Deformation of the self-adjusting file on simulated curved root canals: a time-dependent study

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Objective. This study examined the surface changes of self-adjusting file after operating in different degrees of canal curvatures with a fixed radius of curvature in different operation intervals.
Study design. Artificial canals were manufactured in a 5-mm radius of curvature with 45° and 60° angles of curvature. Forty self-adjusting files were divided into 2 groups and submitted to functional fatigue to failure. Twenty files were tested using the 45° angle and the remaining 20 were tested using the 60° angle at 4 minutes for 7 periods in a total of 28 minutes. The average time frame for each 4-minute inspection period was considered as the moment of failure at 2, 6, 10, 14, 18, 22, and 26 minutes, respectively. Instruments were evaluated using scanning electron microscopy to characterize the material under study.
Results. The lattice detachment began at the second period for both groups and continued to increase along with the ongoing testing time. The detachment that occurred in 60° canal curvature was higher at the third and fourth periods when compared with the 45° group ($P < .05$). For both groups, during the third period, detachment of the arch of the lattice was only one sided; however, this deformation was severe between the fourth and sixth periods with a 2-sided detachment, which was easier to separate. The rough surface became smooth after usage. No full separation of the file was evident for both groups.
Conclusions. In multirooted teeth with severely curved root canals, using more than one self-adjusting file might be recommended to prevent lattice detachment. **(Oral Surg Oral Med Oral Pathol Oral Radiol Endod 2011;xx:xxx)**

Nickel-titanium rotary files are popular in endodontics and have been manufactured since 1988.[1] The cross-sectional design and tapers of these files have been modified and developed rapidly over the past 20 years. New endodontic rotary instruments are being developed with special care to improve performance with improved resistance to cyclic and torsional fatigue through innovative mechanical design and raw material selection,[2] targeting better cleaning and shaping, particularly in flat oval root canals that are impossible to completely debride. ReDent-Nova (Ra'Anana, Israel) recently introduced a self-adjusting file (SAF), which is a hollow file designed as a compressible, thin-walled, pointed cylinder, composed of a thin derivate of nickel-titanium lattice with high torsional and fatigue resistance.[3,4] The lattice surface is slightly abrasive and allows the removal of dentin with a back-and-forth grinding motion.[3] As previously reported by Metzger et al.,[4] the SAF system has high mechanical durability, which overcomes the problem of file separation. Additionally, in more than 100 clinical cases, no file separation was evident; however, no information was given regarding the radius of curvatures or the degree of the canal curvatures that were treated using SAF. Similarly, Hof et al.[3] investigated the mechanical properties of the SAF with various tests that were specifically designed for this file and reported no mechanical failure during up to 29.1 ± 1.2 minutes of operation. They concluded there was no case of a full separation of the SAF file and deformation was limited with the detachment of the arch of the lattice. Both studies reported a lack of information regarding the curvature of the prepared teeth and the artificial root canals were not provided unless reported as a standard endodontic plastic training block. Because cyclic, static torsional, and dynamic torsional fatigue are the most common causes of fracture in NiTi instruments,[5] and studies have determined that the radius of curvature and the degree of canal curvature are the key factors affecting these failures,[5,6] the effect of these variables should be evaluated when determining the mechanical properties of this novel system.

Thus, we hypothesized that the SAF system would perform equally in different degrees of canal curvatures

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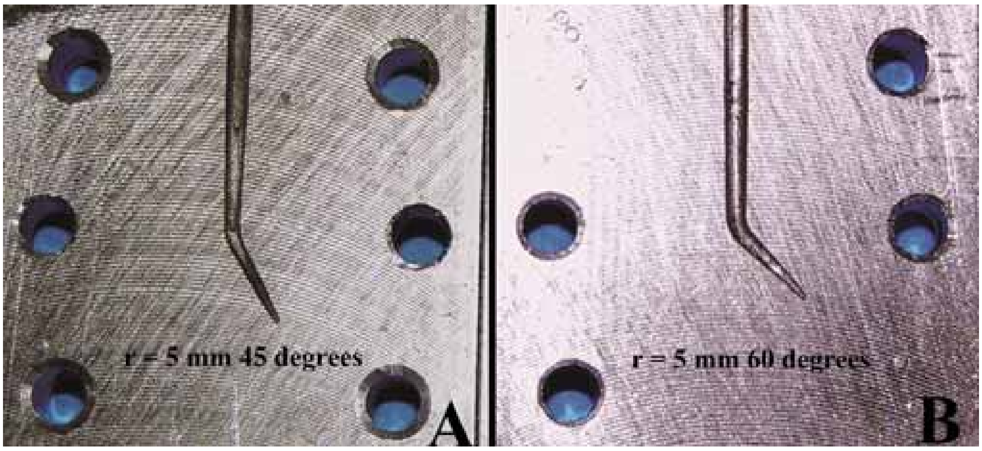

Fig. 1. Artificial metallic canals were manufactured in a 5-mm radius of curvature with 45° (**A**) and 60° (**B**) angles of curvature.

with a fixed radius of curvature without detachment of the lattice in 28 minutes of operation.

MATERIAL AND METHODS

A dental handpiece (Kavo GENTLE Power LUX 7LP, KaVo Dental, Biberach Riss, Germany) combined with an RDT3 head (Re-Dent Nova) was used to operate the SAF with 5000 vibrations per minute and an amplitude of 0.4 mm. This handpiece combination was secured to a custom-made cyclic fatigue instrument (Tekno Mühendislik, İzmir, Turkey) that raised and lowered the handpiece with an up-and-down movement of 7 mm that mimics the clinical operation of the SAF.

Artificial canals were manufactured to provide the instrument with a precise trajectory. To ensure the accuracy of the SAF file, a copper duplicate was milled, increasing the original size of the instrument by 0.2 mm using a computer numeric control machining bench (Tekno Mühendislik). The copper duplicates were constructed with a 5-mm radius of curvature with 45° and 60° angles of curvature (Fig. 1). Using these negative molds, the artificial canals were reconstructed using a die-sinking electrical-discharge machining process in stainless steel blocks. These blocks were hardened through annealing.[7-9]

The artificial canals were inserted into predrilled stainless steel mounting on the platform of the cyclic fatigue instrument. Each SAF file was operated with an in-and-out motion and was removed for inspection every 4 minutes (×50 magnification) for any evidence of mechanical damage. Files that were mechanically damaged were removed from the testing device; if not damaged, the test was resumed until a mechanical damage occurred on the same instrument. To reduce the friction of the file while operating inside the artificial canal, special oil for lubrication (WD-40 Company, San Diego, CA) was used. The evaluation of functional fatigue to failure was performed with 40 SAFs. Twenty files were tested at 45° and the remaining 20 were tested at 60° canals at 4 minutes for 7 periods for a total 28 minutes of working time. Testing was performed by a single operator to minimize procedural errors (A.I.).

All mechanically damaged instruments were evaluated using scanning electron microscopy (JEOL, JSM-5200, Tokyo, Japan) (Figs. 2 and 3). The images were not used for scoring the lattice detachment, but they were used to characterize the material under study (Table I). During the scoring process of mechanical damage, observers were unaware to which group the file belonged. For every 4-minute inspection period, the average observation time was considered as the moment of failure at 2, 6, 10, 14, 18, 22, and 26 minutes, respectively (Table I).

The cumulative percentage of lattice detachment was calculated depending on the moment of failure (Table I). Results were statistically analyzed using nonparametric Mann-Whitney *U* test at a significance level of .05.

RESULTS

When using SAF in 45° of canal curvature, the first lattice detachment was observed at the second period and increased gradually (Fig. 4, Table I). Similarly, when SAF was used in 60° canal curvature, the first lattice detachment was observed at the second period and increased with a higher ratio until the fourth period. Lattice detachment was observed in all files in both groups at the end of the last period. However, when the canal curvature was 60°, lattice detachment was higher in number at the third and fourth periods when compared with the 45° group ($P < .05$) (Fig. 4). The differences between 45° and 60° groups were not sta-

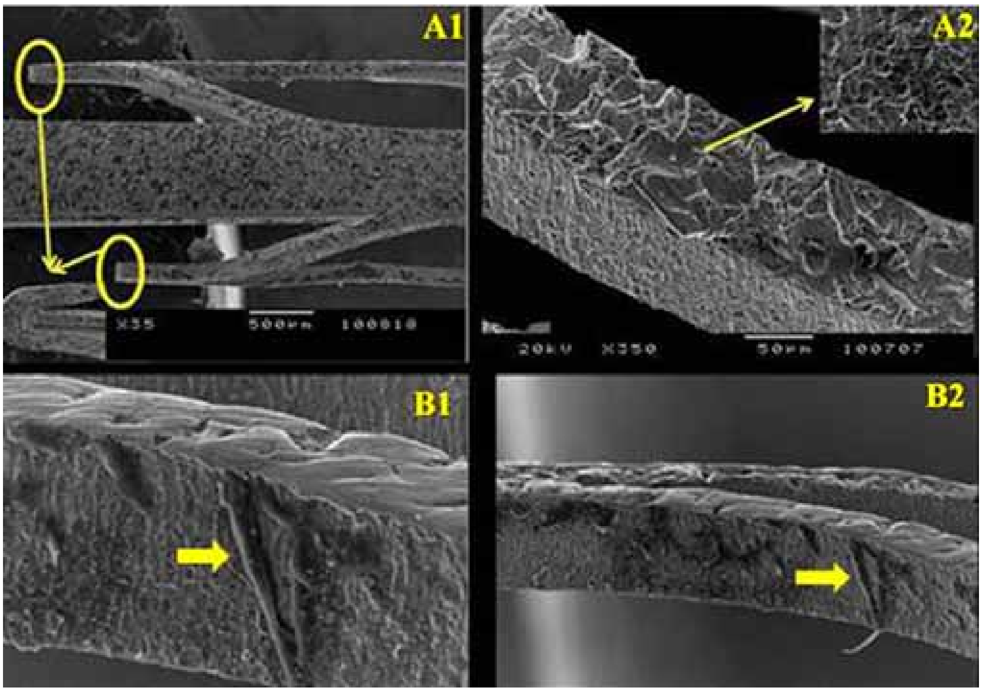

Fig. 2. **A1,** On a nonused SAF, the surface of the lattice has a rough appearance owing to the homogeneously splattered nickel-titanium derivate. The borders of the cutting sides are defined and no metallic fins protrude beyond these borders. **A2,** The rough surface of unused SAF. **B1,** The rough surface becomes smoother after usage and some lattice bulges are evident with creeping (45° group). **B2,** Note the extent of the lattice bulge for usage at 45°.

tistically significant for the first, second, fifth, and sixth periods ($P > .05$); however, the difference was important for the third, and fourth periods ($P < .05$) regarding lattice detachment (Table I). No full file separation was evident in either group.

Scanning electron microscopy (SEM) images show the characterization of mechanical damage in both groups (Figs. 2 and 3). The surface of nonused SAF displayed a porous appearance with defined borders of cutting sides with no metallic fins protruding these borders (Fig. 2, *A1* and *A2*). However, this rough surface became smoother depending on usage and some lattice bulges were evident with creeping (Figs. 2, *B1* and *B2,* and 3*, C1* and *C2*). The creeping motion was more evident when SAF was used in 60° curved canals (Fig. 3, *C1* and *C2*). In addition, the rough surface was completely smooth and some regions did not include any grinding material owing to usage and metal creeping (Fig. 3, *C1*). The metallic fins were longer in the 60° than the 45° group, which could have resulted from greater deformation of the lattice (Fig. 2, *B2* and *C2*). Detachment of the arch of the lattice was only 1-sided for both groups, during the third period (Fig. 3, *D1*); however, this detachment was severe between the fourth and sixth periods (14, 18, and 22 minutes) with a 2-sided detachment, which was easier to separate (Fig. 3, *D2*).

DISCUSSION

The unique mode of operation and design of the SAF system was why we evaluated the setup of functional fatigue-to-failure tests, as described previously.[3,4] Cyclic fatigue tests are irrelevant to the mode of operation of the SAF file because this system does not engage the canal walls with rotation. Previous studies used a standard endodontic plastic training block with a straight canal and reported the first mechanical fatigue failure after 29.1 (±1.2) minutes.[3,4] A typical mechanical failure was noted as detachment of one of the arches of the lattice at one of its connection points to the longitudinal beams. On the other hand, the exact localization was not defined concerning the length of the file. In comparison with Metzger et al.,[4] Hof et al.[3] also reported no full separation of the file.

Although all SAF files showed detachment of the lattice in the present study at the end of the 28-minute period, no full file separation was observed, consistent with previous reports.[3,4] However, deformation was severe in the 60° group during the third and fourth periods ($P < .05$) (Fig. 4, Table I).

The SAF system was reported to be designed for single use. It is understandable for the file to lose its cutting efficiency after use because it has only a grinding surface covered with a derivate of nickel-titanium to remove dentin (Fig. 2, *A1*). In the first report of the

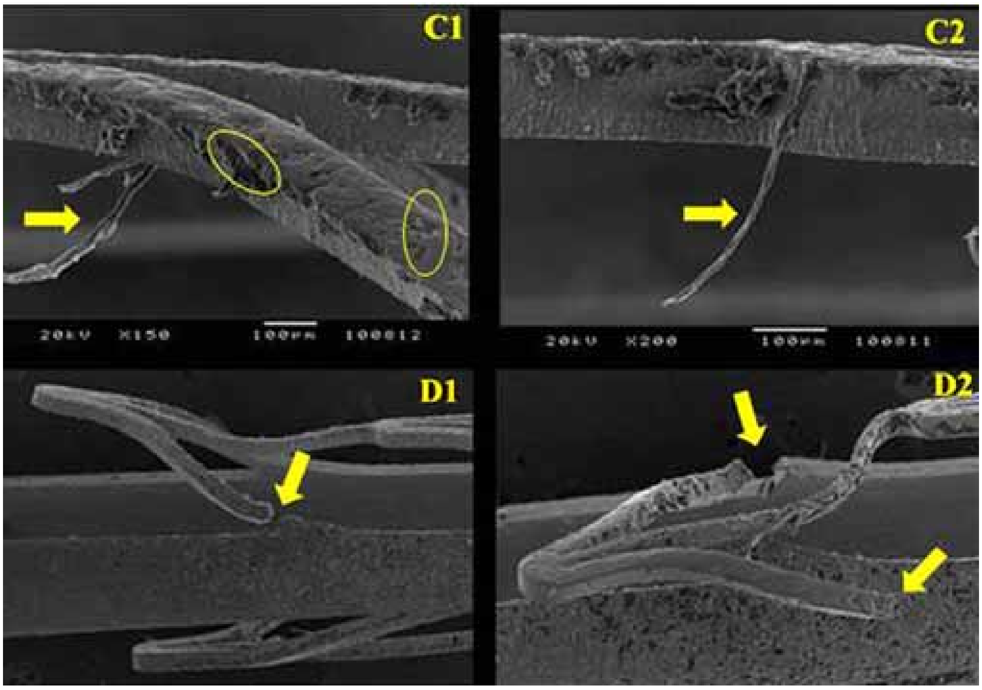

Fig. 3. **C1,** The rough surface is almost smooth and there are some regions that do not include any grinding material owing to usage and metal creeping. **C2,** The extent of creeping is linearly taller than the 45° group when SAF was used under 60° curvature, which might be an indicator of a greater degree of abrasion. **D1,** For both 45° and 60° groups at the third period, detachment of the arch of the lattice was only one-sided. **D2,** Severe lattice deformation during the fifth and sixth periods, which is easier to separate in both groups with a 2-sided detachment.

Table I. The degree of canal curvature is given in (α) for both groups

Moment of failure, min*	*No. of lattice detachment*		*Cumulative mean values*	
	α = 45°	*α = 60°*	*α = 45°*	*α = 60°*
2	0	0	0	0
6	1	3	5	15
10	6	11	35	70[a]
14	4	3	55	85[a]
18	5	2	80	95
22	4	1	100	100
26	0	0	0	0

The self-adjusted file was operated in 7 periods. The number of lattice detachment and mean values for each period are given.
Same superscript letters ([a]) indicate significant differences in percentage of lattice detachment for the given time periods ($P < .05$).
*Lattice detachment is expressed as failure.

SAF,[4] it was stated that the SAF could be operated for 27 minutes in extracted human teeth before any structural failure occurred, representing 6 or 7 turn effects per canal as we planned to simulate this condition using the SAF in 7 periods for 4 minutes. In addition, the effect of the degree of canal curvature was not mentioned in this previous report. In the present study, simulated curved root canals caused lattice detachment and changes on the surface at earlier time points than previously reported. Pointing out the results of lattice detachment in 60° curved root canals in the present study, one can assume that it would be more suitable to limit the operation time to not less than 12 minutes as previously reported,[3] but to less than 10 minutes for the SAF in severely curved root canals. This reveals that 1 SAF may not, in fact, be enough for total root canal enlargement owing to the lattice detachment, particularly in molar teeth, which have curved root canals and most likely possess an extra number of canals, representing as mesio buccal second or disto buccal second. Thus, using 2 SAF files may be better suited for complete root canal shaping to prevent lattice detachment. Nevertheless, an SAF may safely be used within 12 minutes in moderately curved root canals, as it was in 45° curved roots in the present study.

It is interesting that the resulted deformation was observed in the lattice detachment on the coronal portion of the file, which predominantly serves as a desirable failure type among other nickel-titanium file systems. The deformed and detached lattice branch is most likely reported to be easier to remove from the root canal using an irrigation system.[4] This may present an

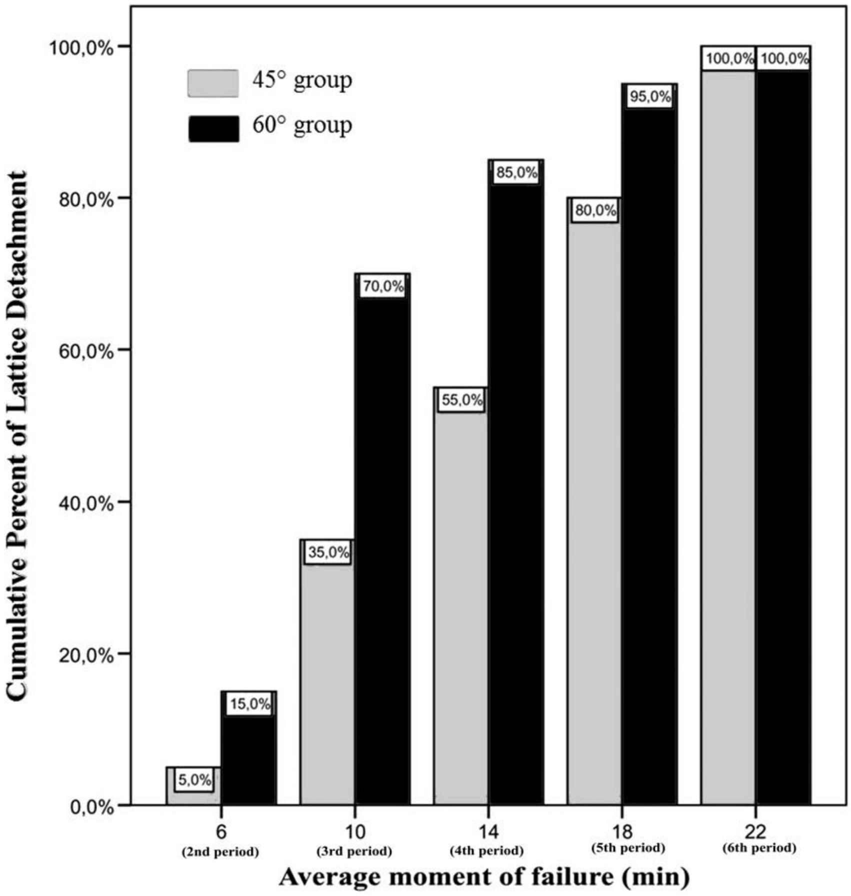

Fig. 4. Cumulative percentage of lattice detachment, which is in relation with the average moment of failure.

important issue to be evaluated in future research. The SAF has a 1-sided surface on the apical portion, having 2 branches of the lattice. It is probable that this portion transmits the compressive forces longitudinally to the middle and coronal areas. However, the middle and coronal portion of the file is composed of opposing surfaces and many branches are tied together, giving the file a mesh appearance. When the stress is transmitted to the lattice, if it exceeds the elastic modulus, then it is probable that the lattice is becomes deformed and one of the branches separates from the mesh. This may present an understandable reason for the lack of deformation of the lattice apically through the SAF system.

Although the extracted tooth model more closely resembles the clinical situation, it is not an ideal model if the study objective is to determine the pure physical properties of the evaluated file system, because no 2 root canals are perfectly identical.[10] An artificial root canal model with the same radius of curvature (r = 5 mm) and different degrees of canal curvature ($\alpha = 45°$ and $\alpha = 60°$) was selected for this study to standardize the conditions as much as possible and to minimize the parameters of the other mechanisms of failure aside from functional fatigue, although some disadvantages of metallic artificial canals should be taken into account when making exact conclusions about a novel system. In the present study, continuous irrigation was not performed using an irrigation solution as advised by the manufacturer; instead, oil was used as a lubricant.[11] One of the reasons for lattice detachment may be the noncontrolled increase in heat during operation that was not measured. Furthermore, abrasivity tests are impossible to perform on these metallic canals, as there is no dentin to be removed with instrumentation. Recently published data reported that compressing the SAF file generated circumferential force and the amplitude of this force gradually declined when the diameter of the canal was increased during root canal enlargement.[3,12] Hof et al.'s study[3] was performed using real dentin and the rate of dentin removal was reported to decrease after 2 minutes of operation because lattice of SAF gradually released free of compressive forces. However, in the present study, metallic artificial canals were impossible to enlarge, which impeded the gradual releasing of the lattice and as a result of this limitation our SAF files were more prone to lattice detachment. Therefore, making an exact comment about the related study's results may be unfair considering these topics as well as the operation time. In a recent study in which the debridement capacity of SAF in extracted human curved root canals was evaluated, this system was reported to produce debris and smear layer–free surfaces in the apical thirds when operated within 12 minutes,[13] however this study was not directly about the cutting efficiency of the system.

CONCLUSIONS

During root canal preparation of curved and multirooted teeth, it might be advisable to use more than one SAF to prevent deformation of the lattice. For this reason, our original hypothesis was not proven. However, one must consider that the instruments were tested in a metal environment in the present study and the conclusions cannot be compared directly with the clinical conditions where dentin is treated. Thus, future research evaluating the cutting ability of this system in extracted teeth with curved root canals may aid our understanding of the efficiency of the SAF.

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The Self-Adjusting File Optimizes Debridement Quality in Oval-shaped Root Canals

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Abstract

Introduction: Oval-shaped canals represent a challenge for rotary nickel-titanium (NiTi) files because buccal and/or lingual recesses are commonly left uninstrumented. The aim of the present study was to evaluate the debridement quality of the Self-Adjusting File (SAF) system in oval canals and compare it with the debridement achieved by a commonly used NiTi rotary system. **Methods:** A careful specimen selection resulted in two equal groups each consisting of 12 extracted mandibular canines with oval canals that had vital pulps before extraction. All canals had a buccolingual diameter that was at least 2.5 times larger than that of the mesiodistal one as defined from radiographs. One group was subjected to the SAF protocol, whereas the other group underwent conventional protocol; the ProTaper system up to the F2 instrument was used with syringe and open end needle irrigation. Sodium hypochlorite (5.25%) was used as an irrigant for both groups. The roots were then histologically processed and 0.6-μm-thick cross-sections were obtained every 0.5 mm from the 1- to 5-mm apical levels. Morphometric evaluation was performed on cross-sections to determine the amount of remaining pulp tissue as a percent of the root canal area. **Results:** The group-by-location interaction was not significant ($P > .05$), which means that the group comparisons were not dependent on the cross-sectional level. There was significantly greater residual pulp tissue left after ProTaper system instrumentation versus SAF instrumentation (21.4% vs 9.3%, $P < .05$). **Conclusions:** The SAF protocol was significantly more efficient for debridement of oval root canals than the rotary ProTaper protocol. *(J Endod 2011;37:701–705)*

Key Words

Debridement, instrumentation, oval canals, ProTaper, Self-Adjusting File

The introduction of nickel-titanium (NiTi) rotary file systems has resulted in significant progress being made in the mechanical preparation of the root canal space. Nevertheless, the results from high-definition micro–computed tomography (micro-CT) scanning studies have underlined the inadequate quality of mechanical preparation by the current NiTi rotary systems. Using micro-CT technology, it has been shown that the amount of mechanically prepared root canal surface is frequently below 60% (1–3). Rotary NiTi techniques leave a substantial amount of untreated dentin areas. The rotary motion of these files tends to prepare the main root canal space into a circular shape, leaving unprepared buccal and lingual extensions (4, 5). This phenomenon cannot be observed in two-dimensional clinical periapical radiographs, which represent a buccolingual projection. On the other hand, it can easily be observed in histological cross-sections.

Proper mechanical instrumentation should uniformly plane the entire perimeter of the root canal, thus completely removing the inner layers of heavily contaminated dentin. This, in turn, will also ensure the removal of as much of the remaining soft tissue and bacterial biofilm as possible, which may adhere to and cover the vast areas of the inner surface of the canal and may predispose to or cause and perpetuate disease (6). The limitations of current technologies should lead to the pursuit for more efficient preparation techniques, which may improve the debridement of the root canal space.

Initial reports of the Self-Adjusting File (SAF; ReDent-Nova, Ra'anana, Israel) system sound promising (7, 8). This innovative instrument consists of a hollow file composed of lattice threads that are lightly abrasive and allow for dentin removal with a back-and-forth grinding motion (9). The SAF is designed as a compressible file with the ability to adapt itself to the root canal cross-section.

Oval-shaped canals represent a critical challenge for any root canal cleaning and shaping protocol. Thus, the present study was designed to assess the tissue debridement efficacy of the SAF protocol in oval-shaped canals and to compare those results with the performance of the ProTaper NiTi system (Dentsply-Maillefer, Balleigues, Switzerland), which served as the control (10). The amount of residual pulp tissue was used as the outcome parameter to test the null hypothesis that there is no difference in the debridement of pulp tissue between the SAF or ProTaper systems for oval-shaped canals.

Materials and Methods

In Vivo Prospective Selection Process of Vital Teeth

One hundred sixty adult subjects voluntarily participated in the present study, which was reviewed and approved by the Ethics Committee. All teeth were scheduled for extraction because of advanced periodontal disease or nonrestorability.

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Only mandibular canines with vital pulp were included in the present study. To ensure pulp vitality, teeth were first tested using Green Endo-Ice refrigerant spray (Hygenic, Akron, OH). Teeth that responded positively were then anesthetized and accessed to verify the presence of a bleeding pulp. Teeth that failed to provide the dual proof for vital pulp were excluded from the study. It took 5 months (November 2009-March 2010) to collect 106 mandibular canines with confirmed vital pulps. After extraction, each tooth was immediately placed into a vial labeled with a four-digit alphanumeric code and containing 10 mL of buffered 10% formalin. Radiographs were taken in buccolingual and mesiodistal projections to select only teeth with a single root canal and to categorize them as either oval or circular shaped. Root canal diameters were measured 5 mm from the apex using image-analysis software (AxioVision software 4.11; Carl Zeiss, Munich, Germany); when the buccolingual diameter was 2.5 or more times larger than that of the mesiodistal diameter, the canals were classified as oval shaped. Round-shaped canals, in which the mesiodistal diameter was similar to the buccolingual diameter, were excluded from the present study.

All teeth presenting isthmus, lateral, accessory, or two canals were also excluded from the study. Furthermore, only root canals with an initial apical size equivalent to a size 10 K-file were included.

This selection process resulted in 68 vital mandibular canines that met all of the previously described criteria. From this collection, 12 pairs of teeth (total 24) were radiographically pair matched, and one tooth from each pair was randomly assigned to one of the two groups in this study. After the groups were established, a flip of a coin was used to define which teeth would be treated with each protocol. Six additional teeth were used as histological controls.

Root Canal Preparation

Tooth length was standardized to 18 mm by cutting off part of the crowns, and the root canal patency was confirmed by inserting a size 15 instrument. The working length (WL) was established at the apical foramen. The same operator performed all preparation procedures.

For the ProTaper preparation, 12 teeth were prepared with the ProTaper Universal instruments driven at 300 rpm with 2 N/cm of torque (XSmart; Dentsply-Maillefer). The sequence followed was (1) S_X file (one half of the WL), (2) S_1 file (one third of the WL), (3) S_2 file (two thirds of the WL), (4) F_1 files (the full WL), and (5) F_2 files (the full WL). Shaping S_X, S_1, and S_2 files were used in the canal with a brushing motion according to the anatomy of each root canal. Irrigation with 1 mL 5.25% sodium hypochlorite (NaOCl) solution was used between each instrument applied with a syringe and an open-end needle. After each instrument, the needle was inserted as far as it reached and retracted 2 mm before irrigation was applied. After the last instrument was used, the needle was placed 2 mm from the WL, and irrigation was applied. The smear layer was then removed using 3 mL 17% EDTA for 3 minutes. Three milliliters of bidistilled water was then used for 3 minutes as a final rinse.

For the SAF preparation, 12 teeth were prepared using the SAF system (ReDent-Nova). A glide path was verified or established using a #20 K-file. The SAF file was operated in each canal for 4 minutes with continuous irrigation. The file was used with a vibrating handpiece head (RDT3, ReDent-Nova) at an amplitude of 0.4 mm and at 5,000 vibrations per minute. An in-and-out manual motion was continuously performed by the operator. Irrigation with 5.25% sodium hypochlorite was applied through the hollow file throughout the 4 minutes of operation. The irrigant was continuously provided by a VATEA peristaltic pump (ReDent-Nova) at a rate of 4 mL/min. A smear layer was then removed with 3 mL of 17% EDTA for 3 minutes. Three milliliters of bidistilled water was then used for 3 minutes as a final rinse.

Histological Assessment

Specimens were immediately immersed in 10% buffered formalin for 48 hours and then demineralized in a 22.5% (vol/vol) formic acid solution and a 10% (wt/vol) sodium citrate solution for a period of 2 to 3 weeks. The endpoint was monitored radiographically. After rinsing for 24 hours in tap water, the specimens were dehydrated and processed for routine histological examination. Teeth were embedded in paraffin blocks, and serial 0.6-μm-thick cross-sections were obtained every 0.5 mm from the 1- to 5-mm apical levels. This resulted in a total of 10 slides per tooth. Sections were mounted on glass slabs and stained with hematoxylin-eosin.

Morphometric Evaluation

The specimens were visualized using an Axioplan 2 Imaging fully motorized light microscope (Carl Zeiss Vision, Hallbergmoos, Germany). Image analysis and processing were completed using the Axion Vision image 4.5 Zeiss system (Carl Zeiss). An outline of the area of the remaining pulp tissue and the cross-sectional area of each root canal was traced. Next, the percentage of remaining pulp

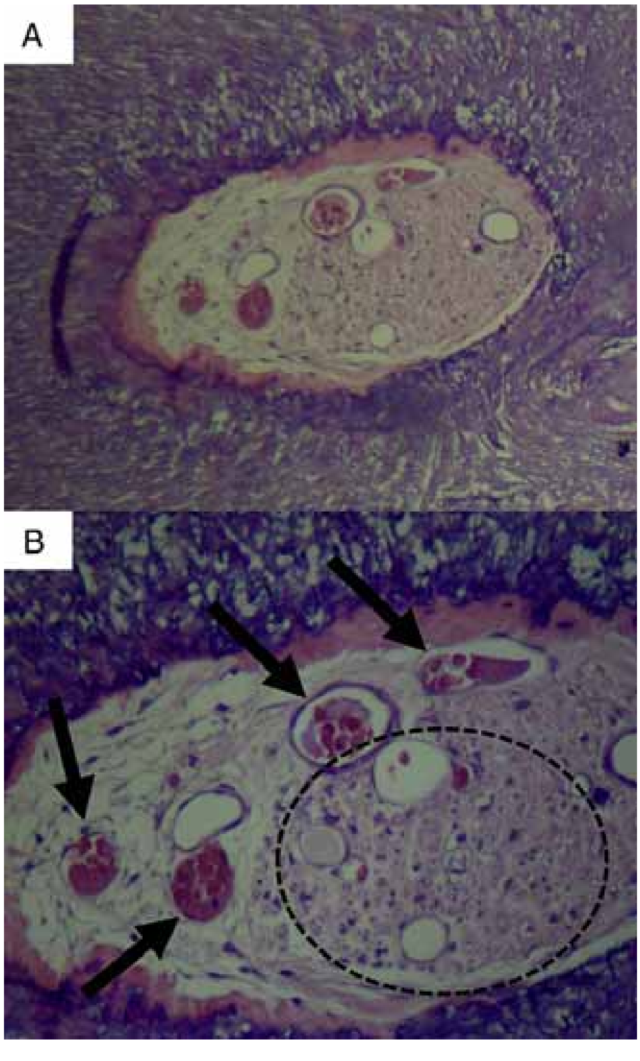

Figure 1. (*A*) A noninstrumented canal from the histologic control group. The root canal space is completely full with pulp tissue. This canal is less oval than those selected to the experimental groups and serves only as a histological control. (*B*) A higher magnification of the same control specimen. Arrows indicate the presence of preserved vessels and nerve bundle is shown in the framed area.

TABLE 1. The Percent of Residual Pulp Tissue Left after the Use of ProTaper and SAF System

Technique	Mean (± standard deviation)
ProTaper	21.4% (±8.2)[a]
SAF System	9.3% (±3.7)[b]

Different letters indicate significant differences between techniques at $P < .05$.

tissue area (PRPT) was calculated for each root canal section by dividing the remaining pulp tissue area by the total area of the root canal in the same section. The operator who made the measurements was blinded as to which samples were treated with which method, and all the measurements were repeated twice to ensure reproducibility.

Statistical Analysis

Statistics were used to compare the effect of each preparation method on the PRPT between teeth of each matched pair. Because preliminary analysis of the raw pooled data showed a Gaussian distribution (D'Agostino and Person omnibus normality test), the *t* test for paired samples was used. Moreover, one-way analysis of variance was used to assess the group-by-location interaction. The alpha-type error was set at 0.05, and Prisma 5.0 (GraphPad Software Inc, La Jolla, CA) was used as an analytic tool.

Results

All microscopic images for the histologic control group displayed a substantial amount of residual pulp tissue (Fig. 1). Thus, this control group confirmed the experimental histologic model as well as the efficiency of the prospective *in vivo* collection of the specimens.

The group-by-location interaction was not significant ($P > .05$), meaning that the group comparisons were not dependent on the cross-sectional level. As a result, data from each specimen were pooled to provide a single mean value. Each experimental group included 120 sections upon which the analysis was based.

Overall, tissue remnants were found mainly in the uninstrumented buccal and/or lingual recesses (Table 1, Figs. 2 and 3). Pair-wise

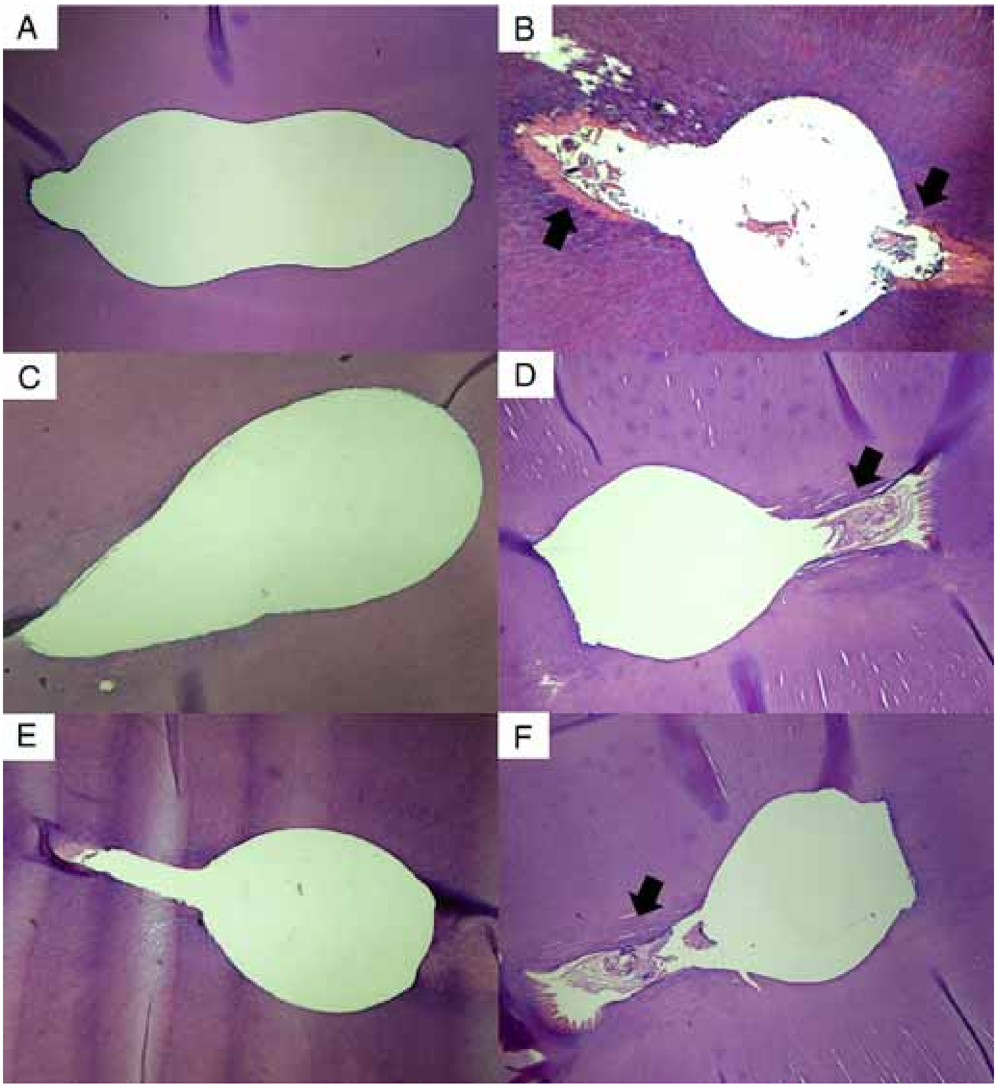

Figure 2. (*A*) An oval-shaped canal instrumented with the SAF system. The root 'canal space is free of remaining pulp tissue. (*B*) The counterpart tooth instrumented with the full range of ProTaper Universal instruments. The arrows indicate the presence of a significant amount of remaining pulp tissue in the unprepared buccal and lingual extensions. (*C*) A clean oval-shaped canal instrumented with the SAF system. (*D*) The counterpart tooth instrumented with the ProTaper system. The arrow indicates the presence of a significant amount of remaining pulp tissue in the unprepared buccal extension. (*E*) An oval-shaped canal instrumented with the SAF system with lingual extension almost completely free of pulp tissue. (*F*) The counterpart tooth instrumented with the ProTaper technique. The arrow indicates the presence of a significant amount of remaining pulp tissue in the unprepared buccal extension.

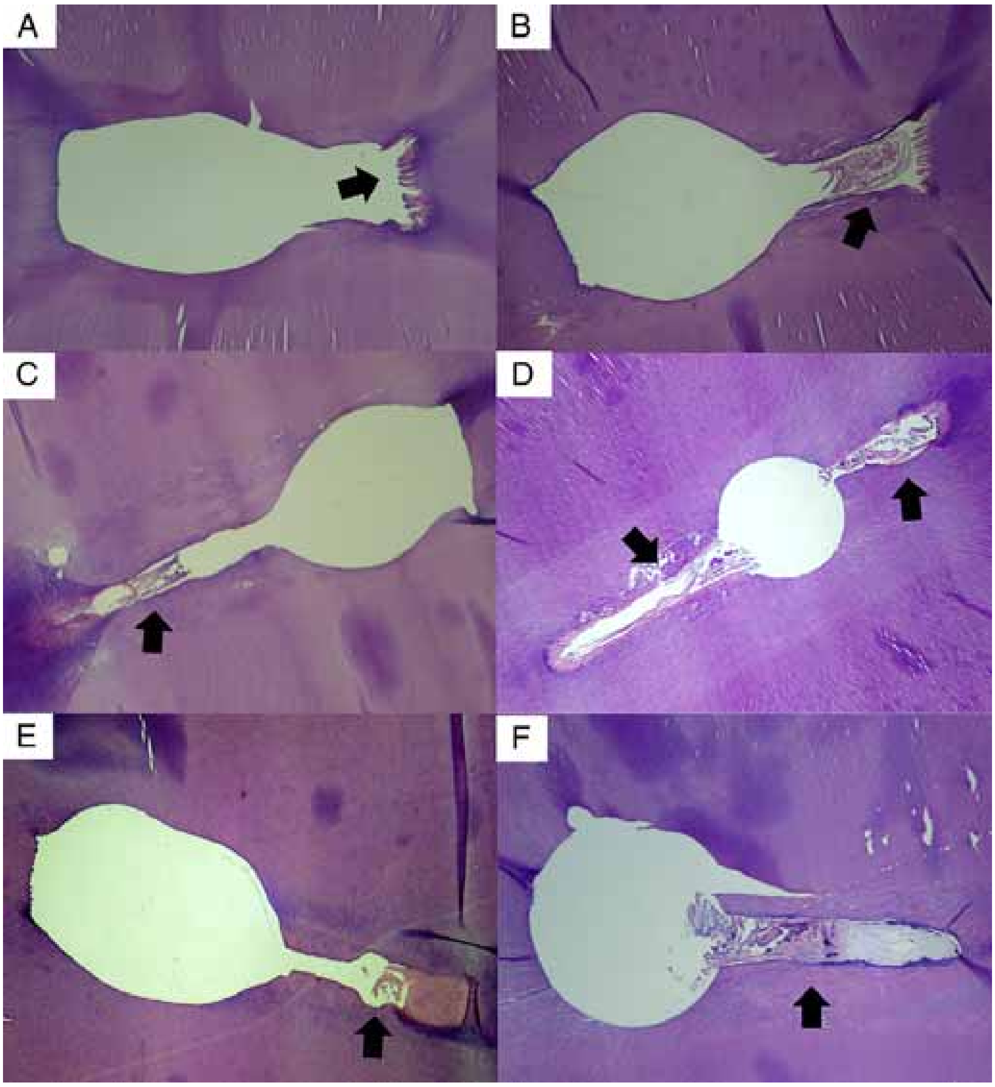

Figure 3. (*A*) An oval-shaped canal instrumented with the SAF system. The root canals space is free of remaining pulp tissue. The arrow indicates the presence of pulp tissue at the end of the lingual extension. (*B*) The counterpart tooth instrumented with the full range of ProTaper Universal instruments. The arrows indicate the presence of a significant amount of remaining pulp tissue in the unprepared lingual extension. (*C*) An oval-shaped canal instrumented with the SAF system. The arrow indicates the presence of pulp tissue in the buccal extension. (*D*) The counterpart tooth instrumented with the full range of ProTaper Universal instruments. The arrow indicates the presence of a significant amount of remaining pulp tissue in the unprepared buccal and lingual extensions. (*E*) An oval-shaped canal instrumented with the SAF system with lingual extension almost completely free of pulp tissue. The arrow indicates some unprepared area at the end of the lingual extension. (*F*) The counterpart tooth instrumented with the full range of ProTaper Universal instruments. The arrow indicates the presence of a significant amount of remaining pulp tissue in the unprepared lingual extension.

comparison showed that the instrumentation technique significantly influenced PRPT ($P < .05$); there was significantly greater residual pulp tissue left after ProTaper system instrumentation versus SAF instrumentation (21.4% vs 9.3%, $P < .05$, Table 1). The SAF-treated canals had a more evident preparation of the buccal and/or lingual recesses (Figs. 2 and 3).

Discussion

The SAF system substantially reduced the amount of remaining pulp tissue by 57% as compared with the conventional full sequence of ProTaper Universal NiTi files. In other words, the SAF system improved the debridement standard produced by the conventional NiTi rotary preparation approach. In the ProTaper system group, substantial amounts of pulp tissue remained in the canals; 21% of the root canal cross-section contained pulp tissue remnants. This represents the inability of most rotary files to access buccal and/or lingual recesses of oval canals (3). Furthermore, it represents the limited ability of the sodium hypochlorite irrigant applied with a syringe and needle to compensate for the inadequacy of the file itself. It seems that the common belief that “the file shapes; the irrigant cleans” is based more on wishful thinking rather than on experimental facts at least in the oval-shaped canals used in the present study.

The present result may have a two-fold basis: (1) the SAF ability to adapt itself to the cross-section of the canal and (2) the continuous irrigation. Because these two characteristics were present in combination during the root canal preparation in the SAF group, it is not possible to determine the contribution’s of each on the final result but probable to conclude that the interplay of both characteristics aided in the performance by the SAF system. The irrigation provided by the SAF system is substantially different from the conventional syringe-needle irrigation that was applied in the ProTaper group. The latter depends on fluid dynamics that have been shown to be of limited efficacy (11–13). This is the reason why Siqueira et al (14) called SAF a cleaning-shaping-irrigation system because it is, in fact, a joint biomechanical preparation system. Moreover, the SAF system irrigation operates on an entirely different principle than the conventional syringe and needle. First, the SAF file vibrates at 5,000 vibrations per minute, which causes sonic activation of the irrigant throughout the procedure. Second, the metal mesh is closely adapted to the canal walls and is moved in and out by the operator, which provides a scrubbing action on the canal walls. Last but not least, the continuous replenishing of fresh irrigant throughout the procedure may also have contributed to the results as well as those reported by Metzger et al (8).

It is worth noting the compressibility of the SAF file because this mechanical feature allows the SAF file to adapt itself to the cross-section of oval canals (7). It may be calculated that if the lattice cylinder of the file, which has a 1.5-mm diameter, is compressed mesiodistally up to 0.2 mm, it may spread buccolingually up to 2.4 mm. This may explain how it spreads to form closer contact with the canal walls, even in the buccal and lingual recesses that were commonly unaffected by the rotary files.

Histologic methods have been used for many years to evaluate root canal instrumentation and are considered archaic when compared with current micro-CT methods. Nevertheless, they provide valuable information that cannot otherwise be obtained; thus, they should be considered an essential complimentary tool to be used with micro-CT.

When selecting teeth with vital pulps, it may be assumed that pulp tissue is present and attached around the entire perimeter of the root canal (15); this was confirmed by the current histologic controls (Fig. 1). Remaining tissue after cleaning and shaping represents an area of the canal in which the instrument failed to reach mechanically. Furthermore, the remaining tissue indicates that even the sodium hypochlorite irrigation, which is expected to clean such recesses, did not complete the task.

Micro-CT provides valuable information about changes that occurred or failed to occur in the calcified tissues surrounding the root canal. However, it provides no information about the soft tissue or biofilm that remained attached to or was cleaned off the canal walls. We assume that if a layer of dentin was removed in a given area, all attached tissue or biofilm was removed from that area as well. Nevertheless, the question always remains regarding whether the area unaffected by the procedure was or was not properly cleaned by the irrigant. Histologic sections were used in the present study as well as in previous studies to shed light on this “gray zone” (5, 15).

Because oval canals represent the major challenge to any file and/or irrigation system, this type of canal was selected for the present study. Nevertheless, high variability exists in shape, size, and dimensions of the pulp space in these teeth. Special care was taken to ensure an equal challenge in both study groups by pair matching and random allocation of the teeth to the groups. Although this process limited the size of the groups studied, it may be considered the only way to expose both instrumentation protocols to the same level of challenge. The flip of a coin to select which group would be treated with each method further helped to avoid any bias in the case selection.

The ProTaper NiTi system was selected to represent the rotary NiTi file system family of instruments because it has been used in a large variety of studies, including one by De-Deus et al (15) who used a similar methodology. It was compared with the new technology of the SAF system, which is currently, to the best of our knowledge, the sole representative of a new family of instruments: the self-adjusting files (16).

The current results indicate that, in addition to its previously reported better efficiency for circumferentially removing dentin from all canal walls, as has been shown by micro-CT studies (8, 17–19), the SAF system also has an improved debridement and cleaning efficacy in the oval-shaped canals used in the present study. This may, in turn, also aid in explaining the recently reported improved disinfection that the SAF system has in oval canals (14). Further studies should be performed to verify if similar results as those for remaining pulp tissue can be attained also with naturally occurring mixed bacterial biofilms. It would also be interesting to compare the SAF system with a combination of rotary files with one or more of the recently introduced irrigation systems, such as negative pressure and passive ultrasonic irrigation methods.

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The authors deny any conflicts of interest related to this study.

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The Self-adjusting File (SAF). Part 2: Mechanical Analysis

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Abstract

Introduction: The study was designed to explore the mechanical properties of the self-adjusting file (SAF) and its application in the root canal using continuous irrigation. **Methods:** The compressibility of the SAF file and the resulting peripheral force were measured using specially designed systems. The abrasivity of the file was tested on dentin blocks representing a flat root canal. The durability of the SAF file was tested using a functional fatigue-to-failure assay. Degradation of the file was evaluated by using files that were previously used for 10, 20, and 30 minutes and comparing their efficacy with that of new, unused files. The potential of extruding irrigant beyond the apex was explored in roots with an open apical foramen. **Results:** The SAF file was elastically compressible from a diameter of 1.5 mm to dimensions similar to those of a #20 stainless steel
K-file. This compression resulted in an evenly applied force to the root canal walls. The in-and-out vibration of the file and the peripheral force, combined with its abrasivity, allow for hard-tissue removal. Under the conditions of the experiment, no mechanical failure was observed with up to 29 minutes of operation in the root canal. The file loses its efficacy after prolonged use, with a 40% reduction after 30 minutes of operation. The operation of the file with continuous irrigation did not push the irrigant beyond an open apical foramen. **Conclusions:** The SAF file is an elastically compressible file that effectively removes dentin and can mechanically endure use under its recommended mode of operation with a minimal loss of efficacy. *(J Endod 2010;36:691–696)*

Key Words

Cleaning and shaping, cyclic fatigue, endodontic files, fatigue, mechanical properties, SAF, self-adjusting file

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The biological objectives of root canal treatment have not changed over the recent decades, but the methods to attain these goals have been greatly modified. The introduction of nickel-titanium rotary files represents a major leap in the development of endodontic instruments, with a wide variety of sophisticated instruments presently available (1, 2).

The superelastic alloy has made it possible to manufacture highly efficient instruments that can be rotated safely, even in curved root canals with a reasonable centingability, reasonably maintaining the long axis of the canal in its original location. Since then, many file designs have been tested and introduced with variations in rake angle, radial lands design, helical pitch, or thickness of the core (3–5). Some designs are highly aggressive and some are more flexible, whereas others offer safe tips or an interrupted helical angles (3–8). Recent advances in nickel-titanium metallurgy are also promising a potential for more elastic instruments (9). Whatever their modification or improvement, all of these instruments have one thing in common: they consist of a metal core with some type of rotating blade that machines the canal with a circular motion using flutes to carry the dentin chips and debris coronally. Consequently, all rotary nickel-titanium files will machine the root canal to a cylindrical bore with a circular cross-section if the clinician applies them in a strict boring manner.

When operated in narrow canals or those with a round cross section, this mode of operation may be adequate. The situation is quite different for flat root canals that have an oval or even ribbon-shaped cross-section.

Several reports have indicated that in oval or flat root canals, rotary files alone fail to perform adequate cleaning and shaping. Untreated "fins" may remain on the buccal and/or lingual aspects of the bore created by the rotary file (10–12). The new self-adjusting file (SAF) represents a totally different approach in endodontic file design and mode of operation that was specially designed to overcome this problem (13).

The SAF is a hollow file designed as a compressible, thin-walled, pointed cylinder, 1.5 mm in diameter, composed of a thin nickel-titanium lattice (Fig. 1*A*). During its operation, the file is designed to be compressed while inserted into a narrow root canal. The file then attempts to regain its original dimensions, thus applying a constant delicate pressure on the canal walls. When inserted into a root canal, it adapts itself to the canal's shape, both longitudinally (as will any nickel-titanium file) and also along the cross-section (13, 14). In a round canal, it will attain a round cross-section, whereas in an oval or flat canal it will attain a flat or oval cross-section, thus providing three-dimensional adaptation during the cleaning and shaping process (13, 14). Thus, its name, SAF, expresses this unique behavior during its application.

The surface of the SAF lattice threads is lightly abrasive, designed for the removal of dentin with a back-and-forth grinding motion. A single SAF file is used throughout the procedure, starting as a compressed file that gradually enlarges in size during dentin removal with close adaptation to the canal walls.

The SAF is operated using a dental handpiece that provides a vertical (in-and-out) vibration, with 3,000 to 5,000 vibrations per minute and a 0.4-mm amplitude (13). A light manual in- and-out motion of 3 to 5 mm is applied by the operator. The hollow SAF file also allows for continuous irrigation throughout the procedure. Irrigation is performed via a silicon tube that is attached to a rotating hub on the shaft of the file (Fig. 1*A*). The irrigant goes into the file, freely escapes into the canal through the lattice wall, and then flows back coronally and escapes through the access cavity. The aim of this study was to mechanically analyze the SAF and to characterize the parameters of its performance, mode of action, and durability.

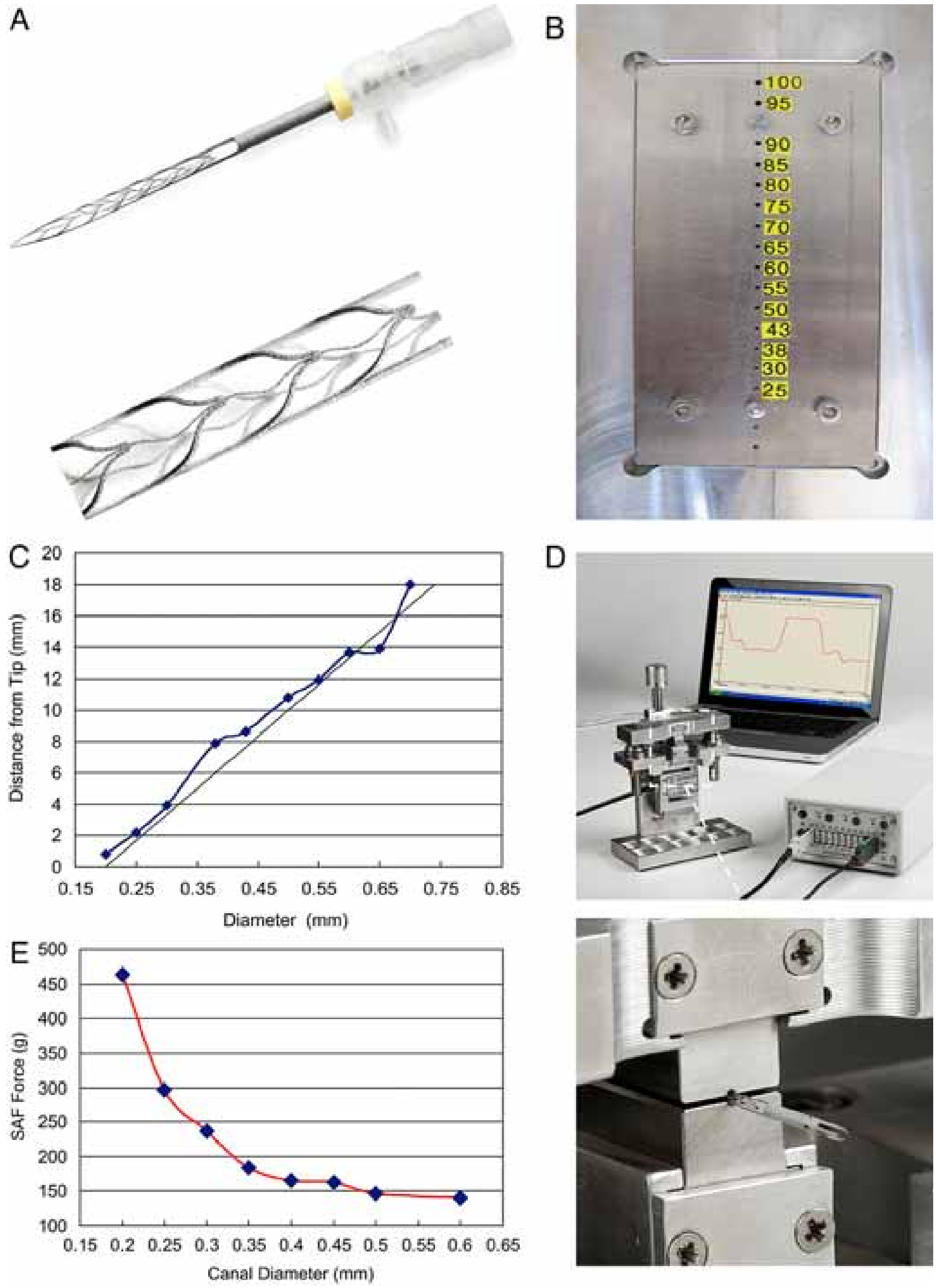

Figure 1. (*A*) The SAF file: longitudinal beams connected by arches, forming a pointed cylinder with a 1.5-mm diameter and wall thickness of 120 μm. The arches are stabilized by thin longitudinal struts. The surface is lightly abrasive. (*B*) Compressibility test: precision drill holes in a stainless steel plate, with diameters from 0.15 to 1.0 mm. The SAF file was manually inserted into each hole to determine depth of penetration. The diameter of the hole represented the maximal compression of the file at this level. (*C*) Compressibility of the SAF: compressed file diameter at given distances from its tip. Each point represents the mean of 50 samples. The standard deviation was less than 3%. The black line represents the dimensions of an ISO #20 K-file. (*D*) Setup for circumferential force measurement: an SAF file is inserted into a precision channel between the upper and lower plates, representing a root canal of a given diameter. Channel diameters ranged from 0.2 to 1.0 mm. The compressed file generates force that is recorded by a computerized system. (*E*) Force applied as result of compression. The force generated by insertion of an SAF file into the precision channels as a function of the channel diameter. Each point represents the mean of 10 samples. The standard deviation was less than 0.5%.

Materials and Methods

Some of the tests that were used in this study were conducted following American National Standard Institute/American Dental Association guidelines, but the unique mode of operation of the SAF called for several tests that were specially designed for this file.

Compressibility of the SAF

This test was conducted to measure to what extent the SAF file can be elastically compressed at any given point along its active part. SAF files were manually inserted into precision drill holes in a measuring device (Fig. 1*B*). The diameter to which the file was compressed (diameter of the hole in millimeters) was recorded and plotted against the distance from the file's tip at which a given compression was recorded; 50 SAF files were tested.

Force Applied as a Result of Compression

The setup for measuring the circumferential force applied by the compressed SAF file consisted of precision drill channels prepared in split metal blocks that were attached to electronic force sensors (Fig. 1*D*). The channels represented a range of root canal diameters from 0.2 to 0.6 mm. The SAF file was inserted into a channel of a given diameter, thus being compressed. The resulting force was recorded using a computerized system. The results were plotted as force versus the artificial canal diameter. Ten SAF files were tested for each channel diameter.

Surface Roughness

To define the extent of roughness of the active surface of the SAF files, their surface roughness was measured by using a Mitutoyo SJ-210P system (Aurora, IL) and expressed in micrometers.

Abrasivity Test

Abrasivity was defined as the ability to remove material with time. The testing setup consisted of two preweighed slices of root dentin held at a distance of 0.2 mm from each other via a micrometer thread in a precise XYZ apparatus (Fig. 2*A*).

At stage one (calibration stage), K-files were used; a #25 K-file (Mani, Tochigi, Japan) was operated with an in-and-out filing motion at a central line between the two dentin slices until loose. The slices were then removed and weighed. The slices were remounted, and the procedure was repeated with #30, 35, 40, and 45 K-files. At stage two (experimental stage), two identical new dentin slices were used. They were also preweighed and set at a 0.2-mm distance from each other, and a SAF file was compressed between them and operated at 5,000 vibrations per minute using a stabilized dental handpiece. This setup represented the SAF operation in a flat root canal.

The amount of dentin removed by the SAF file was determined by weighing the dentin samples before the procedure and after 1, 2, 3, and 4 minutes of operation. The results were converted to representative ISO size enlargement using the results of the calibration stage of the assay. Ten samples were used for each time point.

Durability: Torque Test

Torque durability was measured following the ANSI/ADA guidelines. The shank of each file was attached to a rotary motor that rotated at 2 rpm. The file tip was attached to a stationary torque sensor. The file was rotated by the motor clockwise until failure occurred, and the data were recorded and plotted using a computerized system (15, 16). Two parameters were recorded: (i) the maximal torque and (ii) angular deflection to failure; 10 SAF files were tested.

Durability: ADA Cyclic Fatigue Test

Each file was attached to a rotating device (900 rpm), and the free active tip of the file was deflected by 5 mm from its axis. Rotation time before failure was recorded (15, 16); 10 SAF files were used for this test, five before autoclave and five after autoclave.

Durability: Free Buckling Fatigue Test

The file was freely placed in the cylindrical chamber of a specially designed testing apparatus, and a free 6-mm type I buckling was repeatedly applied. The number of cycles until failure occurred was recorded. Ten SAF files were used for this assay.

Durability: Functional Fatigue-to-Failure Test

The test setup consisted of a stainless steel jig holding a standard endodontic plastic training block with a straight canal (Morita, Kyoto, Japan). A dental handpiece (KaVo, Biberach Riss, Germany) was secured to an upper movable part that raised and lowered the handpiece because of rotation of an asymmetrical cam shaft (Fig. 2*C*). The operation mimics the clinical operation of the SAF with an up and down movement of 10 mm (Fig. 2*C*).

Each SAF file was operated with continuous irrigation in the artificial root canal and removed every 1 minute for inspection (×50 magnification) for any evidence of mechanical damage. The time at which the first mechanical damage was detected was recorded; 50 SAF files from five different lots were tested.

SAF Degradation as a Function of Working Time

To test the efficacy of the SAF after being used for a period of time, instruments that were used initially as described previously (abrasivity test) for 10, 20, and 30 minutes were compared with unused SAF files. The efficacy was measured by measuring the force applied by the compressed files (as done in testing "force applied as result of compression" above) and running the "abrasivity test" above.

Reduction of the force applied by the compressed, used file and reduction in the amount of dentin removal per minute were considered as expressions of the SAF degradation.

Irrigation Experiments

To test for potential extrusion of the irrigant through the apical foramen, because of the in-and-out motion of the SAF file, two sets of roots were endodontically prepared to a size 25 K-file to a working length 1 mm short of the apex. The apical foramen was intentionally opened so that a size 20 K-file could pass through it, whereas a size 25 K-file could reach a working length 1 mm short of the apex but did not pass. The teeth were placed vertically, apex down, and no attempt was made to seal the apical foramen, which was left unobstructed.

The SAF file was operated in the canal with continuous irrigation at 5 mL/min, and the root was continuously observed to detect potential irrigant passage through the apical foramen. The same root canals were then rinsed with a syringe and needle for a similar observation. The needle was free in the canal, and its tip was kept at a distance of 5 mm from the apical foramen.

Results

Compressibility of the SAF

The elastic compressibility of the SAF file is presented in Figure 1*C*. The apical 2 mm of the file could be compressed into a 0.25-mm hole. The compressible diameter gradually increased in size, with its compressed dimensions comparable to those of an ISO #20 file (Fig. 1*C*).

Force Applied as a Result of Compression

SAF files inserted into channels of smaller dimensions applied higher forces in response (Fig. 1*E*). In a channel with a 0.25-mm diameter, a force of 300 g was recorded. With increasing diameter of the canal, the force declined; at a canal diameter of 0.5 mm, it was only 150 g (Fig. 1*E*).

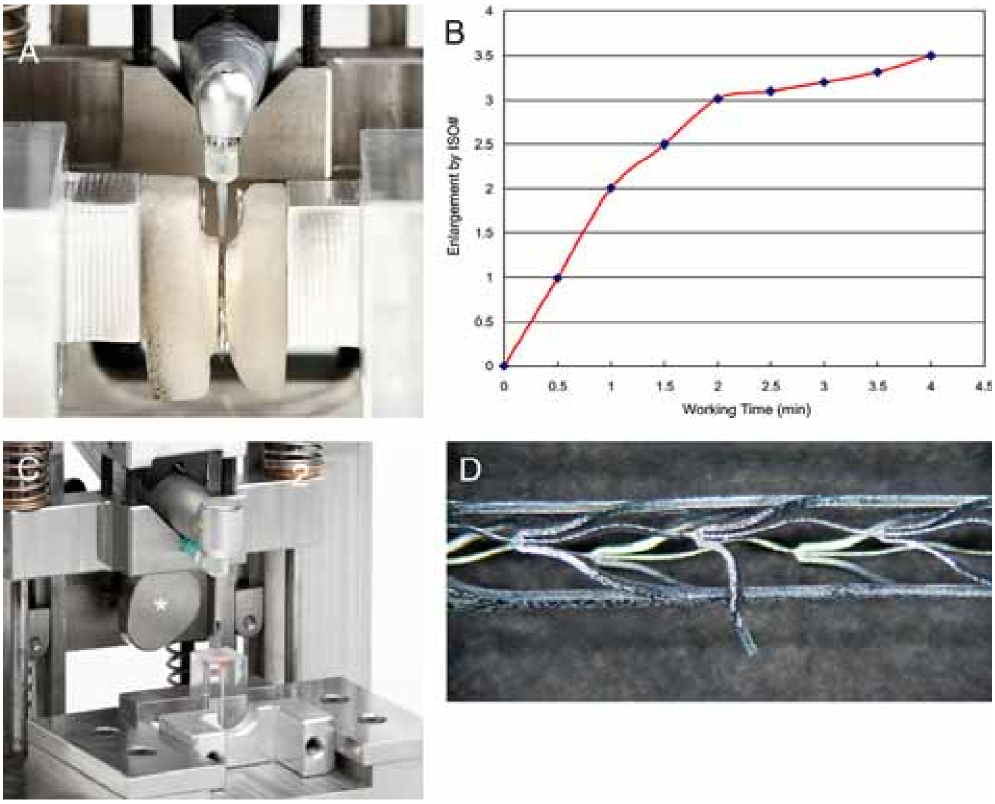

Figure 2. (*A*) Setup for testing abrasivity: two preweighed dentin slices are held in a precision device at a 0.2-mm distance from each other. An SAF file is operated while compressed between the plates. The amount of dentin removed is calculated by weighing the plates before and after the procedure. (B) Abrasivity test: the amount of dentin removed by the SAF file as a function of time is presented as representative ISO sizes. Each point represents the mean of 10 samples. The standard deviation was less than 0.1%. (C) Setup for testing durability of SAF files: the handpiece is operated at 5,000 vibrations per minute with an up-and-down motion generated by the asymmetrical cam (*). This setup mimics the clinical operation of the SAF. The file was removed for inspection every 1 minute. Continuous irrigation was used throughout the test. (D) A typical failure pattern of the SAF files: detachment of an arch at one of its connecting points to the longitudinal beams.

Surface Roughness

The surface roughness of the SAF files, as determined using the Mitutoyo SJ-210P system, was 2.8 μm $\pm$ 10%.

Abrasivity Test

The amount of dentin removed as a function of time is presented in Figure 2*B* expressed as representative ISO sizes, which were defined in the calibration stage. Most of the dentin removal occurred within the first 2 minutes of operation (3 $\pm$0.02 ISO sizes), with a slower removal of dentin thereafter for a total of 3.5 $\pm$0.01 ISO sizes by the end of 4 minutes.

Durability: Torque Test

When torque durability was tested, the SAF could be turned 7 ($\pm$0.4) $\times$ 360° before separation. The SAF's torque durability was 29.7 $\pm$3.2 g/cm.

Durability: ADA Cyclic Fatigue Test

The SAF files could be continuously operated under the test conditions for more than 150 minutes without any sign of failure in any of the 10 files tested.

Durability: Free Buckling Fatigue Test

The SAF files endured 600,500 ($\pm$15,800) buckling cycles before the first sign of mechanical failure appeared. This is equivalent to $\sim$120 minutes of operation at 5,000 vibrations per minute.

Durability: Functional Fatigue-to-Failure Test

When tested in standardized conditions, the first mechanical fatigue failure was detected after 29.1 ($\pm$1.2) minutes (Table 1). A typical failure was detachment of one of the arches at one of its connection points to the longitudinal beams (Fig. 2*D*). Rarely did a strut or a longitudinal beam detachment occur. In no case was there a full separation of the SAF file.

SAF Degradation as a Function of Working Time

The SAF file lost its efficacy after prolonged use. Although new SAF files enlarged the root canal by 3.5 ($\pm$0.01) equivalent ISO sizes within 4 minutes of operation (Fig. 3*A*), the used files were less effective. Prior prolonged use for 30 minutes reduced the efficacy by 40%; at 4 minutes, the increase in size was only 2.1 ($\pm$0.0004) ISO sizes. After 30 minutes of use, the force applied by the compressed SAF files declined as well (by $\sim$30%) as expressed in Figure 3*B*.

Irrigation Experiments

No extrusion of the irrigant was detected when the SAF was operated with continuous irrigation. When a syringe and needle were used in the same root canals, the irrigant leaked through the apical foramen.

TABLE 1. SAF Durability: Functional Fatigue to Failure

SAF Lot*	Mean Time	SD	SD in %
A	29.1[†]	1.29	4.4
B	29.3	1.06	3.6
C	28.9	1.2	4.1
D	29.1	1.29	4.4
E	29.1	1.29	4.4
All 5 lots	29.1	1.2	4.2

SAF, self-adjusting file.

*Each lot consisted of 10 SAF files.

[†]Time of operation (minutes) until first sign of mechanical failure.

Discussion

The SAF file, consisting of a thin-walled cylinder 1.5 mm in diameter, could be elastically compressed substantially to the extent that it assumed dimensions resembling those of an ISO size 20 K-file (Fig. 1*C*). This was possible because of the special design of the file, and it represented the high cumulative elasticity of each of the arches that connects the longitudinal beams (Fig. 1*A*).

When initially compressed, the SAF applied a circumferential force that was applied to the canal walls. This resulted from its high elasticity and its tendency to reassume its initial dimensions. This force combined with the file's surface abrasiveness and the in-and-out movement may allow for dentin removal from the canal walls. The force gradually declined when larger canal diameters were used, representing the later stages of canal preparation with SAF.

The abrasivity test showed that when SAF was operated in a simulation of a flat root canal, most of the dentin removal occurs within the first 2 minutes of operation. The rate of dentin removal was greatly reduced during the next 2 minutes of operation. This occurred most probably because of the enlargement of the canal, which reduced the pressure that the SAF file applied to the dentinal walls. These results indicate that operating the SAF file beyond the recommended four minutes has neither substantial benefit nor substantial risk for overinstrumentation of the canal.

The SAF mode of operation is totally different than that of rotary endodontic files. Rotary torque and fatigue tests, which are the benchmark for testing rotary files, were indeed performed with the SAF file with excellent results compared with other nickel-titanium files and far beyond the ISO3630-1 requirement ($1 \times 360^{\circ}$ rotation and 18 g/cm in the torque durability test) (15). Nevertheless, these tests are irrelevant to the mode of operation of the SAF file because it does not engage the canal wall with rotation. The free buckling fatigue test was more relevant, yet the most meaningful and most relevant test was the functional fatigue-to-failure test.

The typical fatigue failure of the SAF file could have resulted from either repeated compression and release of the arches or from repeated buckling type distortion of the longitudinal beams and struts or both. The results indicate that the most common failure point was the connecting point between the arches and the longitudinal beams. Rarely did the longitudinal beams or the struts show signs of mechanical failure within the limitations of this assay. The mean time to the first functional fatigue failure (29.1 ± 1.2 minutes) represents more than seven times the recommended clinical operation time per canal, which is 4 minutes. Instrument separation, which is the common mechanical failure with rotary nickel-titanium files, did not occur in any of the 50 samples tested.

Based on the evaluative tests, the efficacy of the SAF file declined with time. A file that was preused for 30 minutes (equivalent to ~seven canals with 4 minutes in each) was 40% less effective than a new file. Nevertheless, when used for 12 minutes, according to the manufacturer's instructions (equivalent of three canals $\times$ 4 minutes each),

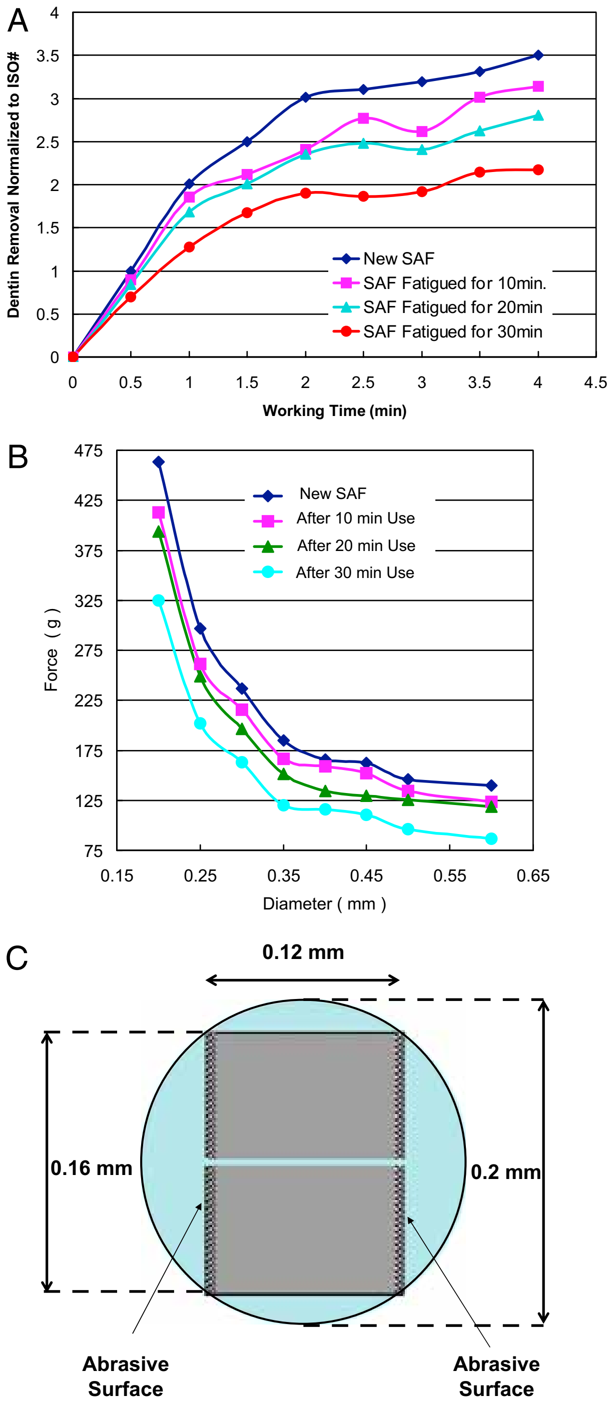

Figure 3. (*A*) SAF efficacy degradation as a function of working time. SAF files were used for 10, 20, or 30 minutes and their efficacy measured and compared with new SAF files. Each point represents the mean of 10 samples. The standard deviation was within $\pm$ 0.1%. (*B*) Degradation of the force applied by compressed SAF as a function of working time. SAF files were used for 10, 20, or 30 minutes with the force they apply when compressed measured and compared with new SAF files. Each point represents the mean of 10 samples. The standard deviation was within $\pm$0.1%. (*C*) The SAF file tip as an inefficient piston: a schematic presentation of the compressed apical part of the SAF file in a root canal with a 0.2-mm diameter. The apical longitudinal beams are maximally compressed against each other. Note that 38% of the canal is free for fluid escape.

the SAF efficacy was not substantially reduced. Because the file is designed for a single use, it can be expected to remain quite effective, even when used for the preparation of three to four canals, as commonly found in multirooted teeth.

It was apparent that no irrigant pressure builds up in the canal during the SAF operation. This was because the metal mesh allows free escape of the irrigant at all times. Even in the narrow apical part of a canal 200 μm in diameter (a canal prepared up to a #20 K-file), the SAF was a very ineffective piston, leaving more than 38% of the canal cross-section free for backflow of fluid and debris (Fig. 3*C*). Under the conditions of the test, no irrigant passed through the apical foramen even though the apical foramen was free of any obstruction. When irrigant was applied in the same canals with a syringe and a needle, the irrigant did pass the foramen. This can be understood if pressure values in this critical area are calculated and analyzed.

Three types of pressure may potentially be present in the apical part of the canal during SAF operation: hydrostatic pressure representing the water column in the root canal, stagnating pressure generated by the vibration of an object in the fluid, and piston pressure resulting from the apical thrust of the SAF. With a root canal length of 20 mm, the hydrostatic pressure was calculated to be 195.78 Pa. With a vibration of 5000 vibrations per minute, the stagnating pressure will be 195.92 Pa, whereas the piston pressure will not be more than 2.72 Pa. All these sum up to a pressure of 394.42 Pa.

The simple surface tension of the external fluid at even a larger apical foramen, 350 μm in diameter, requires an eruption pressure of 832 Pa to allow fluid from the canal to escape beyond the apical foramen. The pressure required will be much higher if tissue is present periapically. Therefore, the passage of irrigant into the periapical area as a result of the SAF's action is highly unlikely.

These values should be compared with (i) the potential calculated piston pressure that a well-adapted K-file might generate when introduced into the apical part of a narrow canal full of irrigant ($\sim$199,700 Pa when a #25 file is pushed with a force of 1 g) and (ii) with the calculated pressure generated when a syringe is used for irrigation, at 5 mL/ min, with a 25-G needle that is loosely adapted into the canal space. Even if 38% of the cross-section area of the canal is left free around the needle to allow the escape of the irrigant's backflow, a pressure of more than 1,270 Pa will occur. This analysis may explain why no extrusion of irrigant occurred when the SAF file was operated in the root canal, but a syringe and needle irrigation did pass the irrigant beyond the apex in the same canal.

Conclusions

The following conclusions were made:

1. The SAF file may be elastically compressed from a diameter of 1.5 mm to dimensions resembling those of an ISO # 20 K-file.
2. Compressing the SAF file generates circumferential force.
3. The rough surface, combined with the above force and the in-and-out vibration, allows for the removal of dentin by filing.
4. The circumferential force and the ability to remove dentin declines as the diameter of the canal enlarges.
5. The ability to remove dentin declines if the file is reused.
6. The SAF file is mechanically durable for continuous operation for 29 minutes.
7. Application of the SAF does not push the irrigant beyond the apical foramen.

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The contributions of Dr. Ehud Teperovich, Dr. Raphaela Cohen, Orit Goldstein, and Yoav Student to this study are recognized and greatly appreciated. The advice, support, leadership, and encouragement provided by Ofer Shalev made a large contribution to the successful completion of this study.

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The Self-adjusting File (SAF). Part 1: Respecting the Root Canal Anatomy—A New Concept of Endodontic Files and Its Implementation

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Abstract

Aim: To introduce a new concept, the self-adjusting file (SAF), and discuss its unique features compared with current rotary nickel-titanium file systems. **The New Concept:** The SAF file is hollow and designed as a thin cylindrical nickel-titanium lattice that adapts to the cross-section of the root canal. A single file is used throughout the procedure. It is inserted into a path initially prepared by a # 20 K-file and operated with a transline- (in-and-out) vibration. The resulting circumferential pressure allows the file's abrasive surface to gradually remove a thin uniform hard-tissue layer from the entire root canal surface, resulting in a canal with a similar cross-section but of larger dimensions. This holds also for canals with an oval or flat cross-section, which will be enlarged to a flat or oval cross-section of larger dimensions. The straightening of curved canals is also reduced because of the high pliability of the file and the absence of a rigid metal core. Thus, the original shape of the root canal is respected both longitudinally and in cross-section. The hollow SAF file is operated with a constant flow of irrigant that enters the full length of the canal and that is activated by the vibration and is replaced continuously throughout the procedure. This results in effective cleaning even at the cul de sac apical part of the canal. The SAF has high mechanical endurance; file separation does not occur; and mechanical failure, if it occurs, is limited to small tears in the latticework. **Conclusion:** The SAF represents a new step forward in endodontic file development that may overcome many of the shortcomings of current rotary nickel-titanium file systems. *(J Endod 2010;36:679–690)*

Key Words

Canal preparation, curved root canals, endodontic files, flat root canals, micro–computed tomography scan, nickel-titanium, SAF, scanning electron microscopy, self-adjusting file

The cleaning and shaping of the root canal is the key step in root canal treatment. Its aim is to remove all tissue debris from the root canal space while removing the inner layers of root canal dentin (1). For many years, it has been a common practice to enlarge the root canal to at least three ISO sizes larger than the first file to bind at the apical part of the canal (2, 3). It was assumed that such preparation will remove the inner layers of the dentin while allowing the irrigant to reach the entire length of the root canal for a thorough cleaning and disinfection of the root canal space (4, 5). This goal is easier to achieve today, even in curved root canals, because of the introduction and use of rotary nickel-titanium file systems. Because of their elasticity, these files can preserve the location of the root canal axis, thus largely preventing its transportation and ledging, which were major problems with stainless steel hand files. Rotary nickel-titanium files do this more efficiently and apparently require less operator expertise. The resulting root canal filling radiographs are impressive, yet the third dimension of the root canal is commonly ignored (6).

The goal of cleaning and shaping may be easily and reproducibly achieved with rotary files as far as relatively straight and narrow root canals with a round cross-section are concerned. In such canals, completion of the file sequence may result in a clean canal with no tissue debris and with removal of all or most of the inner layer of the heavily contaminated dentin. Nevertheless, in flat oval-shaped root canals and in curved ones, this goal is not easy attainable (7, 8).

Flat oval root canals are common in the distal roots of lower molars, upper and lower bicuspids, and lower incisors and canines. Asymmetrical, flat, tear-shaped cross-sections are another challenge. Such canals are common in most roots that contain two root canals in the same root and a potential isthmus. This includes anterior roots of lower molars, mesiobuccal roots of upper molars, first upper bicuspids, and some lower incisors. A systematic and comprehensive study by Wu et al (9) has shown that oval or flat root canal morphology is present in up to 25% of root canals, and in certain root groups it may exceed 50%. The flatness or asymmetry in these canals is usually in the buccolingual dimension; therefore, it fails to be recognized on clinical radiographs, which represent a buccolingual projection (Fig. 1).

The buccal and lingual areas of such flat root canals and the area facing the isthmus in tear-shaped ones cannot be adequately prepared by current rotary files. All current rotary files have one or another type of spiral blade and helical formation that when rotating machines the root canal into a form that has a round cross-section. Substantial untouched areas may be left on the buccal and lingual sides of a flat root

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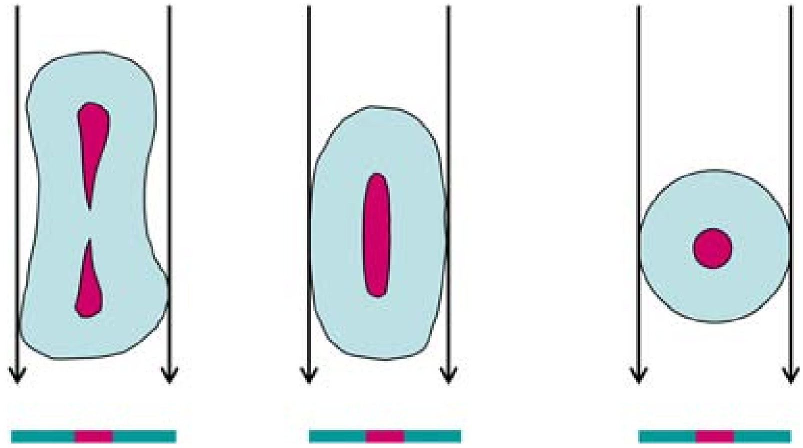

Figure 1. The limited value of two-dimensional radiographs. All three root canal cross-sections look the same on buccolingual projection radiographs.

canal or on the side facing the isthmus in tear-shaped ones (Fig. 2). A similar problem has been shown by Wu et al (7, 8) with hand files.

Current technology may mislead the operator to believe that the canal has been adequately shaped when, in fact, recesses full of infected tissue and debris may have been left on the buccal and/or lingual sides of the area prepared by the rotary file (Fig. 3A). Furthermore, such root canals may never be adequately obturated and sealed because the root canal filling or even the sealer will be separated from the canal wall by

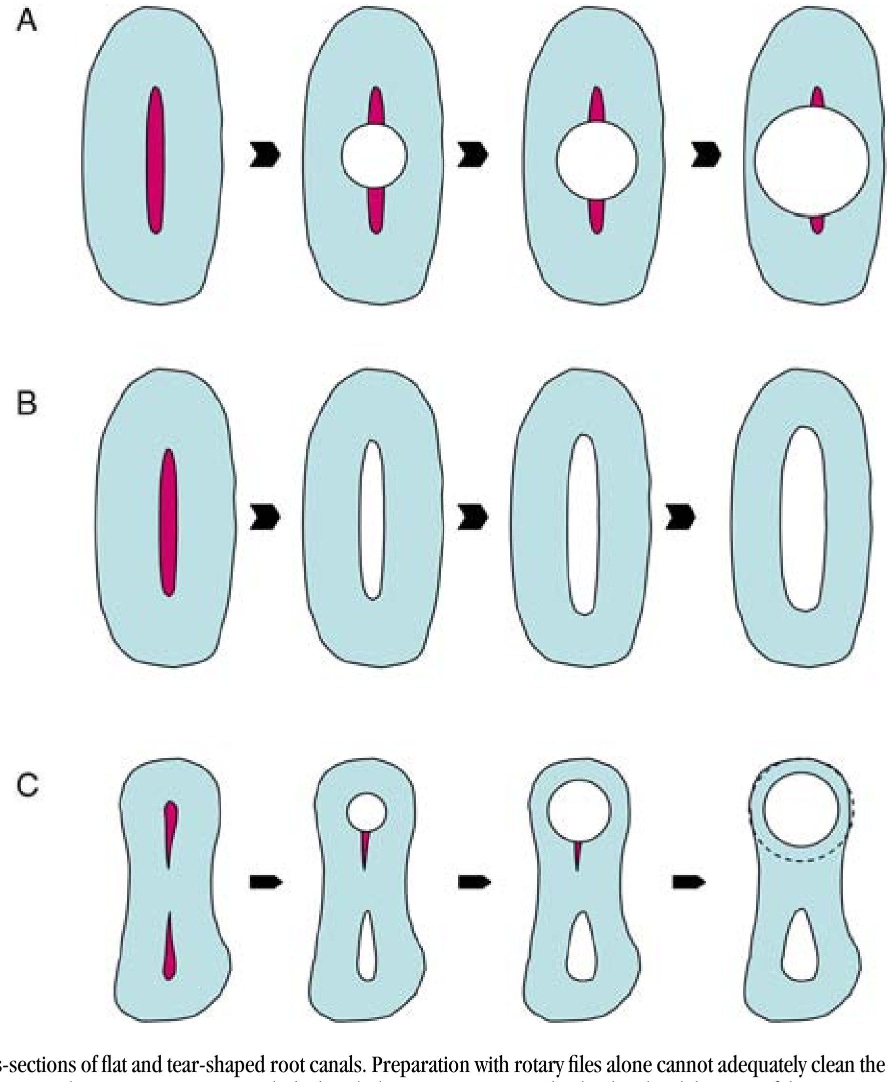

Figure 2. Schematic cross-sections of flat and tear-shaped root canals. Preparation with rotary files alone cannot adequately clean the (*A*) flat or (*upper part of C*) tear-shaped canals. Attempts to use larger instruments to include the whole cross-section may lead to localized thinning of the remaining dentinal wall. (*B* and *lower part of C*) The SAF enlarges the canal to the same shape with bigger dimensions.

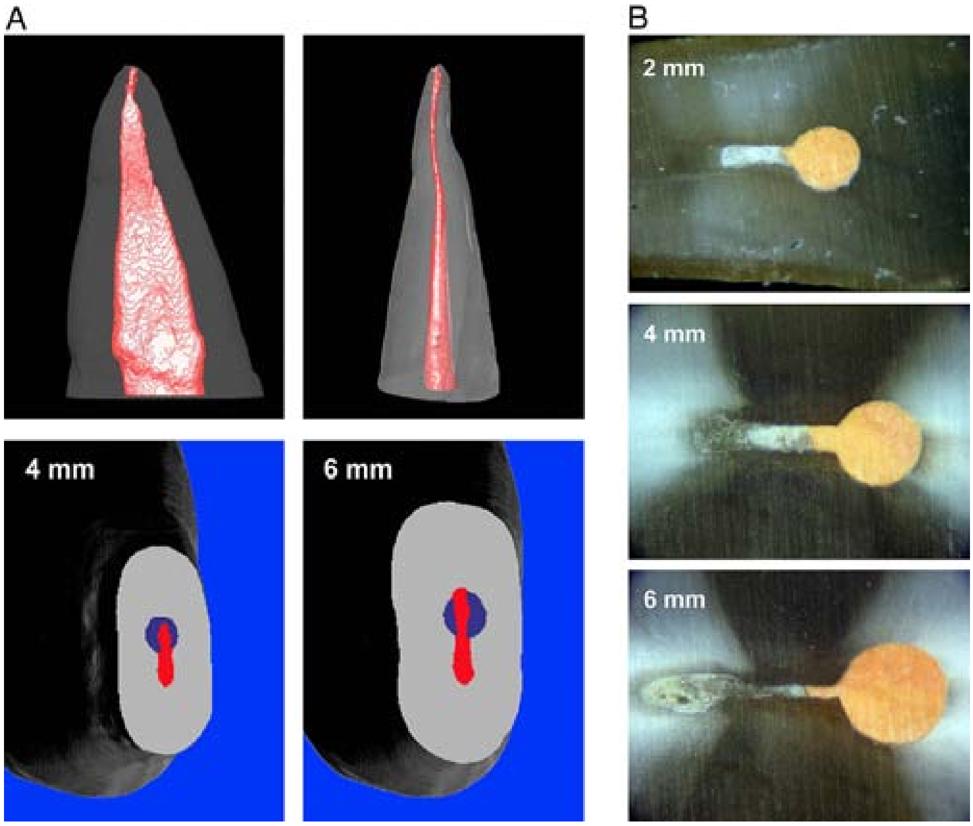

Figure 3. (*A*) A flat root canal prepared with a rotary file. (*Top*) Buccal and mesial views of the root canal before treatment. (*Bottom*) Cross-sections at 4 and 6 mm from the apex. A micro-CT analysis. Red, before; blue, after. (*B*) Obturation of a flat root canal prepared by rotary files. The root canal of a maxillary premolar prepared with rotary files and obturated with warm gutta-percha and AH-26 sealer (Dentsply-DeTrey, Konstanz, Germany). Cross-sections at 2, 4, and 6 mm from the apex. Note the untreated recess full of debris that prevented the flow of the gutta-percha and sealer.

the remaining tissue and debris (Fig. 3*B*), providing a potential space for bacterial growth and/or future recontamination of the root canal with bacteria. Furthermore, the operator may not be aware that anything went wrong because the root canal filling may look satisfactory on the x-ray.

The results of cleaning and shaping with rotary instruments are no better with curved root canals. When the three-dimensional shape of root canals was studied using micro–computed tomography (CT) scans, rotary nickel-titanium files failed to adequately and reproducibly prepare all the inner surfaces of curved canals, such as those of maxillary molars (Fig. 4) (10). Peters et al (10) found that when upper molars were prepared with rotary files 43% ± 29% and 33% ± 19% of the wall of the mesiobuccal and distobuccal canals remained unchanged, respectively. The results were no better even in the larger palatal canal, which is commonly thought to be easier to clean and shape. Rotary nickel-titanium files left 49% ± 29% of the canal surface unchanged. Furthermore, the extremely high standard deviation indicates the high variability of the results; some may have been better, but some were much worse.

A clinician cannot predict what will be the result in any given canal anatomy. This is because of two inherent problems: one macroscopic and the other microscopic. Macroscopically, the palatal roots of the upper molars are frequently curved buccally, a dimension not seen in clinical radiographs. Microscopically, the discrepancies revealed by micro-CT scans at a resolution of 36 μm, as done in the previously mentioned study (10), are hardly detectable by the human eye; nevertheless, they are large relative to the size of the bacteria that might penetrate them ($\sim$1 μm).

Another inherent problem with rotary-nickel titanium files is apical canal transportation in curved root canals (5, 10). Most file systems will adequately maintain the apical part of a curved root canal in place as far as the thin instruments are concerned. However, the larger-diameter instruments are relatively stiffer and have a tendency to remove more dentin on the outer side of the curvature of the apical area, leading to apical canal transportation (5, 10, 11). Rotary file manufacturers made many improvements, such as noncutting tips and more flexible alloys and designs, but the problem still exists. Therefore, the instructions for use usually indicate that the thicker instruments should not be applied in the apical part of a curved canal more than the absolute minimum time required for them to reach the working length; otherwise, apical canal transportation may occur (5).

Transportation of the canal at this critical point can have two major drawbacks: first, the apical part of the canal on the inner side of the curvature may remain untouched and full of debris, and, second, it may lead to ledging or even a subsequent perforation. To date, most if not all file systems have this inherent problem to one extent or another (11–13).

Another closely related problem is straightening of the root canal at the midroot section of curved root canals. Most file systems will straighten this part of the curvature to one extent or another by removing more dentin on the inner side of the curvature (10). This may reduce the thickness of the remaining dentin on the inner side of the curvature to such an extent that it increases the risk of vertical root fracture (14) or even results in a strip perforation.

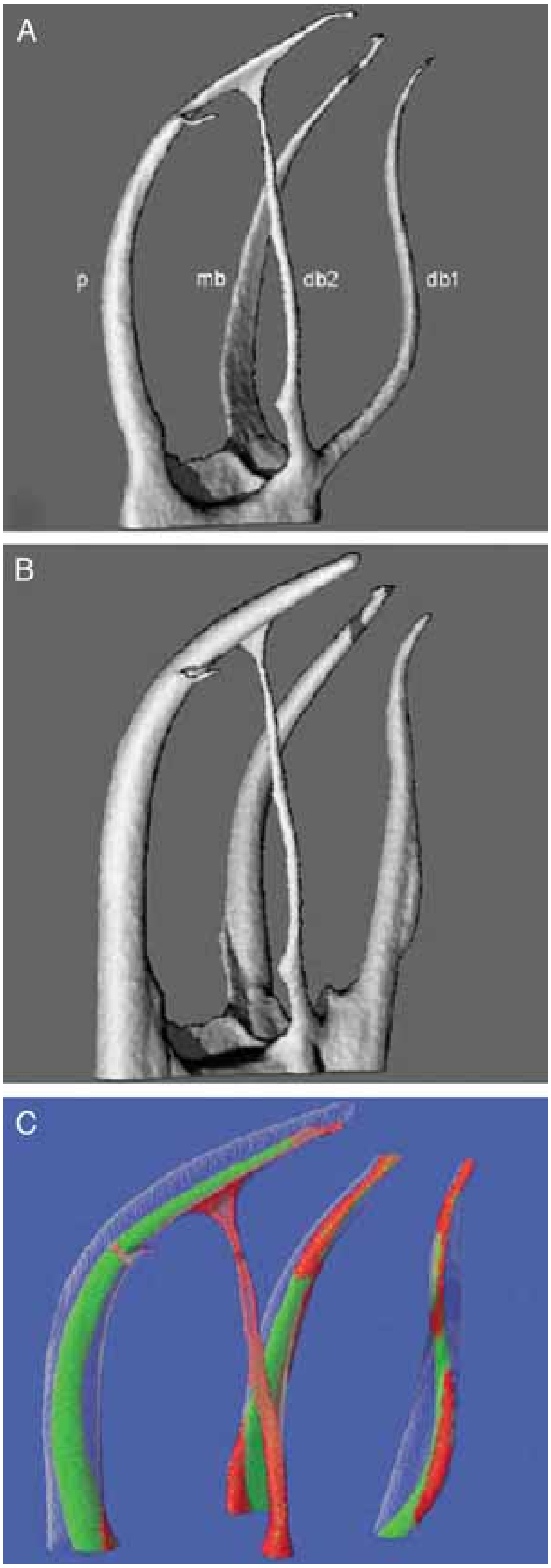

Figure 4. Micro-CT analysis of preparation of curved root canals using rotary nickel-titanium files. (*A*) Before, (*B*) after, and (*C*) three-dimensional analysis. Clear, prepared canal; green, affected surface; red, surface unchanged by the file. Reproduced with permission from Peters OA, Peters CI, Schönenberger K, et al. ProTaper rotary root canal preparation: effects of root canal anatomy on final shape analyzed by micro CT. Int Endod J 2003;36:86-92.

Accurate length measurement is an essential prerequisite for the use of any rotary file. The thin nickel-titanium rotary files are extremely flexible and may negotiate even a canal with a rather sharp apical curve. When a rotary file accidentally passes the apical foramen of such a curved canal, because of either misleading length measurement or failure to keep the marker on the file in place, it may soon lacerate or zip the apical foramen and form an oval opening with potential loss of the apical constriction. This may turn a simple root canal anatomy into a more complex one that is more difficult to handle. Slipping of the master cone beyond the apex during lateral condensation or extrusion of heat-softened gutta-percha may be one of the results.

Unexpected separation of rotary nickel titanium files was and still is the major drawback. Improvements in metallurgy, design, surface treatment, quality control, and, above all, the introduction of hands-on training, have significantly reduced the extent of this problem, nevertheless it is still with us. As opposed to stainless steel files that may give a "warning" by some distortion that appears in an abused file, usually no such macroscopic sign will appear in a rotary nickel titanium file. Furthermore, even in the era of microscope-assisted root canal treatment, a separated nickel-titanium file screwed in at the apical part of an even slightly curved canal is much more difficult to remove than a similar segment of a stainless steel file.

Rotary nickel-titanium files have been a great step forward in modern root canal treatment. They allow efficient shaping in curved canals that were hardly negotiable before while reasonably maintaining their original long axis in its original position. Nevertheless, to overcome the inherent remaining problems of the nickel-titanium instruments, a new concept in cleaning and shaping is warranted; hence, the self-adjusting file (SAF) was developed.

The SAF

Design and Mode of Operation

The SAF is a hollow file designed as a compressible, thin-walled pointed cylinder either 1.5 or 2.0 mm in diameter composed of 120-μm-thick nickel-titanium lattice (Fig. 5*A*). The 1.5-mm file may easily be compressed to the extent of being inserted into any canal previously prepared or negotiated with a # 20 K-file (Fig. 5*B*) (15). The 2.0-mm file will easily compress into a canal that was prepared with a #30 K-file. The file will then attempt to regain its original dimensions, thus applying a constant delicate pressure on the canal walls (15). When inserted into a root canal, it adapts itself to the canal's shape, both longitudinally (as will any nickel titanium file) and along the cross-section. In a round canal, it will attain a round cross-section, whereas in an oval or flat canal it will attain a flat or oval cross-section, providing a three-dimensional adaptation (Fig. 5*C*). The surface of the lattice threads is lightly abrasive (Fig. 5*D*), which allows it to remove dentin with a back-and-forth grinding motion (15).

The SAF is operated with transline (in and out) vibrating handpieces with 3,000 to 5,000 vibrations per minute and an amplitude of 0.4 mm. Such a handpiece may be the KaVo GENTLEpower or equivalent combined with either a 3LDSY head (360° free rotation; Kavo, Biberach Riss Germany) (Fig. 6) or MK-Dent head (360° free rotation; MK-Dent, Bargteheide, Germany) or RDT3 head (80 rpm when free and stops rotating when engaging the canal walls, recently developed by Re-Dent-Nova, Ra'anana, Israel). The vibrating movement combined with intimate contact along the entire circumference and length of the canal removes a layer of dentin with a grinding motion (see later).

The hollow design allows for continuous irrigation throughout the procedure. A special irrigation device (VATEA, ReDent-Nova) is connected by a silicon tube to the irrigation hub on the file (Fig. 5*A* and 6) and provides continuous flow of the irrigant of choice at a low

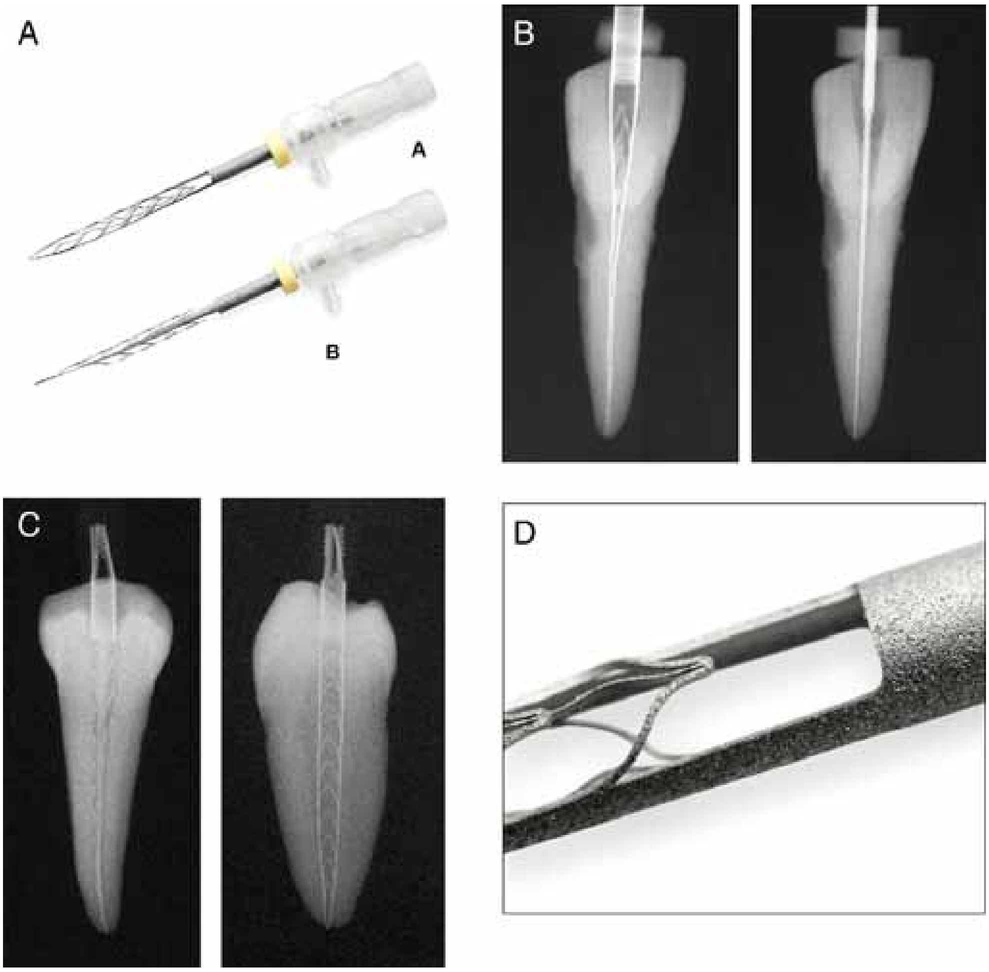

Figure 5. (*A*) The SAF. (*A*) Shank for attachment to a transline vibrating handpiece (in-and-out motion). (*B*) Connector (hub) for the irrigation tube. (*B*) The SAF compressed into a canal prepared by a # 20 K file. Right: A # 20 K file. (*Left*) The SAF compressed into the same canal. (*C*) Three dimensional adaptation of the SAF file. The SAF inserted into the root canal of a lower bicuspid with a flat canal. Left: bucco-lingual projection. (*Right*) Mesiodistal projection. (*D*) Abrasive surface of the SAF file (25× magnification).

pressure and at flow rates of 1 to 10 mL/min. Alternatively, any physiodispenser type of irrigation device (ie, NSK Surgic XT Micro Motor System, Kanuma, Japan, or W&H ImplantMed, Burmoos, Austria) that is primarily designed for implantology may also be used.

The SAF is inserted into the canal while vibrating and is delicately pushed in until it reaches the predetermined working length. It is then operated with in-and-out manual motion and with continuous irrigation using two cycles of 2 minutes each for a total of 4 minutes per canal. This procedure will remove a uniform dentin layer 60- to 75-μm thick from the canal circumference (15) (Fig. 7*A* and *B*). The SAF file is designed for single use.

An Self-adjusting File that Adapts Itself to the Three-Dimensional Anatomy of Root Canals

The SAF file is different from any current nickel-titanium rotary file. Most rotary file systems will find the widest part of the canal and gradually machine it, using several files of increasing diameter, to a wider canal with a round cross section. If the canal happens to be relatively narrow, the whole original canal may be included in the preparation. However, if the canal is flat, oval, tear shaped, or simply large, this mode of preparation may leave untreated recesses, mainly buccally or lingually to the machined part of the canal (Figs. 2 and 3*A* and *B*).

The SAF is used as a single file (of either 1.5- or 2.0-mm diameter) that starts as a narrow, compressed, shape and gradually expands in the canal while removing a uniform layer of dentin from its walls. Because the file adapts itself to the cross-section of a given canal, a canal with a round cross-section is enlarged as a round canal, whereas an oval canal is enlarged as an oval canal of larger dimensions (Figs. 2 and 7*A*). Even an extreme root canal anatomy, such as presented in Figure 7*B*, lends itself to this mode of operation. High-resolution three-dimensional micro-CT analysis showed that high percentage (83.2%) of the canal wall is affected by the SAF file even in oval, flat root canals (Table 1).

Uniform Removal of Dentin and Remaining Wall Thickness

When operated in flat root canals, rotary nickel-titanium files may result in uneven thickness of the remaining dentin wall. In places in which the round bore has been created, the remaining dentin will be thinner in the mesial and distal aspects than in the untreated areas (Fig. 2). When excessive apical preparations are used in an attempt to include as much of the irregular canal space in the preparation as possible (16, 17), the uneven thickness may be even more pronounced. This uneven thickness of the remaining dentin wall may be

Figure 6. A KaVo transline vibrating handpiece. The irrigation tube is connected to a continuous-flow source and has an on-off switch (white).

a predisposing factor for vertical root fractures (14). On the other hand, the SAF removes a uniform layer of dentin from the canal walls, thus resulting in a relatively uniform remaining dentin wall thickness and avoiding the previously mentioned risk (Figs. 2 and 7*A* and *B*).

Prevention of Canal Transportation

The SAF file is extremely flexible and pliable. It does not impose its shape on the canal but rather complies with its original shape. This is true both circumferentially and longitudinally. The long axis of the apical part of curved canals is kept closer to its original place than reported for rotary files: a mean center-of-mass shift of 68.8 ± 7.7 μm compared with the shift of 120 to 135 μm previously reported by Peters et al with rotary files in similar canals (10) (Table 2 and Fig. 8*A*). In curved canals, the thicker rotary nickel-titanium files have a tendency to transport the canal to the outer side of the curvature (Fig. 4) (10). When the SAF is used to enlarge the canal to similar dimensions, it tends to keep the apical part of curved canals closer to its original location (Fig. 8*A*).

When rotary files accidentally pass the apical foramen of an apically curved canal, because of misleading length measurement or failure to maintain the marker in place, they may soon “zip” the apical foramen and form an oval opening. The SAF, on the other hand, may be operated in such conditions even for few minutes with no zipping whatsoever (Fig. 8*B*).

High Durability

The SAF file is extremely durable and may go through rather severe abuse before a mechanical failure will occur. It does not have a core as do other nickel-titanium instruments. Any strain applied to it is distributed along many of its delicate parts, and the total endurance is a function of the accumulated endurance of each of these individual parts.

Some of the tests used to compare the endurance of endodontic files are not directly relevant to this file’s mode of operation; nevertheless, they are indicative of its high durability (15). When torque durability was tested, the SAF can be turned $7 \times 360°$ before separation with a torque durability of 29.7 g/cm (15). These values are well beyond the ISO3630-1 requirement ($1 \times 360°$ rotation and 18 g/cm in the torque durability test) and above that of many of the instruments compared in a recent American Dental Association Professional Product Review (18).

When the American Dental Association cyclic fatigue test is applied, SAF can be rotated for more than 150 hours at 900 rpm with a 5-mm deflection with no mechanical failure (15), whereas some of the nickel-titanium rotary instruments separated within the first hour or even within a few minutes (18). As mentioned previously, these tests are indicative of the SAF’s durability, even though the SAF’s mode of operation is a transline vibrating motion. A buckling test is more relevant to study the endurance of the SAF. The SAF can endure more than 600,500 consecutive 6-mm type I free buckling cycles before any mechanical damage could be observed (15). This represents an equivalent of ~120 minutes of a rather abusive operation at 5,000 vibrations per minute.

A specially designed test apparatus (Fig. 9*A*) allows the SAF to be continuously operated in simulated canals using the up and down motion of the handpiece, as used clinically. During this testing, the instruments were taken out and inspected every 1 minute. The SAF file was operated in this test for 29.1 ± 1.2 minute before any structural failure appeared (15) (Fig. 9*A*).

After all this, the ultimate endurance test is the real-life test: operation in root canals. The SAF can be operated for 27 minutes in extracted human teeth before any structural failure appears. This represents more than 6 times the 4-minute operation time per canal, which is sufficient to achieve the desired results (15).

It is of particular importance to note that even when structural failure did occur, it was not of the separation type that is encountered with other nickel-titanium files. Detachment of one of the arches at one of its ends was the typical mechanical failure (15) (Fig. 9*B*). The damaged file could easily be retrieved from the canal, facing none of the challenges that a separated rotary nickel-titanium file presents.

Continuous Irrigation with Sodium Hypochlorite

Irrigation of the root canal with copious amounts of sodium hypochlorite during root canal treatment is widely recommended (19, 20). It has been well documented that when exposed to its target of bacteria and tissue debris, sodium hypochlorite loses its activity rather quickly (21). Taking into account the extremely small volume of the root canal, the amount of sodium hypochlorite contained in the canal loses its activity within a very short time. Therefore, as frequent replacement of the irrigant as possible is mandatory for maintaining its optimal potency and effect.

The SAF operates with a continuous flow of the irrigant, thus allowing continuous fresh irrigant to be present in the canal at all times. The vibration of the file’s metal lattice within the irrigant facilitates its cleaning and debridement effects (22, 23).

Effective sodium hypochlorite replacement in the apical part of the canal is essential to provide its full effect and benefits in this critical area during root canal treatment. The extent of irrigant replacement in the apical part of curved narrow canals was previously studied using clear resin blocks with simulated curved canals filled with colored liquid

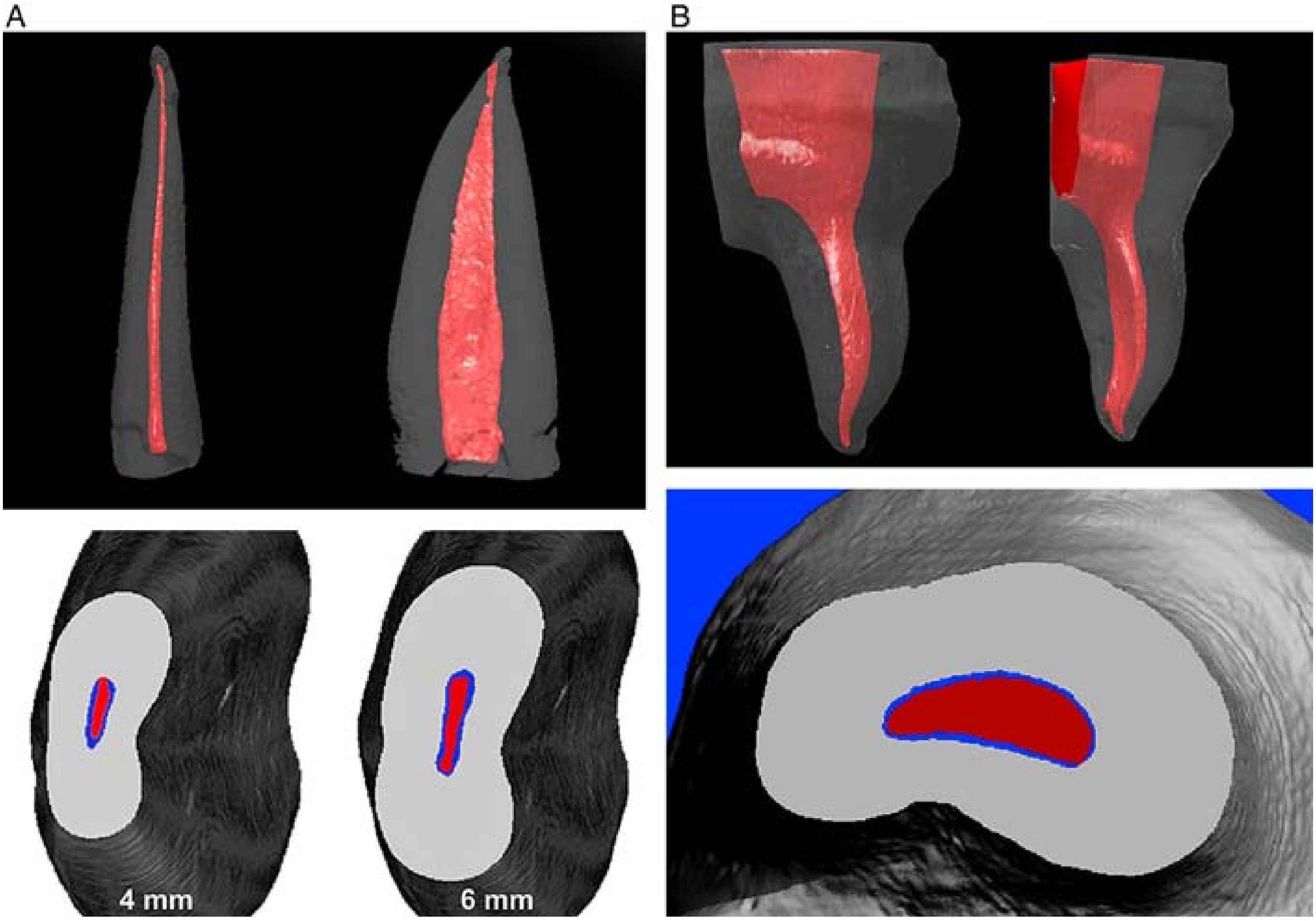

Figure 7. (*A*) SAF preparation: an upper second bicuspid with a flat root canal. (*Top*) Buccal and mesial views. (*Bottom*) Cross-sections at 4 and 6 mm from the apex. A micro-CT analysis. Red, before; blue, after. (*B*) SAF preparation: distal root of a first lower molar. (*Top*) Two views presenting a curved flat canal with a mesial, spoon-shaped concavity. (*Bottom*) Cross-section at 6 mm from the apex. A micro-CT analysis. Red, before; blue, after.

(24). Using the same model, it was evident that syringe and needle irrigation was ineffective in replacing the liquid in the apical part of a narrow curved canal. On the other hand, the SAF, which was used with continuous irrigation, combined with the vibrating action of the metal lattice, was effective at replacing the liquids in the apical part of the canal (Fig. 10*A*).

The effective replacement of irrigant in the apical part of the canal occurs with no clinically significant positive pressure. No pressure builds up in the canal during the SAF operation because the metal mesh allows free escape of the irrigant at all times. Even in the narrow apical part of a canal 200 μm in diameter (a canal prepared up to a #20 K-file), the SAF represents a very ineffective piston, with 38% of the canal cross-section area free for the irrigants backflow (Fig. 10*B*) (15).

No irrigant passes the apical foramen during SAF operation (15). This may be understood if pressure analysis in this critical area is studied. Three pressure types may potentially be present in the apical part of the canal during SAF operation: hydrostatic pressure representing the water column in the canal, stagnating pressure generated by the vibration of an object in the fluid, and piston pressure resulting from the apical thrust of the SAF. All these may be calculated and sum up to a total pressure of 394 Pa (15).

The simple surface tension of the external fluid at an even larger apical foramen 350 μm in diameter requires a calculated eruption pressure of 832 Pa to allow fluid from the canal to escape beyond the apical foramen (15). The pressure required will be much higher if tissue is present periapically. Therefore, the passage of irrigant to the periapical area as a result of the SAF's action is highly unlikely. This is in agreement with the lack of any postoperative pain when the SAF is used clinically.

These values should be compared with (i) the potential calculated piston pressure that a well-adapted K-file might generate when introduced into the apical part of a narrow canal full of irrigant ($\sim$199,700 Pa when a #25 file is pushed with a force of 1 g) (15) and (ii) with the pressure generated when a syringe is used for irrigation at 5 mL/min with a 25-G needle that is loosely adapted into the canal space. Even if 38% of the cross-section area of the canal is left free around the needle, for the escape of the irrigant's backflow, a calculated pressure of 1,270 Pa will occur (15).

Removal of the Smear Layer in the Apical Part of the Canal

As with any other mechanical device, the SAF forms a smear layer on the canal walls (23). This layer should be removed in order to allow intimate, unobstructed contact of antibacterial agents with bacteria at the orifices of dentinal tubules and also to optimize the sealer's adaptation to the canal walls and thus prevent the future formation of a gap between them (25–27). A final wash with a chelating agent

TABLE 1. Micro-CT Analysis of SAF Preparation in Oval and Flat Root Canals

	Tooth type	B-L: M-D ratio*	Percent unchanged† (±SEM)
1	Mandibular premolar	1:3	15.9
2	Maxillary premolar	1:2	5.8
3	Mandibular incisor	1:3	29.6
4	Maxillary premolar	1:4	20.0
5	Mandibular incisor	1:2	20.2
6	Maxillary premolar	1:4	13
7	Mandibular incisor	1:3	21.1
8	Maxillary lat. incisor	1:2	5.2
9	Mandibular incisor	1:2	7.1
10	Maxillary lat. incisor	1:3	30.5
Mean			16.8 (±2.9)

SAF, self-adjusting file; SEM, standard error of the mean.

*Ratio between buccolingual and mesiodistal dimensions of the root canal, at 4 mm from the apex, used as a measure of the canal's flatness.

†Percent of root canal walls pixels before the procedure unaffected by the file, calculated from before and after micro-CT scans, as done by Peters et al (10).

such as EDTA or citric acid has recently become widely used to remove the smear layer before obturation. Nevertheless, scanning electron microscopic studies indicate that the removal of the smear layer and ultramicroscopic debris in the apical third of the canal using either a syringe and a needle or a chelator paste leaves much to be desired (28–31).

When 3% sodium hypochlorite and 17% EDTA were used as alternating irrigants with the SAF file, the root canal surface (including its

TABLE 2. Canal Transportation by the SAF File in the Apical Third of Curved Root Canals: Center-of-Mass Shift Analysis*

Root type	Center of mass shift in the apical third
MB root of maxillary molar	104.7*
DB root of maxillary molar	92.6
Palatal root of maxillary molar	41.3
Palatal toot of maxillary molar	58.5
DB root of maxillary molar	35.8
Palatal root of maxillary molar	86.3
MB root of maxillary molar	58.3
Palatal root of maxillary molar	74.9
MB root of maxillary molar	35.38
Palatal root of maxillary molar	68.8
Mean (± SEM)	68.8 (± 7.65)

DB, distobuccal; MB, mesiobuccal; SAF, self-adjusting file; SEM, standard error of the mean.

*Mean center of mass shift (μm) calculated from before and after micro-CT scans (10).

apical third) was rendered clean of debris and the smear layer (23) (Fig. 11). This may be attributed to both the effective continuous replacement of the chelator in the apical region and to the mechanical

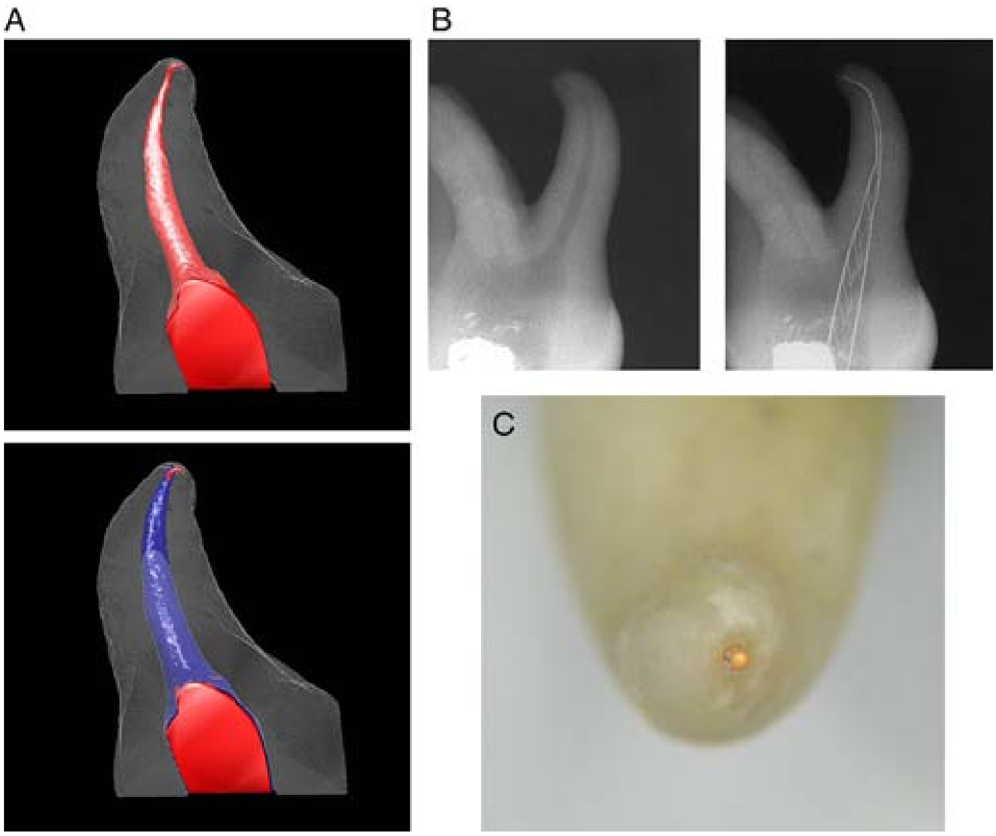

Figure 8. (*A*) SAF preparation in a curved canal. A micro-CT scan and analysis. (*Top*) Before treatment (red) and (*bottom*) after treatment (blue). (*B*) Preservation of the apical foramen. (*A*) A sharp apical curve with the foramen facing laterally. (*B*) A SAF file was passed through the apical foramen and operated for 4 minutes. (*C*) The apical foramen was kept round and was not zipped by the procedure.

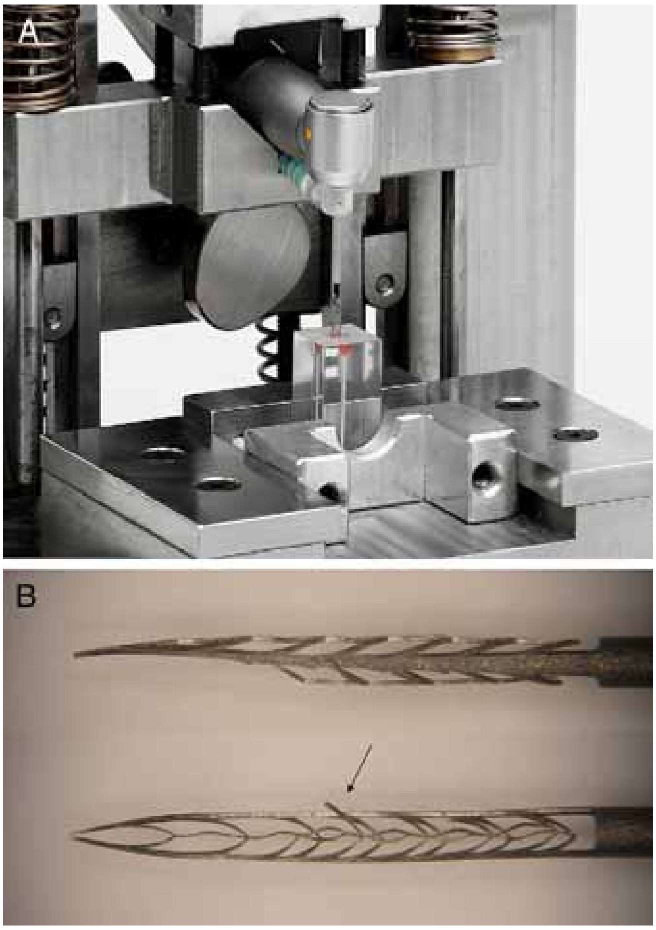

Figure 9. (*A*) A testing setup for SAF file durability. The file is operated using a vibrating handpiece which is moved slowly up and down, mimicking the clinical operation. (*B*) Mechanical failure of the SAF. One connector detached at one of its ends. The instrument was easily retrieved from the canal.

vibrating action of the SAF in this region. This combination results in a cleaner apical canal surface than most other reported methods can achieve (23, 28–31).

Root Canal Obturation

Root canal obturation of SAF-prepared root canals may be done by any of the common methods. Adaptation to the canal walls is possible even in flat canals because of the thorough cleaning of the otherwise difficult to clean recesses (Fig. 12*A*).

Obturation using lateral compaction using chloroform-dipped customized master cones (3, 32) is of particular interest because it allows the operator to actually visualize the shape of the SAF-treated root canal as reproduced on the customized master cone. Such master cones are presented in Figure 12*B*. It is evident that the apical part of the preparation is far from being round in the cross-section but rather represents the enlarged 3D shape of the canal. It is also clear that if a standardized master cone is used to gauge the prepared canal size, it may provide rather limited and misleading information (Fig. 12*B*).

Clinical Use

The SAF file has been approved for clinical use in Israel (Israeli Ministry of Health, License no. 11940000) as well as in Europe (CE mark no. 0483). A series of clinical vital and nonvital cases have already

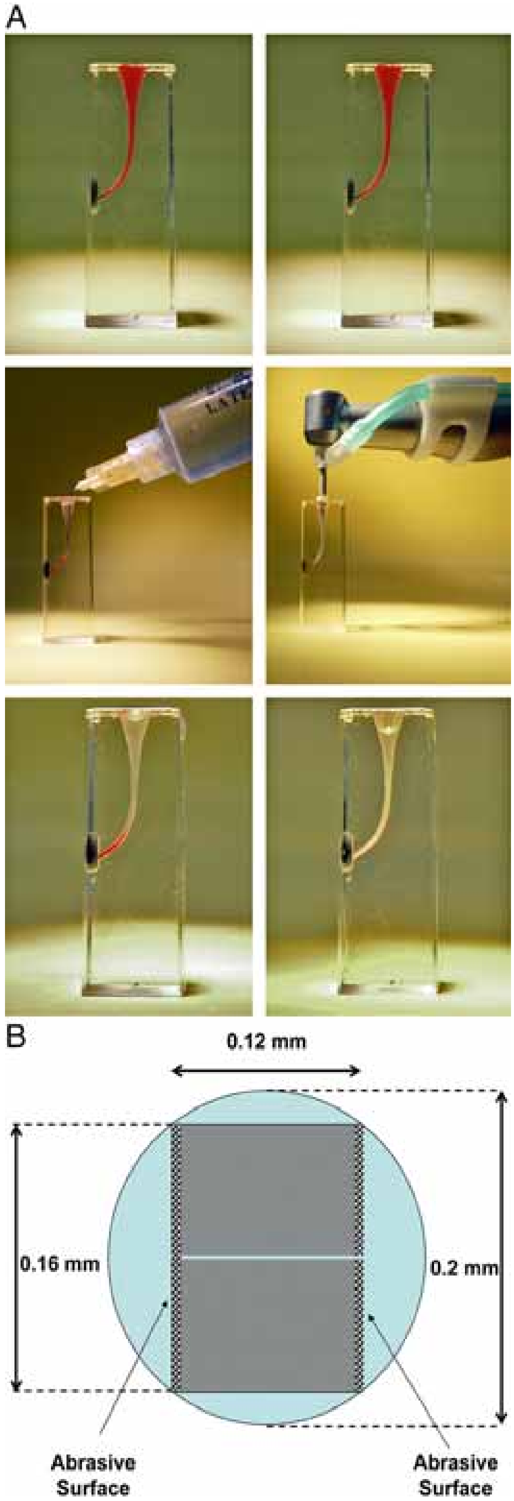

Figure 10. (*A*) Replacement of irrigant in the apical third of a curved canal. Curved canals in clear training blocks were filled with colored liquid. (*A*) Needle irrigation failed to wash out the colored liquid. (*B*) The SAF operated with continuous irrigation and vibration washed the colored liquid out. (*B*) A schematic presentation of the apical part of the SAF in a narrow root canal that was prepared to #20 K-file. The apical part of the SAF collapses to a dual layer of metal, each element of which is 0.12-mm thick and 0.8-mm wide, thus forming a potential piston with a 0.12×0.16 mm rectangular cross-section. When moving into the canal, 40% of the cross-section of the canal is free and allows backflow of the irrigant, thus being a poor piston that cannot significantly raise the pressure.

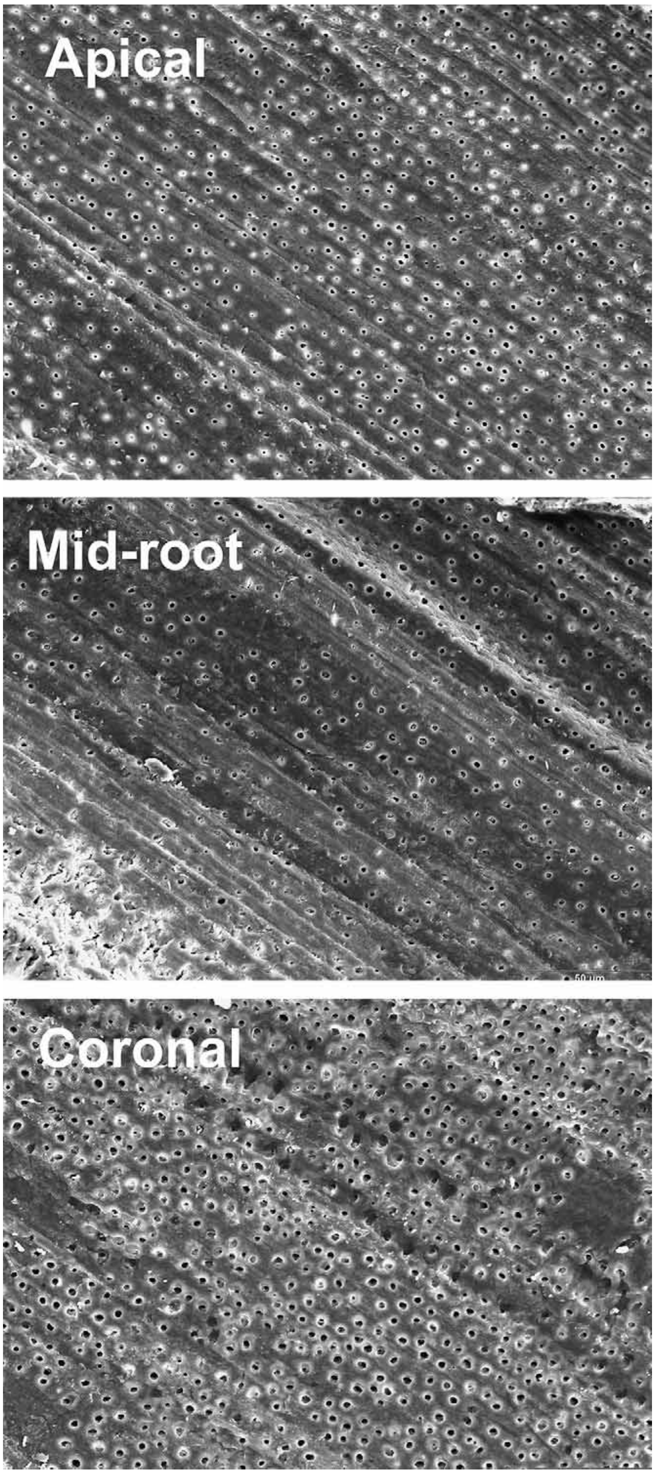

Figure 11. Removal of the smear layer. The SAF was operated for two cycles of 2 minutes with a continuous flow of 5% sodium hypochlorite during the first minute of each cycle and 17% EDTA during the second minute. This was followed by a 0.5-minute EDTA flush through a passive SAF and a final short flush with sodium hypochlorite to remove the EDTA. Representative fields from the apical, midroot, and coronal thirds of the root canal. Scanning electron microscopic magnification: ×1,000.

been completed (Fig. 13). The radiographic images of root canal fillings in SAF-prepared canals are no different than those of root canal fillings in root canals prepared by other file systems (Fig. 13). No file separation event was recorded in more than 100 clinical cases.

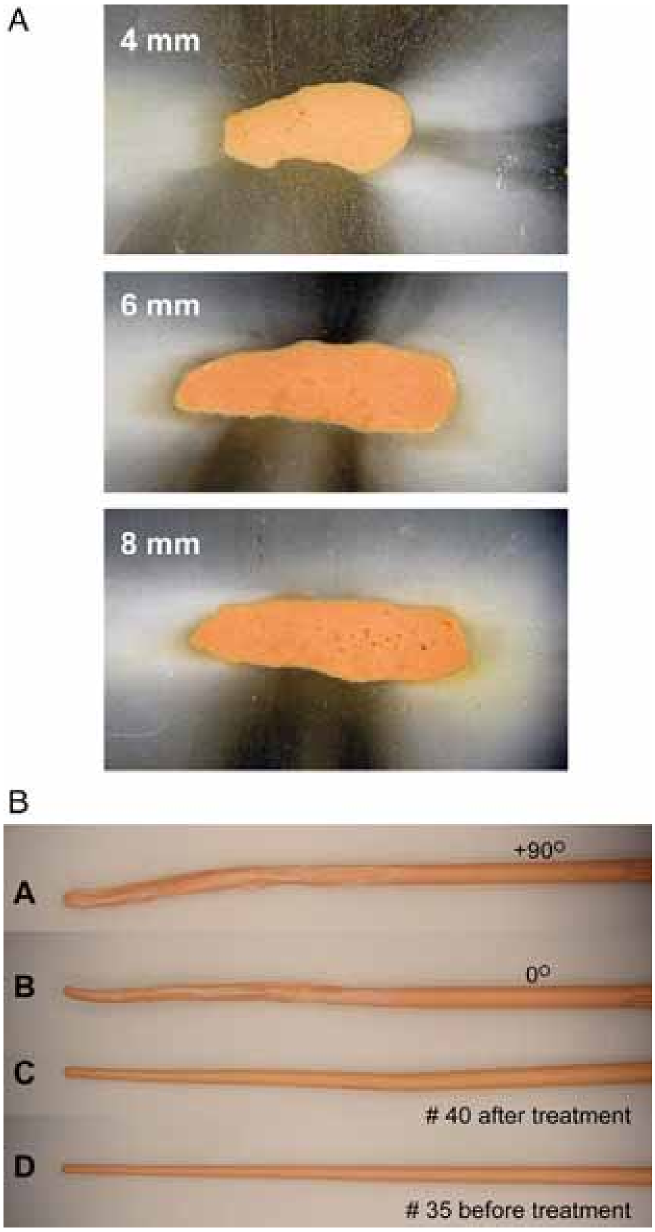

Figure 12. (*A*) Root canal filling adaptation in a SAF-prepared flat root canal. The entire circumference of the canal was prepared, thus allowing root canal filling penetration into the buccal and lingual areas of the canal. Cross-sections at 2, 4, and 6 mm from the apex. (*B*) Chloroform-dipped customized master cones. They present a three-dimensional reproduction of the SAF-prepared canal (*A*, *B*, rotated by 90°). (*C*) The standardized master cone fit with a tug-back sensation in the same prepared canal. (*D*) A master cone that fit into the canal before SAF preparation.

Conclusions

The SAF represents a new approach in endodontic file design and operation. Its main features are as follows:

1. A three-dimensional adaptation to the shape of the root canal, including adaptation to its cross-section.
2. One file is used throughout the procedure, during which it changes from an initially compressed form to larger dimensions.

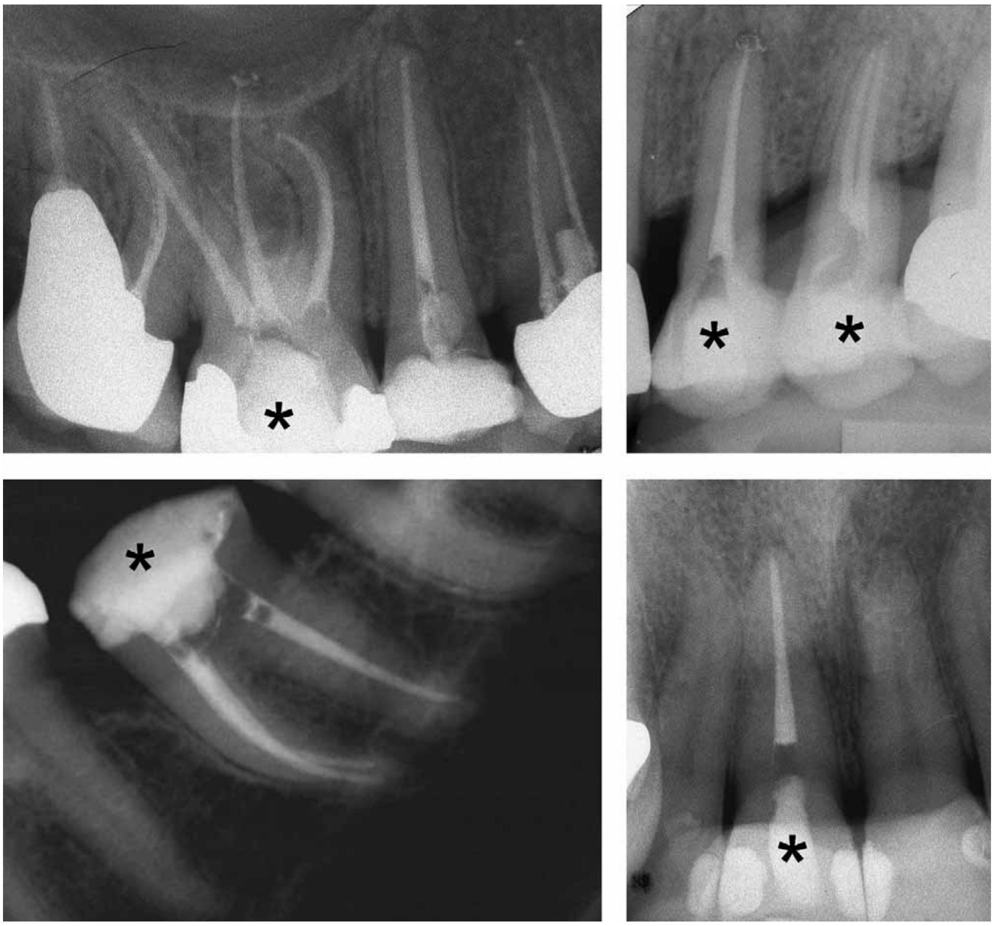

Figure 13. SAF in clinical use. Postoperative radiographs of clinical cases treated with the SAF file. *SAF-treated teeth.

3. Canal straightening and canal transportation of curved canals are largely avoided because of the lack of a rigid metal core. The file does not have "a will of its own."
4. High mechanical durability, thus overcoming the issue of separated nickel-titanium instruments.
5. Hollow design that allows continuous irrigation with constant refreshment of the irrigant throughout the procedure.

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The Self-adjusting File (SAF). Part 3: Removal of Debris and Smear Layer—A Scanning Electron Microscope Study

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Abstract

Aim: The aim of this study was to evaluate the cleaning ability of the Self-Adjusting File (SAF) system in terms of removal of debris and smear layer. **Methodology:** Root canal preparations were performed in 20 root canals using an SAF operated with a continuous irrigation device. The glide path was initially established using a size 20 K-file followed by the SAF file that was operated in the root canal via a vibrating motion for a total of 4 minutes. Sodium hypochlorite (3%) and EDTA (17%) were used as continuous irrigants and were alternated every minute during this initial 4-minute period. This was followed by a 30-second rinse using EDTA applied through a nonactivated SAF and a final flush with sodium hypochlorite. The roots were split longitudinally and subjected to scanning electron microscopy (SEM). The presence of debris and a smear layer in the coronal, middle, and apical thirds of the canal were evaluated through the analysis of the SEM images using five-score evaluation systems based on reference photographs. **Results:** The SAF operation with continuous irrigation, using alternating irrigants, resulted in root canal walls that were free of debris in all thirds of the canal in all (100%) of the samples. In addition, smear layer–free surfaces were observed in 100% and 80% of the coronal and middle thirds of the canal, respectively. In the apical third of the canal, smear layer–free surfaces were found in 65% of the root canals. **Conclusions:** The operation of the SAF system with continuous irrigation coupled with alternating sodium hypochlorite and EDTA treatment resulted in a clean and mostly smear layer–free dentinal surface in all parts of the root canal. *(J Endod 2010;36:697–702)*

Key Words

Apical third of root canal, cleaning debris, irrigation, irrigation protocol, SAF, self-adjusting file, smear layer

The cleaning and shaping of root canals is a key step in root canal treatment procedures. Unless all tissue remnants and debris are removed, the subsequent stage of root canal obturation may also be jeopardized, leading to the potential failure of treatment (1, 2). Any material left between the canal wall and the root canal filling may prevent intimate adaptation between the two and may provide a space for bacterial leakage and bacterial proliferation.

Accordingly, the cleaning efficacy of any endodontic file system is of major importance and has been studied intensively (3, 4). The presence of a significant amount of debris is commonly encountered when either rotary or hand files are used in root canals with flat cross-sections. The debris accumulation in the uninstrumented "fins" may not allow for proper disinfection and may prevent the root canal filling from reaching these recesses, even when warm gutta-percha compaction is applied (1, 2). Such a gross accumulation of debris may readily be visualized even when using light microscopy at a magnification of ×50 (1, 2).

Furthermore, the smear layer and some amounts of debris may be present on the walls of the root canals, even with the simplest morphology. A 5-μm-thick smear layer represents a potential gap between the root canal filling and the root canal wall that may be capable of accommodating approximately five layers of bacteria. Moreover, the smear layer may block or prevent the free access of antibacterial agents to the bacteria that may have penetrated into the dentinal tubules. The evaluation of fine debris and the presence of the smear layer require higher magnification levels (200×-1,000×) that are achievable only through the use of scanning electron microscopy (SEM).

SEM has been applied by numerous investigators to study the efficacy of various rinsing protocols and file systems in the removal of debris and smear layer (5–16). Every available file system generates a smear layer and leaves debris in the root canal, and rinsing with sodium hypochlorite alone is unable to render the canal free of debris and smear layers (5–13, 15, 16). In addition, the application of chelating agents such as EDTA may dramatically improve the overall efficiency of the procedure (8-13). Finally, even when the coronal and middle thirds of the canal are relatively clean, the apical third of the root canal always presents a problem in regard to the ability to achieve the same level of cleanliness (5, 6, 9, 12). This may be of great importance because the presence of a smear layer and debris may prevent sealer adaptation to the canal walls and allow penetration of irritants into the periradicular tissues, initiating or sustaining periradicular inflammation (17, 18).

The Self-Adjusting File system (SAF; ReDent-Nova, Ra'anana, Israel) is different from any available file system in two major respects (19). First, the SAF is a hollow and flexible file that adapts itself three-dimensionally to the shape of the root canal, including the ability to adapt to its cross-section (19). The SAF vibrates when

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operated and removes a uniform dentin layer from the canal walls even in oval, flat root canals (19). Rather than machining a central portion of the root canal into a round cross-section, the SAF allows for maintaining a flat canal as a flat canal with slightly larger dimensions. Second, this hollow file allows for the continuous irrigation of the root canal throughout the procedure, with additional activation of the irrigant by its vibrating motion that creates turbulence in the root canal. Irrigation may be provided by any physio-dispenser type of device (ie, NSK Surgic XT Micro Motor System, Kanuma, Japan, or W&H ImplantMed, Burmoos, Austria) or by a special rinsing unit such as the one used in the current study, which delivered the irrigant at a flow rate of 5 mL/min (VATEA, ReDent-Nova).

The adaptation of the file to the root canal's cross-section is expected to limit the potential gross debris accumulation in untreated areas of oval, flat canals. The continuous flow of the irrigant through the file combined with the vibrating motion may have an effect on the cleaning ability of the file in the root canal at large and particularly in its difficult-to-clean cul de sac region, the apical third of the root canal (20). This challenging portion of the root canal may benefit from the unique mode of action of the SAF file.

The present study was designed to evaluate the cleaning ability of the SAF in terms of removal of debris and smear layer, using SEM.

Figure 1. The SAF file with its irrigation tube. The file was operated with a KaVo (Biberach Riss, Germany) vibrating handpiece. An irrigation tube with an on-off switch (white) was attached to a continuous-flow source (VATEA, ReDent-Nova, [19]) that provided either 3% sodium hypochlorite or 17% EDTA at 5 mL/min.

Materials and Methods

Selection of Teeth

Twenty-three single-rooted teeth were selected from a random collection of human teeth that were extracted within the last 3 months and stored in 10% buffered formalin until they were used. Each root was radiographed in buccolingual and mesiodistal projections to evaluate the shape of the root canal and to detect any possible obstruction. The inclusion criteria were single-rooted teeth with straight root canal and an intact pulp chamber, whereas the exclusion criteria were previous root canal treatment and teeth with an irregular root canal anatomy.

Root Canal Treatment

An endodontic access cavity was prepared in each tooth, and the root canal was negotiated using a size 15 K-file. The working length was determined to be 1 mm short of the apical foramen that was sealed from the outside using an impression compound (Kerr, Orange, CA).

A glide path was established by manual instrumentation up to a size 20 K-file using 3% sodium hypochlorite and RC-Prep paste (Premiere, Philadelphia, PA) as a lubricant.

An SAF file (ReDent-Nova) was used for cleaning and shaping the root canal using an in-and-out vibrating handpiece as described by Metzger et al (19). The hollow SAF file allowed for continuous irrigation throughout the procedure. Irrigation was performed via a silicon tube (inner and outer diameters of 1.587 × 3.175 mm, respectively; Degania-Silicone, Degania, Israel) that was attached to a rotating hub on the shaft of the file (Fig. 1). The irrigant went into the file and freely escaped into the canal through the lattice wall to backflow coronally and escape through the access cavity. No positive pressure was generated in the root canal.

The irrigation was performed continuously during the operation using a special irrigation apparatus (VATEA Irrigation Device). This apparatus contained two separate irrigation fluid reservoirs, each with its own irrigation tubing, which was attached to the hollow SAF file via a dual silicone tube with a Y-type ending that allowed each irrigant to be separated from the other until the delivery point.

The SAF file was operated in two cycles of 2 minutes each for a total of 4 minutes. The SAF was removed for inspection after each cycle. During the first minute of each cycle, sodium hypochlorite (3%) was used as the irrigant, wheras EDTA (17%) was used during the second minute. The flow rate of the irrigants was set at 5 mL/min, resulting in a total volume of 10 mL of each irrigant used during the procedure. After completion of the two cycles, an additional irrigation with EDTA (17%) was performed for 0.5 minutes with the vibrational mechanism turned off followed by a final flush with sodium hypochlorite (3%, 5 mL) in order to remove the remaining EDTA. The root canal was dried using paper points, and the tooth was left to dry at room temperature for 24 hours before being prepared for the SEM examination. The experimental group was composed of 20 roots, which were subjected to the protocol described previously. Three roots were used as a positive control for the smear layer in which only sodium hypochlorite (no application of EDTA) was used as an irrigant through the total 4-minute period of the SAF operation.

SEM

Each root was split longitudinally and subjected to SEM processing and examination. The samples were dried and coated with gold (Polaron SEM Coating Unit E5100; Quorum Technologies, East Sussex, UK) and examined using a JEOL JSM 840A scanning electron microscope (JEOL, Tokyo, Japan). Representative sections of the coronal, middle, and apical thirds of the canal were used for evaluation at a magnification of 200× and 1,000×.

Selection of Representative Sections

After the central beam of the SEM had been directed to the center of the object by the SEM operator at 10× magnification, the magnification was increased to 200× and subsequently 1,000×, respectively, and the canal wall region appearing on the screen was photographed (5).

SEM Image Analysis and Scoring

The cleaning ability of the SAF file was evaluated using the debris and smear layer score systems introduced by Hülsmann et al (5). These scoring systems were applied to the coronal, middle, and apical thirds of the canal. Three examiners independently scored each of these images, which were coded and randomly mixed so that the examiners were blinded to the area from which a given sample originated. The reference set of SEM images that was used by Hülsmann et al (5), Versümer et al (9), and Paqué et al (12) was also available and was used in the present study. The examiners were initially calibrated using the reference SEM images.

When all three examiners independently agreed on a score, it was recorded. When disagreement occurred, all three discussed the sample and its scoring, and an agreed score was reached.

The presence of debris was evaluated from images at 200× magnification using a scale of 5 scores (5) as follows: (1) score 1: clean root canal wall and only a few small debris particles, (2) score 2: a few small agglomerations of debris, (3) score 3: many agglomerations of debris covering less than 50% of the root canal wall, (4) score 4: more than 50% of the root canal walls were covered with debris, and (5) score 5: complete or nearly complete root canal wall coverage with debris.

The results were then dichotomized into "clean canal wall" that included scores 1 and 2 or "debris present" that included scores of 3, 4, and 5.

The smear layer was evaluated from images at 1,000× magnification on a scale of the following five scores (5): (1) score 1: no smear layer, and all dentinal tubules were open; (2) score 2: a small amount of smear layer, and some dentinal tubules were open; (3) score 3: homogenous smear layer covering the root canal wall, and only a few dentinal tubules open; (4) score 4: complete root canal wall covered by a homogeneous smear layer, and no open dentinal tubules were observed; and (5) score 5: heavy, homogeneous smear layer covering the complete root canal wall.

The results were then dichotomized into "clean canal wall" that included scores 1 and 2 and "smear layer present" that included scores 3, 4, and 5.

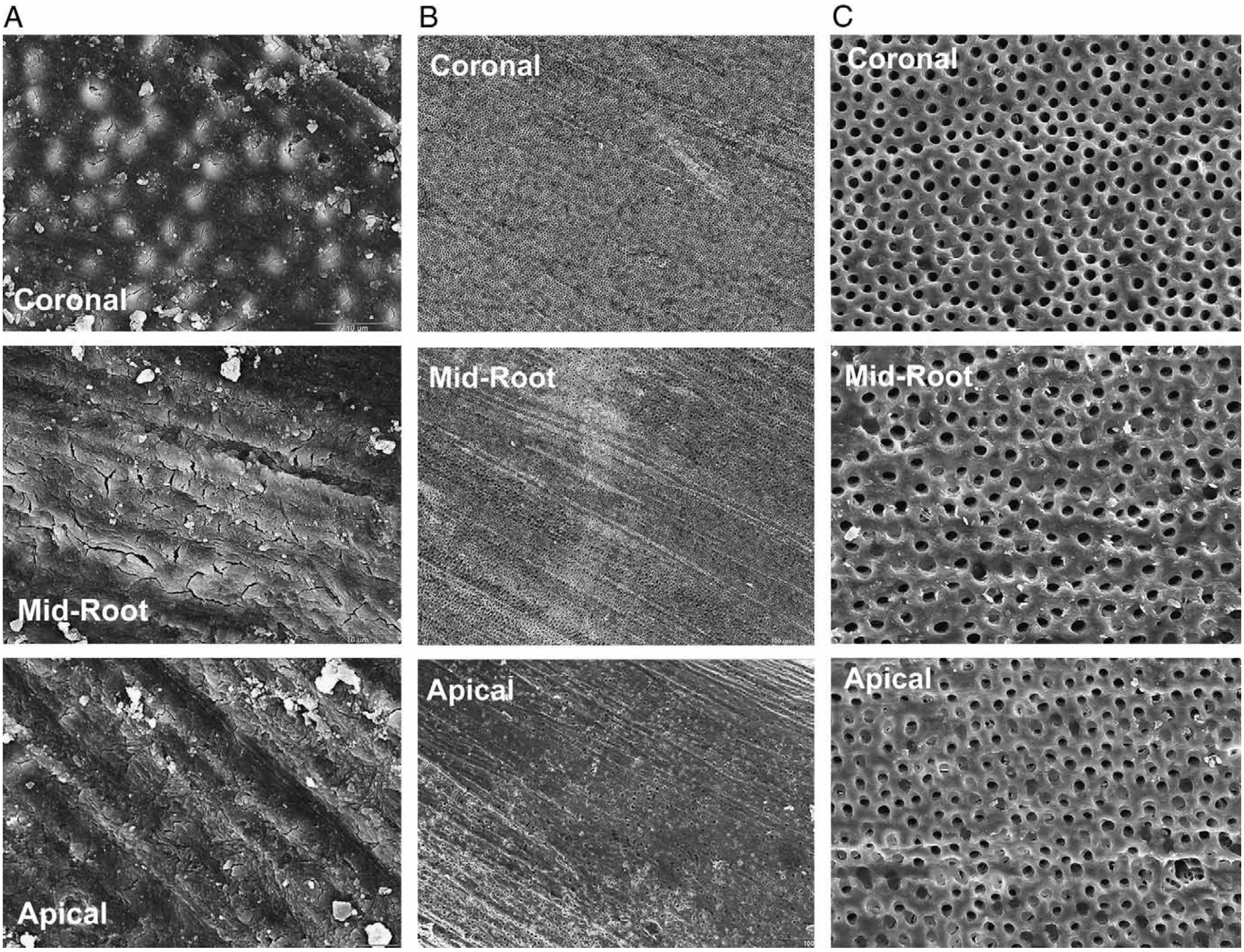

Figure 2. (*A*) The smear layer in a root canal treated using the SAF file and sodium hypochlorite alone. When sodium hypochlorite alone was used as the irrigant, the smear layer was present in the coronal, midroot, and apical portions of the root canal. A representative case from the positive control group. Smear layer scores: coronal = 4 and midroot and apical = 5 using the Hülsmann smear layer score system (5). Original magnification: 1,000×. (*B*) A root canal surface free of debris in a root canal which was treated using the SAF system and the alternating irrigation protocol. The coronal, midroot, and apical thirds of the canal recieved all a score of 1 using the debris scoring system described by Hülsmann et al (5). A representative case from the experimental group. Original magnification: 200×. (*C*) The smear layer-free surface in a root canal treated using SAF and the alternating irrigation protocol. The coronal, midroot, and apical thirds of the canal received a score of 1 using the smear layer scoring system of Hülsmann et al (5). A representative case from the experimental group. Original magnification: 1,000×.

Results

Examiner Agreement

Initial independent agreement of all three examiners was 78% and 58% for debris and smear layer scores, respectively. As for debris scoring, in an additional 17% of the cases, there was initial agreement between two examiners and in only 5% of the cases was there a difference between examiners by more than one level of scoring. When scoring smear layer, in an additional 22% of the cases, there was agreement between two examiners, and in no case was the difference between the examiners by more than one level of scoring.

Control Group

A smear layer and much debris were found in all three root canals that were treated using the SAF with sodium hypochlorite alone (Fig. 2*A*). The smear layer and debris were present in the coronal, midroot, and apical parts of the root canals.

Debris

Root canal preparation using the SAF combined with the alternating irrigation protocol rendered all root canals clean of debris (Fig. 2*B*). Debris evaluation of the root canal dentinal surfaces resulted in debris scores of 1 or 2, representing a clean root canal surface in 100% of the cases in the coronal, midroot, and apical thirds of the root canals (Table 1). None of the samples were characterized as having debris score of 3 to 5.

Smear Layer

The combined action of the SAF with the continuous irrigation regimen resulted in a root canal surface clean of smear layer (Fig. 2*C*). In the coronal and midroot areas, 20 out of 20 (100%) and 16 out of 20 (80%) samples were scored as either 1 or 2, respectively, representing a clean dentin surface (Table 2). Notably, no samples were characterized with scores of 3 to 5 in the coronal part, and only 4 of 20 (20%) had these scores in the middle third of the root.

In the apical third of the canal, scores of 1 or 2, representing clean canal walls, were reported for 13 of 20 (65%) of the samples, whereas smear layer scores of 3 to 5 were reported for only 7 of 20 (35%) of the samples.

Discussion

The SAF, as any mechanical device that is designed to remove dentin layers, produces a smear layer when operated in conjunction with sodium hypochlorite alone (15,16). This occurred despite the continuous irrigation method used by the SAF (Fig. 2*A*). Nevertheless, the application of an irrigation protocol with alternating administration of 3% sodium hypochlorite and 17% EDTA rendered the root canal dentin surface free of the smear layer. Similar results could also be achieved in the coronal and midroot areas with other instruments and protocols using EDTA or other chelator preparations to remove the smear layer (9-14). However, although several studies indicate that achieving this goal in the apical third of the root canal may be difficult if not impossible, the use of the SAF in combination with the current irrigation protocol resulted in a clean dentin surface in the apical portion of most root canals.

Previously published studies that used the same scoring system as used in the present study (9, 12) showed that debris scores of 3 to 5 were recorded in the coronal, middle, and apical thirds of the root canal in 24% to 50%, 32% to 48%, and 40% to 73% of the samples, respectively. The results in the SAF-treated root canals were clearly different; scores of 1 or 2 were recorded in all samples in all parts of the root canals with no 3 to 5 scores.

Similar analysis of these studies (9, 12) showed that smear layer scores of 3 to 5, representing a substantial smear layer, were reported for the coronal and middle thirds of the canal in 46% to 82% and 60% to 68% of the cases, respectively. In these aforementioned studies, the smear layer scores of 3 to 5 were reported for the apical third of the root canal in 48% to 95% of the samples. The results of the current study were clearly different; scores of 1 or 2, representing root canal wall free of smear layer, were recorded in 100% of the coronal third of the samples, whereas this score was recorded in 80% and 65% of the samples in the midroot and apical thirds of the root canal, respectively.

The cul de sac portion of the root canal presents a distinct challenge for any irrigation method. A syringe and needle will only be effective if the tip of the needle reaches the end of the prepared canal (20). The process of simply injecting the fluid into the canal will not achieve any results more than 1 or 2 mm beyond the tip of the needle. This presents a problem particularly in curved canals. Inserting an irrigation needle deep into the root canal coupled with the application of positive pressure may enhance the risk for injecting the irrigation solution beyond the apex, potentially causing a "sodium hypochlorite accident" (21). This recently led to the development of alternative irrigation devices based on negative pressure to overcome this problem (20, 22).

The SAF operates in a totally different manner than syringe and needle irrigation. The hollow file is operated with continuous irrigation provided by a special device (VATEA). The chosen irrigation fluid enters the file through a free-rotating hub and is continuously replaced throughout the procedure, thus providing a fresh, fully active, supply of sodium hypochlorite and chelator solution (eg, EDTA). The operator has a choice of which of the two solutions to use at a given moment and at what flow rate to infuse the canal. No positive pressure can develop in the root canal because the solution can always easily escape through openings in the lattice of the file (19, 23).

The fluids in the apical part of the root canal are effectively replaced by the SAF file even in simulated canals that are curved (19). This occurs, most probably, not because of the apical flow of the

TABLE 1. Debris Scores of Root Canals Treated Using the SAF File

Coronal third					Middle third					Apical third				
Clean		Debris present			Clean		Debris present			Clean		Debris present		
1*	2	3	4	5	1	2	3	4	5	1	2	3	4	5
20/20†	0	0	0	0	16/20	4/20	0	0	0	14/20	6/20	0	0	0
20/20 (100%)‡		0 (0%)			20/20 (100%)		0 (0%)			20/20 (100%)		0 (0%)		

SAF, self-adjusting file.

*Debris scores (Hülsmann et al, 1997 [5]).

†Number of canals presenting with a given score.

‡Dichotomized scores: scores 1 to 2 (clean canal wall) versus 3 to 5 (debris present).

TABLE 2. The Smear Layer Scores of Root Canals Treated Using the SAF File

Coronal third					Middle third					Apical third				
Clean		Smear layer present			Clean		Smear layer present			Clean		Smear layer present		
1*	2	3	4	5	1	2	3	4	5	1	2	3	4	5
14/20†	6/20	0	0	0	10/20	6/20	3/20	1/20	0	3/20	10/20	5/20	2/20	0
20/20 (100%)‡		0 (0%)			16/20 (80%)		4/20 (20%)			13/20 (65%)		7/20 (35%)		

SAF, self-adjusting file.

*Smear layer scores (Hülsmann et al, 1997 [5]).

†Number of canals presenting with a given score.

‡Dichotomized scores: scores 1 to 2 (clean canal wall) versus 3 to 5 (smear layer present).

solution but rather because of the vibrating motion of the file's delicate mesh within the fluid that is continuously replaced.

The concept that the vibration of the irrigation solution has beneficial effects has been widely recognized and, as such, has led to the development of a variety of "activating" devices for the final irrigation once the canal preparation has been completed (20, 24). The SAF is the first device that activates the irrigation solution throughout the entire procedure. This, in addition to the continuous replacement of the irrigant, may explain the excellent cleaning efficiency observed in the present study. The canal was rendered free of even ultramicroscopic debris that have a tendency to accumulate during the root canal preparation, especially in the apical portion of the root canal, when other protocols are used (5, 9, 12).

Even though the total irrigation time with each of the irrigants in the current study was relatively short (2 minutes for sodium hypochlorite and 2.5 minutes for EDTA), it resulted in an extremely clean root canal wall. It is likely that the efficacy of the sodium hypochlorite treatment was also enhanced by the removal of the smear layer during this procedure, which provides a better access of the sodium hypochlorite and better access into the openings of the dentinal tubules, thus potentially increasing its range of antibacterial activity. Nevertheless, this issue is beyond the scope of the present study and requires further investigation.

In addition to effectively replacing the irrigant from the apical portion of the root canal and the simple activation of the irrigant through the creation of turbulence, the SAF file also induces a scrubbing motion on the canal walls that must have obviously contributed to the exceptionally clean surface that resulted even in the cul de sac portion of the canal.

Comparing the results of the various studies that addressed the issue at hand is complicated because many of them used a great variety of evaluation methods. From the numerous studies published on this subject, we compared the current results with those of the two studies that used the same evaluation methods for the smear layer and for the presence of debris (9, 12). Furthermore, two of the evaluators of the present study (MH and FP) were also involved in the scoring of both the present study and the previous studies to which the current data were compared. Even though the experimental design of these studies was quite different from the current one, this comparison showed that the conventional rotary file systems used in conjunction with sodium hypochlorite and with either RC-Prep or a Calcinase-Slide chelator paste (Lege Artis, Dettenhausen, Germany), which were both used with each new file (9, 12), failed to render the canal free of debris and of the smear layer. The difference was particularly pronounced in the apical portion of the canal in which the protocols used in these two studies, as well as those used in other studies, failed to achieve clean canals walls in a manner equivalent to those achieved in the more coronal portions of the root canal.

A recent study by Lottanti et al (14) has questioned the validity of the previously published data that indicated that the smear layer is difficult to remove from the apical portion of the root canal. This study suggested that sclerotic dentin, which is more common in the apical portion of the root, may have been mistaken for a smear layer. This could be true when an evaluation method based on simple counting of the number of tubules per unit area was the only criterion. Nevertheless, the finding that the current cleaning protocol was able to render the apical portion of the root canals free of the smear layer and of debris offers indirect support to the previously published data and those of the two studies that used the same evaluation method and were used as a source of comparison with the current study (9, 12). The effective removal of the smear layer observed by Lottanti et al (14) most probably resulted from the wide apical preparations used in this study and from the relatively short root canals (12 mm) with the coronal portion of the tooth removed. Long irrigation times (15 minutes during instrumentation and 3 minutes after) may also have contributed to the observed results.

Several methods were recently introduced to try to overcome the problem of debris accumulation in the apical part of root canals during root canal treatment (22, 24). It would be of interest to compare their cleaning efficacy in this challenging part of the root canal with that of the SAF system. A recent report about massive accumulation of debris in the isthmus area of root canals treated with rotary file systems (25) presents yet another challenge to these new irrigation methods and should also be addressed in such comparative studies.

Conclusions

The SAF, operated with the continuous flow of irrigants alternating between sodium hypochlorite and EDTA, resulted in root canals that were free of debris and almost completely free of the smear layer.

The results were better than those previously published for the coronal and midroot portions of the root canal.

The difference was also pronounced in the apical third of the canal, in which previously published protocols failed to adequately clean the canal, whereas the SAF protocol resulted in debris-free canal walls in all samples and smear layer-free surfaces in most of the samples.

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The Quality of Root Canal Preparation and Root Canal Obturation in Canals Treated with Rotary *versus* Self-adjusting Files: A Three-dimensional Micro-computed Tomographic Study

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Abstract

Aim: The study was designed to quantitatively evaluate the quality of root canal preparation and root canal obturation in canals treated with either rotary or self adjusting files, using three-dimensional micro–computed tomographic (CT) analysis. **Methodology:** Pair-matched root canals were instrumented with either rotary nickel-titanium files or self-adjusting files following the manufacturers' instructions. The area of the canal wall unaffected by the preparation procedure was analyzed using before and after micro-CT images. Root canal obturation was done using lateral compaction with gutta-percha and AH26 (Dentsply-DeTrey, Konstanz, Germany). Teeth were scanned a third time, and the adaptation of the filling material to the canal walls was evaluated three-dimensionally by micro-CT analysis and the area of canal wall untouched by the filling was determined. The correlation between these two parameters within each of the groups was studied using the Pearson correlation test. **Results:** A high percentage of unaffected root canal walls (60% ±14%) and areas untouched by the root canal filling (45% ± 15%) were found in canals treated with rotary files. Both parameters were significantly smaller in canals treated with self-adjusting files (17% ± 9% and 17% ± 11%, respectively) ($p < 0.01$). No correlation was found between these parameters within each of the groups. **Conclusion:** Within the limitations of the present study, the self-adjusting files allowed better cleaning and shaping and better adaptation of the root canal filling than those allowed by rotary files. *(J Endod 2010;36:1569–1573)*

Key Words

MicroCT, obturation, root canal filling, SAF, self adjusting file

Root canal obturation is an essential stage of root canal treatment aimed to seal the root canal in order to prevent future bacterial contamination/recontamination of the canal space (1). Many obturation methods have been introduced over the years, each attempting to provide a better seal of the root canal (2). All have in common the assumption that the root canal is properly cleaned and shaped before the obturation stage. It is assumed by all that if the root canal is not adequately prepared and if tissue remnants and debris are present along the walls, proper sealing may be jeopardized, even with the best root canal filling method (3, 4).

When simple, narrow, straight root canals with round cross-sections are considered, most current rotary nickel-titanium file systems will adequately clean and shape the canal with favorable results. The case is different in oval, flat, or curved root canals.

In flat root canals, rotary file systems often fail to adequately clean and shape the canal, leaving "fins" that may have not been prepared (2–4). In such a case, even warm gutta-percha obturation methods will fail to adequately seal the root canal (4). Clinical buccolingual radiographs will fail to detect such discrepancy.

Micro–computed tomographic (CT) studies by Peters et al (6) have further extended the understanding of the limitations of rotary file systems. They clearly showed that inadequate preparation also often occurs in curved root canals, even if they do not have a flat cross-section. In upper molars treated with the ProTaper system (Dentsply-Maillefer, Ballaigues, Switzerland), 49% (±29%) of the canal wall was left untouched, even in the larger palatal canals (6). Again, two-dimensional, clinical periapical radiographs cannot disclose the discrepancies.

This led to the recent introduction of a new self-adjusting file (SAF), which not only adapts itself longitudinally to a curved canal, as most rotary nickel-titanium files do, but also adapts itself to the cross-section of the canal (5). Rather than machining each canal into one with a circular cross-section, it removes an even dentin layer from all around the root canal, thus respecting the shape of a given root canal rather than imposing a circular cross-section on every canal no matter what its shape (5). Recent micro-CT analysis of root canals prepared with this new file indicated that this new technology allows for a higher percent of the root canal surface to be affected by the procedure (5). The resulting apical size is usually at least equivalent to a #40 file.

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Following the concept of the previously mentioned micro-CT analysis methods, a new method for quantitative three-dimensional analysis of the adaptation of root canal filling material to the canal walls was designed. This new method was applied in the present study to quantitatively evaluate and compare the results of instrumentation with an SAF to those obtained with nickel-titanium rotary files.

Materials and Methods

Experimental Design

The study was designed to compare two instrumentation methods using two three-dimensional parameters: (1) the quality of root canal cleaning and shaping, as expressed by the root canal wall area affected/unaffected by the procedure, and (2) the quality of obturation, as expressed by the percent of the root canal wall area (after preparation) touched/untouched by the root canal filling material.

Teeth

Teeth were selected from a large random collection of extracted human teeth that were recently extracted for reasons unrelated to the present study and kept in 10% buffered formalin. Both three-dimensional images and two-dimensional cross-sections obtained using micro-CT scanning were available for each tooth in this collection.

Ten pairs of roots were selected based on matching root canal morphology. These 20 roots included two mesial roots of lower molars, two distal roots of lower molars, six premolars, eight incisors, and two canines. Pair selection was based on visual similarity in shape, size, flatness, and curvature of the root canals, as seen in a set of three-dimensional micro-CT images of each of the roots. The two roots of each pair were randomly assigned to one of the two treatment groups (rotary files or SAFs).

Root Canal Cleaning and Shaping

Two file systems were used: rotary nickel-titanium files (ProTaper, Dentsply-Maillefer, Ballaigues, Switzerland) and SAFs (ReDent-Nova Ltd, Ra'anana, Israel). Each instrument was applied following its manufacturer's instructions.

Rotary Files

The rotary files (ProTaper) were operated with a handpiece attached to a speed- and torque-controlled motor (X-Smart, Dentsply-Maillefer) at 250 rpm. The sequence used was ProTaper S_1, S_2, F_1, F_2, and F_3 with RC-Prep (Premier, Plymouth Meeting, PA) used as a chelator/lubricant with each file. The canal was irrigated with 5 mL 3% NaOCl between the instruments. A final flush with 5 mL 17% EDTA was applied, followed by an additional flush with 5 mL 3% NaOCl to remove the EDTA, and the canal was dried using paper points.

SAF

The SAF (ReDent) was operated for 4 minutes using a GentlePower Lux 20LP KaVo handpiece, (KaVo, Biberach, Germany) adapted with a RDT3 head (ReDent-Nova, Raanana, Israel) (5). The micromotor rotation speed was set at 5,000 rpm, which resulted in an in-and-out operation of 5,000 vibrations per minute with an amplitude of 0.4 mm. The file was used with a manual in-and-out motion to the working length. Continuous irrigation was applied throughout the procedure (5) at 5 mL/min using a special irrigation apparatus (VATEA irrigation device, part of the SAF-System, ReDent); 3% NaOCl was used for irrigation during the first 3 minutes of the operation, followed by 1 minute of irrigation with 17% EDTA. A final flush with 5 mL 3% NaOCl was used to remove the EDTA, and the canal was dried using paper points.

Micro-CT Evaluation of the Root Canal Preparation

Before preparation and scanning, each experimental tooth was mounted on scanning electron microscopy carriers (014001-T; Bal-Tec AG, Balzers, Liechtenstein) to allow exact repositioning in the scanning system. Specimens were scanned before and after preparation by using a commercially available micro-CT system (μCT 40; Scanco Medical, Brüttisellen, Switzerland). Teeth were scanned at 70 kV and 114 μA with an isotropic resolution of 18 μm. Although the mounting device ensured almost exact repositioning of the specimens, superimposition was further calculated with newly developed software (IPL Register 1.01, Scanco Medical), as previously reported by Paqué et al. (7). The final exact superimposition of the teeth before and after preparation was with a precision better than one voxel.

Individual root canal models were reconstructed up to the level of the cementoenamel junction using specially developed software (IPL V5.06B, Scanco Medical). Superimposition of the root canals before and after preparation enabled visualization and quantitatively three-dimensional evaluation of the amount of un-instrumented areas (Fig. 1). This parameter was expressed as a percentage of the number of static surface voxels of the total number of surface voxels.

Root Canal Obturation

Root canal obturation was performed using the lateral compaction technique with gutta-percha and AH26 sealer (Dentsply-DeTrey, Konstanz, Germany). A gutta-percha master cone (DiaDent, Almere, The Netherlands) was fitted with tug-back in each root canal. Sealer was placed into the canal using a lentulo spiral followed by insertion of the master cone to the predetermined working length. Nickel-titanium finger spreaders (Dentsply-Maillefer) were used to conduct the lateral compaction using XXF/ XF accessory cones (Sure-Endo, Paris, France). When no additional cones could be inserted, the gutta-percha mass was cut off 1 mm apical to the canal orifice using a heated plugger (Dentsply-Maillefer). The freshly cut surface was vertically condensed using a cold plugger (Dentsply-Maillefer). The sealer was then allowed to set for 4 days at 37°C and 100% humidity.

Evaluation of Obturation Quality by Three-Dimensional Micro-CT Analysis

Each tooth was subjected to a third micro-CT scan as detailed earlier. Differences in the radiopacity between the root canal filling and the root dentin allowed differentiation between the two. For each root, the filling material was three-dimensionally reconstructed and superimposed with the image of the root canal after cleaning and shaping. Superimposition of root fillings and the prepared root canals (third and second scanning) allowed a three-dimensional analysis of the areas of the root canal surface, which were touched/untouched by the root canal filling.

Statistical Methods

The area unaffected by instrumentation and the area untouched by the root canal filling of the two instrumentation groups were compared with each other using the Student *t* test. The one-tailed Pearson correlation test was used to study the correlation within each group between the unaffected surface in a given root canal and the area untouched by the root canal filling in the same canal.

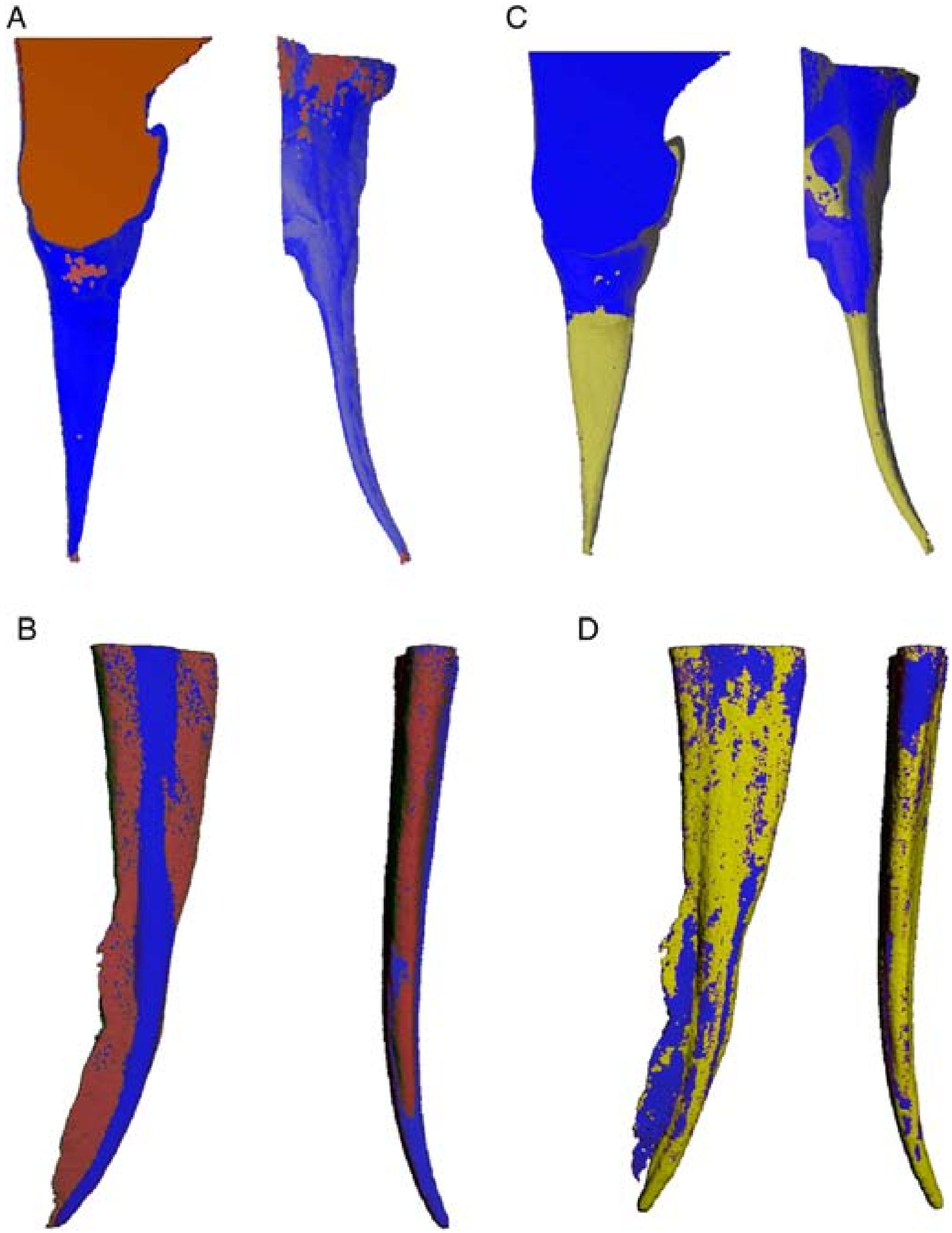

Figure 1. Three-dimensionally reconstructed micro-CT images of root canal preparation and obturation. (*A*) A flat root canal prepared with the SAF file. (*B*) A flat root canal prepared with a rotary file. (*C*) A good root canal filling adaptation with 98.1% of the canal wall in contact with the root canal filling material. (*D*) A poor root canal filling adaptation with only 68.9% of the root canal wall in contact with the root canal filling material. Note the uninstumented lingual "fin" in *B* that was most probably full of debris, which prevented the sealer from flowing into it in *D*. *Red*: root canal surface before treatment. *Blue*: root canal surface post-treatment. *Yellow*: area touched by the root canal filling. *Right*, in each panel: buccal view, *left*: distal view. (resolution = 18 μm). (This figure is available in color online at www.aae.org/joe/.)

Results

Percent Root Canal Surface Unaffected by Root Canal Preparation

The root canal surface unaffected by root canal preparation was calculated as a percent of the root canal surface area before preparation (Table 1 and Fig. 1*A* and *B*). A wide range of this three-dimensional parameter was recorded, between 5.3% and 76.6%. The mean unaffected area was 16.7% (±8.9%) and 60.2% (±13.6%) in the self SAF and rotary file groups, respectively (Fig. 2).

Percent Root Canal Surface After Preparation Untouched by the Root Canal Filling Material

The root canal surface untouched by the root canal filling material was calculated as a percent of the root canal surface area after root canal preparation (Table 1 and Fig. 1*C* and *D*). A wide range of this parameter was recorded, between 1.9% and 75.1%. The mean area untouched by the root canal filling was 17.0% (±11.0%) and 44.6% (±14.5%) in the SAF and rotary file groups, respectively (Fig. 2).

TABLE 1. A Three-Dimensional Micro-CT Analysis of the Quality of Cleaning and Shaping and Root Canal Filling Adaptation to the Canal Walls

Pair #	Type of canal	Method	Area unaffected by root canal preparation (%)	Area untouched by root canal filling (%)
1	R-S	RF	66.7	28.9
		SAF	14.9	1.9
2	R-S	RF	64.4	64.3
		SAF	7.1	15.8
3	R-S	RF	49.4	42.4
		SAF	20.8	8.5
4	R-C	RF	28.0	38.8
		SAF	33.8	23.5
5	R-C	RF	76.6	37.6
		SAF	5.3	5.8
6	F-S	RF	63.0	44.1
		SAF	21.6	30.5
7	F-S	RF	73.0	75.1
		SAF	5.8	15.1
8	F-S	RF	60.9	47.0
		SAF	20.2	8.0
9	F-S	RF	59.3	37.1
		SAF	21.1	29.4
10	F-C	RF	61.1	31.1
		SAF	15.9	31.2

R-S, round cross-section, straight; R-C, round cross-section, curved; F-S, flat cross-section, straight; F-C, flat cross-section, curved; RF, Rotary files.

Correlation Between the Area Unchanged by the Root Canal Preparation and the Area Untouched by the Root Canal Filling

No correlation was found within each of the groups between the percent of the area unaffected by the root canal preparation and the area untouched by the root canal filling.

Discussion

Many obturation methods are used today, ranging from traditional lateral compaction to a variety of heat-softened gutta-percha techniques. All are aimed at providing a good adaptation of the root canal filling material to the canal walls, thus ensuring an adequate seal that will prevent bacterial contamination/re-contamination of the root canal system.

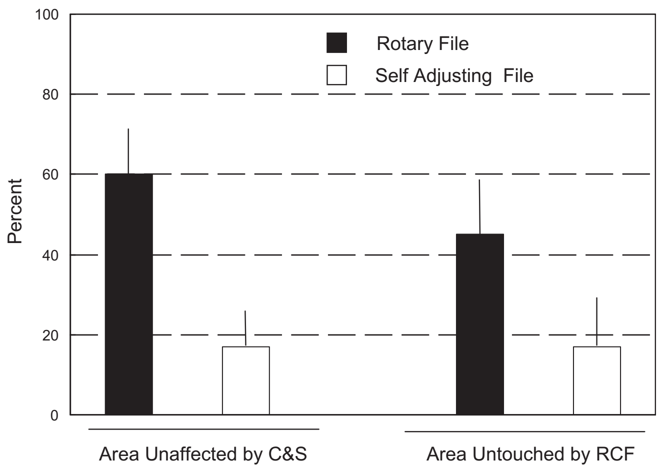

Figure 2. Comparison between the quality of the root canal preparation and adaptation of the root canal filling in root canals treated with rotary files or SAFs. The quality of root canal preparation is expressed as a percent of the root canal surface that was unaffected by the file. Adaptation of the root canal filling is expressed as a percent of the root canal surface after preparation that was untouched by the root canal filling. RCF, root canal filling; C&S, cleaning and shaping.

When applied in adequately prepared canals with no tissue remnants and with a clean, prepared dentin surface, this goal may be rather easily achieved. The case may be different in root canals that were inadequately cleaned and shaped. Tissue and debris remaining in parts of the canal that were unaffected by the procedure may present a barrier that does not allow for the root canal filling to intimately touch the root canal wall, thus forming the weakest link in the chain of steps aimed to properly seal the canal.

This may happen in curved canals in which the files failed to touch some of the walls (6) but constitutes an even greater problem in the case of flat or ribbon-shaped canals. In these canals, a rotary nickel-titanium file alone may be unable to adequately prepare the canal (Fig. 1*B* and *D*). Its action may result in a canal prepared to accommodate a certain thickness of master cone or root canal filling but may allow for buccal and/or lingual “fins” full of tissue remnants and debris to remain untouched (3, 4). These buccal and/or lingual defects may go unobserved in regular periapical radiographs; the root canal filling that is present in the central part of the canal will most likely mask them. Bacterial retention in or penetration into and through these defects may result in endodontic failure in an apparently radiographically acceptable case.

Even though the relation between the quality of cleaning and shaping and the potential of the root canal filling to intimately touch the walls of the prepared root canal is readily understood, it has never, to the best of our knowledge, been established quantitatively for the whole canal. A study aimed to investigate the correlation between these parameters calls for a high variety of root canal cleaning and shaping scores that could later be analyzed against root canal filling adaptation to the walls of the same canals.

The roots selected for the present study intentionally included a random variety of root canal morphologic shapes. This was done so that a wide spectrum of cleaning and shaping results would be available for analysis. These roots ranged from simple straight root canals with a round cross-section, which were likely to score high in effective cleaning and shaping using any file system, to curved roots or those with flat root canals that were likely to result in a higher percent of root canal wall unaffected by rotary nickel-titanium files (5, 6).

The present study clearly showed that the two instrumentations groups differed from each other. This difference was found in both the quality of cleaning and shaping, as expressed by the percent of the root canal surface affected/unaffected by the procedure, and in the quality of root canal obturation, as expressed by the percent of the canal wall that is/is not in intimate contact with the root canal filling material. Treatment with the SAF allowed for better results with both parameters (Fig. 2).

No correlation could be found between the two parameters within each group. This could result from the relatively small number of specimens in each of the groups. Further studies with larger groups may be needed to establish such correlation.

Lateral compaction was used in the present study because it is the most commonly used obturation method. It may be of interest to test the same concept with heat-softened gutta-percha obturation methods, which are commonly expected to provide a better adaptation to the canal walls; nevertheless, this was beyond the scope of the present study.

Micro-CT scanning has been used previously to evaluate the quality of root canal fillings. Jung et al (7) have shown that the root canal filling may be differentiated from the canal wall in a micro-CT scan using digital root slices. Former studies of root canal obturation quality commonly used two-dimensional analysis of either root slices (7–10) or digital cross-sections generated from micro-CT scans (7). These could at best serve as a semiquantitative representation of what happens in the canal at large.

A three-dimensional analysis of micro-CT images, similar to the one used in the present study, was first applied by Zakizadeb et al (11) to evaluate intraorifice barriers. It was also recently applied by Hammad et al (12) for the analysis of the volume of voids and gaps present in root canal fillings.

The present study was, to the best of our knowledge, the first to use a three-dimensional micro-CT analysis to quantitatively measure the adaptation of the root canal filling material to the walls in the whole canal. As such, it provides far more comprehensive information about the adaptation of the whole root canal filling, which is unaffected by the choice of the plane in which a given section or digital cross-section happens to be.

Conclusions

A micro-CT-based quantitative three-dimensional method for analysis of root canal filling adaptation to the canal walls was presented. It may serve as a useful tool to study and compare the quality of root canal fillings. Within the limitations of the present study, the SAFs allowed better cleaning and shaping and better adaptation of the root canal filling than those allowed by rotary files.

Acknowledgment

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Micro–computed Tomography Evaluation of the Preparation of Long Oval Root Canals in Mandibular Molars with the Self-adjusting File

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Abstract

Introduction: The aim of this study was to assess the shaping potential of a novel nickel-titanium instrument, the self-adjusting file (SAF), in long oval root canals in distal roots in mandibular molars. **Methods:** Twenty mandibular molars with long oval distal root canals were selected and scanned preoperatively and postoperatively by using micro–computed tomography at an original resolution of 20 μm. Canals were shaped with the SAF, three-dimensionally reconstructed, and evaluated for volume, surface area, canal transportation, and prepared surface. Data were statistically contrasted by using paired t tests and regression analysis. **Results:** Preoperatively, canal volume was 7.73 ± 2.13 mm^3, and canal area was 42.83 ± 8.14 mm^2. Volumes and surface areas increased significantly ($P < .001$) by 4.84 ± 1.73 mm^3 and 3.34 ± 1.73 mm^2, respectively, and no gross preparation errors were detected. Unprepared canal surface varied between individual canals, and mean unprepared surface was 23.5% $\pm$ 8.9%. Prepared areas were significantly larger compared with rotary canal preparation done in a previous study. Canal transportation scores were higher in the coronal root canal third (106 ± 50 μm) compared with the apical third (81 ± 49 μm). **Conclusions:** *In vitro*, preparation of long oval-shaped root canals in mandibular molars with the SAF was effective and safe. Moreover, shapes generated with the SAF were more complete compared with rotary canal preparation. *(J Endod 2011;37:517–521)*

Key Words

Long oval root canals, micro-computed tomography, nickel-titanium instruments, root canal preparation, self-adjusting file

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One of the major procedural steps in root canal therapy is to thoroughly remove debris, pulp tissue, and microorganisms from the root canal system, which can be accomplished by chemomechanical preparation (1). To this end, it has been suggested to prepare canals to a homogenous tapered shape with the prepared canal including the preoperative outline (1, 2). However, the root canal system is anatomically complex, and mechanical instrumentation might result in preparation errors. Moreover, the use of both conventional hand files and current nickel-titanium (NiTi) rotary instruments does not result in a fully prepared root canal surface (3).

A funnel-shaped canal with a circular base is not the common configuration in root canal anatomy (2). Recently, cross-sectional root canal configurations have been classified as round, oval, long oval, flattened, or irregular (4). Metrically, Jou et al (4) defined oval as having a maximum diameter of up to 2 times greater than the minimum diameter and long oval as having a maximum diameter of 2–4 times greater than the minimum diameter.

A high prevalence of oval and long oval root canals even in the apical root canal portion has been reported (5–7). According to Wu et al (5), the prevalence of long oval root canals in the apical third of human teeth is generally about 25%; in some groups of teeth such as mandibular incisors and maxillary second premolars the prevalence is greater than 50%, and in distal roots of mandibular molars the prevalence is 25%–30%. This complex anatomy might be regarded as one of the major challenges in infection control through root canal preparation.

One aim in the preparation of infected root canals is to remove the inner layer of dentin (8, 9). This is particularly hard to achieve when preparing long oval root canals. Furthermore, after preparation, uninstrumented recesses might be left in many oval canals, irrespective of the instrumentation technique, thus leaving debris and unprepared root canal surfaces behind (8, 10–14).

All the mentioned studies were done *in vitro* by using extracted teeth that had been sectioned before root canal preparation. Then, root cross sections were assessed before and after preparation, thus representing two-dimensional analyses. In contrast, the technique of micro–computed tomography (MCT) allows a complete description of three-dimensional effects that root canal preparation exerts on root canal anatomy without altering the root during the experiments (3). This research tool allows calculation of the root canal area that is not mechanically prepared and remains as a so-called untreated surface (15).

Recently, a new instrument type, the self-adjusting file (SAF) (ReDent Nova, Ra'anana, Israel), was introduced (16); because of its construction out of a NiTi meshwork, this instrument is believed to expand into long oval root canals and therefore promote a canal preparation that circumferentially removes a layer of dentin in oval as well as round canals (17).

In fact, a recent MCT-based study indicated a superior potential to prepare long oval mesiobuccal canals in maxillary molars with the SAF compared with rotary instrumentation techniques (18), as measured by lesser amounts of untreated canal surface. This measure might be conceived as a three-dimensional indicator for the completeness of a root canal shape, depending on instrument and canal type (19). Preparations of mandibular molar canals with the SAF have not been assessed; therefore, the aim of the current study was to evaluate the prepared surface areas of long oval–shaped root canals in mandibular molars with this instrument.

Materials and Methods

Selection of Teeth

From teeth that had been extracted for reasons unrelated to the current study, 20 human mandibular molars were collected and stored in 0.1% thymol solution at 4°C until further use. Teeth were initially scanned at an isotropic resolution of 80 μm in a desktop MCT unit (μCT 40; Scanco Medical, Brüttisellen, Switzerland) by using previously established methods (15, 19). All slices were checked carefully, with the distal root tip serving as reference point to count back the slices until the exact slice 6 mm coronal to the apex was found. The minimum diameter of the root canal was measured mesiodistally, and the maximum diameter was measured buccolingually. Only teeth with a ratio of the maximum to the minimum diameter of more than 2 were selected for further investigation. The mean diameter ratio (maximum divided by minimum cross-sectional distance) in the selected sample was 3.8. Subsequently, teeth were mounted on scanning electron microscopy stubs, accessed by using high-speed diamond burs, and patency of the coronal canal was confirmed. Pre-enlargement restricted to the coronal canal third was accomplished with Gates Glidden burs (Dentsply Maillefer, Ballaigues, Switzerland). Subsequently, canal lengths and apical patency were determined with size #10 K-files (Dentsply Maillefer) and radiographs; working lengths were set 1 mm shorter than the radiographic apex. A glide path was confirmed at least to a size #20 K-file.

Root Canal Instrumentation with the SAF

The SAF was operated by using a trans-line (in-and-out) vibrating handpiece (GENTLEpower; KaVo, Bieberach a. d. Riß, Germany) combined with a RDT3 head (ReDent-Nova) (16) at a frequency of 83.3 Hz and amplitude of 0.4 mm. This movement combined with intimate contact along the entire circumference and length of the canal and the slightly rough surface of the file removes a layer of dentin with a filing motion. The hollow design allows for continuous irrigation throughout the procedure. A special irrigation device (VATEA; ReDent-Nova) was connected to the irrigation hub on the file and provided flow of the irrigant (3% NaOCl) at a flow rate of 5 mL/min.

An SAF 1.5 mm was inserted into each distal canal while vibrating and was delicately advanced apically with an intermittent in-and-out hand movement of about 5-mm amplitude until it reached the predetermined working length. Each SAF was operated for 4 minutes per canal with continuous irrigation (16); preparations were done by a general practitioner who had been specifically trained with the SAF instrument. The clinician had also prepared canals with the SAF in maxillary incisors and molars in earlier studies (20).

The clinician was not allowed to see the virtual models of reconstructed teeth before preparing the root canals and during the course of the treatment. This was done to avoid bias by an attempt to manually direct the preparation instrument into any potentially uninstrumented areas.

Evaluation

Virtual root canal models were reconstructed on the basis of MCT scans and superimposed with a precision of better than 1 voxel. Precise repositioning of pre-preparation and various post-preparation images was ensured by a combination of a custom-made mounting device and a software-controlled iterative superimposition algorithm (19, 21, 22); the resulting color-coded root canal models (green indicates preoperative, red indicates postoperative canal surfaces) enabled quantitative comparison of the matched root canals before and after shaping. From individual canal models, canal volumes up to the level of the cementoenamel junction (CEJ) as well as in the apical 4 mm were determined by using custom-made software (IPL; Scanco Medical) as described previously (19).

Increases in volume and surface area were calculated by subtracting the scores for the treated canals from those recorded for the untreated counterparts. Matched images of the surface areas of the canals before and after preparation were examined to evaluate the amount of uninstrumented area. This parameter was expressed as a percentage of the number of static voxel surface to the total number of surface voxels. The cross-sectional appearance, round or more ribbon-shaped, was expressed as the structure model index (SMI). This stereological index varies from 1 (parallel plates) to 4 (perfect ball) and was described earlier in more detail (21). Canal transportation was assessed from centers of gravity that were calculated for each slice and connected along the z-axis with a fitted line. Mean transportation scores were then calculated by comparing the centers of gravity before and after treatment for the apical, middle, and coronal thirds of the canals.

Comparison Data and Statistical Analysis

A data set from a previously published study (23) done with the same experimental design was selected to compare the present results. Specifically, the data used refer to group PT/2, in which shaping with ProTaper (Dentsply Tulsa Dental, Tulsa, OK) was done, considering buccal and oral aspects each as 2 individual canals. Normality assumptions in both data sets were verified, and therefore data were reported as means ± standard deviation (SD). Original voxel volume in this data set was 8×10^{-6} mm^3; volume data were rounded to the nearest 1/100 mm^3, and area data were reported to the nearest 1/100 mm^2.

Data for prepared canal surface area were presented as percentages relative to preoperative canal surface areas, and canal transportation was rounded to the nearest 1/100 mm distance. For comparison, untreated canal surface scores in the present study were recalculated for 34-μm resolution, because this resolution had been used in a previous study (23).

Regression analysis was used to correlate canal dimension with the amount of untreated surface and preoperative SMI, respectively. Because normality assumptions were verified, means were compared by using one-way as well as repeated-measures analyses of variance (ANOVAs), followed by Bonferroni/Dunn tests for post hoc comparisons or paired t tests; the level of statistical significance was set at $\alpha = 0.05$.

Results

SAF Preparation

Distal canals included in the present study had long oval cross sections, as indicated by an SMI, a three-dimensional measure for cross-sectional "flatness," ranging from 1.3–2.6. Volumes and areas ranged from 5–13.5 mm^3 and from 33.5–60.3 mm^2, respectively (Table 1). Canal preparation with the SAF led to enlarged canal shapes with no evidence of preparation errors (Fig. 1). No SAF instrument fractured during the course of this study; on the basis of red-green color-

TABLE 1. Morphometric Data (Means ± SD, n = 20) for Distal Root Canals in Mandibular Molars before Preparation with the SAF and NiTi Rotaries*

	SAF (20 μm)	SAF (34 μm)	PT/2*
Volume (mm^3)	7.73 ± 2.13	7.69 ± 2.14	7.23 ± 3.23
Area (mm^2)	42.83 ± 8.14	41.82 ± 7.9	37.52 ± 8.32
SMI (units)	1.98 ± 0.35	2.03 ± 0.30	1.98 ± 0.42
Diameter ratio	3.80 ± 1.24	3.80 ± 1.24	3.90 ± 1.54

*ProTaper group PT/2, data from reference 23.

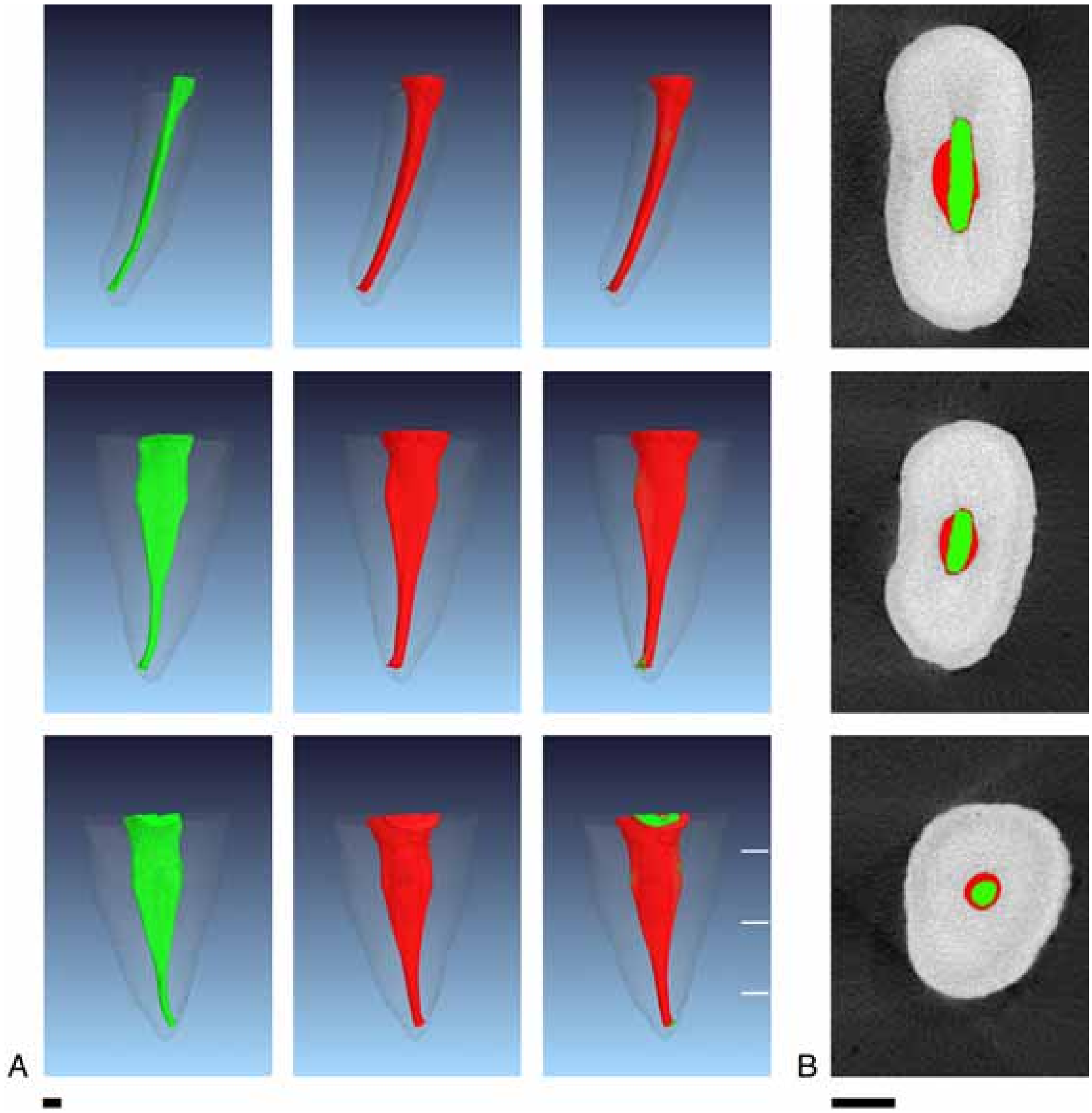

Figure 1. Representative example of MCT data of distal canals in mandibular molars, initially (left column) and prepared with the SAF (2 middle columns). Preparation time was 4 minutes; length bars 1 mm. (*A*) Three-dimensional views from the buccal, distal, and mesial in the top, middle, and bottom rows, respectively. Green area is unprepared; red area is prepared. (*B*) Cross sections at the levels indicated in (*A*). Note that unprepared canal is completely enclosed by prepared shape, and that Gates Glidden use led to a rounded shape in the coronal section.

coded superimposed images, shapes were judged satisfactory, with evidence of circular dentin removal in most cross sections (Fig. 1).

Shaping with an SAF for 4 minutes resulted in significantly increased volumes and surface areas ($P < .001$); dentin removal in individual canals varied between 2.7 and 9.6 mm^3, with a mean of 4.84 $\pm$ 1.73 mm^3 (Table 2). Canal surface areas increased by 3.34 $\pm$ 1.73 mm^2.

The SMI showed a small but significant increase to 2.71 $\pm$ 0.30 ($P < .05$). There was no significant correlation between SMI scores and amounts of untreated canal surface ($r^2 = 0.001$).

Mechanically untreated canal areas overall ranged from 6.7%–44%. Mean untreated canal surface was 23.4% $\pm$ 8.9% for the whole canal length for the apical; correspondingly in the apical 4 mm, 40.1% $\pm$ 13.4% canal surface was counted as untreated.

Mean canal transportations in coronal, middle, and apical canal thirds were 106 $\pm$ 50, 64 $\pm$ 36, and 81 $\pm$ 49 μm, respectively. Canal transportation of 150 μm or more was noted in 8 of 60 root sections assessed, the majority of which was found in the coronal root canal third. Furthermore, mean canal transportation was larger in the coronal third compared with the middle third ($P < .01$).

Comparison to NiTi Rotary Preparation

To facilitate direct comparisons, all data were recalculated with 34-μm resolution. This resulted in slight changes in canal volume, area, and SMI ($\sim$0.5%–2%) but in larger amounts of untreated surface when 34-μm resolution was chosen (Table 2). Mean scores describing preoperative canal morphology for specimens included in the present experiment were statistically similar to those in an earlier study (23) on rotary preparation of long oval root canals in mandibular molars (Table 1).

Comparing the 2 shaping techniques, canal enlargement was significantly more pronounced with the SAF ($P < .002$), and changes in SMI were similar ($P = .176$). However, SAF preparation resulted in significantly less untreated surface for both the full canal length ($P < .001$) as well as the apical 4 mm ($P < .05$) (Table 2).

Discussion

The main aim of this third study in a series was to assess, by using the novel SAF, the preparation of root canals with long oval cross section, on the basis of MCT reconstructions. Distal root canals in

TABLE 2. Quantitative Assessment of Preparation Effects (Means ± SD) for Distal Canals in Mandibular Molars Prepared with the SAF (n = 20) or with NiTi Rotaries (n = 12)

	SAF (20 μm)	SAF (34 μm)	PT/2*
Δ Volume (mm^3)	4.84 ± 1.73	4.90 ± 1.77	2.43 ± 1.13
Δ Area (mm^2)	3.34 ± 1.73	3.99 ± 1.75	ND
Δ SMI (units)	0.74 ± 0.17	0.66 ± 0.12	0.57 ± 0.26
Untreated surface (%)	23.5 ± 8.9	37.4 ± 11.9	66.1 ± 15.3

Data for SAF preparation are presented for the original resolution and recalculated.

ND, not determined.

*ProTaper group PT/2, data from reference 23.

mandibular molars represented an adequate model for this experiment, and the presented data suggest that preparation of non-round canals with the SAF can be done safely and effectively.

This study can be directly compared with earlier material that used the same experimental setup and rotary NiTi instruments. The MCT methodology has been used earlier in studies detailing preparation outcomes with various rotary instruments in maxillary molars. In that tooth group, shaping outcomes appeared to be correlated with preoperative anatomy determined by canal volume (15, 19). However, long oval cross sections constitute a different challenge in mandibular molars.

The number of canals included in the present study (n = 20) is higher than in the earlier material (n = 10 and 12 per group, respectively) (15, 23), and very stringent inclusion criteria were applied in selecting long oval canals; therefore, the demonstrated effect of canal preparation strategy on shaping outcomes appears to be robust.

Earlier studies (8, 13, 24) used destructive two-dimensional methods to determine the amount of prepared surface. With that technique Weiger et al (13) showed that when any amount of preparation was included, between 44% and 68% of the canal surface was unprepared in long oval canals. Similarly, when preparing to an apical size #40 with Hedström files EndoWave (Morita, Osaka, Japan) or AET (Ultradent, South Jordan, UT), Taha et al (25) found between 0% and 79% untreated canal wall in oval canals.

The MCT methodology used in the present study describes the three-dimensional removal of canal wall dentin by the change in surface voxels, requiring on average the preparation of 20 and 34 μm, respectively, dentin to register as prepared surface. A major question addressed with MCT studies is the amount of unprepared surface. The software used in the present study, described in more detail earlier (21, 22), counts a surface voxel as belonging to any given structure when the full voxel belongs to it. Therefore, to be counted as treated, at least 1 full voxel has to be registered as removed from the preoperative canal model after superimposition. In other words, it might very well be the case that a sub-voxel amount of dentin is being shaved off canal wall (the walls were "touched"), and no canal wall preparation is registered.

The finer resolution originally used resulted in higher amounts of prepared surface (~14%) before a recalculation to 34-μm resolution was performed to facilitate direct comparison with rotary instrumentation. The amount of untreated canal surface after SAF preparation was still significantly lower than after rotary instrumentation. Moreover, compared with other studies done with rotaries on rounder maxillary molar canals (15, 19), unprepared areas in mandibular molars in the present study were similar when the SAF was used, indicating a particular advantage of this instrument in shaping long oval canals.

Root canal disinfection appears to be critical for endodontic outcomes (26); eradication of microorganisms occurs as a combination of mechanical preparation (27) and irrigation (28). Irrigation alone is not always effective (29), and mechanical disinfection, related to removal of a layer of infected dentin, is required (30). Continuous irrigation and a homogenous cutting action of the SAF have been shown to lead to smear layer–free and clean canal surfaces (31). Moreover, a recent study demonstrated a significantly more effective disinfection of oval canals *in vitro* with the SAF compared with rotary preparation to a size #40 .04 (32). However, it has not yet been demonstrated that apical irrigant flow and mechanical action of the SAF against canal will predictably remove biofilm in the apical root canal third.

Preparation safety was another factor assessed in the current study. Canal transportation typically was below 100 μm on average and was in the same range as that seen for rotary instrumentation in maxillary molars (15) and distal canals in mandibular molars (data not shown). Moreover, no instrument fractures were noted in the present study, and there were little changes to the overall canal shape, which was suggested by comparatively small increases of the respective SMI. Taken together with the lack of correlation between treated surface and canal shape, indicators suggest that the SAF respects the initial canal anatomy and creates adequate preparations largely independent of preoperative canal anatomy.

Future studies should address clinical outcomes of cases after SAF preparation. Such clinical studies will require postoperative observation times of 1 year and longer, but it is anticipated that long oval root canals in particular will be advantageously prepared with the SAF. Another important clinical question is how best to obturate canals prepared with the SAF; initial data (33) suggest that lateral compaction resulted in a better obturation quality after SAF preparation compared with rotary instrumentation.

In conclusion, preparation of long oval–shaped root canals in mandibular molars *in vitro* with the SAF was effective and safe. Moreover, shapes generated with the SAF were more complete compared with rotary canal preparation.

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The authors deny any conflicts of interest related to this study.

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Root Canal Preparation of Maxillary Molars With the Self-adjusting File: A Micro-computed Tomography Study

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Abstract

Introduction: The aim of this study was to describe the canal shaping properties of a novel nickel-titanium instrument, the self-adjusting file (SAF), in maxillary molars. **Methods:** Twenty maxillary molars were scanned by using micro–computed tomography at 20-μm resolution. Canals were shaped with the SAF, which was operated with continuous irrigation in a handpiece that provided an in-and-out vibrating movement. Changes in canal volumes, surface areas, and cross-sectional geometry were compared with preoperative values. Canal transportation and the fraction of unprepared canal surface area were also determined. Data were normally distributed and compared by analyses of variance. **Results:** Preoperatively, mean canal volumes were 2.88 $\pm$ 1.32, 1.50 $\pm$ 0.99, and 4.30 $\pm$ 1.89 mm^3 for mesiobuccal (MB), distobuccal (DB), and palatal (P) canals, respectively; these values were statistically similar to earlier studies with the same protocol. Volumes and surface areas increased significantly in MB, DB, and P canals; mean canal transportation scores in the apical and middle root canal thirds ranged between 31 and 89 μm. Mean unprepared surfaces were 25.8% $\pm$ 12.4%, 22.1% $\pm$12.0%, and 25.2% $\pm$ 11.3% in MB, DB, and P canals, respectively ($P > .05$) when assessed at high resolution. **Conclusions:** By using SAF instruments *in vitro*, canals in maxillary molars were homogenously and circumferentially prepared with little canal transportation. *(J Endod 2011;37:53–57)*

Key Words

Micro-computed tomography, nickel-titanium instruments, root canal preparation, self-adjusting file

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Cleaning and shaping of root canals successfully require the presence of irrigation solutions that can only be applied to the apical root canal third after enlargement with instruments (1–4). Nickel-titanium (NiTi) rotary instruments have become an important adjunct for root canal shaping, and outcomes with these instruments are fairly predictable (5). However, rotary instruments perform comparably poorly in long-oval canals such as distal canals in lower molars, specifically because they do not mechanically prepare 60% or more canal surface under these conditions (6).

Very recently a new concept, the so-called self-adjusting file (SAF), has emerged that might allow uniform dentin removal along the perimeter of oval canals. Root canal preparation with this file has been quantitatively described only in anterior teeth (7) but not in molar root canals.

The effects of root canal shaping were assessed, besides other approaches, from double-exposure radiographs (8), from cross sections by using the Bramante technique (9), and more recently by using micro–computed tomography (MCT) data (10). The latter technique allows nondestructive quantitative analyses of variables such as volume, surface areas, cross-sectional shape, taper, and the fraction of affected surface (11).

Earlier studies had indicated that differences in canal anatomy between palatal (P), mesiobuccal (MB), and distobuccal (DB) canals would play a significant role for shaping outcomes (12). More ribbon-shaped or flat canals such as the MB canal would have more unprepared canal area; moreover, on average, smaller more curved MB canals would have greater canal transportation than P canals.

On the basis of the fact that the SAF is capable of addressing non-round canal cross sections, we hypothesized that various canals in maxillary molars can be prepared to similar outcomes with respect to canal transportation and amount of prepared surface.

Studies based on MCT done in our laboratory during the last decade provided data on preparation effects for hand and rotary instruments in maxillary molars (10, 12–14). Therefore, the aim of this study was to describe the canal shaping properties of the SAF in maxillary molars.

Materials and Methods

Selection of Teeth

From teeth that had been extracted for reasons unrelated to the current study, 20 human maxillary molars were collected and stored in 0.1% thymol solution at 4°C until further use. Teeth had mature apices and were free of fractures and artificial alterations. They were mounted on scanning electron microscopy stubs and then scanned in a desktop MCT unit at an isotropic resolution of 20 μm (μCT 40; Scanco Medical, Brüttisellen, Switzerland) by using previously established methods (10, 15). Care was taken to specifically select teeth that did not have a distinct fourth canal orifice so as to include a buccolingually flat mesiobuccal canal, as judged from a preoperative MCT scan in low resolution. Teeth were then accessed by using high-speed diamond burs, and patency of the coronal canal was confirmed. Coronal flaring was accomplished with #2 Gates Glidden burs (Dentsply Maillefer, Ballaigues, Switzerland) placed to 2–3 mm below the cemento-enamel junction. Subsequently, canal lengths and patency were determined with size 10 K-files (Dentsply Maillefer) and radiographs; working lengths (WLs) were set 1 mm shorter than the radiographic apex. Each canal was then probed with #20 K-file. If it reached the WL, no further preparation was done. If the canal was narrower than that, it was prepared until #20 K-file could freely reach the WL to provide a glide path.

Root Canal Instrumentation with the SAF

The SAF was operated by using a trans-line (in-and-out) vibrating handpiece (GENTLEpower; KaVo, Bieberach a. d. Riß, Germany, combined with a RDT3 head, ReDent Nova, Ra'anana, Israel) (16) at a frequency of 83.3 Hz (5000 movements per minute) and an amplitude of 0.4 mm. This movement combined with intimate contact along the entire circumference and length of the canal and the slightly rough surface of the file removed a layer of dentin with a filing motion. The hollow design allowed for continuous irrigation throughout the procedure. A special irrigation device (VATEA; ReDent Nova) was connected to the irrigation hub on the file and provided flow of the irrigant (3% NaOCl) at a flow rate of 5 mL/min.

An SAF of 1.5 mm was inserted into each canal while vibrating and delicately advanced apically with an intermittent in-and-out hand movement of 5-mm amplitude until it reached the predetermined WL. Each SAF was operated for 4 minutes per canal with continuous irrigation (16); all preparations were done by a single general practitioner who had been specifically trained with the SAF instrument. Each maxillary molar was prepared with a new SAF, and canals were instrumented in a random sequence, ie, an equal number of MB, DB, and P canals was instrumented as the first canal with a new file.

The clinician was not allowed to see the virtual models of reconstructed teeth before preparing the root canals and during the course of the treatment. This was done to avoid bias by an attempt to manually direct the preparation instrument into any potentially uninstrumented area.

Evaluation

Virtual root canal models were reconstructed on the basis of MCT scans and superimposed with a precision of better than 1 voxel. Precise repositioning of pre-preparation and various post-preparation images was ensured by a combination of a custom-made mounting device and a software-controlled iterative superimposition algorithm (11, 15, 17); the resulting color-coded root canal models (green indicates preoperative, red postoperative canal surfaces) enabled qualitative comparison of the matched root canals before and after shaping.

Original data sets with 20-μm resolution were reformatted with a resolution of 34 μm to facilitate direct comparison with earlier studies by using the same experimental setup (10, 12), resulting in a total of 80 MCT data sets with 2 different resolutions (20 μm and 34 μm). For individual canals, evaluation was done for the full canal length up to the level of the cemento-enamel junction as well as in the apical 4 mm by using custom-made software (IPL; Scanco Medical) as described previously (15). The cross-sectional appearance, round or more ribbon-shaped, was expressed as the structure model index (SMI). This stereological index varies from 1 (parallel plates) to 4 (perfect ball) and was described earlier in detail (11).

Increases in volumes and surface areas were calculated by subtracting the scores for the treated canals from those recorded for the untreated counterparts. Matched images of the surface areas of the canals, before and after preparation, were examined to quantify the amount of uninstrumented area. This parameter was expressed as a percentage of the number of static surface voxels to the total number of surface voxels. As detailed earlier (11), canal transportation was assessed from "centers of gravity" that were calculated for each slice and connected along the z-axis with a fitted line. Mean transportation scores were then calculated by comparing the centers of gravity before and after treatment for the apical, mid, and coronal thirds of the canals.

Statistical Analysis

Normality assumptions were verified, and therefore data are reported as mean ± standard deviation. Original voxel volume in this data set was 8×10^{-6} mm^3; volume data are rounded to the nearest 1/100 mm^3, area data are reported to the nearest 1/100 mm^2, data for prepared canal surface area are presented as percentages relative to preoperative canal surface areas, and canal transportation is reported to the nearest in 1/mm distance.

Because normality assumptions could be verified, means were compared by using one-way and two-way analyses of variance (ANOVAs) with Bonferroni/Dunn tests for post hoc comparison; the level of statistical significance was set at $\alpha = 0.05$.

Results

Preoperatively, mean canal volumes ranged from 1.50–4.30 mm^3 in maxillary molar canals (Table 1). Reformatting the data set to a resolution of 34 μm resulted in, on average, 0.07 ± 0.04 mm^3 smaller volumes. Mean initial canal volumes in the apical 4 mm were 0.69, 0.31, and 0.91 mm^3 in MB, DB, and P canals, respectively ($P < .01$). Canal cross sections were rounder in DB and P canals compared with MB canals ($P < .01$, Table 1). Both preoperative volumes and SMI scores were statistically similar compared with samples of maxillary molars used in earlier studies (10, 12–14).

Preoperatively, maxillary molar root canals presented with various curves and accessory canals. Most accessory canals remained visible in postoperative canal models (Fig. 1*A*). Canal cross sections, as assessed by the SMI, varied as well, with significantly flatter canals mesiobuccally (Table 1). Overall, canal preparation of root canals in maxillary molars with the SAF resulted in adequate canal shapes with no major shaping errors. In particular, no SAF fractured during the course of the study. On the basis of superimposed red-green coded surface areas (Fig. 1*A*), overall shapes were satisfactory, with similar amounts of dentin removed around the perimeter in most cross sections (Fig. 1*A*) and overall fully prepared canal surface areas.

Preparing with the SAF for 4 minutes resulted in mean dentin removal ranging from 2.00–2.87 mm^3; this represented significant volume changes compared with preoperative data ($P < .01$). Differences in volume increase were small but significantly different when comparing the 3 canal types investigated (Table 1). Increases in SMI were only significant for MB canals; 8 of 60 canals had SMI increases of 1 or more, all of which were MB canals. Slice-by-slice observation indicated that rounding of MB canals occurred mostly in the coronal third.

Mechanically untreated canal areas, calculated by using superimposed MCT data sets (Fig. 1), were 25.8% ± 12.4%, 22.1% ± 12.0%,

TABLE 1. Morphometric Data (mean ± standard deviation, n = 20 each) and Their Changes for Root Canals in Maxillary Molars and Changes after Preparation with SAF

	Mesiobuccal	Distobuccal	Palatal
Volume (mm^3)	2.88 ± 1.32^{ab}	1.50 ± 0.99^{ac}	4.30 ± 1.89^{bc}
Δ Volume (mm^3)	2.87 ± 1.14^{de}	2.00 ± 0.53^{d}	2.20 ± 0.71^{e}
Area (mm^2)	25.54 ± 8.42^{f}	13.26 ± 4.77^{fg}	23.30 ± 5.20^{g}
Δ Area (mm^2)	4.89 ± 1.82^{h}	7.13 ± 2.41^{hi}	5.31 ± 2.00^{i}
SMI (units)	2.11 ± 0.47^{jk}	3.14 ± 0.23^{j}	3.29 ± 0.18^{k}
Δ SMI (units)	0.85 ± 0.31^{lm}	0.19 ± 0.18^{l}	0.11 ± 0.11^{m}

SAF, self-adjusting file; SMI, structure model index.

Significantly different results among root types are indicated by the same superscripted letter ($P < .05$).

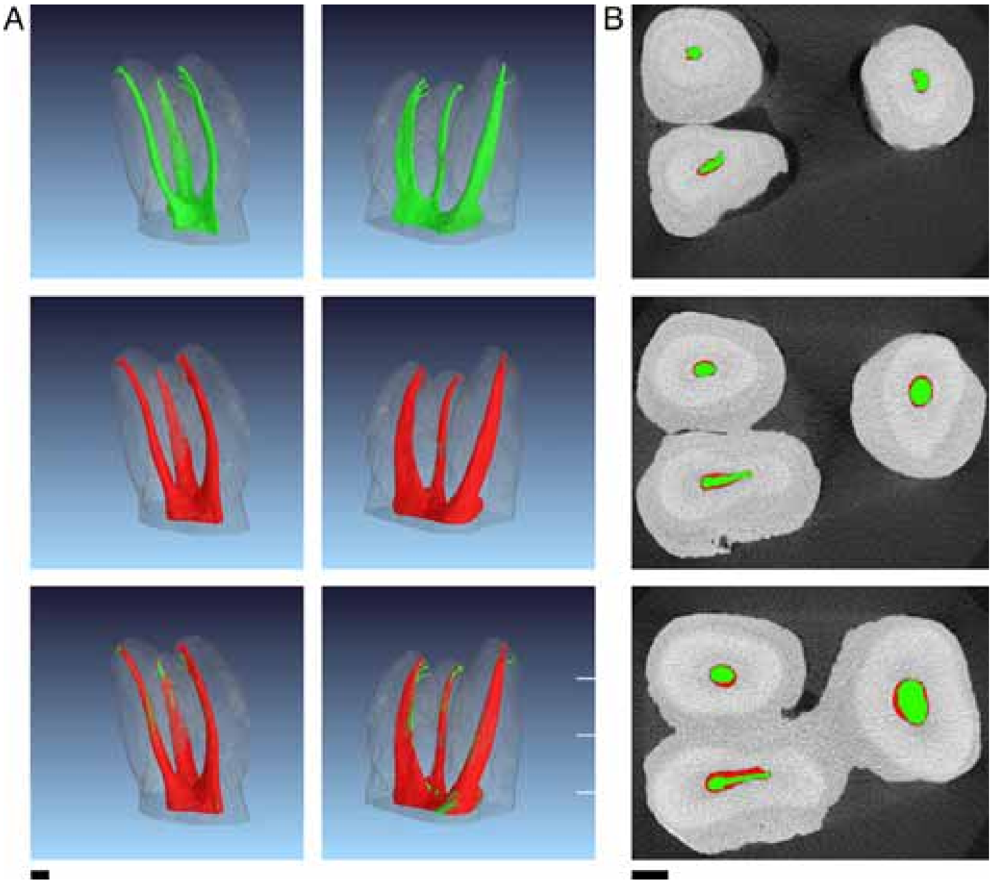

Figure 1. Representative example of MCT data of maxillary molar root canals prepared with SAF. Preparation time was 4 minutes; black length bars are 1 mm. Note accessory canals that are visible in postoperative images. (*A*) Preoperative, postoperative, and superimposed reconstructions (from top to bottom) and in clinical and angled views (left and right columns). (*B*) Cross sections in the apical, middle, and coronal root canal thirds showing the amount of removed dentin in the canal periphery. Green and red areas are preoperative and postoperative cross sections; white lines in (*A*) indicate section levels.

and 25.2% ± 11.3% for MB, DB, and P canals, respectively (Table 2); untreated canal areas were not statistically different when comparing the 3 canal types ($P > .05$). When restricted to the apical 4 mm, uninstrumented canal areas ranged from 28.8% in DB canals to 47.4% in P canals. When canal models were reformatted to 34-μm resolution, overall uninstrumented areas were 38.5% (Table 2).

Mean canal transportation ranged from 31–149 μm and was larger in the coronal third compared with the apical and middle canal thirds ($P < .01$, Table 3). Canal transportation was lowest in the palatal canal. Differences between all canal types with respect to canal transportation at the middle and apical levels were significant; however, the individual canal transportation values exceeded 100 μm only in 15 of 120 cases at those 2 levels. No differences were registered when surface areas or canal transportation were recalculated on the basis of 34 μm compared with 20 μm.

Discussion

This study is the second part of a comprehensive, MCT-based evaluation of the shaping potential of a novel root canal preparation instrument, the SAF. Design (16) and various mechanical parameters (18) of this new system have been described in detail previously. The first MCT study of the current series detailed shaping in anterior teeth and dentin removal over time (7). The current report focuses on preparation of maxillary molars with curved canals and various cross sections, for example, round DB canals and ribbon-shaped or flat MB canals.

Teeth selected for this study were statistically similar to teeth used in earlier studies (10, 12–14) on maxillary molars with respect to morphologic parameters such as preoperative canal volume, SMI, and canal curvature.

Dentin removal with the SAF is most effective during the first 2 minutes of use (18). However, additional time might be needed to ensure a full canal wall preparation in some cases; for example, 4 and possibly 5 minutes of activation were required in anterior teeth (7). Preparation with the SAF did not result in obvious preparation errors such as perforation and ledging, with canal transportation values typically below 100 μm for the middle and apical canal sections. The slightly larger canal transportation in the coronal section, particularly in MB canals, could have been possibly caused by Gates Glidden drills in an attempt to facilitate straight-line access. Overall, canal

TABLE 2. Root Canal Surface Area (%) Not Affected by Preparation with SAF (mean ± standard deviation, n = 20 each) for Root Canals in Maxillary Molars

	Mesiobuccal	Distobuccal	Palatal
Unprepared area (20-μm resolution)	25.8 ± 12.4	22.1 ± 12.0	25.2 ± 11.3
Unprepared area (34-μm resolution)	37.8 ± 13.0	35.6 ± 13.6	42.1 ± 12.3

There were no significantly different results among root types.

TABLE 3. Mean (± standard deviation, n = 20 each) Canal Transportation (mm) and Range Determined for Coronal, Middle, and Apical Root Canal Thirds after Preparation with SAF

	Mesiobuccal	Distobuccal	Palatal
Coronal 1/3	113 ± 37 (60–189)[ab]	149 ± 58 (63–295)[bc]	65 ± 24 (31–113)[ac]
Middle 1/3	59 ± 27 (20–138)[de]	89 ± 45 (29–174)[ef]	31 ± 15 (10–62)[df]
Apical 1/3	78 ± 30 (33–146)[g]	81 ± 34 (22–18)[h]	47 ± 21 (22–92)[gh]

[abcdefgh]Significantly different results within levels are indicated by ($P < .05$).

transportation is likely a cumulated effect of coronal flaring, glide path preparation, and the action of the SAF. Similarly, adding instruments for further apical enlargement tends to increase canal transportation, as shown in an MCT-based pilot study with sequential scanning (19).

An earlier study with the same experimental setup had shown overall canal transportation scores of 123.7, 89.8, and 97.7 μm for the coronal, middle, and apical thirds, respectively, after preparation with NiTi rotary instruments or K-files (10). These scores and also those described for MB, DB, and P canals shaped with ProTaper (12) and FlexMaster (13) indicate larger canal transportation for rotary instruments than for the SAF in maxillary molar canals.

The present study used MCT to evaluate canal preparation with the SAF. MCT evaluation was introduced to experimental endodontics more than a decade ago (11); it has been used to assess, in a quantitative and three-dimensional approach, the performance of various canal instrumentation techniques (10, 15, 20–22). The cited studies vary with regard to the type of the MCT systems used and their spatial resolution as well as in the software used for evaluation. However, a direct comparison between existing MCT data regarding NiTi rotary instruments generated by the authors (10, 12–14) and the present study was made possible with the recalculation of the data in a 34-μm resolution, which had been used earlier. The reformatting did not result in significant changes for canal volume, surface area, or canal transportation data.

A potential limitation of this study as in the majority of MCT-based studies is the relatively small sample size of 60 canals in total. It is, however, larger compared with earlier (10, 12, 21) and similar to more recent (22) MCT-based studies.

An obvious strength of the present nondestructive approach was that it permitted repeated evaluation before and after canal preparation. Moreover, quantitative data for morphologic parameters and canal transportation were obtained.

As in the previous study on the use of the SAF in maxillary incisors (7), cases with accessory canals were present in this study sample, and larger accessory canals might contribute relevantly to the amount of unprepared surface. Therefore, manual editing was used to eliminate such accessory canals from the evaluation.

A major question addressed with MCT studies is the amount of unprepared surface. The software used in the present study, described in more detail earlier (11, 17), counts a surface voxel as belonging to any given structure when the full voxel belongs to it. Therefore, to be counted as "treated," at least one full voxel has to be registered as removed from the preoperative canal model after superimposition. In other words, it might very well be the case that a sub-voxel amount of dentin is being shaved off canal wall (the walls were "touched"), and no canal wall preparation is registered. In fact, our earlier study on the effect of SAF preparation on maxillary incisors (7) indicated that 5 minutes of shaping with the 2.0-mm SAF resulted in 91.4% treated surface, but only 56.6% surface had more than 100 μm dentin shaved off.

The present study, on the basis of 20-μm resolution, demonstrates overall unaffected canal area of 25.2%. However, a recalculation to 34-μm resolution results in overall 38.5% unaffected area. One earlier study on canals prepared to apical sizes #40 (MB, DB) and #45 (P) (10) indicated similar amounts of overall unprepared surface as in the present study (38.1%). However, rotary preparation of flat MB canals in maxillary molars in earlier studies (12, 13) resulted in 43.0% and 47.4% mean unaffected areas, respectively, which is higher than the scores in the present study.

Taken together, cross sections from various slices (Fig. 1) and low scores for unaffected canal surface, in particular for flat canals, suggest that canal preparation with the SAF does indeed result in homogenous preparation and circumferential removal of a layer of hard tissue.

In the present study, there were no significant differences in respect to affected canal surface among the canal types. Nevertheless, when the same SAF size is used (eg, 1.5 mm) for multiple canals in the same tooth, it might be prudent to increase preparation time for larger canal diameters. This will compensate for lesser forces of the cutting SAF elements against canal walls (18) in larger canals such as the palatal or the distal canal in molars. Alternatively, it might be advisable to instrument large canals before any smaller canals, on the basis of the tactile feedback during confirmation of the glide path.

Preparation with the SAF resulted in less SMI changes in P and DB canals compared with earlier results (10); slice-by-slice evaluation indicated that the increase in cross-sectional roundness in coronal canal third of MB canals, as opposed to retaining the buccolingual flat shape, could be explained by the use of Gates Glidden burs. A recent study (22) detailed SMI scores after rotary preparation in the apical 1 mm of shaped canal and found scores of 2.63–2.83 for a sample of maxillary and mandibular molars; this is similar to findings in the present study for the apical 4 mm (data not shown) and might indicate that apical canal sections might be prepared round with the SAF.

Rotary NiTi root canal files have been linked to 3%–5% incidence of intracanal breakage (23); although a retained instrument fragment per se might not significantly alter healing outcomes of periapical lesions, it is preferable to have no impediment to disinfection inside canals. In the present study we did not observe any SAF breakage with retained fragments.

Eradication of microorganisms, a critical step for endodontic outcomes (24), is the result of a combination of mechanical preparation (25) and irrigation (26). Irrigation alone is not always effective (27), and mechanical action of instruments on canal walls, including removal of infected dentin, might be needed. In fact, a recent scanning electron microscopic study suggested that preparation with the SAF leaves very clean dentin walls, probably as a result of concurrent irrigation possible with this system (6). Moreover, accessory canals remained visible in postoperative canal models after SAF preparation, suggesting little or no deposition of dentin shavings under the conditions of the current study (17).

The preparation of the most apical canal section remains a challenge. In the present study, mechanical preparation with the SAF resulted in limited prepared surface. Hence, sufficient deposition of disinfecting irrigation solutions remains important. Antibacterial efficacy of canal surface preparation was not directly determined in the present study. Mechanical preparation per se might affect bacterial biofilms (28) rather than only microorganisms in their planktonic state.

With further improvement in hardware and software, it might be possible in the future to directly determine the amount of biofilm removed from canal surfaces on the basis of MCT-based experiments. Furthermore, it is presently unknown whether canal preparation with the SAF and in particular its potential to debride canal walls better will lead to improved clinical outcomes, but clinical studies are underway to address this question. Another important clinical question is how best to obturate canals prepared with the SAF; initial data (29) suggest that lateral compaction resulted in better obturation quality after SAF preparation compared with rotary instrumentation.

In conclusion, by using SAF instruments *in vitro*, canals in maxillary molars were homogenously and circumferentially prepared with little canal transportation or other procedural errors.

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Root Canal Preparation with a Novel Nickel-Titanium Instrument Evaluated with Micro-computed Tomography: Canal Surface Preparation over Time

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Abstract

Introduction: The aim of this part of an ongoing study was to describe the dentin removal ability of a novel nickel-titanium instrument, the self-adjusting file (SAF), by using micro–computed tomography. **Methods:** Twenty maxillary incisors were scanned preoperatively at 20-μm resolution and postoperatively after up to 6 minutes of preparation with an SAF with 1.5-mm or 2-mm diameter. SAFs were operated with continuous irrigation in a handpiece that provided an oscillating, in-and-out movement. Changes in canal volume compared with preoperative values as well as unprepared canal surface area were determined. Data were normally distributed and compared by analysis of variance and regression analyses. **Results:** Preoperatively canal volumes were statistically similar in both groups (9.86 $\pm$ 3.97 mm^3 and 9.80 $\pm$ 2.67 mm^3). Volumes increased during preparation to 13.58 $\pm$ 3.85 mm^3 (after 6 minutes with SAF 1.5 mm) and 16.43 $\pm$ 3.64 mm^3 (after 5 minutes with SAF 2.0 mm), and overall canal shapes were adequate. Unprepared canal surface area decreased from 63.0% $\pm$ 15.1% (2 minutes with SAF 1.5 mm) to 8.6% $\pm$ 4.1% (5 minutes with SAF 2.0 mm). **Conclusions:** Preparation of straight root canals in maxillary anterior teeth left little canal surface uninstrumented after shaping with the SAF. The time-frame of clinical application will depend on the amount of desired dentin removal and done with an SAF selected on the basis of apical gauging. *(J Endod 2010;36:1068–1072)*

Key Words

Micro–computed tomography, nickel-titanium instruments, root canal preparation, self-adjusting file

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The purpose of root canal preparation in the context of endodontic therapy is to (i) shape the canals to an adequate geometry and (ii) clean the canal system by promoting access for disinfection solutions; this strategy has been termed chemomechanical canal preparation (1). Importantly, mechanical canal preparation supports disinfection via disturbing biofilms that adhere to canal surfaces (2, 3) and, second, by removing a layer of infected dentin (4, 5).

Root canal preparation should be done with little or no shaping errors such as zipping or perforation. Many current preparation techniques, including the use of engine-driven nickel-titanium (NiTi) instruments, promote adequate canal shapes (6). Although rotary systems do prepare many canals without major procedural errors, they do not address canal types with long-oval or flat cross sections. Typically radicular walls of such canals will be incompletely prepared and buccal and lingual extensions uncleaned (7).

Various approaches have been described in the literature pertaining to testing of root canal preparation instruments. During the last decade high-resolution micro–computed tomography (MCT) has emerged as a powerful approach to study canal preparation techniques (8–11). This analytical tool permits detailed and nondestructive evaluation of root canal geometry. In addition, the approach yields quantitative data detailing the performance of any given root canal shaping instrument. With MCT, it has been shown that the amount of mechanically prepared canal surface and perhaps equally disturbed biofilm in main root canal, depending on canal type, is frequently below 60% of the canal surface (10, 12).

A newly developed self-adjusting file (SAF) (ReDent-Nova, Ra'anana, Israel) was designed to address the shortcomings of traditional rotary files by adjusting itself to the canal cross section (13). This instrument consists of a compressible opened NiTi tube that, on placement into a root canal, will exert pressure against the canal wall (Fig. 1, insert). The SAF is used in an in-and-out motion powered by a handpiece and under constant irrigation. The canal shaping performance of this novel instrument has not been described at this point in time.

The aim of this study was to detail dentin removal when the SAF is applied to root canals in maxillary anterior teeth. By using MCT, we specifically assessed in anterior teeth the decrease of untreated surface area over time as well as changes in overall and apical dentin volume.

Materials and Methods

Selection of Teeth

From teeth that had been extracted for reasons unrelated to the current study, 50 human maxillary incisors were collected and stored in 0.1% thymol solution at 4°C until further use. Teeth were mounted on scanning electron microscopy stubs and scanned in a desktop MCT unit at an isotropic resolution of 20 μm (μCT 40; Scanco Medical, Brüttisellen, Switzerland) by using previously established methods (10, 12). A total of 20 teeth were then selected on the basis of similar canal volumes and overall canal geometries; they were then accessed by using high-speed diamond burs, and patency of the coronal canal was confirmed. Coronal flaring was accomplished with #2 Gates Glidden burs (Dentsply Maillefer, Ballaigues, Switzerland) placed to 2–3 mm below the cementoenamel junction. Subsequently, canal lengths and patency were determined with size 10 K-files (Dentsply Maillefer) and radiographs;

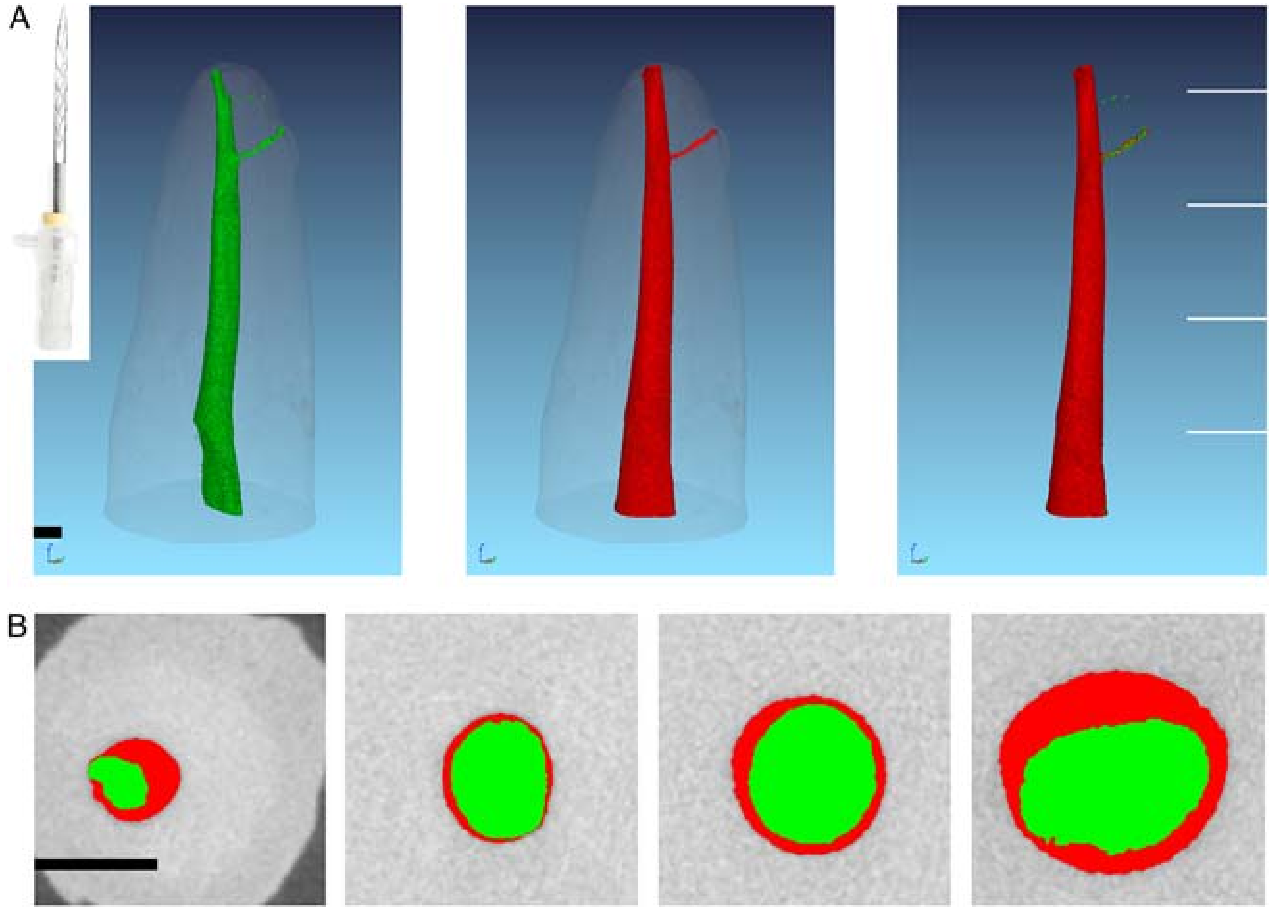

Figure 1. Representative example of MCT data of maxillary anterior root canals prepared with the SAF (inset, A). Preparation time was 5 minutes; note almost complete preparation of canal surface. Black length bars are 1 mm; green and red areas are preoperative and postoperative cross sections, respectively. (*A*) Preoperative, postoperative, and superimposed MCT reconstructions (from left to right) demonstrating a patent lateral canal in the apical 1/3 of the root (volume, 0.033 mm^3). (*B*) Cross sections at 1, 5, 9, and 13 mm coronal of the apex (white lines in *A*) detailing the amount of removed dentin along the canal perimeter.

working lengths were set 1 mm shorter than the radiographic apex. A glide path was confirmed at least to a size #20 K-file; however, apical gauging with increasing sizes of Nitiflex K-files (Dentsply Maillefer) revealed typical apical sizes to be #30 or #35 for the maxillary anteriors included in this study. Specimens were then randomly allocated to 2 groups with n = 10 each. That sample size was based on the following assumptions: an approximated prepared canal surface area for conventional preparation of about 65% ± 15% (14), α error = 0.05, 80% power, and at least 80% ± 5% prepared canal area for the SAF. Surface area preparation assumptions were supported by data from pilot experiments with maxillary anteriors prepared with NiTi rotaries as well as molars prepared with the SAF.

Root Canal Instrumentation with the SAF

The SAF was operated by using a trans-line (in-and-out) vibrating handpiece (GENTLEpower; KaVo, Bieberach a. d. Riß, Germany) combined with a RDT3 head (ReDent-Nova) (13) at a frequency of 83.3 Hz (5000 movements per minute) and an amplitude of 0.4 mm. This movement combined with intimate contact along the entire circumference and length of the canal and the slightly rough surface of the file removes a layer of dentin with a filing motion. The hollow design allows for continuous irrigation throughout the procedure. A special irrigation device (VATEA; ReDent-Nova) was connected to the irrigation hub on the file and provided flow of the irrigant (3% NaOCl) at a flow rate of 5 mL/min.

The SAF was inserted into the canal while vibrating and delicately advanced apically with an intermittent in-and-out hand movement of 5-mm amplitude until it reached the predetermined working length. It was operated with continuous irrigation (13). Canals in both groups were shaped by a single general practitioner, who had been specifically trained with the SAF instrument and participated during a pilot study.

In group 1, canals were prepared with the 1.5-mm diameter SAF; in group 2, canals were prepared with the 2.0-mm SAF. Preparation initially continued for 2 minutes, and teeth were then submitted to a postoperative MCT scan. Similarly, scans were done after 3, 4, 5, and 6 minutes of canal preparation; in group 2 no scans were done after 6 minutes. An individual SAF was assigned to each specimen; therefore, each SAF 1.5 and 2 mm instrument was used for a total of 6 and 5 minutes, respectively. Teeth were kept in containers with thymol solution during transport and scanning.

The clinicians were not allowed to see virtual models of the specimens before and during root canal preparation. This was done to avoid bias by an attempt to manually direct the preparation instrument into any potentially uninstrumented area.

Evaluation

Virtual root canal models were reconstructed on the basis of MCT scans and superimposed with a precision of better than 1 voxel. Precise repositioning of pre-preparation and various postpreparation images was ensured by a combination of a custom-made mounting device and a software-controlled iterative superimposition algorithm (9, 10, 15); the resulting color-coded root canal models (green indicates preoperative, red indicates postoperative canal surfaces) enabled quantitative comparison of the matched root canals before and after shaping.

From individual canal models, canal volumes up to the level of the cementoenamel junction as well as in the apical 4 mm were determined by using custom-made software (IPL; Scanco Medical) as described previously (10). Subsequently, the percentage of unprepared canal surface was assessed for the full canal length and the apical 4 mm. Analyses were done for each postoperative scan for a total of 90 MCT data sets.

With superimposed models and commercially available measurement software (VGStudioMax 2.0; VolumeGraphics, Heidelberg, Germany), canal areas with more than 100 μm dentin removal were determined. To this end, a threshold of 100 μm was preset for the distance measurement tool, and the surface fraction was determined at the end of the canal shaping period.

Statistical Analysis

Voxel volume in this data set was 8×10^{-6} mm^3, and such data are reported as means $\pm$ standard deviations, rounded to the nearest 1/100 mm^3. Data for prepared canal surface area are presented as percentages relative to preoperative canal surface areas. Because normality assumptions were verified, parametric methods were used for comparison; the level of statistical significance was set at $\alpha = 0.05$. Volumes and prepared areas, respectively, were compared with repeated-measures analysis of variance (ANOVA) within groups. The t tests were used for between-group comparisons. A regression analysis was done to correlate the amount of uninstrumented canal surface with the preparation time.

Results

Preoperatively, 7 root canals in maxillary anteriors demonstrated between 1 and 6 accessory canals, mainly in middle and apical root canal thirds, which were large enough to be detected by MCT with the selected resolution (Fig. 1*A*).

Overall, main canals were typically straight and relatively round in cross section (Fig 1*B*, green areas). Postoperative shapes were overall visibly error-free, and no instrument fragments remained in the root canals at the end of the preparation period (Fig. 1), except for one case with a small metal particle that was observed after 5 minutes of shaping. It was no longer present in the subsequent 6-minute MCT scan. Canal shapes were satisfactory, with similar amounts of dentin removed around the perimeter in most cross sections (Fig. 1*B*) and overall fully prepared canal surface areas.

Calculations based on postoperative MCT reconstructions showed a gradual increase in canal size, which was more pronounced after preparation with SAF 2.0 mm. Color-coded superimposed models of preoperative and postoperative MCT data demonstrated an increase in prepared canal surface, shown in red (Fig. 1), with canal preparation over time with both SAF 1.5 and 2.0 mm.

Quantitative assessment of canals assigned to the 2 groups yielded statistically similar canal volumes, with 9.86 $\pm$ 3.97 mm^3 and 9.80 $\pm$ 2.67 mm^3, respectively (Fig. 2, insert). Volume of accessory canals (n = 17) varied between 0.0002 and 0.038 mm^3 and averaged 0.01 $\pm$ 0.01 mm^3. Final canal volumes were 13.58 $\pm$ 3.85 mm^3 (after 6 minutes with SAF 1.5 mm) and 16.43 $\pm$ 3.64 mm^3 (after 5 minutes with SAF 2.0 mm).

Canal volume increased by 3.63 $\pm$ 1.80 mm^3 for SAF 2.0 mm and 1.65 $\pm$ 0.88 mm^3 for SAF 1.5 mm during the first 2 minutes of preparation. This amount was significantly greater ($P < .01$) than during the subsequent 2-minute period in both groups (Fig. 2*A*). Incremental smaller canal volume increases then occurred from minute 3 of activation onward in both groups.

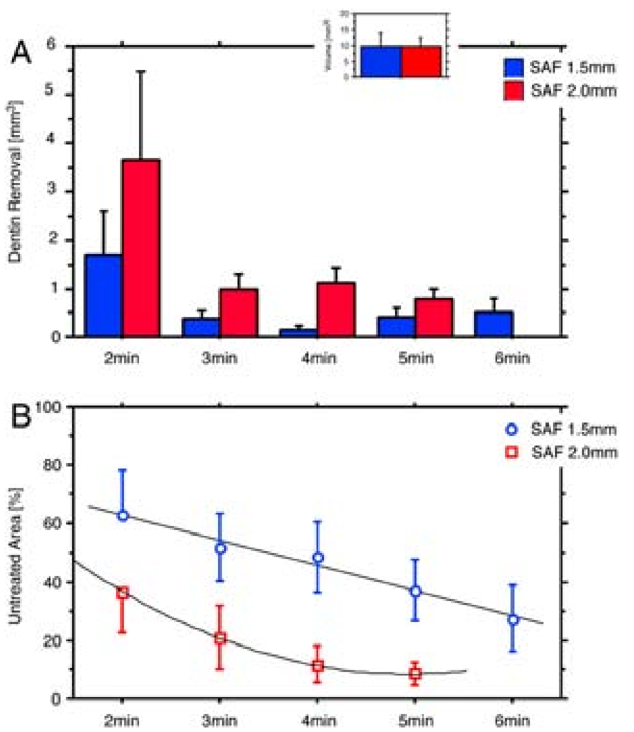

Figure 2. Effect of progressive preparation of root canals with SAF 1.5 mm and 2.0 mm. Initial canal volumes in both groups (n = 10 each) were statistically similar (insert). Preparation was done with 1.5 mm SAF (blue symbols) and 2.0 mm SAF (red symbols). (*A*) Canal volume increase with preparation over time. (*B*) Reduction in uninstrumented canal surface with progressive preparation. Data approximated by linear regression line (blue; untreated area = 80.02–8.59 $\times$ time) and second-order polynomial curve (red; untreated area = 89.31–32.91 $\times$ time + 3.35 $\times$ time^2).

A key variable for MCT assessment of canal preparation is untreated surface area. Overall untreated surface area decreased from 63.0% $\pm$ 15.1% (2 minutes with SAF 1.5 mm) to 8.6% $\pm$ 4.1% (5 minutes with SAF 2.0 mm) (Fig. 2*B*). Similarly, unprepared area in the apical 4 mm decreased from 88.0% $\pm$ 7.1% (2 minutes with SAF 1.5 mm) to 28.6% $\pm$ 12.6% (5 minutes with SAF 2.0 mm).

Regression analysis indicated a linear relationship of the reduction in overall unprepared area over time for SAF 1.5 mm (r^2 = 0.98, P < .0012). Linear regression was first also performed for the SAF 2 mm (r^2 = 0.909, P < .0468). However, a second-order polynomial yielded a better approximation, with an optimum in prepared surface area reached after 5 minutes of preparation (r^2 = 1, P < .0182; Fig. 2*B*).

There was a significant (P < .001) difference in the fraction of prepared surface with greater than 100-μm dentin removal, 23.2% $\pm$ 10.6% for SAF 1.5 mm after 6 minutes and 56.6% $\pm$ 10.3% after 5 minutes of preparation with the larger instrument.

Discussion

This study is a part of a comprehensive, MCT-based evaluation of the shaping potential of a novel root canal preparation instrument, the SAF. The design and mechanical parameters of this new system have been described in detail previously (13, 16). This report focuses on dentin removal over time in maxillary anterior canals and specifically the fraction of prepared surface area. The intention was to give clinicians guidelines as to how long a canal needs to be shaped with the SAF for a desired result. Moreover, information was gained for the selection of SAF 1.5 versus the larger diameter SAF 2.0 mm.

For this study, teeth with straight canals were selected. Such canal anatomy will likely not lead to preparation errors such as canal transportation; therefore, this parameter was not assessed here. However, subsequent studies on mandibular and maxillary molars will address that question, permitting in principle comparison of the SAF performance in curved canals with earlier MCT-based studies (10, 17). Canals in the present study also had larger initial canal volumes than buccal canals in maxillary molars (12), mirrored in gauged apical sizes of #30 or #35 in the majority of the present specimens. Data for canal surface preparation provided here suggest that the SAF 2.0 mm is adequate for such a canal size and might be also selected for palatal canals in maxillary molars that have similar sizes.

According to the presented data and earlier pilot trials (16), the SAF is most effective during the first 2 minutes of use, and hence under the present experimental conditions, the bulk of dentin removal was accomplished during the first 2 minutes of preparation. However, there is about 40% unprepared canal area even with the SAF 2.0 mm at that time. Regression analysis indicated that an optimum of prepared canal surface of more than 90% on average is reached after 5 minutes of activation.

Direct comparison of SAF performance with dentin removal over time by NiTi rotaries is difficult. However, one study with MCT of trenched bone slabs described similar result to what was seen in the present study, a leveling off in cutting ability after 300–400 cycles ($\sim$2 minutes of use in that experiment) (18).

This study is the first to focus on canal preparation with the SAF by using MCT. The latter technique was introduced to experimental endodontics about a decade ago (9); it has been used to assess, in a quantitative and 3-dimensional approach, the performance of current NiTi rotaries (10, 12). A direct comparison between MCT data on NiTi rotaries and the present study is possible; however, one has to keep in mind that resolutions differ from study to study, impacting the potential to detect canal surface preparation. In a pilot study maxillary anteriors were scanned at the same resolution as in the present study; preparation with ProTaper (Dentsply Maillefer) used to an apical size of #50 (F5) resulted in mean unprepared canal areas of about 57%. Moreover, compared with rotary NiTi preparation in oval canals in molars (11), it appears that the amount of prepared surface in such canals with the SAF is higher (data not shown).

A potential limitation of this study is the relatively small sample size of 20 canals in total. It is, however, in the same range as in earlier (12, 14, 17) and recent (19) MCT-based studies. The selected maxillary anterior teeth were also very similar in canal anatomy; hence a power analysis, which depends on the variance in the outcome variable, suggested that n = 10 samples per group were sufficient.

One strength of the selected nondestructive approach was to permit repeated evaluation after incremental preparation over time. This provided information for the clinically recommended usage time; 3 or 4 minutes of activation might be sufficient to address most of the canal surface.

Previous studies with an MCT system with 36-μm resolution documented on average untreated canal areas for rather large and straight palatal canals in maxillary molars of up to 49%, whereas smaller and relatively round distobuccal canals had up to 33% surface area unprepared (14). In the present study, the preparation even with the smaller SAF for 3 minutes accomplished about the same. Regarding removal of dentin, the observed values are similar to or slightly larger than those determined earlier for NiTi rotary instruments (12, 14).

By using canal cross sections in a 2-dimensional assessment, uninstrumented canal perimeters varied between 44% and 68% in long oval canals (20). In a recent study (21), the same group found less unprepared canal perimeter for canal shapes created with rotary instruments, ranging from 25%–35%. However, when material removal of at least 200 μm was required, 80% or more of the canal surface was counted as not prepared (21). In the present study after 5 minutes with SAF preparation, on average about 57% of the canal surface, at least 100 μm, was removed. This was circumferential, and no thinning of the radicular walls was noted.

Rotary NiTi root canal files have been linked to a 3%–5% incidence of intracanal breakage (22); although a retained instrument fragment per se does not significantly alter healing of periapical lesions, it is preferable to have no impediment to disinfection inside canals. In the present study only 1 of a total of 20 canals (90 preparation cycles) presented with a retained NiTi fragment, which was likely too small to pose any obstacle for disinfection. Moreover, pilot data and the present results suggest that probably as a result of the design of the SAF, any retained instrument fragments might be small and loose in the canal. Consequently, the one fragment observed in the present study was flushed out in the subsequent preparation cycle.

Eradication of microorganisms, a critical step for endodontic outcomes (23), is the result of a combination of mechanical preparation (24) and irrigation (25). Irrigation alone is not always effective (26), and mechanical action of instruments on canal walls, including removal of infected dentin, might be needed.

Mechanical disinfection can also be related to removal of a layer of infected dentin, at least of incompletely mineralized predentin (27). It has been shown, however, that bacteria might penetrate dentinal tubules to depths of 200 μm and more (5). The present study indicated that complete uniform enlargement of a root canal by 200 μm is not achieved with a novel instrument; this appears to be an unattainable goal for any contemporary mechanical canal preparation technique (10, 21).

Specifically, the preparation of the most apical canal section remains a challenge. With the SAF, unprepared area amounted up to 28.6% $\pm$ 12.6% after 5 minutes of shaping with SAF 2.0 mm, which still compares favorably to preparation with several popular NiTi rotaries (10). In this area, sufficient deposition of disinfecting irrigation solutions is particularly important. Antibacterial efficacy of canal surface preparation was not directly determined in the present study. However, another experiment involving the SAF suggested enhanced irrigation capacity promoted by continued application through the hollow center of the instrument (28).

Mechanical preparation might affect bacterial biofilms (29) rather than only microorganisms in their planktonic state. With further improvement in hardware and software, it might be possible in the future to directly determine the amount of biofilm removed from MCT-based experiments.

In conclusion, preparation of straight root canals in anterior teeth with the novel SAF left little canal surface uninstrumented after 5 minutes of activation; there were also no significant procedural errors. The timeframe of clinical application will depend on the amount of desired dentin removal and will be done with an SAF selected on the basis of apical gauging.

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Ability of Chemomechanical Preparation with Either Rotary Instruments or Self-adjusting File to Disinfect Oval-shaped Root Canals

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Abstract

Introduction: Oval-shaped root canals might represent a great challenge for proper disinfection. This study compared the capability of a newly developed instrument, the self-adjusting file (SAF), and rotary nickel-titanium (NiTi) instrumentation to eliminate *Enterococcus faecalis* populations from long oval root canals of extracted human teeth. As a secondary purpose, the ability of a modification in sampling technique to recover bacteria lodged in recesses of oval canals was evaluated. **Methods:** Long oval canals from mandibular incisors and maxillary second premolars were infected with *E. faecalis* (ATCC 29212) for 30 days and then randomly distributed into 2 experimental groups. In group 1, canals were prepared up to a 40/04 rotary BioRaCe instrument by using irrigation with NaviTip needles; in group 2, canals were prepared by using the SAF system with continuous irrigation. NaOCl and ethylenediaminetetraacetic acid were used as irrigants. Bacteriologic samples were taken before (S1) and after preparation (S2a and S2b). **Results:** Reduction in the bacterial populations was highly significant in both groups ($P < .001$). Preparation of long oval canals with the SAF was significantly more effective than rotary NiTi instrumentation in reducing intracanal *E. faecalis* counts ($P = .01$). Frequency of positive cultures in S2 samples was 11 of 20 (55%) for rotary instrumentation and 4 of 20 (20%) for SAF instrumentation ($P = .048$). S2b samples (modified method) yielded more positive samples than S2a (12/40 vs 5/40), but this difference reached no statistical significance ($P > .05$). **Conclusions:** The SAF system was significantly more effective than rotary NiTi instrumentation used with syringe/needle irrigation in disinfecting long oval root canals *in vitro*. A modified sampling technique might be necessary for oval canals. *(J Endod 2010;36:1860–1865)*

Key Words

Endodontic treatment, *Enterococcus faecalis*, nickel-titanium instruments, root canal infection, self-adjusting file, sodium hypochlorite

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The ultimate microbiological goals of chemomechanical preparation are to completely eradicate intracanal bacterial populations or at least reduce them to levels that are compatible with periradicular tissue healing (1). Bacteria persisting after chemomechanical procedures at levels detectable by culture-dependent techniques have been shown to influence negatively the endodontic treatment outcome (2, 3). Therefore, efforts should be directed toward the development of chemomechanical strategies that maximize root canal disinfection before filling.

Anatomic complexities might represent physical constraints that pose a serious challenge to adequate root canal disinfection. An example includes the cross-sectional root canal configuration, which has been classified as round, oval, long oval, flattened, or irregular (4). Whereas oval canals have been described as those exhibiting a maximum cross-sectional diameter of up to 2 times greater than the minimum diameter, long oval canals have a maximum diameter of 2–4 times greater than the minimum diameter (4). The overall prevalence of long oval root canals in the apical third is about 25%, with mandibular incisors and maxillary second premolars showing an even increased prevalence of this canal configuration (>50%) (5). In canals with these anatomical conditions, hand and rotary instruments working in reaming motion have been reported to leave untouched fins or recesses (6–11). In addition to harboring remnants of pulp tissue or bacterial biofilms, such recesses might also be packed with dentin chips generated and pushed therein by rotating instruments (12). Packed debris can interfere with the quality of obturation (13) and, in infected root canals, can harbor bacteria to serve as a potential source of persistent infection (14).

The self-adjusting file (SAF) (ReDent-Nova, Ra'anana, Israel) has been devised with the purpose of sidestepping some of the limitations of rotary nickel-titanium (NiTi) instruments (15). The SAF is a hollow and flexible instrument designed as a compressible thin-walled pointed cylinder composed of 120-μm-thick NiTi lattice (15). When inserted into the root canal, the instrument is claimed to adapt itself to the canal shape, both longitudinally and cross-sectionally, providing a three-dimensional adaptation (15). The surface of the lattice threads is lightly abrasive to promote a uniform removal of dentin during a back-and-forth grinding motion. The SAF is operated with reciprocating vibrating handpieces, and its hollow design allows for continuous delivery of irrigants throughout the procedure by a special rinsing unit.

A recent micro–computed tomography study showed that the percent of root canal area affected by the SAF method is larger than that affected by popular rotary instrumentation systems (16). Consequently, less unprepared areas that might potentially harbor bacterial biofilm remnants are observed (16). Another study reported that SAF operation with continuous irrigation resulted in root canal walls that were free of debris in all specimens and almost completely free of smear layer (17). The SAF system has the potential to be particularly advantageous in promoting disinfection of oval-shaped canals. However, there is no study that has examined the disinfecting ability of this novel system.

Therefore, the present study was undertaken to investigate the ability of the newly developed SAF system to eliminate viable *Enterococcus faecalis* populations from long oval root canals of extracted human teeth as compared with rotary NiTi instrumentation with syringe and needle irrigation. Furthermore, because common sampling methods with paper points have limitations in attaining a good representative sample from the root canal (18, 19), which might be especially aggravated in oval-shaped canals, a secondary purpose of this study was to evaluate the ability of a modification in the sampling technique to recover bacteria lodged in fins or recesses of long oval canals.

Materials and Methods

Specimen Selection and Preparation

This study included 44 teeth (single-rooted and single-canalled mandibular incisors and maxillary second premolars) with long oval root canals, which were selected from a collection of teeth that had been extracted for reasons not related to this study. Each tooth was radiographed from both buccolingual and mesiodistal projections, and only those teeth whose root canals presented a >2.5:1 ratio between the buccolingual and mesiodistal dimensions at a level 5 mm from the root apex were selected. Pairs of teeth were selected on the basis of similar radiographic root canal morphology, and each tooth from each pair was randomly assigned to either rotary instrumentation group or the SAF group. The study protocol was approved by the ethics committee of the Estácio de Sá University.

Conventional access cavities were prepared by using round burs and Endo-Z burs (Dentsply/Maillefer, Ballaigues, Switzerland). All root canals were instrumented at the apical foramen up to a hand #25 K-type file in alternated rotation motions under continuous irrigation with running water. Smear layer was removed by using ethylenediaminetetraacetic acid (EDTA) for 3 minutes, followed by 2.5% NaOCl irrigation. After inactivation of residual NaOCl with 10% sodium thiosulfate, the teeth were immersed in trypticase soy broth (TSB) (Difco, Detroit, MI), ultrasonicated for 1 minute to release entrapped air and allow penetration of culture media into root canal irregularities, and then sterilized in autoclave for 20 minutes at 121°C. Each flask contained 10 teeth immersed in 200 mL of TSB. The experiment was planned so that 10 specimens could be prepared and the respective bacteriologic samples processed per day.

Bacterial Biofilm Formation

E. faecalis strain ATCC 29212 was used to infect the root canals. A suspension was prepared by adding 1 mL of a pure culture of *E. faecalis*, grown in TSB for 24 hours, to 5 mL of fresh TSB. One milliliter of this suspension was used to inoculate each of the flasks. *E. faecalis* was allowed to grow for 30 days at 37°C under gentle shaking. Culture media were replenished every week.

Forty teeth were used in the antibacterial experiment, and 4 teeth were subjected to scanning electron microscopy to confirm bacterial colonization and biofilm formation. These 4 teeth were fixed in 10% buffered formalin, longitudinally split, and then dried in ascending ethanol concentrations. They were then dehydrated to their critical point in CO_2 and sputter-coated with gold under vacuum. Specimens were examined by using a scanning electron microscope (JSM-5800LV; JEOL, Tokyo, Japan).

The teeth that were subjected to further study had the excess culture medium dripped off, and their external root surface was wiped with sterile gauze. The apical foramen was sealed with a fast set epoxy resin to prevent bacterial leakage and create a closed-end channel that produces the vapor lock effect (20). To make both handling and identification easier, teeth were mounted vertically up to the cervical region in blocks made of a silicone impression material (President Jet; Coltène AG, Cuyahoga Falls, OH). The tooth crown, including the pulp chamber walls, and the silicone surface were disinfected with 2.5% NaOCl, followed by inactivation of this substance with 10% sodium thiosulfate. For working length (WL) determination, a #20 K-file was introduced in the canal until it reached the apical foramen. The initial (S1) sample was then taken from each canal.

Rotary NiTi Instrumentation Group

BioRaCe instruments (FKG Dentaire, La Chaux-de-Fonds, Switzerland) were used in this group as described by Debelian and Trope (21). Twenty root canals were prepared at the WL by using the BR2 instrument (25/04, size/taper) up to the BR5 instrument (40/04), with 2.5% NaOCl as the irrigant. Irrigation was performed with disposable 5-mL syringes and 30-gauge NaviTip needles (Ultradent, South Jordan, UT) taken up to 3 mm short of the WL. After preparation was complete, the canal was rinsed with 5 mL of 17% EDTA, followed by 5 mL of 2.5% NaOCl. The total volume of NaOCl was 15 mL per canal (Fig. 1). The average total time NaOCl remained in the canal was 10.7 minutes (range, 8–13 minutes). The average WL in this group was 19.9 mm (range, 17–23 mm). Chemomechanical procedures were conducted by an operator who had been specifically trained with BioRaCe instruments.

SAF Group

The SAF system (Fig. 2*A, B*) was used with the instrument operated by an in-and-out vibrating handpiece (GENTLEpower; KaVo, Bieberach a. d. Riß, Germany) combined with a RDT3 head (ReDent-Nova) at a frequency of 5000 movements per minute and amplitude of 0.4 mm. The SAF instrument was inserted in the canal and operated with in-and-out motion to WL for a total of 5 minutes. Continuous irrigation with 2.5% NaOCl or 17% EDTA was applied by using a special irrigation device (VATEA; ReDent-Nova). This device was connected to the irrigation hub on the file and allowed irrigants to be delivered at a flow rate of 5 mL/min. During the first 2 minutes, NaOCl was used, followed by 1 minute of EDTA and then another 2 minutes of NaOCl. The total volume of NaOCl was 20 mL per canal (Fig. 1). The average total time NaOCl remained in the canal in this group was 5.8 minutes (range, 5.5–8 minutes). The average WL in this group was 20.1 mm (range, 16–22 mm). Chemomechanical procedures in this group were performed by an operator who had been specifically trained with the SAF instrument.

After preparation in both groups, each root canal was washed with 1 mL of 10% sodium thiosulfate to inactivate NaOCl, dried, and refilled with sodium thiosulfate, which remained in the canal for 5 minutes. Postpreparation (S2) samples were taken.

Sampling Procedures Processing

Root canals were sampled before (S1) and after (S2) chemomechanical procedures.

S1 Sample. The root canal was gently rinsed with 1 mL of sterile saline solution to remove unattached cells, and an initial sample was taken by the sequential use of 3–5 paper points placed to the WL. Each paper point remained in the canal for 1 minute. Paper points were transferred to tubes containing 1 mL of sterile 0.85% saline solution and immediately processed.

S2 Samples. Initially, the root canal flooded with 10% sodium thiosulfate was sampled by agitating the fluid in the canal with a sterile #35 or #40 gutta-percha point by using a pumping motion and then absorbing the contents with sterile paper points until the canal was

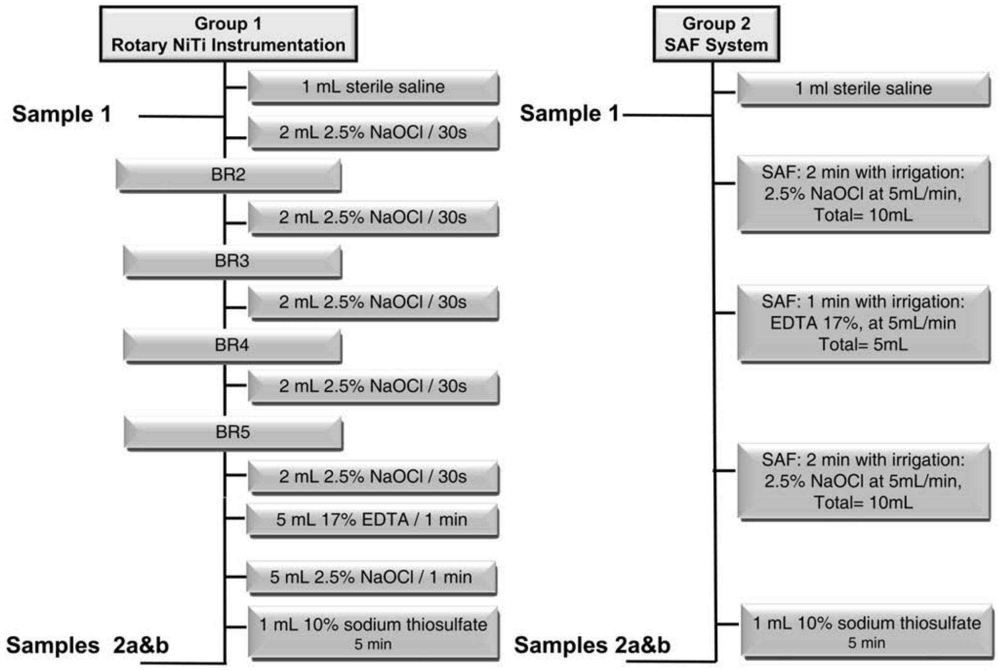

Figure 1. Flowchart of the experimental procedures.

dry. These samples were called S2a. Another S2 sample was taken following a slight modification from the method described by Metzger et al (22). The root canal was refilled with sodium thiosulfate, and then a sterile precurved stainless steel hand #20 K-file was inserted in the canal up to the WL. The curvature applied to the instrument was gentle and involved approximately the last 3 mm near the instrument's tip. The precurved instrument was turned so that its tip faced the buccal recess and then moved 3 times with a pulling motion. This motion was repeated after turning the file so that its tip now faced the lingual recess. This approach was intended to disrupt and dislodge

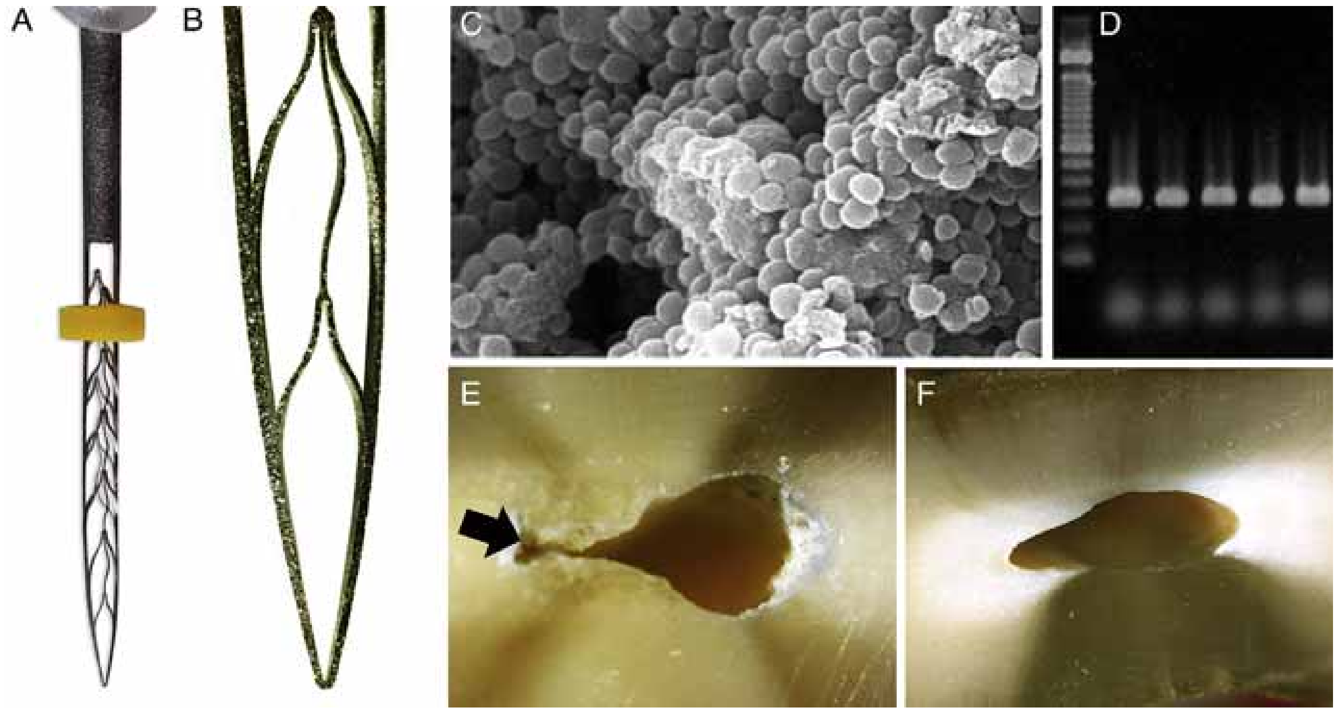

Figure 2. (*A*) The SAF. (*B*) Higher view of the SAF tip. (*C*) Scanning electron micrograph showing heavy colonization of the root canal wall by *E. faecalis* ATCC 29212 (original magnification, ×10,000). (*D*) Representative electrophoretic gel showing PCR products of the predicted size for *E. faecalis* to confirm identification in positive samples. (*E*) Representative specimen from the rotary NiTi instrumentation group showing a recess that remained apparently untouched (arrow). Cross section at 5 mm short of the root apex. (*F*) Representative specimen from the SAF group showing an apparently uniform preparation of the oval-shaped canal at 5 mm from the apex. (This figure is available in color online at www.aae.org/joe/.)

biofilm remnants and dentinal debris packed or unaffected in the recesses. Root canal contents were then absorbed with sterile paper points until the canal was dry. This sample was called S2b. Paper points used for taking S2a and S2b samples were transferred to tubes containing 1 mL of sterile saline and immediately processed.

Sample processing involved agitation in vortex for 1 minute, followed by 10-fold serial dilutions in saline. Afterwards, aliquots of 100 μL were plated onto Mitis-Salivarius agar plates (Difco) and incubated at 37°C for 48 hours. The colony-forming units (CFUs) grown were counted and then transformed into actual counts on the basis of the known dilution factors. Two parameters were evaluated per sample, qualitative (positive versus negative culture) and quantitative (number of CFUs).

To confirm identification of *E. faecalis* in all culture-positive samples, species-specific polymerase chain reaction (PCR) was performed as described previously (23). PCR amplicons were separated by electrophoresis in 1.5% agarose gel in Tris-borate-EDTA buffer, and positive reactions were determined by the presence of the predicted 310-base pair amplicon.

Statistical Analysis

The Mann-Whitney test was used for intragroup analysis comparing the reduction in the number of CFU counts from S1 to S2a, S2b, or S2ab. S2ab was considered as the overall S2 results, and data were mounted by using only the highest counts of either S2a or S2b for each tooth (ie, the worst S2 results per tooth). Because comparisons of baseline samples (S1) between groups by using the Mann-Whitney test revealed no significant differences, comparison between the efficacy of rotary NiTi instruments and the SAF to disinfect oval-shaped canals was performed by using S2a, S2b, or S2ab data in the Mann-Whitney test. Because S2ab data were the worst case scenario, they were chosen for final presentation and discussion. The incidence of negative cultures was compared between the 2 groups by using the two-tailed Fisher exact test. S2a and S2b samples were compared by using the overall data (n = 40 per S2 sample) in quantitative (Mann-Whitney test) or qualitative (χ^2 test with Yates correction) analyses. Significance level for all analyses was always set at $P < .05$.

Results

Scanning electron microscopy analysis of 4 specimens revealed that the root canal walls were densely colonized by *E. faecalis* cells forming biofilm-like structures (Fig. 2*C*). Successful colonization of the root canal was further confirmed by bacterial growth in all S1 samples. PCR confirmed identification of *E. faecalis* in all positive samples (Fig. 2*D*).

Table 1 reveals the mean, median, range, and percent reduction of CFUs observed for groups with either rotary BioRaCe instruments or the SAF. Intragroup analyses evaluating the reduction in the number of CFUs from S1 to S2a, S2b, or S2ab demonstrated that both preparation techniques were highly effective ($P < .001$).

Intergroup analysis of S1 samples revealed no significant difference ($P = .98$), indicating that the method of experimental contamination was capable of providing a homogeneous and reliable baseline of bacterial load. Consequently, data from S2 could be used for direct intergroup comparison. No significant differences were observed between the 2 techniques when either S2a ($P = .1$) or S2b ($P = .08$) data were used in the analysis. However, analysis involving S2ab data indicated that preparation of long oval canals with the SAF was significantly more effective than rotary NiTi instrumentation in reducing intracanal *E. faecalis* counts ($P = .01$). Frequency of positive cultures in S2ab was 11 of 20 (55%) for rotary instrumentation and 4 of 20

TABLE 1. Counts of *E. faecalis* CFUs before (S1) and after (S2a and S2b) Chemomechanical Procedures by Using Either Rotary NiTi Instrumentation with BioRaCe Instruments or the SAF System

Groups	S1			S2a			S2b			%Reduction
	Mean	Median	Range	Mean	Median	Range	Mean	Median	Range	Median S1-S2ab*
Rotary instruments	2.05×10^6	1.00×10^5	2.58×10^3–2.67×10^7	9.62×10^2	0	0–1.28×10^4	1.14×10^4	0	0–2.1×10^5	99.98
SAF	6.28×10^5	8.00×10^4	8.32×10^3–9.8×10^6	1.70×10^1	0	0–3.4×10^2	1.25×10^1	0	0–1.6×10^2	100

S2a, sample taken by paper points after pumping root canal contents with gutta-percha point; S2b, sample taken by paper points after moving precurved hand #20 file into buccal and lingual canal recesses; SAF, self-adjusting file.

*S2ab data entail the highest counts of either S2a or S2b for each tooth.

TABLE 2. Incidence of Positive Cultures after (S2a and S2b) Chemomechanical Preparation by Using Either Rotary NiTi Instrumentation with BioRaCe Instruments or the SAF System

Group	S2a	S2b	S2ab*
Rotary instruments	4/20 (20)[†]	8/20 (40)	11/20 (55)
SAF	1/20 (5)	4/20 (20)	4/20 (20)

S2a, sample taken by paper points after pumping root canal contents with gutta-percha point; S2b, sample taken by paper points after moving precurved hand #20 file into buccal and lingual canal recesses; SAF, self-adjusting file.

*S2ab data entail the highest bacterial counts of either S2a or S2b for each tooth.

[†]Number of cases with positive culture/number of cases examined (%).

(20%) for SAF instrumentation (Table 2). This 35% difference was statistically significant, although it should be considered that the *P* value was very close to the significance level (P = .048).

S2b samples exhibited more positive samples than S2a (12/40 versus 5/40), but the results were not statistically significant after qualitative (χ^2, P = .1) and quantitative (Mann-Whitney, P = .08) analyses. Ten specimens revealed positive results in S2b samples but not in S2a, whereas the opposite occurred in 3 specimens.

Discussion

The present *in vitro* study was conducted to evaluate the ability of chemomechanical preparation with either rotary NiTi instruments or the SAF in reducing *E. faecalis* populations within long oval root canals. Intragroup analysis indicated that both methods succeeded in promoting a significantly high reduction in intracanal bacterial populations. This is in line with several previous reports on the antibacterial efficacy of chemomechanical procedures (24–28). When the 2 groups were compared (intergroup analysis), quantitative data (CFU counts) revealed that the SAF method was significantly more effective than rotary NiTi instrumentation. Data regarding the incidence of negative and positive cultures (qualitative analysis) revealed that whereas in the SAF group 80% of the samples were rendered free of detectable levels of *E. faecalis*, instrumentation with rotary NiTi instruments resulted in only 45% of culture-negative samples. Although this difference was apparently very high and reached statistical significance, it is worth pointing out that the *P* value in the two-tailed Fisher exact test was close to the limit of significance. This is highly likely to be related to the sample size (number of specimens analyzed).

Because there were samples showing positive results either in S2a or in S2b and different quantitative findings were observed for these 2 sampling procedures, the worst results of S2 for each tooth were used in the comparison between the 2 instrumentation techniques. For instance, if a given S2a sample was negative and the corresponding S2b sample was positive or if S2a yielded lower CFU counts than S2b, the value of S2b was used for comparing the techniques. The same was true for the opposite condition. This was done because two S2 samples were taken for each root canal, regardless of the sampling technique used, and ultimately they reflected the bacteriologic conditions of the canal after preparation.

The results with rotary instrumentation do not come as a surprise, because it has already been widely demonstrated that rotary or hand-operated instruments in reaming motion do not prepare all root canal walls, especially in oval-shaped canals, where recesses are commonly left untouched (6–11, 29). A recent study compared the prepared surface areas of oval-shaped canals by using different instrumentation techniques and revealed that the mean unaffected areas ranged from about 60%–80% for the total canal length (10). At the apical portion of the canal, the mean of untouched areas ranged from 65%–75% (10). Another recent study comparing the cleaning effects of 3 instrumentation techniques in oval-shaped canals reported that none of the techniques resulted in completely prepared and cleaned canals (11).

In the present study, a 40/04 BioRaCe instrument was used to carve a relatively large apical preparation as recommended for mandibular incisors and maxillary second premolars (4, 30). Irrigation was performed with small-sized needles taken close to the WL, which has been shown to enhance antibacterial effectiveness (25, 31). Even so, detectable bacteria were still observed in about one half of the postpreparation samples. Because the number of positive cultures in S2b was higher than in S2a samples, it is reasonable to surmise that remaining bacteria were mostly located in buccal and/or lingual root canal recesses, which remained untouched as a result of the physical limitations of conventional instruments (Fig. 2*E*). It is also possible to speculate that the time NaOCl remained in the canal was not sufficient for this substance to penetrate into these narrow recesses in sufficient concentration, volume, and flow rate to disrupt biofilm structures adhered to the unaffected walls. It is still worth pointing out that the total time NaOCl remained within the root canal in the rotary instrumentation group was longer than in the SAF group.

The SAF system uses a hollow vibrating instrument, which allows for continuous irrigation with NaOCl or EDTA throughout preparation. Irrigants are exchanged and claimed to be taken to the apical root canal as a result of the vibration and in-and-out motion of the SAF (15). This compressible opened NiTi tube can adapt itself to the oval-shaped canal at the same time its abrasive blades are pressed against the walls to promote root canal enlargement. When compared with NiTi instrumentation, it has been reported that the SAF leaves less unprepared areas (16). The present results apparently confirm the superiority of the SAF system to prepare long oval canals. The higher antibacterial efficacy of the SAF method might be related to the instrument's ability to affect a higher surface area of the canal walls (including the larger diameter of the oval canal) (Fig. 2*F*), to the continuous delivery of fresh antibacterial irrigants throughout preparation, or both. Better instrumentation of fins is also expected to result in better access of irrigants deep within these areas, contributing to elimination of bacterial biofilms. Nonetheless, it should be noticed that although the overall time of NaOCl permanence in the canal was shorter for the SAF group, the total volume was larger (20 versus 15 mL). Whether this affected the results cannot be established at this time.

Common sampling methods have limitations because of the physical difficulties of paper points to reach irregularities and other regions of the root canal system (18, 19). Consequently, this approach might fail to detect viable bacteria in the deepest part of recesses. To allow for a more predictable sampling of narrow canal recesses, a modification in the technique was made by introducing and moving the tip of a slightly precurved hand instrument along the buccal and lingual aspects of the oval canal. Although the results displayed no statistical significance, much more positive samples were observed when using this approach (12 positive samples for S2b and 5 for S2a). Therefore, it might be advisable to use this modified approach to sample oval-shaped canal in microbiological studies.

Because of the inherent limitations of *in vitro* studies, data interpretation and extrapolation to the clinical setting should be made with caution. In addition to the obvious limitations of using extracted teeth in an optimized laboratory environment, it is important to consider that only the main canal was sampled, and no efforts were made toward collecting dentinal shavings or sampling other areas of the root canal system. Thus, because the present study reports exclusively on the ability of instrumentation to eliminate bacterial populations in the main canal, no inference can be made as to disinfection of the whole root canal system. Also, the bacterial markers used in this study consisted of a pure culture of a bacterial species growing under optimal conditions of nutrients and with no influence from competitors. This is a condition that is rarely, if ever, found in the clinical setting, where mixed bacterial communities are usually present and arguably enduring famine conditions.

In conclusion, the SAF cleaning-shaping-irrigation system was significantly more effective than rotary NiTi instrumentation used with syringe and needle irrigation in eliminating viable *E. faecalis* cells from long oval root canals *in vitro*. Also, a modification of the sampling technique might be considered to improve bacterial recovery in oval-shaped canals.

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The authors deny any conflicts of interest.

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Flat-Oval Root Canal Preparation with Self-Adjusting File Instrument: A Micro–Computed Tomography Study

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Abstract

Introduction: The aim of this study was to evaluate the root canal preparation in flat-oval canals treated with either rotary or self-adjusting file (SAF) by using microtomography analysis. **Methods:** Forty mandibular incisors were scanned before and after root canal instrumentation with rotary instruments (n = 20) or SAF (n = 20). Changes in canal volume, surface area, and cross-sectional geometry were compared with preoperative values. Data were compared by independent sample *t* test and χ^2 test between groups and paired sample *t* test within the group (α = 0.05). **Results:** Overall, area, perimeter, roundness, and major and minor diameters revealed no statistical difference between groups ($P > .05$). In the coronal third, percentage of prepared root canal walls and mean increases of volume and area were significantly higher with SAF (92.0%, 1.44 $\pm$ 0.49 mm^3, 0.40 $\pm$ 0.14 mm^2, respectively) than rotary instrumentation (62.0%, 0.81 $\pm$ 0.45 mm^3, 0.23 $\pm$ 0.15 mm^2, respectively) ($P < .05$). SAF removed dentin layer from all around the canal, whereas rotary instrumentation showed substantial untouched areas. **Conclusions:** In the coronal third, mean increases of area and volume of the canal as well as the percentage of prepared walls were significantly higher with SAF than with rotary instrumentation. By using SAF instruments, flat-oval canals were homogenously and circumferentially prepared. The size of the SAF preparation in the apical third of the canal was equivalent to those prepared with #40 rotary file with a 0.02 taper. *(J Endod 2011;37:1002–1007)*

Key Words

Micro-computed tomography, nickel-titanium instruments, root canal preparation, self-adjusting file

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The ultimate goal of chemomechanical preparation is to remove the inner layer of the dentin, while allowing the irrigant to reach the entire length of the root canal, eradicating bacterial populations or at least reducing them to levels that are compatible with periradicular tissue healing (1, 2). Although many technical advances have been made in endodontics, canal preparation is still adversely influenced by the highly variable anatomy (1, 3, 4), especially in oval, flat, or curved root canals (5–9). In flat-oval canals, rotary files have failed to perform adequate cleaning and shaping, leaving untouched fins or recesses on the buccal and/or lingual aspects of the central canal area prepared by the instrument (5, 6, 9, 10).

The self-adjusting file (SAF) (ReDent-Nova, Ra'anana, Israel) has been devised with the purpose of sidestepping some of the limitations of nickel-titanium (NiTi) rotary instruments (1, 11–14). During its operation, the file is designed to adapt itself three-dimensionally to the shape of the root canal. Rather than machining a central portion of the root canal into a round cross section, the SAF is claimed to maintain a flat canal as a flat canal with slightly larger dimensions (12, 13). Hence, SAF system has the potential to be particularly advantageous in promoting cleaning and shaping of flat-oval–shaped canals (1, 11, 12).

The development of x-ray micro–computed tomography (μCT) has gained increasing significance in the study of hard tissues (4). μCT offers a noninvasive reproducible technique for three-dimensional assessment of the root canal system and can be applied quantitatively as well as qualitatively (3, 4, 13, 15). Recent *ex vivo* μCT studies showed that the percentage of root canal area affected by the SAF method is larger than that affected by popular rotary instrumentation systems in different teeth (10, 13, 16).

To date, root canal preparation with SAF has been quantitatively and qualitatively described in different teeth, but not in mandibular incisors. Thus, the purpose of this study was to evaluate the root canal preparation in flat-oval root canals of mandibular incisors treated with either rotary or SAF by using three-dimensional μCT analysis.

Materials and Methods

Selection of Teeth

After ethics committee approval, 40 single-rooted freshly extracted human mandibular incisor teeth with fully formed apices were selected and stored in 9°C aqueous 0.1% thymol solution until further use. Each root was radiographed in buccolingual and mesiodistal projections to categorize them and to detect any possible obstruction. When the buccolingual diameter was 4 or more times larger than that of the mesiodistal diameter, the canals were classified as flat-oval. All teeth presenting isthmus, lateral, accessory, apical curvature, or 2 canals were excluded from the study.

After being washed in running water for 24 hours, each tooth was dried, mounted on a custom attachment, and scanned in a desktop x-ray microfocus CT scanner (SkyScan 1174v2; SkyScan N.V., Kontich, Belgium) at an isotropic resolution of 19.7 μm. The system consisted of a sealed air-cooled x-ray tube, 20–50 kV/40W/800 μA, with a precision object manipulator with 2 translations and 1 rotation direction. The system also included a 14-bit charge-coupled device (CCD) camera based on a 1.3 megapixel (1304 $\times$ 1024 pixels) CCD sensor.

Teeth were accessed by using high-speed diamond burs, and patency of the coronal canal was confirmed. Coronal flaring was accomplished with #2 and #3 Gates Glidden burs (Dentsply Maillefer, Ballaigues, Switzerland), in a low-speed contra-angle handpiece, placed to 2–4 mm below the cementoenamel junction. Flaring was followed

TABLE 1. Morphometric Two-dimensional Data (mean ± standard deviation) and Their Changes for Root Canal in Lower Incisors before and after Preparation with SAF or Rotary Systems

	All thirds		Coronal third		Middle third		Apical third	
	Rotary	SAF	Rotary	SAF	Rotary	SAF	Rotary	SAF
Area (mm^2)								
Δ	0.14 ± 0.07	0.22 ± 0.10	0.23 ± 0.15*	0.40 ± 0.14*	0.13 ± 0.06	0.18 ± 0.10	0.07 ± 0.03	0.06 ± 0.06
% Δ	43.11 ± 28.01	61.88 ± 24.22	38.02 ± 29.3*	65.07 ± 18.4*	47.40 ± 28.73	61.52 ± 32.91	65.19 ± 41.58	57.74 ± 58.33
Perimeter (mm)								
Δ	0.31 ± 0.18	0.37 ± 0.23	0.33 ± 0.27	0.50 ± 0.22	0.25 ± 0.19	0.37 ± 0.27	0.34 ± 0.17	0.25 ± 0.27
% Δ	12.10 ± 9.14	15.22 ± 9.75	9.11 ± 8.33	14.4 ± 6.75	9.75 ± 10.11	15.46 ± 12.23	25.85 ± 14.79	19.02 ± 21.62
Roundness								
Δ	0.07 ± 0.04	0.11 ± 0.06	0.09 ± 0.06	0.14 ± 0.07	0.10 ± 0.07	0.11 ± 0.06	0.03 ± 0.03	0.07 ± 0.07
% Δ	12.47 ± 8.35	19.13 ± 12.92	17.03 ± 15.9	26.05 ± 13.91	21.84 ± 17.83	23.11 ± 17.78	4.31 ± 5.07	11.55 ± 14.0
Minor diameter (mm)								
Δ	0.09 ± 0.07	0.09 ± 0.07	0.08 ± 0.10	0.10 ± 0.05	0.07 ± 0.08	0.08 ± 0.12	0.11 ± 0.07	0.09 ± 0.09
% Δ	8.70 ± 8.57	9.70 ± 8.66	5.41 ± 7.22	8.21 ± 5.95	7.65 ± 9.52	8.97 ± 12.64	21.33 ± 14.32	17.13 ± 19.56
Major diameter (mm)								
Δ	0.15 ± 0.08	0.13 ± 0.07	0.19 ± 0.13	0.22 ± 0.11	0.16 ± 0.09	0.11 ± 0.08	0.11 ± 0.07	0.07 ± 0.05
% Δ	40.88 ± 31.66	27.71 ± 18.12	37.67 ± 36.4	32.81 ± 22.55	46.92 ± 34.92	24.38 ± 19.05	42.87 ± 30.74	24.10 ± 15.76

For each specimen, evaluation was done for full canal length in approximately 400 slices. Statistically significant difference between groups is marked with * in the same row (independent sample t test, $P < .05$). Within group, there was significant statistical difference between preoperative and postoperative results (paired sample t test, $P < .05$).

Δ, mean increase (± standard deviation) of each analyzed parameter; % Δ, percentage mean increase (± standard deviation) of each analyzed parameter.

by irrigation with 5 mL of 2.5% NaOCl delivered in a syringe with a 27-gauge needle (Endo Eze; Ultradent Products Inc, South Jordan, UT). Subsequently, apical patency was determined by inserting a size 10 K-file into the root canal until its tip was visible at the apical foramen; working length (WL) was set 0.5 mm shorter of this measurement. A glide path was confirmed at least to a size #20 K-file. Specimens were then randomly assigned to 2 experimental groups (n = 20) according to the instrumentation technique: SAF (group A) and rotary (group B). Canals in group A were shaped by a general practitioner who had been specifically trained with the SAF instrument and in group B by a specialist (M.A.V.) with 12 years of clinical experience with rotary instruments.

Root Canal Preparation with SAF

A 1.5-mm diameter SAF (ReDent-Nova) was operated for 4 minutes by using a trans-line (in-and-out) vibrating handpiece (Gentle-Power Lux 20LP; KaVo, Biberach, Germany) adapted with a RDT3 head (ReDent-Nova) at a frequency of 83.3 Hz (5000 rpm) and amplitude of 0.4 mm. The instrument was used with a manual in-and-out motion to the WL. Continuous irrigation with 2.5% NaOCl was applied throughout the procedure at 5 mL/min by using a special irrigation apparatus (VATEA; ReDent-Nova) (2).

Root Canal Preparation with Rotary Instruments

The coronal and middle thirds were serially enlarged with NiTi rotary instruments sizes #25, 0.12 taper, #25, 0.10 taper, and #25, 0.08 taper (K3; SybronEndo, West Collins, CA) in a crown-down manner by using gentle in-and-out motion toward the apex. Then, instruments of sizes #25, 0.02 taper, #25, 0.04 taper, #30, 0.02 taper, #30, 0.04 taper, #35, 0.02 taper, #35, 0.04 taper, and #40, 0.02 taper were used to the WL. To avoid fracture, 5 canals were instrumented with 1 set of instruments at the WL, which were driven by a torque-controlled motor (X-Smart; Dentsply Maillefer) set to 300 rpm. The instruments were withdrawn when resistance was felt and changed for the next instrument. Passive ultrasonic irrigation was performed between each instrument by using a size #20 K-file mounted on a piezoelectric handpiece (JetSonic Four; Gnatus, Ribeirão Preto, SP, Brazil) at a power setting of 3, which was activated for 10 seconds at the WL. Each canal was irrigated with a total of 20 mL of 2.5% NaOCl.

In all groups after root canal preparation, a final rinse with 5 mL of normal saline solution was performed, the root canals were dried with paper points, and teeth were resubmitted to a postoperative μCT scan by applying the initial parameter settings.

Evaluation of the Root Canal Preparation

Images were reconstructed from the apex to the level of the cementoenamel junction (NRecon v1.6.1.5; SkyScan), providing axial cross sections of the inner structure of the samples. For each tooth, evaluation was done for the full canal length in approximately 400 slices per specimen.

CTAn v1.10.1.0 software (Skyscan) was used for two- and three-dimensional volumetric analysis and measurements of area, perimeter, roundness, major diameter, minor diameter, volume, and surface area. The cross-sectional appearance, round or more ribbon-shaped, was expressed as roundness. This index varies from 0 (parallel plates) to 1 (perfect ball). Mean increase (Δ) of each analyzed parameter was calculated by subtracting the scores for the treated canals from those recorded for the untreated counterparts. The percentage of increase of each parameter (%Δ) was calculated by using the scores measured before (B) and after (A) root canal preparation, according to the formula:

TABLE 2. Morphometric Three-dimensional Data (mean ± standard deviation, n = 20 each) and Their Changes for Root Canal in Lower Incisors before and after Preparation with SAF or Rotary Systems

	All thirds		Coronal third		Middle third		Apical third	
	Rotary	SAF	Rotary	SAF	Rotary	SAF	Rotary	SAF
Volume (mm^3)								
Δ	1.47 ± 0.67*	2.32 ± 1.0*	0.81 ± 0.45*	1.44 ± 0.49*	0.42 ± 0.24	0.67 ± 0.35	0.24 ± 0.10	0.22 ± 0.19
% Δ	41.63 ± 27.0	62.77 ± 24.45	37.25 ± 27.93*	65.77 ± 18.46*	45.0 ± 32.66	63.23 ± 32.97	63.51 ± 35.66	56.95 ± 59.11
Surface (mm^2)								
Δ	4.06 ± 1.92	4.77 ± 3.27	1.67 ± 1.22	2.24 ± 1.19	0.95 ± 0.53	1.51 ± 1.26	1.45 ± 0.57	1.02 ± 0.99
% Δ	13.29 ± 9.01	15.90 ± 11.16	11.26 ± 10.10	15.33 ± 7.98	9.35 ± 8.08	15.83 ± 1.26	27.99 ± 13.52	19.52 ± 21.64

Statistically significant difference between groups is marked with * in the same row (independent sample *t* test, $P < .05$). Within group, volume and surface area showed significant statistical difference between preoperative and postoperative results (paired sample *t* test, $P < .05$).

Δ, mean increase (± standard deviation) of each analyzed parameter; % Δ, percentage mean increase (± standard deviation) of each analyzed parameter.

$$\%\Delta = (A * 100/B) - 100.$$

CTVol software (Skyscan) was used for three-dimensional visualization and qualitative evaluation of the preinstrumented and postinstrumented canals. Color-coded root canal models (green indicates preoperative, red postoperative canal surfaces) enabled qualitative comparison of the matched root canals before and after shaping.

OnDemand 3D software (Cybermed Inc, Irvine, CA) was used for the analysis of the 15 superimposed cross-sectional images of each specimen (n = 300 per group) regarding the percentage of instrumented and noninstrumented walls. The root canal preparation was classified into 2 categories: (1) cross section in which the whole perimeter or almost all the perimeter was treated (80% or more of the perimeter treated) and (2) cross section in which most of the perimeter was untreated (20% or less of the perimeter treated).

Statistical Analysis

The results were statistically analyzed with independent sample *t* test and χ^2 test (with Yates correction) between groups and paired sample *t* test within the group, with the null hypothesis set as 5%, by using SPSS v17.0 for Windows (SPSS Inc, Chicago, IL).

Results

Quantitative Evaluation

Two-Dimensional Analysis. The results of two-dimensional analysis are detailed in Table 1. Overall, area, perimeter, roundness, and major and minor diameters revealed no statistically significant difference between SAF and rotary preparation ($P > .05$). However, percentage mean increase of the root canal area in the coronal third was significantly higher with SAF (65.07% ± 18.4%) than with rotary instrumentation (38.02% ± 29.3%) ($P = .03$). Despite differences between groups in the postoperative results in relation to roundness ($P = .02$) and minor diameter ($P = .01$), no difference was observed in the preoperative and postoperative increase of these parameters ($P > .05$). No statistical difference was observed regarding the analyzed parameters in the middle and apical thirds ($P > .05$). Within group, there was a significant statistical difference between preoperative and postoperative results ($P < .05$).

Three-Dimensional Analysis. The results of three-dimensional analysis are detailed in Table 2. No statistical difference in volume or surface area was observed in the middle or apical thirds between the groups ($P > .05$). Despite that the mean increase of the canal volume in the coronal third was significantly higher with SAF (1.44 ± 0.49 mm^3) than with rotary instrumentation (0.81 ± 0.45 mm^3) ($P = .01$), the same was not observed with the surface area ($P > .05$). Within group, volume and surface area showed a significant statistical difference between preoperative and postoperative results ($P < .05$).

Qualitative Evaluation

Preoperatively, root canal cross sections presented significantly flatter in the mesiodistal view than in the buccolingual aspect. Its geometry was changed after root canal preparation with both instruments. Superimposed μCT reconstructions in all thirds demonstrated that the use of SAF resulted in a more uniform dentin removal along the perimeter of the canals than with rotary instrumentation. The latter showed substantial untouched areas mainly on the lingual side of the canal. The number of samples in which all or most of the root canal perimeter was untreated, considering the coronal, middle, and apical thirds, was 58 (19.3%) for SAF group and 119 (39.7%) for rotary group. There was a statistically significant difference between the

TABLE 3. Statistical Comparison of Percentage of Root Canal Wall Preparation by Using SAF System or Rotary Instruments at Different Thirds

	Coronal third			Middle third			Apical third		
Category	Rotary	SAF	*P* value	Rotary	SAF	*P* value	Rotary	SAF	*P* value
All or most of root canal perimeter is treated (80% or more treated)	62	92	.0001*	44	65	.005*	75	85	.112
All or most of root canal perimeter is untreated (20% or less treated)	38	8		56	35		25	15	
Total (%)	100	100		100	100		100	100	

Statistically significant difference between groups is marked with * in the same row (χ^2 test with Yates correction, α = 0.05).

instrumented and the noninstrumented walls between groups at coronal and middle thirds (Table 3). Cross sections and tridimensional analysis showed that the use of SAF resulted in a more homogenous preparation of the root canal walls compared with rotary instruments (Figs. 1 and 2).

Discussion

Variations in canal geometry before shaping and cleaning procedures seem to have more influence on the changes that occurred during preparation than the instrumentation techniques themselves (3). Therefore, in the present study care was taken to ensure that the sample was balanced in terms of preoperative morphologic parameters between groups. The root canals in both groups were preflared and a #20 K-file was used for apical sizing because this procedure reflects clinical conditions under which root canal treatment is performed, as recommended by SAF's manufacturer (1, 11, 12). Because the operator tactile skills have been considered more important than the technique in the thoroughness of canal debridement (4, 17), root canal preparations were carried out by dentists with expertise in each of the tested techniques. Nonetheless, as previously pointed out (10), a potential limitation of this study could also be a result from the relatively small sample size of 20 teeth per group; however, it is similar to recent μCT studies (3, 4, 10, 16).

When compared with rotary NiTi instrumentation, it has been reported that SAF leaves less unprepared areas (16) and was significantly more effective in disinfecting long oval root canals *in vitro* (14). In the present study, SAF presented a higher increase of area (two-dimensional analysis) and volume (three-dimensional analysis) than the rotary group only at the coronal third. It might be explained as the relative softness of dentin near the pulp chamber as a result of the higher dentinal diameter and density (18), compared with the other canal regions. Besides, preflaring with Gates Glidden burs facilitated endodontic instrumentation and allowed SAF to act freely at this portion, promoting more dentin removal than with rotary instruments.

At middle third, although no differences have been observed regarding area or volume between groups, SAF system presented significantly higher percentage of prepared root canal walls (65%) than rotary instrumentation (44%). It might be inferred that this result would be due mainly to the anatomic feature of the flat-oval–shaped canal of mandibular incisor (19).

The preparation of the most apical canal section remains a challenge (20). At this region, previous studies on root canal preparation with SAF have left uninstrumented areas ranging from 28.8%–47.4% in maxillary molar root canals (10). Although there is disagreement among endodontic specialists about the maximal enlargement at WL (4, 21), in the present study the final apical preparation with size

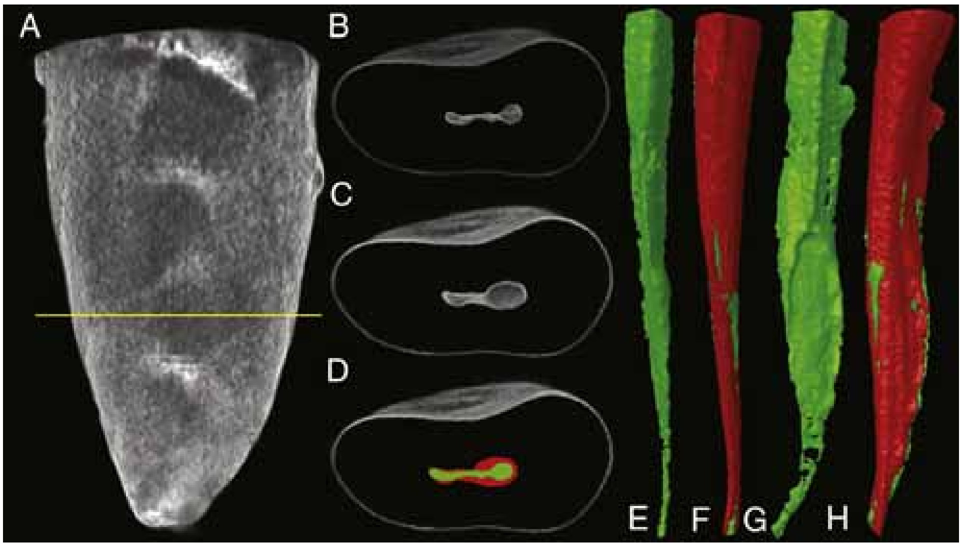

Figure 1. Representative example of μCT data of flat-oval–shaped root canal of mandibular incisor prepared with SAF system at middle level of the root (*yellow line, A*). Two-dimensional analysis shows the preoperative (*B*), postoperative (*C*), and superimposed reconstructions (*D*) of the root canal (*green* and *red areas* are preoperative and postoperative superimposed cross sections, respectively). Note that SAF instrumentation removed a uniform layer of dentin from root canal walls (*D*). In the qualitative evaluation, three-dimensionally reconstructed μCT images show the root canal before preparation in buccal (*E*) and distal views (*G*). The superimposed μCT reconstructions in buccal (*F*) and distal (*H*) views demonstrate a uniform preparation of the canal surface with SAF system.

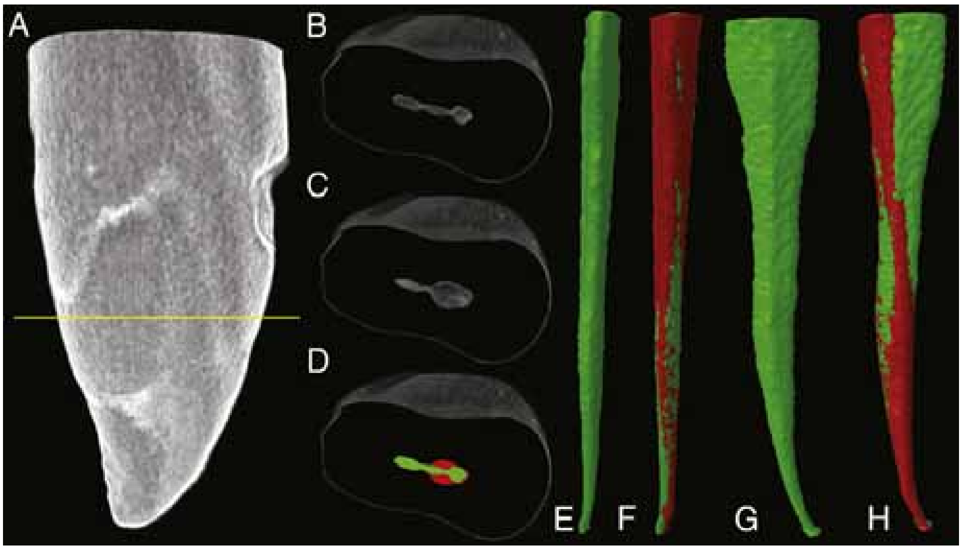

Figure 2. Representative example of μCT data of flat-oval–shaped root canal of mandibular incisor prepared with K3 rotary system at middle level of the root (*yellow line, A*). Two-dimensional analysis shows the preoperative (*B*), postoperative (*C*), and superimposed reconstructions (*D*) of the root canal (*green* and *red areas* are preoperative and postoperative superimposed cross sections, respectively). Note that rotary instrumentation increased the diameter of the canal, with a round cross section only in its buccal aspect (*D*). In the qualitative evaluation, three-dimensionally reconstructed μCT images show the root canal before preparation in buccal (*E*) and distal views (*G*). The superimposed μCT reconstructions in buccal (*F*) and distal (*H*) views demonstrate substantial untouched areas after root canal preparation with rotary instruments.

#40, taper 0.02 in the rotary group was used as previously recommended for mandibular incisors (21). Despite the differences in file design, it should be noted that the final apical preparation was identical to both groups, considering either two-dimensional or three-dimensional analyzed quantitative parameters. As a consequence, no statistical difference was also found in the percentage of unprepared root canal walls by using SAF (15%) or rotary (25%) instruments. It might be explained as root canals of lower incisors tend toward a rounder cross section at this region, favoring the action of rotary instruments (22). This result demonstrates the action of SAF at the apical region and confirms the statement that the resulting apical size with SAF is usually at least equivalent to size #40 file (16).

Although the overall quantitative analysis of middle and apical thirds showed no difference between groups, the results clearly showed that instrumentation groups differed from each other in the qualitative analysis. As previously demonstrated, the present results suggest that rotary NiTi instrument alone was unable to adequately prepare the root canal (3, 4, 17), and SAF does indeed result in homogenous preparation and circumferential removal of a layer of hard tissue, favoring root canal disinfection (14) and the accommodation of the root canal filling (16).

Further studies should be performed to compare the cleaning efficacy of the SAF system with a combination of rotary files with passive ultrasonic irrigation method in the flat-oval–shaped canals.

Conclusions

Within the limitations of this *ex vivo* study, it can be concluded that in the coronal third, mean increases of area and volume of the root canal, as well as the percentage of prepared walls, were significantly higher with SAF than with rotary instrumentation. By using SAF instrument, flat-oval–shaped canals of mandibular incisors were homogenously and circumferentially prepared. The size of the SAF preparation in the apical third of the canal was equivalent to those prepared with #40 rotary file with 0.02 taper.

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The authors deny any conflicts of interest related to this study.

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ERRATUM

Due to an oversight, the authors omitted follow-up data from the article titled, "Squamous Odontogenic Tumor-like Proliferations in Radicular Cysts: A Clinicopathologic Study of Forty-two Cases," by Rinku M. Parmar, Robert B. Brannon, and Craig B. Fowler, which was published in J Endod 2011;37:623–6. In the article, this data should follow the section, "Histopathologic Features." The missing text appears below.

Data on Cases with Follow-up Information

Follow-up information was available for 11 cases. The range of follow-up was 1 month to 10 years, and the average length of follow-up was 2.5 years. There were no recurrences or unexpected clinical behavior reported among the 11 cases with follow-up.