals. In past studies to date, various methods have been utilized to evaluate the transportation. Iqbal *et al.* and Kunnert *et al.* evaluated it by superimposing the preoperative and post-operative images at various levels^{27,28}. Uyanik *et al.* calculated the vectorial cumulative transport value with Pythagorean formula²⁴. Because all measurements were derived only from a specific two dimensional cross-section, we consider that these types of measurements cannot be reliable to assess the actual amount of transportation. In order to eliminate this limitation, we used a new formula to evaluate the vectorial displacement. If these x, y and z coordinate values were related to a specific point, we

could get displacement of one single point. However, we have analyzed a whole volume of a part of the root canal, and assessed the displacement of this volume after root canal preparation; thus, we can say that this is a vectorial displacement. Both systems showed vectorial displacement in all thirds of the canals, but no significant differences between the systems were observed. As another method to establish the transportation, centers of gravity can be calculated from each slice of the μ CT images and then, can be connected along the z-axis with a fitted line. However, this procedure is costly when compared to our methodology and for this reason it was not utilized in the present study.

Contrary to distal canals, PTU system has left significantly less uninstrumented areas than the SAF in mesial canals. It might be inferred that this would be due to the degree of the F3 instruments taper. Similarly, it has been reported that, depending on the type of teeth enrolled, the uninstrumented areas ranged between 16.7–41% with SAF^{11,29,30} and 18.7–79.9% with Protaper^{8,31,32} in the previous studies. Considering that complete instrumentation of the root canal walls cannot be achieved with the current technology, we suggest to focus on the continuous irrigation of the SAF system in further studies in order to provide the activation of the irrigation solution to eliminate the microbial flora from the root canals.

As well as the effective cleaning of the root canals, working time is also a critical factor for the patient's and dentist's comfort. It is clearly that Ni-Ti files reduce the preparation time when compared with the hand files^{33,34}. However, it can be influenced by different factors such as preparation technique, numbers of instrument used and the experience of the dentist¹. Additionally, when evaluating active filing, the file changing and irrigation time together, frequency of the irrigation and the amount of irrigation solution used also cause variations in working time. So, because of these reasons, we evaluated the total working time in our study. Since PTU is a multi-file rotary system and SAF can irrigate and prepare at the same time, preparation time with PTU was longer than that of SAF. In some studies, the time was defined as only active filing time^{33,35}; however, the other study similar to ours added file changing and irrigation time to the active working time and found similar results with us³⁶.

In order to help the SAF file to reach working length with straight access, glide path preparation with #20 K file is recommended for 1.5 mm SAF instrument. If glide path preparation was not adequate enough, the file cannot prepare the canal³⁷ and may buckle³⁸. However, in clinical conditions, even though glide path was created, the file may not reach to the working length without using endodontic motor especially in narrow and curved canals. In most of the studies, root canals were shaped with SAF system for 4 min. However, in the present study, the working length was not reached within 4 min in some of the curved mesial canals and we had to extend the duration of root canal shaping. Provided that each tooth has unique dentine hardness¹

depending on both its chronological and physiological aging status, this factor might be responsible for the requirement of lengthened shaping procedure in this *in-vitro* study. We also observed a correlation between the working time and the root canal curvature with both SAF and PTU systems, and this finding was also observed by Park *et al.* who reported similar results with reciprocation motion³⁹.

Although *in-vitro* studies are important part of the researches, it is difficult to reflect the clinical conditions. To increase the cleaning and shaping efficiency of the systems, further studies should be designed to evaluate the effect of using 2.0 mm SAF after preparation of the canals with rotary instruments.

CONCLUSION

Within the limitations of the current *in-vitro* study, both systems performed similar efficacy in cleaning and shaping of the root canals of mandibular first molar. However the uninstrumented area provided by PTU was significantly lower than that of the SAF. Also, the working-time extended as the canal-curvature increased mesial canals for both groups.

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