ISSN: 0972-0707

Journal of Conservative Dentistry

Volume 17 Issue 5 Sep - Oct 2014

Official Publication of
Indian Association of Conservative Dentistry and Endodontics

Online full text at
www.jcd.org.in

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Review Article

The self-adjusting file (SAF) system: An evidence-based update

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Abstract

Current rotary file systems are effective tools. Nevertheless, they have two main shortcomings:

a. They are unable to effectively clean and shape oval canals and depend too much on the irrigant to do the cleaning, which is an unrealistic illusion
b. They may jeopardize the long-term survival of the tooth via unnecessary, excessive removal of sound dentin and creation of micro-cracks in the remaining root dentin.

The new Self-adjusting File (SAF) technology uses a hollow, compressible NiTi file, with no central metal core, through which a continuous flow of irrigant is provided throughout the procedure. The SAF technology allows for effective cleaning of all root canals including oval canals, thus allowing for the effective disinfection and obturation of all canal morphologies. This technology uses a new concept of cleaning and shaping in which a uniform layer of dentin is removed from around the entire perimeter of the root canal, thus avoiding unnecessary excessive removal of sound dentin. Furthermore, the mode of action used by this file system does not apply the machining of all root canals to a circular bore, as do all other rotary file systems, and does not cause micro-cracks in the remaining root dentin. The new SAF technology allows for a new concept in cleaning and shaping root canals: Minimally Invasive 3D Endodontics.

Keywords: Cleaning and shaping, instrumentation, irrigation, minimally invasive, NiTi files, obturation, root filling, rotary files, SAF, self-adjusting file

INTRODUCTION

Rotary nickel titanium (NiTi) files were first introduced clinically in 1993. They were a major turning point and represented a real paradigm shift in endodontics.[1,2] New designs have been introduced over the years, attempting to make these instruments more efficient, more flexible, and safer in terms of file separation.[3] Recently, innovative metallurgy and reciprocating movement were combined to allow for the creation of "single file" systems, such as Wave One (Maillefer-Dentsply, Ballaigues, Switzerland) and Reciproc (VDW, Munich, Germany).[4]

Both new and traditional rotary file systems utilize the same basic concept. In all currently used systems, the files consist of a solid central metal shaft with a rotating blade and flutes to either contain or carry off the cut material. As long as the canals are simple, straight and narrow, with a round cross-section, such instruments are likely to achieve the goals of root canal instrumentation and shaping. In such canals, instrumentation of the canal to the shape of the file may be sufficient and result in adequate cleaning of the canal.

Nevertheless, rotary instruments, both new and old, may fail to meet the challenge of either oval or curved canals.[5-18] This need currently remains unmet due to (a) the challenge of three-dimensional (3D) cleaning and shaping of oval and curved canals,[5,8,9,12] (b) the microbiological challenge of infected oval canals[10] and (c) the challenge of 3D obturation of oval canals.[11,13] Above and beyond all of these, (d) the challenge of maintaining the integrity of the remaining radicular dentin, was recently recognized. All rotary file systems tested so far create micro-cracks in the radicular dentin in a high percentage of treated roots, which may predispose them to vertical root fractures.[6,7,14,15,18,19] This last challenge applies to roots with round cross-sections as well.

The targets of endodontic treatment are the complete cleaning, adequate disinfection, and effective obturation of the root canal. Each of these challenging targets is critical for the success of endodontic treatment. Operators are expected to do as complete a job as possible in each of these targets to ensure endodontic success. Unfortunately, the results achievable in oval and curved canals using the

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Date of submission : 20.05.2014
Review completed : 01.08.2014
Date of acceptance : 04.08.2014

Access this article online	
Quick Response Code:	Website: www.jcd.org.in
	DOI: 10.4103/0972-0707.139820

old or new rotary instruments currently available are far from complete.[5-19] This incompleteness is due to a basic conceptual fault — the current instruments were designed ignoring the natural 3D shape of many of the root canals, and therefore, they clean and shape all canals as if they were narrow, straight canals with round cross-sections.[20-22] By using these instruments, operators are often actually treating an imaginary tooth rather than addressing the 3D reality of a given root canal.

With the introduction of the Self-Adjusting File (SAF) System, the definition of "possible" in "as complete a job as possible" has substantially changed.[10-12,15-20,23-27] Although the treatment results achievable with the help of this new system are not perfect, they are closer to the operator's idea when performing a root canal treatment compared with treatment using any existing rotary file system.

The aim of this review is to introduce the reader to the SAF System and its mode of operation. The challenges that remain unmet by the current rotary file systems will be discussed one by one, leading to the unavoidable conclusion that we do need a change of concept in root canal treatment. The manner by which the SAF System can overcome each of these challenges will be presented based on more than 50 studies published over the last four years by various research teams. Consequently, the new concept of minimally invasive 3D endodontics has emerged, made possible by the new SAF technology. This concept aims to achieve all of the basic aims of root canal treatment without causing the unnecessary damage to the radicular dentin often observed in roots treated with traditional, old, or new rotary file instrumentation.[6,7,14,15,18,19]

THE SELF-ADJUSTING FILE (SAF) SYSTEM

The SAF System is a shaping and cleaning system designed for minimally invasive endodontic treatment. The system consists of a self-adjusting file operated with a special RDT handpiece-head and an irrigation pump (either the VATEA pump or the all-in-one EndoStation unit, see below) that delivers a continuous flow of irrigant through the hollow file. Because the file is built as a lattice-walled cylinder (see below), no pressure is generated within the file; any small pressure that is generated by the pump to deliver the irrigant through the tube is eliminated the moment the irrigant enters the file.

The Self-adjusting File (SAF)

The SAF is the first file that does not have a solid metal shaft.[20,22,28] The file is designed as a hollow tube, the walls of which are made from a thin nickel titanium lattice [Figure 1] with a rough outer surface [Figure 2]. The file has an asymmetrically positioned tip [Figure 2], located at the wall of the tube as opposed to the symmetrically centered tips found in all conventional nickel titanium rotary files. The SAF system is extremely flexible [Figure 2] and also extremely compressible, so that a 1.5-mm diameter SAF may be compressed into a root canal in which only a #20 K file could previously be inserted[20,28] [Figure 3]. This compressibility also enables the file to adapt to the cross-sectional shape of the canal. When inserted into an oval canal with a 0.2-mm mesiodistal diameter, a 1.5-mm SAF will be compressed mesiodistally and thus spread buccolingually as far as 2.4 mm [Figure 4]. This will occur even if the operator is not aware that the canal is oval; hence, the name "self-adjusting file".[20] Naturally, such a flattened file cannot rotate in the canal and is therefore

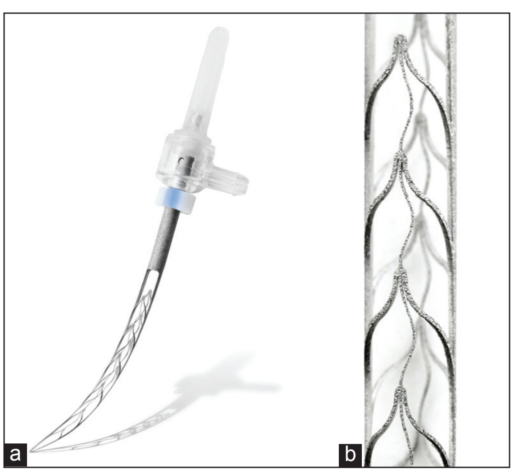

Figure 1: The Self-adjusting File. (a) The file. (b) Magnification of the lattice structure. Note the two longitudinal beams connected to each other by specially designed arches. The arches are connected to each other with thin struts to prevent them from being pulled out of the tube-like structure

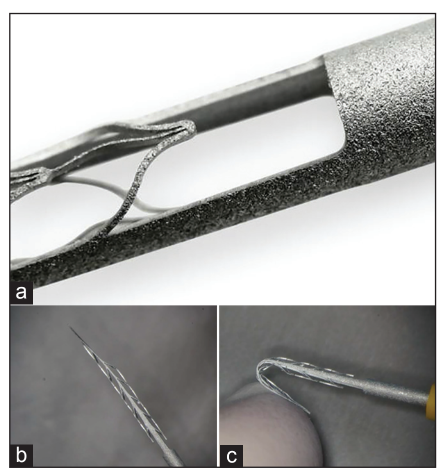

Figure 2: The Self-adjusting File. (a) The rough surface of the file. All components of the file have this rough surface. (b) The asymmetrical tip of the file. (c) Flexibility of the file. As this file is used as the final file, its flexibility should be compared to that of the last, largest file of any rotary file system

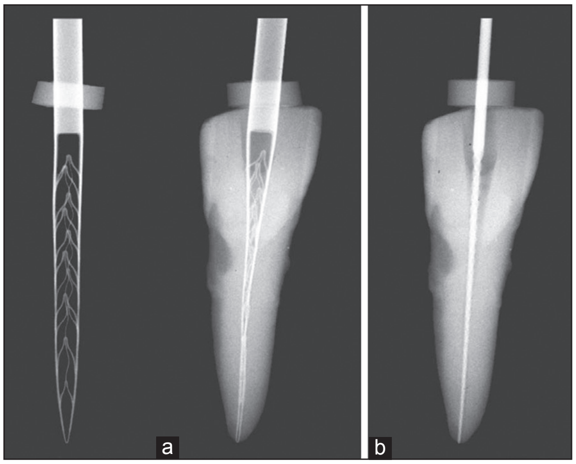

Figure 3: Compressibility of the SAF. Left: The file in its relaxed form. (a) The SAF inserted into a canal prepared by a #20 K file. (b) The #20 K file with which the canal was prepared

operated with in-and-out vibrations created by the RDT handpiece-head.

The RDT handpiece-head

The RDT handpiece-head [Figure 5] has a dual mechanical function. It turns the rotation of the micro-motor into a trans-line in-and-out vibration with an amplitude of 0.4 mm. It also contains a clutch mechanism that allows the SAF to rotate slowly when not engaged in the canal but completely stops the rotation once the file is engaged with the canal walls. The micromotor is operated at 5000 rpm, which results in 5000 vibrations/min, and the operator uses pecking motions when using the SAF. Free rotation of the file should occur at every out-bound part of every pecking stroke, when the SAF file is disengaged from the canal walls. This is required to ensure that when the SAF enters the canal during the in-bound pecking motion, it will do so at a different, random circular position every time, thus ensuring uniform treatment of the canal walls.[20,22,24] This random circular position also allows the asymmetrical tip of the file to negotiate curvatures that may be found in the root canal. RDT heads are available in several configurations and may be adapted to a large variety of endodontic motors/handpieces [Figure 5].

The VATEA irrigation pump

The VATEA (ReDent) [Figure 6a] is a self-contained peristaltic pump with a built-in irrigant reservoir of 500 mL operated using a foot switch and powered by a rechargeable battery.[20] The SAF file is provided with a freely rotating hub connected to a polyethylene tube [Figure 7], thus allowing for flow of the irrigant through the hollow file and into the root canal. The irrigant can be delivered into the tube at a rate ranging from 1-10 mL per minute, with the typical recommended setting of 4 mL per minute.

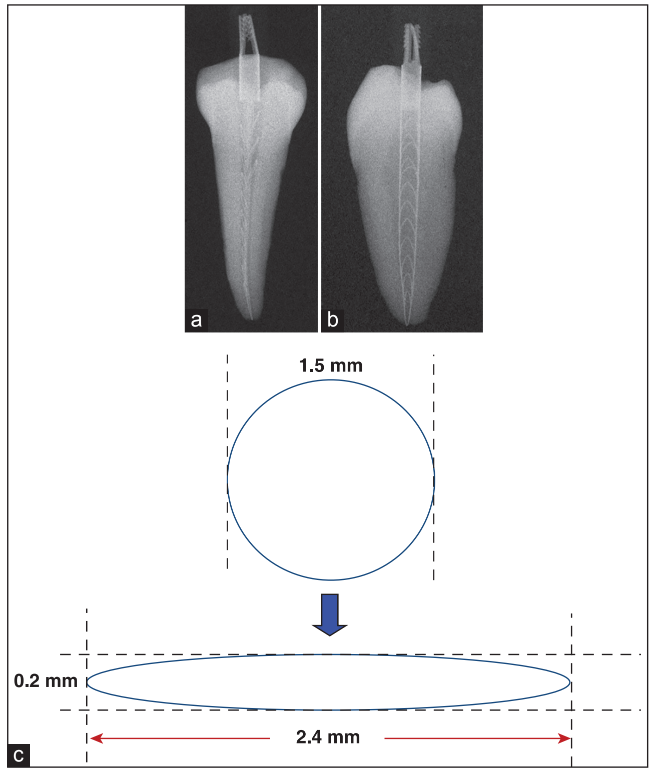

Figure 4: Adaptation of the SAF to an oval cross-section. The SAF inserted into a premolar with an oval cross-section. (a) Buccolingual projection: The file is narrower than when relaxed. (b) Mesiodistal projection: The file is wider than when relaxed. (c) When a file with a 1.5 mm diameter is inserted into a canal with a mesiodistal dimension of 0.2 mm, it will spread buccally and lingually, assuming a buccolingual dimension of 2.4 mm. This will happen even when the operator is not aware that the canal is oval, hence the name "Self-adjusting File"

The EndoStation: An all-in-one endodontic unit

The EndoStation (ReDent and Acteon) [Figure 6b] is a compound machine specifically designed for the SAF that uses a special RDT handpiece. Nevertheless, it can also be operated using a conventional handpiece with either rotary or reciprocating files. The EndoStation is equipped with a peristaltic pump that enables continuous irrigation when used in "SAF mode". An external bottle is used as the irrigant container of the EndoStation, from which the irrigant is drawn by the peristaltic pump into the tube and through it to the attached file. When used in "SAF mode", both the micromotor and the irrigation pump are simultaneously operated using a single foot pedal.

No-pressure irrigation with scrubbing

Syringe and needle is the most common irrigation method. This method uses positive pressure to get the irrigant to the WL and consequently involves the risk of a "sodium hypochlorite accident" in which the irrigant is passed beyond the apex. Negative pressure systems, such as

Figure 5: The RDT handpiece-heads. (a) RDT3 head. (b) RDT3-NX head with an NSK adaptor, attached to an X-Smart endomotor

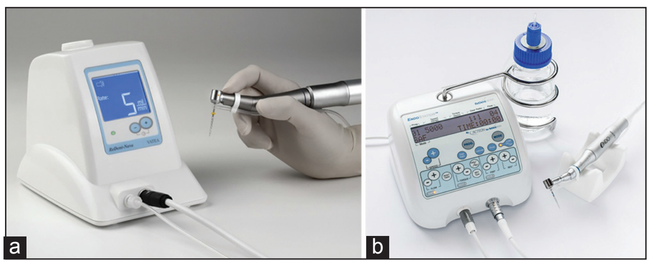

Figure 6: SAF System irrigation pumps. (a) The VATEA irrigation pump. (b) The all-in-one Endostation machine. This endomotor can be used in SAF, rotary, and reciprocation modes. When operated in SAF mode, the peristaltic pump delivers the irrigant through the tube and into the file

Figure 7: Irrigation tube connector on the SAF. A freely rotating hub on the SAF is provided with a connector for the irrigation tube

EndoVac (SybronEndo), were designed to overcome this problem by using negative pressure to draw the irrigant to the apical part of the canal.[29-32] In both the concepts described above, the irrigation is applied intermittently, only when the file is withdrawn from the canal.

One should remember that sodium hypochlorite is gradually inactivated as it acts to dissolve the pulp tissue or bacterial biofilm.[33-35]

When pulp tissue is inserted into a test tube containing sodium hypochlorite, the tissue is quickly dissolved.[36,37] Under these conditions, the volume of sodium hypochlorite is infinitely larger than that of the pulp tissue; therefore, the inactivation of the solution may not be noticeable. However, *in vivo*, in the presence of pulp tissue and/or bacterial biofilm, the action of sodium hypochlorite on such substances consumes, weakens, and inactivates the sodium hypochlorite.[38]

When placed in a root canal, the volume of sodium hypochlorite is rather limited (approximately 10 μL in the maxillary central incisors), and when pulp tissue or bacteria is present, the sodium hypochlorite may thus be quickly consumed and inactivated. Therefore, simply flooding the canal with sodium hypochlorite during the procedure may be ineffective; frequent replacement of the irrigant is commonly suggested to maintain the desired activity.[38,39] During syringe and needle irrigation, fresh fully active sodium hypochlorite may be present, but only up to 2 mm from the distance at which the needle can be inserted at that time point of instrumentation. This means that as long as the needle cannot be safely inserted to WL, no fully active sodium hypochlorite will be present at the apical part of the canal.[40] Any sodium hypochlorite that seeps into this area will be readily inactivated. Thus, during traditional endodontic procedures with intermittent irrigation, the total time that fully active sodium hypochlorite is present at the apical part of the canal is limited.

Additionally, the size of the canal is also a limiting factor for the use of negative pressure irrigation during the instrumentation process. Fully active sodium hypochlorite can only reach the apical part of the canal when this area is enlarged sufficiently, enough to insert the micro-cannula to WL.

The SAF System may be defined as a no-pressure irrigation system that is applied throughout the instrumentation process.[20,22,41] Once the irrigant enters the SAF, any pressure that may have existed in the delivery tube disappears due to the lattice structure of the file. The irrigant is continuously delivered into the root canal, and the vibrations of the file combined with the pecking motion applied by the operator result in the continuous mixing of the irrigant that is present in the root canal with fresh, fully active irrigant. This mode of action raises two questions:

a. will the freshly applied irrigant be able to reach the apical part of the canal?; and
b. what is the potential of the pecking motion, applied all the way to the working length, to push the irrigant beyond the apex?

The setup in Figure 8 was used to answer the first question. The simulated canal in the transparent block was filled with green liquid, representing the irrigant that is present in the canal. The SAF was operated in the simulated canal with vibrations and pecking motion. At a given time, red liquid representing fresh, fully active sodium hypochlorite was injected into the tube, and the time required for the apical part of the canal to turn completely red was measured. Total replacement of the irrigant in the apical part occurred within 30 seconds. Thus, when using the SAF for 4 min, as required by the manufacturer's instructions, the sodium hypochlorite in the apical part of the canal is replaced with fresh, fully active solution at least 8 times; this replacement occurs continuously throughout the process.

The setup in Figure 9 was used to answer the second question. The tooth was mounted in the bottom of a plastic container with its tip protruding below the container. The canal was prepared to the working length with a #20 K file, and the patency of the apical foramen was verified by passing a #15 K file through it [Figure 9a]. The SAF was used in the canal for 4 min with continuous irrigation, vibrations, and pecking motion and the apical foramen was checked visually for any liquid passage. No liquid passed through the apical foramen throughout the procedure [Figure 9b]. When syringe and needle irrigation was applied immediately after the SAF and the needle was kept at 5 mm distance from the WL, the liquid passed freely beyond the apex [Figure 9c].

Why did the pecking motion not cause liquid extrusion while the syringe and needle kept away from the apical foramen cause a free flow? Fluid mechanics analysis provides the answer to this question.[28] Even with a much larger apical foramen with a diameter of 0.35 mm, the liquid in the canal is kept contained by surface tension. The bursting pressure needed to break this surface tension is 832 Pa. The hydrostatic pressure of a 20-mm column of water is 195 Pa, the stagnating pressure caused by 5000 vibrations per min within the liquid is 196 Pa, and the piston pressure caused by the SAF pecking motion is only 3 Pa. Therefore, the total pressure in the root canal (394 Pa) is not large enough to reach the bursting pressure, and the liquid stays contained in the canal.[28]

The reason why such a low piston pressure results from the apical motion of the SAF is demonstrated in Figure 10. Even in the extreme case where the diameter of the apical part of the canal is 0.2 mm (created by a #20 K file), the fully compressed tip of the SAF has a rectangular cross-section (0.16 mm × 0.12 mm) [Figure 10]. This leaves 38% of the canal cross-section free for backflow of the irrigant and therefore results in a very ineffective piston.[28]

In a canal similar to that described above, syringe and needle irrigation, where the needle is kept in a position in which 38% of the canal cross-section is also free for back flow, results in a pressure of more than 1270 Pa. This pressure is generated by the flow of liquid, even though the needle is not tightly fitted to the canal walls. This brings the total pressure in the canal above the eruption pressure and allows for the free passage of liquid.[28]

The experiment described above was conducted in a canal with an open apical foramen and with the apex surrounded only by air. One may assume that if no liquid passed even under these conditions, the chance that the irrigant will be pushed beyond the apex when SAF is used under clinical conditions, with the apex surrounded by tissue, is rather low.[42]

In this context, it is interesting to note that when a #20 hand file is pushed towards the apex in a tight canal with a 0.2 mm diameter, the calculated piston pressure may reach the range of hydraulic pressure: 199,700 Pa. This, in turn, may explain some of the post-operative pain that patients often experience after hand file instrumentation; such high pressure likely pushes a small volume of irrigant beyond the apical foramen.[28]

The scrubbing effect

All other irrigation systems rely on the chemical action of the sodium hypochlorite irrigant, the streaming motion of the irrigant, or both.[29,30,32,43-47] Enhanced motion of the irrigant in the canal either by enhancing its flow or by inducing acoustic streaming in it has been used to improve the cleaning action of the irrigant.[30,32,43-47] Nevertheless, there is a more effective way to clean surfaces of materials that are attached to them: Mechanical scrubbing.[41]

The model in Figure 11 clearly illustrates the issue. The burnt porridge on the bottom of the pot represents either pulp tissue remnants or an established bacterial biofilm, tightly attached to the walls of the root canal. In a canal that is subjected to retreatment, remnants of an old root filling may represent another material that is a challenging target for cleaning.[48-54]

A simple stream of liquid is unlikely to remove the burnt porridge effectively. The addition of chemical agents to attack the burnt layer may help, but will take a long time to become effective. Mechanical scrubbing of the surface [Figure 11c and d] is the most effective way to clean such a surface within a few minutes.

The SAF has a scrubbing mode of action similar to that of the metal scrubbing pad used in the model above. The metal mesh of the SAF wall is intimately adapted to the canal wall and is continuously in motion, thus providing a scrubbing effect. The combination of scrubbing with the continuous flow of fresh, fully chemically active sodium hypochlorite results in highly effective cleaning of the canal walls from any attached materials.[23,41,55-57]

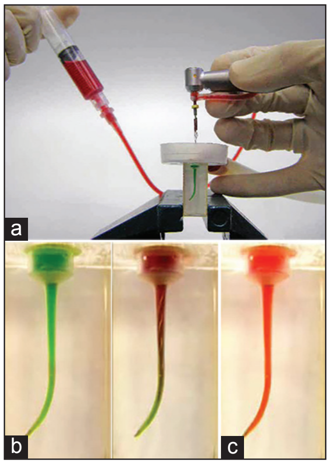

Figure 8: Rate of irrigant exchange. An experimental setup: The canal in the block is filled with green liquid and the SAF is operated in the canal with an in-and-out pecking motion, at 5000 vibrations per min. At a given time point, a red liquid is injected into the irrigation tube. The time until the green liquid in the apical part (b) turns completely red (c) is measured. The red liquid represents fresh, fully active sodium hypochlorite. The time until full exchange of the irrigant occurred in the apical part was 30 s. During the recommended operation time of 4 min, the irrigant is fully replaced in the apical part of the canal 8 times

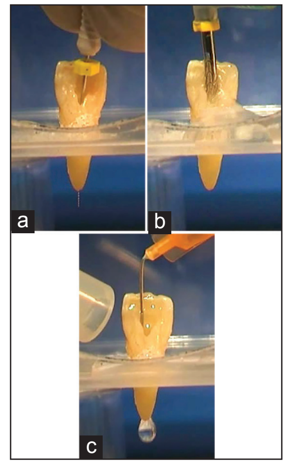

Figure 9: Irrigation to the working length with no extrusion. An experimental setup: (a) The canal is prepared with a #20 K file to a working length 1 mm short of the apex. Patency is verified with a #15 K file. (b) The SAF System was used for 4 min with pecking motions that reach the WL at 5000 vibrations per min. No passage of irrigant beyond the apex occurred. (c) Syringe and needle irrigation of the same canal, after the SAF operation. Although the needle is far from the WL and free in the canal, the irrigant passes freely due to the pressure created by the stream of irrigant emerging from the needle

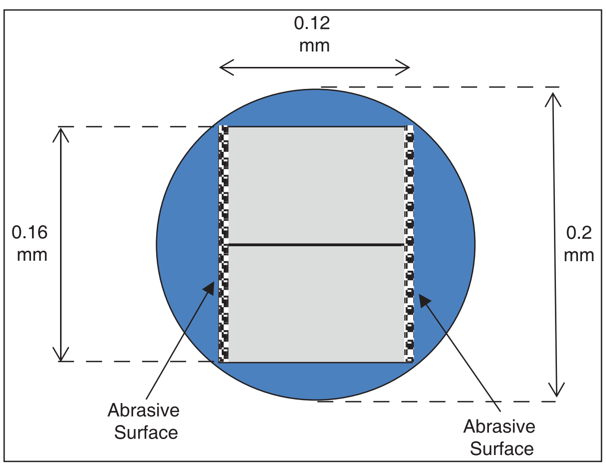

Figure 10: The apical part of the canal containing the SAF. A schematic representation. The canal was prepared with a #20 K file and has a 0.2 mm diameter. The fully compressed tip of the SAF has a rectangular cross-section with 0.12 mm × 0.16 mm dimensions. This leaves 38% of the cross-section of the canal free for backflow of the irrigant. Consequently, the SAF creates no piston action in the canal and no extrusion of the irrigant occurs. (Adapted from Hof *et al*. 2010)[28]

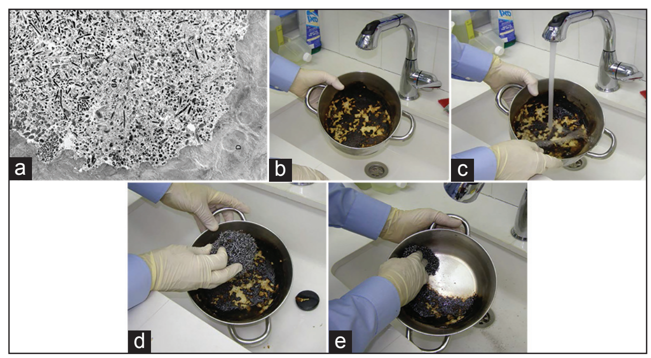

Figure 11: Mechanical scrubbing. (a) Bacterial biofilm tightly attached to the canal dentin wall. The biofilm was not removed by copious irrigation with sodium hypochlorite that was applied with syringe and needle irrigation in this clinical case. (b) A model: The burnt porridge is tightly attached to the bottom of the pot, representing either a biofilm or pulp tissue remnants. (c) A stream of liquid is unlikely to remove the tightly attached material. (d and e) A metal scrubbing pad is extremely effective in removing the tightly attached material. The SAF cleans the canal walls with a scrubbing motion, equivalent to the action of the metal scrubbing pad. ("a" is adapted from Nair *et al*. 2005)[75]

Furthermore, such scrubbing can also be effectively applied beyond the canal curvatures, which is a limiting factor for passive ultrasonic irrigation (PUI) and negative pressure irrigation systems such as the EndoVac. PUI may be ineffective beyond the point at which the ultrasonic file touches the wall of the canal at a curvature. The negative pressure systems require apical preparations as large as #40/.04 or #40/.06 to be effective,[58] but such apical preparations may endanger the integrity of the root in curved canals.[15,59,60]

The effectiveness of cleaning the root canal has been studied using scanning electron microscopy (SEM).[61-66] All such studies indicate that the coronal and mid-root thirds of the canal can be reproducibly cleaned. However, the situation is different in the apical third of the canal. Almost all SEM-based studies indicate that the cul-de-sac area of the apical part of the canal is not readily cleaned.[61-66] Debris is usually found in the apical part of the canal and, even when EDTA was used for the final irrigation, most of the apical area was covered with a smear layer. When sodium hypochlorite and EDTA were used, the unique mode of action of the SAF resulted in apical parts of canals that were clean of debris in all cases and in 65% of the cases, also free of the smear layer[23,41,55] [Figure 12].

3D CLEANING AND SHAPING OF ROOT CANALS

The clinical result of the cleaning, shaping and obturation of root canals is commonly evaluated from periapical radiographs. One should keep in mind that periapical radiographs are only a 2D projection of the 3D reality. Taking such projections as true representations of the 3D shape is similar to comparing the 2D projections of a cylinder, a sphere, and a flat round disk, all of which have the same diameter; unless 3D observation is possible, one may be led to believe that all three are the same object.

When rotary files are used in an oval canal, the resulting radiograph may look nice [Figure 13] but may be meaningless in terms of adequate 3D cleaning and obturation of the root canal. The long-oval canal in Figure 13a was instrumented with rotary files. The buccal view shows a satisfactory preparation [Figure 13b], but the mesial view reveals the true condition of the root canal [Figure 13c].

Such discrepancies may often result in failure in clinical cases [Figure 13d and e]. The radiograph [Figure 13d] shows generous instrumentation and adequate obturation but the case failed clinically. When treated surgically the reason for failure became clear: Inadequate cleaning and inadequate obturation of the canal [Figure 13e].

Therefore, tools other than periapical radiographs should be applied for more realistic evaluation of the 3D cleaning, shaping, and obturation of root canals.

One such tool is micro-computed tomography (micro-CT). This tool has numerous benefits: Micro-CT allows for the comprehensive evaluation of the entire root canal as opposed to the simple slices produced with a diamond saw, as well as the ability to conduct computerized evaluations and measurements at a high resolution.

This tool was used to evaluate and compare the shaping ability of the rotary file systems *vs.* the SAF System. The common parameter used in such studies is the “percentage of the canal wall unaffected by the procedure”.[5,9,12,24,67] The assumption made in such studies is that wherever a layer of dentin had been removed by the file, anything that was attached to the wall had also been removed, be it pulp tissue or bacterial biofilm. When a dentist is instrumenting a root canal, his goal and expectation is that the entire canal surface is instrumented. When round, narrow, and straight canals are instrumented with rotary files, such complete instrumentation of the entire canal wall is possible. The situation is quite different in oval canals and in curved canals, such as those found in maxillary molars and in the mesial roots of mandibular molars.

3D cleaning and shaping of oval canals

Even though a random set of 2D periapical radiographs will not reveal this, oval canals are quite common. Such canals may be found in 25% of all roots, and in certain types of teeth, the incidence of oval canals may be as high a 90%.[68] When scans generated with Cone-Beam Computed Tomography (CBCT) are presented in an axial view, the presence of oval canals is rather obvious [Figure 14]. Paqué *et al*. studied the efficacy of shaping oval root canals in the distal roots of mandibular molars and found that when ProTaper files were used with circumferential motion and brushing, 69% of the canal wall was unaffected by the procedure.[9] This is far from what a dentist expects and intends when performing root canal treatment in such roots. When SAF was used in similar canals, with the results studied and evaluated by the same team using the same methods, 23% of the canal wall was unaffected by the procedure.[12] This is not a perfect result, but is much closer to what the operator has in mind when performing root canal treatment in such canals. Similar results were reported by Metzger *et al*., further showing the efficacy of the SAF System in removing a uniform layer of dentin from the walls of an oval root canal without machining the canal to generate a round cross-section with the hope of including the entire perimeter of the canal within the preparation.[20,22] [Figure 15].

A recent study Versiani *et al*.[69] attempted to check whether rotary files could achieve a similar result to the SAF in oval canals.[69] To achieve similar results, this required providing the rotary files with every handicap possible, including:

a. De-coronation of the canines followed by funneling the coronal third of the canal with stainless steel burs;
b. Using thick, rigid rotary files (WaveOne #40/.08, Reciproc #40.06 and Protaper Universal F4);
c. Using an incorrect 1.5-mm SAF file in canals requiring a 2.0-mm SAF file.[69]

If a 2.0-mm SAF file was used and de-coronation was not applied, the superiority of the SAF would likely have been demonstrated, with greatly decreased unnecessary removal of sound dentin.

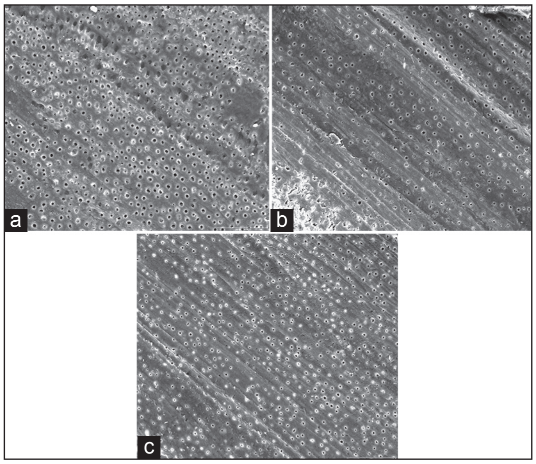

Figure 12: SEM of a root canal treated with the SAF System. (a) Coronal part of the canal. (b) Middle part of the canal. (c) Apical part of the canal. All of these images are at 500× magnification. Canals were treated with the SAF system, with sodium hypochlorite and EDTA used as irrigants. All of the coronal and mid-root surfaces were clean of debris as well as of the smear layer. All of the apical parts of the canals were also free of debris, and in 65% of the cases, they were also free of the smear layer (Adapted from Metzger *et al*. 2010)[23]

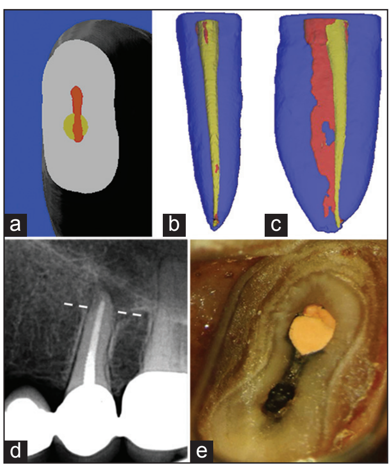

Figure 13: The illusion of evaluating root canal instrumentation and filling by 2D periapical radiographs. (a-c) A long-oval root canal that was instrumented using rotary files. Red: Before; yellow: After. (a) A cross-section, 5 mm from the apex. Note the round preparation and the un-instrumented "fin". (b) Buccal view of the same root canal: This preparation, when obturated, is likely to produce a nice periapical radiograph. (c) Mesial view of the same root revealing the extent of the un-instrumented "fin". (d and e) A clinical case (courtesy of Dr. Amir Weisman, Tel Aviv). (d) Left maxillary second premolar with apparently adequate preparation and obturation. The case failed clinically. Apical surgery (sectioning along the dotted line) revealed the reason for failure

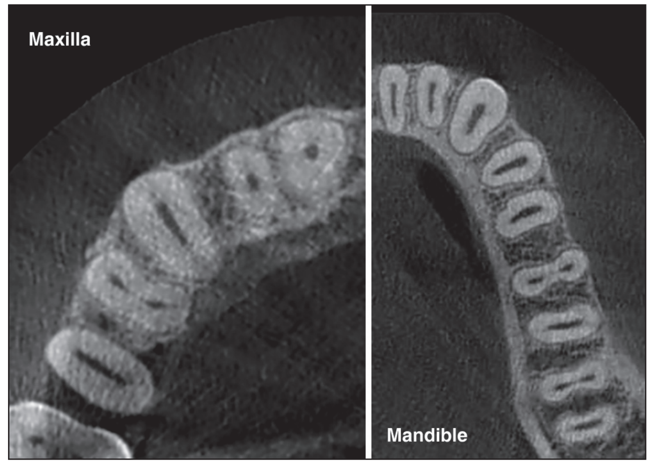

Figure 14: Oval canals. An axial view of CBCT often reveals the true cross-section of the canals. Maxillary canines and second premolars commonly have oval canals. Mandibular incisors, canines, and premolars, as well as distal roots of molars, commonly have oval canals

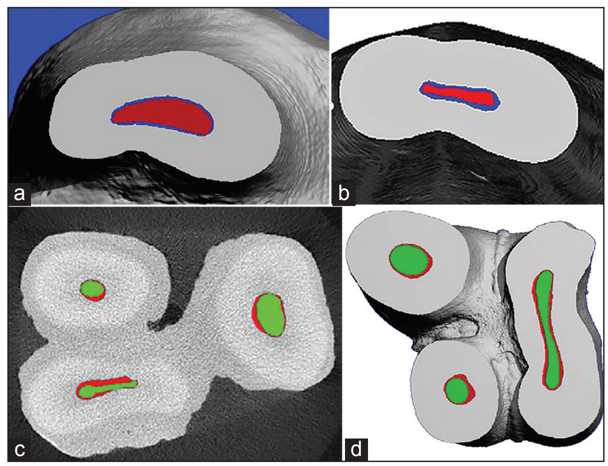

Figure 15: Minimally invasive instrumentation of root canals. (a) An oval canal of a distal root of a mandibular molar. (b) A long-oval canal of a maxillary second premolar. Red: Before; blue: After instrumentation with the SAF. Note the uniform dentin layer that was removed from the entire perimeter of the canal, with no attempt to machine the canal into a round cross-section (adapted from: Metzger *et al*. 2010).[20] (c) A maxillary molar instrumented with the SAF System. Green: Before; red: After. Note that the slightly oval palatal canal and the extremely oval mesiobuccal canal were prepared with the SAF according to their original shape (adapted from Peters and Paqué 2011).[24] (d) An extremely oval palatal canal that was prepared with the SAF. Green: Before; red: After. A uniform layer of dentin was removed from the entire canal perimeter. The round buccal canals were prepared as round canals (adapted from Solomonov 2011).[96] Note that any attempt to machine the oval canals in "a", "b" and the palatal canal in "d" to a round cross-section would have led to extreme removal of sound dentin while failing to clean the canal

C-shaped canals

C-shaped canals represent the most complicated and challenging case of flat oval canals.[70] Such canals are found in 5-7% of second mandibular molars in populations of Caucasian origin.[71] However, in populations of Chinese origin, the incidence is as high as 52%.[72] Rotary instrumentation has great limitations in these challenging root canal systems.[27] However, the SAF system may handle such extreme cases of flat oval canals with greater efficacy[27] [Figure 16]. Furthermore, C-shaped canals also often present with a hidden "danger zone" in which the SAF mode of instrumentation is much safer (see below).

Isthmuses

Roots that contain two canals in a single root may often contain an isthmus connecting the two canals.[73] Cleaning and obturation of such isthmuses has remained a major challenge without a satisfactory solution.[74,75] If the isthmus is wide, with a thickness of more than 0.2 mm, it may be treated effectively by the SAF system, similar to the way C-shaped canals are treated (see above). However, narrow long isthmuses with thicknesses lesser than 0.2 mm, represent a limiting factor even for the SAF System.

When fully flattened, a SAF with a 1.5 mm diameter may assume a mesiodistal dimension of 0.2 mm. Thus, a SAF cannot enter into and/or clean isthmuses thinner than 0.2 mm. One should keep in mind that a 0.1-mm thick isthmus may contain a substantial biofilm approximately 100-bacterial cells thick. In such narrow isthmuses, the SAF can be expected to clean the entrance to the isthmus and avoid packing debris into the opening (see below). Such narrow isthmuses represent a limitation even for the SAF adaptive technology.

Packing canal recesses with debris

Recently, the challenge of cleaning and shaping of oval canals and isthmuses has been further complicated.[76-78] A study by Paqué *et al*. indicated that rotary instruments tend to pack the isthmus with dentin chips actively[76,77] [Figure 17]. This phenomenon can be easily explained: When a rotating instrument removes dentin chips and tissue debris, the chips and debris are more readily and easily pushed sidewise into a non-resisting isthmus or into a fin-like recess [Figure 18] rather than carried coronally or packed tightly within the instrument flutes. One should keep in mind that such isthmuses or recesses are not usually empty: They generally contain either pulp tissue or a bacterial biofilm. Pushing dentin chips into either of these soft substances likely forms a composite of dentin chips embedded in pulp tissue or bacterial biofilm. Indeed, such composites were found by Nair *et al*.[75] in isthmuses of the mesial roots of mandibular molars that were endodontically treated with rotary files; notably, these cases resulted in clinically satisfactory radiographic results[75] [Figure 19].

With this in mind, it is easy to understand the results showing that attempts to remove the material packed into such isthmuses have been of limited efficacy.[77,78] Paqué *et al*.[77] found that neither conventional irrigation methods nor passive ultrasonic irrigation could remove all of the radiopaque material packed into the isthmus by the action of a rotary nickel-titanium file.[77] Even with passive ultrasonic irrigation, 50% of the packed dentin particles remained in place. A similar effect likely occurs in long-oval canals containing untreated longitudinal "fins"[13] [Figure 18]. Consequently, such lateral packing of debris may explain the limited efficiency of the disinfection and obturation of such flat-oval canals that were treated using rotary files (see below).[10,11,79-81]

It is conceivable that in the case of infected canals, the packed composite of dentin chips and biofilm protects the bacteria in the inner parts of the isthmus or fin from the action of the sodium hypochlorite irrigant, thus explaining the results of Siqueira *et al*.[10] (see below). In both vital and infected root canals, a composite of dentin chips and pulp tissue or biofilm may (a) prevent the root canal filling from entering these occluded areas[11,79-81] and (b) later serve as a potential place for bacterial growth and proliferation either from the original bacteria that survived there or in vital cases once leakage has occurred.

The SAF works in a totally different manner than rotary instruments.[20,22,28] It does not rotate in the canal and does not cut the dentin. The gentle abrasive action of the SAF file removes a layer of dentin by converting it into a thin powder that is continuously suspended and carried coronally by the flow of the irrigant. The SAF system produces no cut dentin chips and therefore does not have the tendency to pack such chips into the isthmus. It is not surprising, then, that a recent study has shown that packing of the isthmus with dentin particles by the SAF is almost negligible: 1.7% of the isthmus volume is packed with dentin by the SAF *vs.* 10.1% by rotary files[78] [Figure 20].

3D cleaning and shaping of curved canals

Curved canals are common in maxillary molars and in the mesial roots of mandibular molars. Apparently, rotary nickel titanium files should have the greatest benefit in such canals. Nevertheless, several micro-CT studies have shown that even though rotary nickel titanium files can negotiate curved canals, their ability to clean such canals is limited.[5,24,82]

When the evaluation of a case is limited to periapical radiographs, one may be misled to ignore the actual 3D result. If a rotary file could negotiate a curved canal to the extent of allowing the insertion of a master cone or a thermo-plasticized obturator, it would give a good radiographic impression. However, such evaluation ignores the 3D reality of the canal. When Peters *et al*.[5] used micro-CT to study the performance of ProTaper in curved canals of maxillary molars, the real 3D reality was revealed. In the mesiobuccal and distobuccal canals, 43%

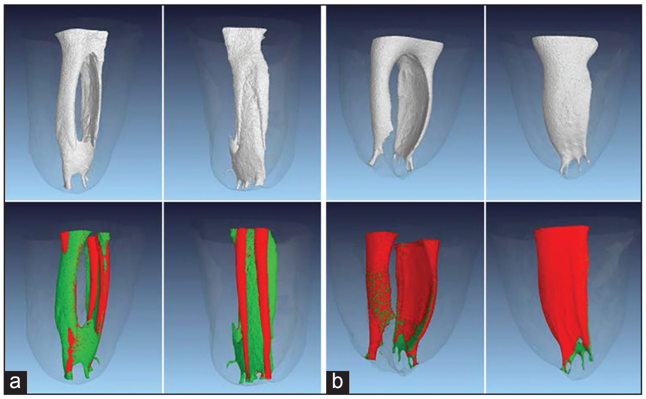

Figure 16: C-shaped canals instrumented with SAF *vs*. rotary files. (a) C-shaped canal instrumented with the ProTaper. Green: Before; red: After. (b) C-shaped canal instrumented with the SAF. Green: Before; red: After. Note that the SAF removed a uniform layer of dentin from most of the canal surface, while the rotary file instrumentation prepared a space for the master cones while failing to address the extremely complex oval shape of the canal (adapted from Solomonov *et al*. 2012)[27]

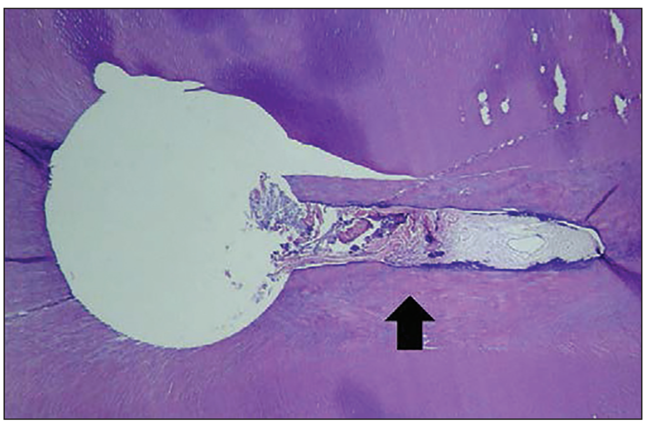

Figure 18: Packing of a "fin" with dentin particles. Mandibular canines with oval canals and vital pulp were treated with a rotary file (the ProTaper), with copious irrigation with sodium hypochlorite applied with syringe and needle. Note the intact vital pulp in the deep part of the un-instrumented "fin", which was likely to be protected from the action of sodium hypochlorite by the dentin chips that were packed into the "fin" entrance by the rotating files (arrow) (adapted from DeDeus *et al*. 2011)[13]

and 33% of the canal wall was unaffected by the procedure, respectively.[5] Furthermore, even in the palatal canal, considered as an easier canal to treat, 49% (± 29%) of the canal wall was unaffected by the procedure.[5] Additionally, the relatively high standard error indicates that the results are unpredictable: In some cases, the results were better than 49% while in others, they were worse.

Similar results were also obtained in other studies: A high percentage of the curved canals wall was unaffected by the instrumentation, with a relatively high standard

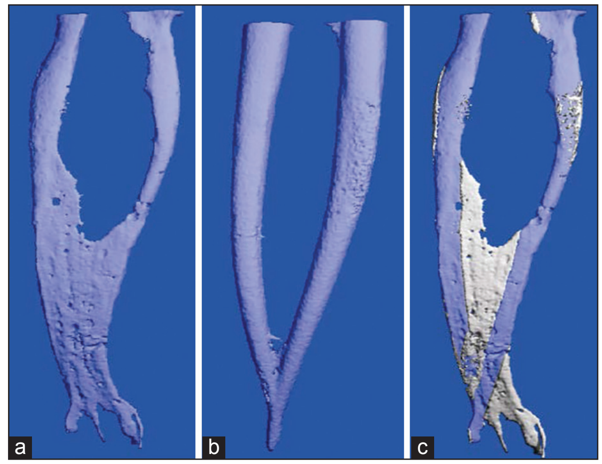

Figure 17: Packing an isthmus with radiopaque debris. The radiolucent space of a mesial root of a mandibular molar with two canals connected by an isthmus. (a) Before treatment. (b) After treatment with rotary files. Nice preparations, but the isthmus disappeared due to active packing of the isthmus with radiopaque dentin particles. (c) The volume of the isthmus that disappeared (white) due to packing with dentin particles (adapted from Paque *et al*. 2009)[76]

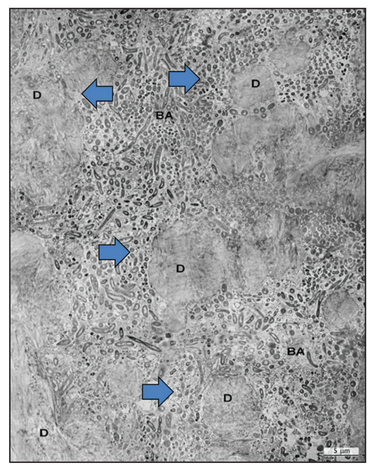

Figure 19: Dentin particles packed into bacterial biofilm in an isthmus. A mesial root of a mandibular molar was treated endodontically and clinically, gave a radiographically satisfactory result. The tip of the root was then surgically removed and subjected to transmission electron microscopy. Note the bacterial biofilm that remained in the isthmus, unaffected by the action of sodium hypochlorite and the dentin particles (arrows) that were pushed into the isthmus by the rotary files (adapted from Nair *et al*. 2005)[75]

error.[82] The results of several such studies, all of which used the same methodology, were reviewed by Paque *et al*. [Figure 21].[82]

When SAF files were used in similar curved canals and the result were analyzed using the same methodology, the percentage of the canal wall that was unaffected by the procedure dropped to 25% (± 11%).[24] This is not a perfect result, but is certainly improved:

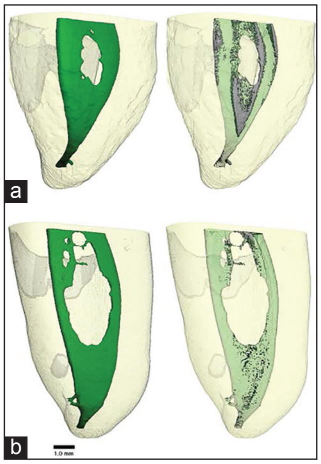

Figure 20: Packing of dentin particles into an isthmus: Rotary file *vs.* SAF. Mesial roots of mandibular molars that contained two canals connected by an isthmus were treated with either (a) rotary files with syringe and needle irrigation or (b) the SAF System with its continuous irrigation. Left: Before instrumentation; right: After instrumentation. Gray: Area of the isthmus that was radiolucent before and turned radiopaque after instrumentation due to the packing of dentin particles. Note the massive amount of packed debris in the rotary files-treated case compared with the limited amount in the SAF-treated case. The SAF file does not rotate in the canal and does not cut dentin chips. The SAF removes dentin from the walls as a thin powder, which is suspended in and carried out by the continuous flow of irrigant, thus avoiding the packing phenomenon (adapted from Paque *et al*. 2012)[78]

a. It is much closer to what the operator has in mind when treating such canals and
b. The smaller standard error indicates that the result is more predictable than that achieved with rotary files [Figure 21].

DISINFECTION OF OVAL CANALS

Disinfection of the root canal is a central concept in endodontic treatment of infected cases. In a series of studies conducted in straight, round canals, Siqueira and his co-investigators have found that most instrumentation and irrigation systems do not differ from each other in terms of disinfection efficacy.[83,84] Nevertheless, the situation is quite different concerning oval root canals. When infected oval root canals were subjected to treatment with rotary files with syringe and needle irrigation, 55% of canals still harbored viable bacteria after completion of the procedure.[10] When the SAF System was used in similar canals, positive cultures were found in only 20%.[10] This difference can easily be understood when looking at Figure 22, adapted from the study described above. The untreated recesses may have harbored bacteria that were likely to be further protected from the effects of sodium hypochlorite by dentin-chip-containing debris that was

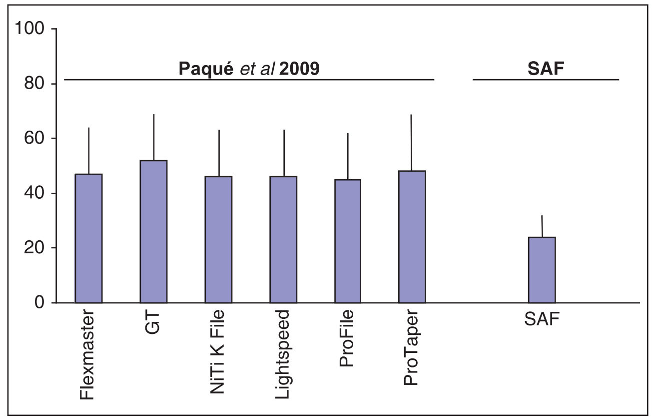

Figure 21: Limited efficiency of instrumentation of curved canals of maxillary molars. Percentage of the canal wall that was unaffected by instrumentation. When curved canals of maxillary molars were treated, all rotary and hand instruments tested resulted in 45-50% of the canal wall unaffected by the procedure, with a relatively large standard deviation (adapted from Paque *et al*. 2009).[82] The SAF resulted in 23% of the wall unaffected and a smaller standard deviation, giving both a better and more predictable result

most likely packed into the entrance of the recess by the rotary file (see above).

In a further study from the same laboratory, Alves *et al.* demonstrated that the disinfection by the SAF system was both time- and sodium hypochlorite concentration-dependent.[16] The results of their study led Alves *et al*. to conclude the following: "Whether comparable results using the SAF after 6 minutes can be reproduced in the real clinical setting against a mixed bacterial community, this system holds the potential to significantly improve single-visit disinfection".[16]

A recent clinical study verified the high efficiency of the SAF System in the disinfection of naturally infected root canals.[85] The authors attributed this effect to both the mechanical action and the continuous flow of fresh, fully active irrigant.

A study by Paranjpe *et al*.,[86] in which a protocol similar to that used by Siqueira *et al*.[10] was used, found different results. They attributed this difference to what they considered lack of control of the apical enlargement by the SAF.[86] It is possible that if the 2.0-mm SAF was used rather than the 1.5 mm SAF that was used by them the results would have been different.

OBTURATION OF OVAL CANALS

A variety of obturation methods are available to the operator, starting with traditional lateral compaction and going through single cone methods, warm lateral compaction, warm vertical gutta percha compaction, injectable gutta percha and

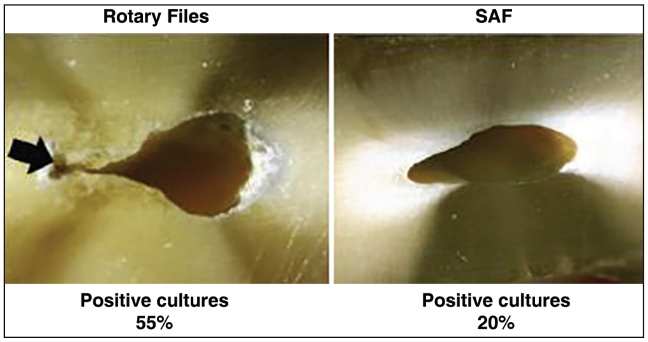

Figure 22: Rotary files *vs*. SAF in oval canals: Disinfection. Oval canals of mandibular incisors were treated with either rotary files with syringe and needle irrigation (left) or the SAF system (right). Of the canals treated with rotary files with syringe and needle irrigation, 55% still contained viable bacteria (positive cultures) after completion of the procedure. In the SAF-treated group, positive cultures were found in only 20% of the canals. The image of the cross-sections explains these findings. The un-instrumented area in "left", marked with an arrow, likely served as a sanctuary for the bacteria, which were protected from the action of sodium hypochlorite (adapted from Siqueira *et al*. 2010)[10]

obturators. Each of these methods assumes that the canal is clean, thus allowing the gutta percha and the sealer to come into intimate contact with all of the canal walls. As long as the canal is straight, round, and narrow, rotary file systems coupled with syringe and needle irrigation may produce a canal fitting this assumption. Nevertheless, when oval canals are cleaned and shaped using the method described above, major defects in obturation are often encountered.

DeDeus and co-investigators have shown that when rotary files were used, even the most flowable, thermo-plasticized gutta percha could not adequately fill the buccal and or lingual recesses that were (a) untouched by the rotary file and (b) likely packed with debris[79-81] (see above).

When comparing the obturation of pair-matched oval canals that were instrumented with either rotary files with syringe and needle irrigation or with the SAF System with continuous irrigation, a major difference was found, which could be attributed to the effective *vs*. ineffective cleaning of the root canals.[81] The debris that were packed and/or left in the uninstrumented buccal or lingual recesses clearly prevented the thermoplasticized gutta percha from entering these recesses [Figure 23]. In canals treated with the SAF System, no such debris were found and the gutta percha was well adapted to the entire circumference of the canal[81] [Figure 23].

Metzger *et al*. studied the correlation between the parameter of "percentage of the canal wall that was unaffected by the instrumentation" and the quality of adaptation of the root canal filling to the canal walls using microCT.[11] It was clearly demonstrated three-dimensionally that when a thin,

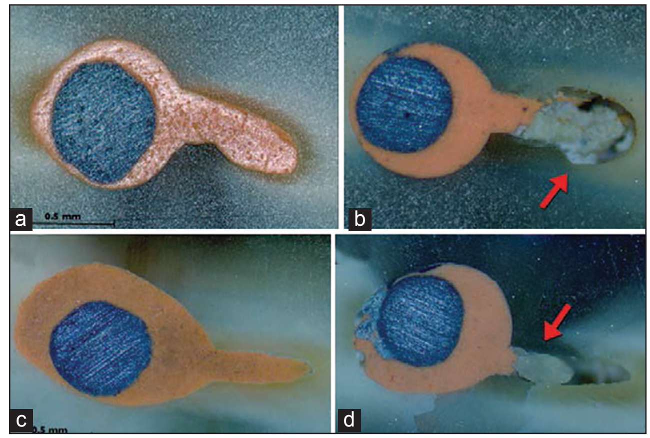

Figure 23: Obturation of canals treated with rotary files *vs*. SAF. Pair-matched oval canals were treated with either rotary files (the ProTaper) with syringe and needle irrigation or with the SAF System with its continuous irrigation. The total amount and the concentration of the irrigant used were similar. The root canals of both groups were then obturated with ThermaFill obturators, with no sealer. a and b are pair-matched root canals, as are c and d. a and c were treated with the SAF System, while b and d were treated with a rotary file and syringe and needle irrigation. Note that the debris left in or packed into the "fin" part of the canal in the rotary file-treated group prevented the flow of gutta percha into this area. The clean canals treated with the SAF System allowed for better adaptation of the root filling to the canal walls (adapted from DeDeus *et al*. 2012)[81]

uniform layer of dentin was removed from a high percentage of the canal wall, the 3D adaptation of the root canal filling to these walls was better than in canals cleaned and shaped with rotary files with syringe and needle irrigation, which presented a high percentage of canal wall unaffected by the procedure[11] [Figure 24].

INTEGRITY OF THE REMAINING RADICULAR DENTIN

A root canal-treated tooth is expected to serve the patient for many years. Therefore, any process that may jeopardize the integrity of the remaining radicular dentin must be avoided as much as possible. Two types of risks should be considered, as they may predispose the root to a vertical root fracture (VRF). One is excessive removal of sound dentin and the other is the creation of micro-cracks that may later propagate into full thickness fractures (VRFs).

The right "look" of root canal fillings has changed over the years. While massive enlargement of the root canal used to be an indication of good root canal instrumentation, this is looked upon negatively today. The excessive removal of radicular dentin has been recognized to weaken the root and therefore should be avoided.[87]

Including the whole perimeter of a root canal within the root canal preparation may be possible in straight, round,

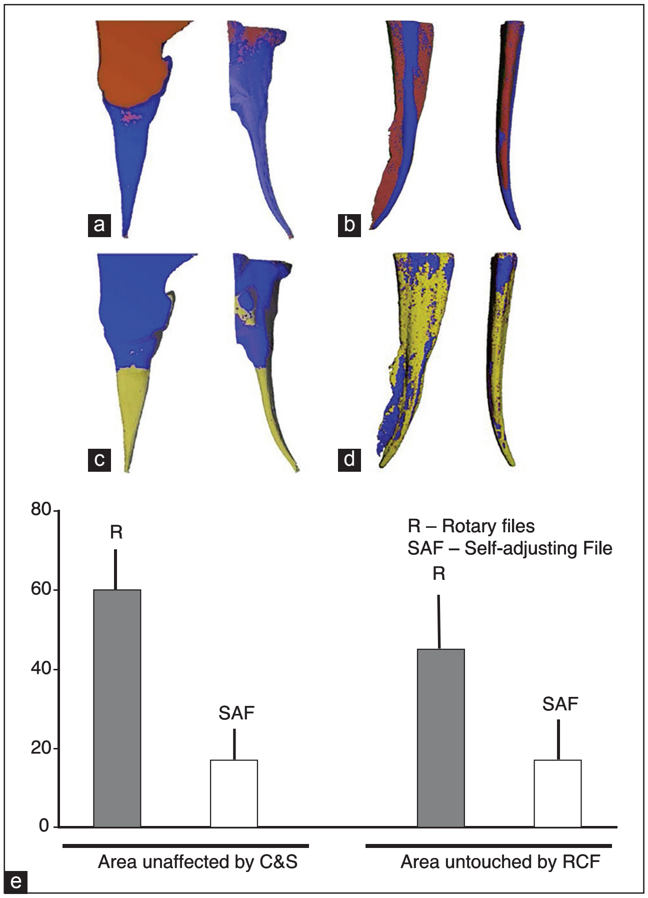

Figure 24: The effect of the quality of cleaning and shaping on root-filling adaptation. Root canals were treated with either rotary files with syringe and needle irrigation or the SAF System with continuous irrigation. Before and after, micro-CT scans were used to define the "percent of canal wall that was unaffected by the procedure". Obturation was performed using lateral compaction with a sealer, and a third scan was taken after obturation. The last two scans were used to define the "percent of canal wall untouched by the root filling". (a) Oval canal treated with the SAF; red: Before; blue: After instrumentation. Almost the entire wall was affected by the procedure. (b) Oval canal treated with a rotary file; red: Before; blue: After instrumentation. A high percent of the canal wall was unaffected by instrumentation. (c and d) Same canals as in "a" and "b" but after obturation. Blue: Area untouched by the root filling; yellow: Area touched by the root filling. Note the un-instrumented fin of "b", which is also likely not clean, as the sealer failed to enter this area (Blue in "d"). (e) The correlation between the two parameters: The rotary file-treated group had a higher percent of "area unaffected by cleaning and shaping" and, accordingly, had a high percent of "area untouched by the root filling". (adapted from Metzger *et al.* 2010)[11]

and narrow root canals. Attempts to do so using rotary files, in either curved or oval root canals, often leads to the excessive removal of sound dentin.

In curved canals, the thicker rotary files are likely to transport the apical part of the canal to the outer side of the curvature[5] [Figure 25]. In "S"-shaped canals, rotary instrumentation may

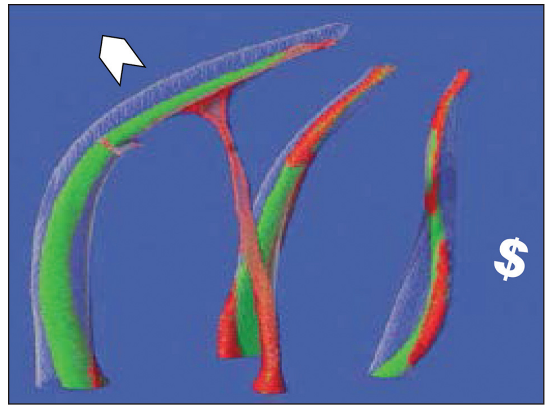

Figure 25: Canal transportation and canal straightening by rotary files. Maxillary molars were instrumented with rotary files (the ProTaper). While the thinner instruments (such as the S1) could likely follow the curvature or S-shape of the canals, the thicker instruments were more rigid and caused transportation of the palatal canal (arrow) and straightening of the S-shaped canal ($ sign). Both represent damage to the remaining dentin by the excessive removal of sound dentin. In both cases, the "percent of canal wall unaffected by the procedure" was also compromised (adapted from Peters *et al.* 2003)[5]

straighten the canal by excessive removal of dentin both at the inner side of the more coronal curvature and the outer side of the apical curvature[5] [Figure 25]. Both of the events described above occur due to the relatively high rigidity of the thicker rotary files, which is unavoidable due to their central solid metal shaft. The thinner rotary files are quite flexible, but those used in the final stages of the preparation are thicker and thus more rigid.

The SAF does not have a central metal shaft. It is extremely flexible and thus has much smaller tendency to transport or straighten curved and "S"-shaped canals [Figure 26].

When instrumenting canals in curved mesial roots of mandibular molars, one should also consider the "danger zone" on the distal side of such roots. A longitudinal depression often exists on the distal aspect of the root that cannot be recognized in a 2D periapical radiograph. Excessive enlargement combined with straightening at the curvature of the canal may lead to dangerous local thinning of the remaining distal dentin in that area, predisposing it to VRF when additional stress is applied during lateral compaction. Such unnoticed excessive removal of dentin may also lead to a "strip perforation" in this area.

The SAF uses a minimally invasive approach, removing only a thin uniform layer of dentin from the entire perimeter of the canal. This, combined with the lower tendency to straighten curved root canals, makes using the SAF safer in terms of maintaining dentin integrity.

The discrepancy between the apical size of many rotary files (i.e., size 25) and the actual cross-section of the apical part

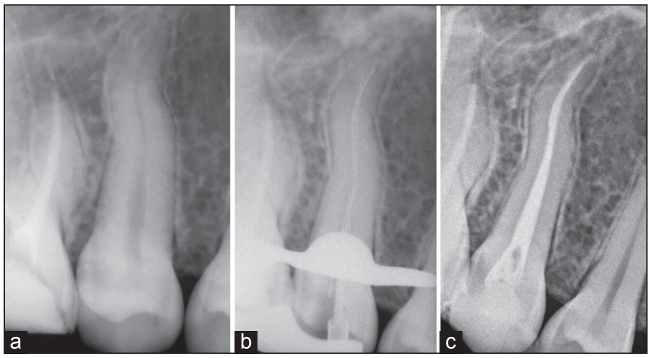

Figure 26: Preservation of S-shaped root canal anatomy. A clinical case (courtesy: Dr. Ajinkya Pawar, Mumbai, India). (a) S-shaped second right maxillary premolar. (b) SAF in the canal during preparation. (c) Obturated canal. Note that the S-shaped anatomy was well preserved due to the flexibility of the SAF

of many canals led to the recommendation to use larger apical preparations in order to include the whole perimeter of the canal wall within a round apical preparation.[88,89]

This often may result in excessive removal of dentin that may have been considered unavoidable by those who suggested this method, if a true cleaning of the apical part of the canal was desired.

The SAF, on the other hand, adapts itself to the shape of the canal, be it round, oval, or triangular and removes a thin uniform layer of dentin from the entire perimeter of the canal, thus making larger apical preparations unnecessary.[20,22,41]

Innovative negative-pressure irrigation tools such as the EndoVac (SybronEndo) represent another reason for the excessive enlargement of the apical part of the canal. For the EndoVac to be truly effective, an apical preparation to #40/0.04 or #40/0.06 is required.[58,90] Such preparations are often acceptable in straight canals, but may be considered excessive in many curved root canals, resulting in the danger of canal transportation when thick rotary files are used. Such apical enlargement could be justified if the tool described above was the only effective cleaning device for the apical area. However, because the SAF can effectively clean the apical parts of root canals without creating such a large preparation, the enlargement of apical parts of curved root canals to such a large size should be considered an unnecessary and excessive removal of sound dentin, at least in curved root canals.

C-shaped canals also often have a “danger zone” that is not recognized in periapical radiographs [Figure 27]. Attempts to instrument such canal configurations using either rotary files or ultrasonic files may endanger the tooth by excessive removal of dentin in the “danger zone”, close to the buccal or lingual depression of the root surface that is typically present in such teeth [Figure 27]. The SAF mode of operation represents

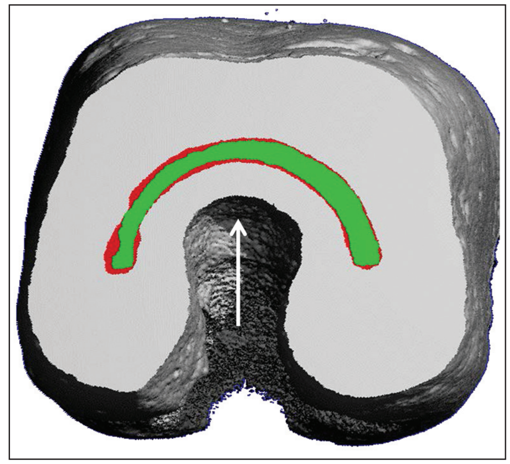

Figure 27: “Danger zone” in a C-shaped canal. This C-shaped canal was instrumented with the SAF System. Green: Before; red: After. If such a canal was treated with ultrasonic files, the only current effective alternative, the chance of excessively thinning the wall or even causing a strip perforation in the area marked by the arrow would be high. Such danger zones cannot be recognized from within the root canals or from periapical radiographs. Minimally invasive shaping with the SAF System represents a safe alternative

the safest way to clean such complicated root canal systems[22,41] [Figure 27].

Recently, another element was recognized that can jeopardize the integrity of the remaining radicular dentin: The creation of micro-cracks in the remaining radicular dentin[6,7,14,15,18,19,91] [Figure 28]. All tapered nickel titanium file systems tested so far create micro-cracks in a substantial percentage of treated roots, ranging from 18-60% of the roots.[6,7,14,15,18,19,91] This phenomenon was first recognized by Shemesh *et al*.[6] and was later studied by several research groups. The tendency of reciprocating files, such as the WaveOne and the Reciproc, to create such micro-cracks is 3 times greater than that of the ProTaper and Mtwo, their respective predecessor multi-file systems.[91]

The formation of such micro-cracks has been documented so far in more than 10 papers published in the leading endodontic journals, yet some leaders within the profession prefer to ignore this phenomenon or deny its potential importance as a predisposing factor for the formation of VRFs.

Kim *et al*. recently explained the biomechanical basis for the phenomenon of micro-crack formation.[60] They used finite element analysis models to explore the stress that is created in the radicular dentin when rotary files such as the ProFile or ProTaper are used in root canals [Figure 29a]. Their findings indicate that extent of the von Mises stress created in the outer surface of the radicular dentin may reach values of 386 MPa and 311 MPa for the ProTaper F3 and ProFile #30/.06, respectively.[60] The tensile strength

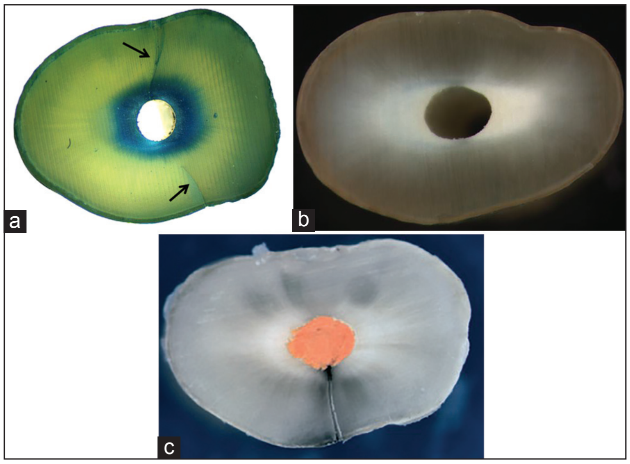

Figure 28: Micro-cracks and VRFs generated by rotary files. (a) Micro-cracks in the remaining dentin of a root instrumented with rotary files. The lower arrow indicates a partial micro-crack originating at the root surface. The upper arrow indicates a full thickness crack that may be defined as VRF. (Adapted from Bürklein *et al.* 2013).[91] (b) Hand instrumentation: No micro-cracks (courtesy: Dr. Hagay Shemesh, Amsterdam). (c) Instrumentation with rotary files resulted in micro-cracks in 25% of the roots but only 5% of the cracks were full thickness (VRFs). Obturation of the canals using lateral compaction increased the total incidence of micro-cracks to 55% of the roots and increased the incidence of full thickness fractures (VRFs) to 30% of the roots. This indicates that in many cases, the formation of partial thickness micro-cracks may serve as a predisposing factor for the formation of VRFs in roots treated with rotary files (adapted from Shemesh *et al.* 2009)[6]

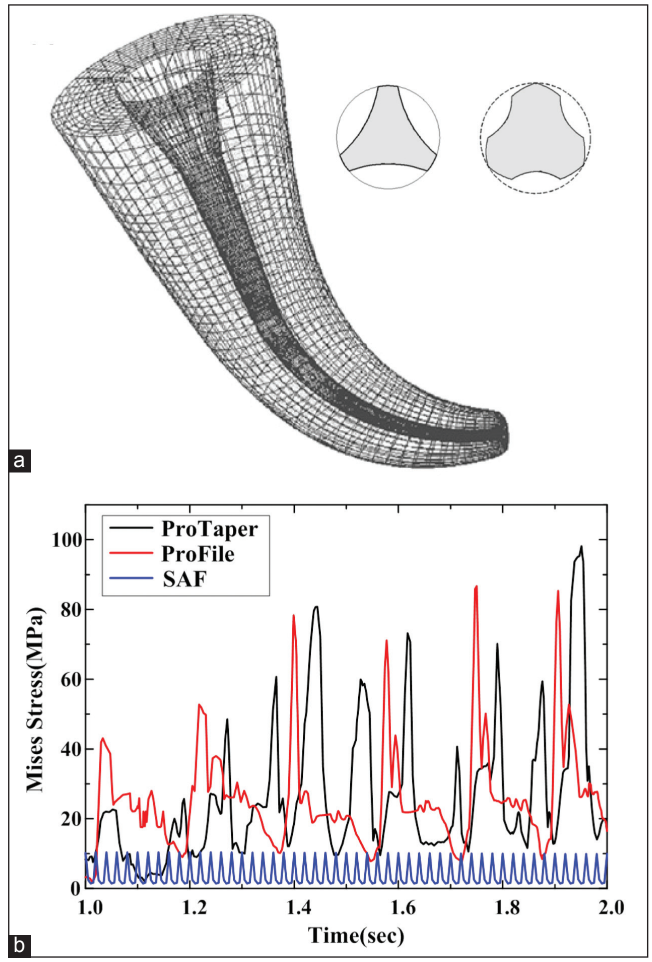

Figure 29: Stress analysis using a finite element analysis model. (a) A finite element analysis model of a root canal. When the ProTaper F3 and ProFile #30/.06 were used, they generated von Mises stress of 386 MPa and 311 MPa, respectively, in the outer layer of the root. These stress values were 3 times higher than the tensile strength of dentin, 106 MPa (adapted from Kim *et al.* 2010).[60] (b) The von Mises stress generated by the action of the ProFile #20/.06, ProTaper F1 and the SAF in a finite element analysis model. Black: The ProTaper F1; red: The ProFile #20/06; blue: The SAF. Please note: The thin (size 20 tip) ProTaper and ProFile generate stress within the limits of the tensile strength of dentin (100 MPa) (adapted from Kim *et al.* 2013).[92] The clinical implication is that thin rotary files, such as the ProFile #20/.04, may be used for glide path preparation of the SAF without risking the integrity of the dentin

of dentin is 106 MPa, which means that these instruments create stress that is 3 times larger than the strength of the dentin. The thinner instruments, ProTaper F1 and ProFile #20/.06, created lower stress values of 98 MPA and 88 MPa, respectively.[92] Thus, it seems that the potential to create micro-cracks is increased with the thicker rotary files.

The stress created by the SAF during its operation was also studied by the same group and was found to be approximately 10 MPa[92] [Figure 29b]. This result is in accordance with the finding that the SAF creates very few[18] to no micro-cracks[15] in the radicular dentin.

Such a major difference between the SAF and the tapered rotary files may be explained by their different modes of action. Rotary files have blades of one design or another that machine the root canal by cutting the dentin. The SAF, on the other hand, does not have blades and instead removes dentin using a grinding motion similar to the use of sandpaper. Thus, the mode of action of the SAF does not create any significant stress on the radicular dentin.[92]

The potential clinical significance of micro-cracks created by rotary files has been illustrated in two studies by Shemesh *et al*.[5,93] When lateral compaction was used for the obturation of canals that were instrumented by rotary files, the incidence of full thickness fractures (VRFs) increased from the 5% found after rotary instrumentation alone up to 30% when the additional stress of lateral compaction was applied[5] [Figure 28c]. Similarly, when retreatment was performed in roots that were initially instrumented with rotary files and then obturated, the incidence of full thickness fractures increased.[93] From these data, the natural conclusion is that any additional stress applied to a root in which micro-cracks were initially created by rotary instrumentation may turn some of those micro-cracks into full thickness fractures (VRFs).

To date, no clinical study has been conducted regarding the effect of repeated occlusal forces, applied either during mastication or by occlusal para-function over the years, on teeth with micro-cracks in their roots. Nevertheless, the discipline of fracture mechanics, at large, indicates that catastrophic (full thickness) fractures in materials start with micro-cracks that gradually propagate under the influence of repeated stress.[94] It is reasonable to believe that dentin does not differ from other biomaterials in this respect.

In conclusion, the SAF is the first instrument of its kind to allow preservation of the integrity of radicular dentin by avoiding both the unnecessary, excessive removal of sound dentin and the formation of micro-cracks in the radicular dentin.

CLEANING CANALS DURING RETREATMENT

Retreatment procedures may be roughly divided into two stages. First, the bulk of root filling is removed. Then, the walls of the canal are cleaned of any residue, which may consist of sealer, gutta percha, tissue debris, bacterial biofilm, or a mixture of any or all of the above.

The first stage of removing the main bulk of the root filling may be accomplished quite effectively using rotary files.[48-54] Nevertheless, many studies have indicated that a substantial amount of residue is left attached to the canal walls after the use of rotary files.[48-54] Cleaning the canal from the root-filling residue cannot be accomplished by simple irrigation with sodium hypochlorite. This usually requires mechanical scraping of the walls, as the root filling and the sealer residue, especially, are strongly attached to the canal walls.

Abramovitz *et al*. were the first to suggest the use of the scrubbing action of the SAF to remove such root-filling residue.[53] They prepared curved canals of mesial roots of mandibular molars with files up to #40 K and then obturated the canals with gutta percha and AH26 using lateral compaction. After the sealer was fully set, a retreatment procedure was applied, starting with ProTaper retreatment files D1-D3.[53] After this stage, the amount of radiopaque residue was evaluated from buccolingual radiographs. After this first stage, 35% of the apical third area of the canal was still covered with radiopaque residue. The most common location for the residue was in the inner side of the curvature, attached to the distal wall of the apical third of the canal [Figure 29b]. The canal was then dried with paper points and a drop of chloroform was placed in the canal (approximately 10 μL). The SAF was operated in the canal for one minute, with the irrigation pump turned off. Later, the irrigation pump was turned on, and the SAF was operated in the canal with a continuous flow of sodium hypochlorite. The amount of residue in the apical third of the canal was reduced from 35% after the first stage to 7% after the second[53] [Figure 30a-c]. This was due in combination to the softening effect of the chloroform and the scrubbing effect of the SAF.

Similar results were reported by Solomonov *et al*., who studied the retreatment of distal roots of mandibular molars with oval cross-sections using microCT as the investigation tool.[54] When Protaper retreatment files were used, followed by the ProTaper F2 instrument, 5.39% of the original volume of the root filling was retained in the canal at the end of the procedure. When the ProFile #20/.06 was used for the first stage followed by the SAF in the second, only 0.41% of the root-filling residue was left in the canal after the procedure[54] [Figure 30d]. A third study was conducted without chloroform, using only the scrubbing action of the SAF and the continuous flow of irrigant.[95] The results indicated that the addition of SAF removed more gutta percha than the ProTaper alone. Thus, it seems that the combination

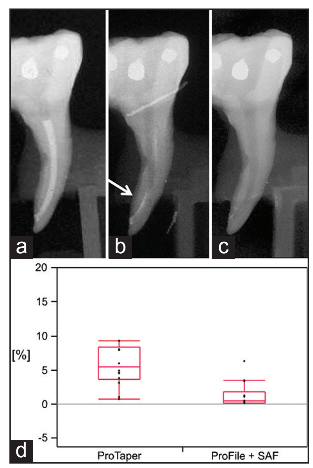

Figure 30: The use of SAF in retreatment. (a) Mesial roots of mandibular molars were initially prepared with #40 curved K files and then obturated. (b) When retreatment was performed using D1-D3 ProTaper retreatment files, 35% of the apical third of the canal was still covered with radiopaque residue. (c) Supplementary treatment where the residue was softened with chloroform and the residue was scrubbed using the SAF resulted in a reduction of the residue to 7% of the apical third area of the canal. Please note: In such curved canals, larger rotary instruments are not an option as they may cause severe damage to the remaining dentin of the root (adapted from Abramovitz *et al*. 2012).[53] (d) A similar 3D micro-CT study in oval canals found that ProTaper retreatment files followed by the Protaper F2 left root filling debris that represented 5.39% of the volume of the root filling. Using the ProFile #20/06 followed by a 2.0-mm diameter SAF left only 0.41% of residue in the root canal (adapted from Solomonov *et al*. 2012)[54]

of a rotary file used to remove the bulk of the root filling followed by cleaning of the canal using the scrubbing effect of the SAF is an effective cleaning method for retreatment.

MINIMALLY INVASIVE SHAPING AND CLEANING

The concept of minimally invasive shaping and cleaning has the same basic endodontic principles as the conventional, traditional shaping and cleaning procedures. However, it applies a minimally invasive technology to achieve these principles. Conventional shaping and cleaning using rotary files involves (a) the removal of large amounts of sound dentin in an attempt to include as much of the area of the canal wall within the round preparation as possible, and to allow effective irrigation at the apical end of the canal, and (b) the creation of unnoticed micro-cracks in the remaining radicular dentin via the machining process applied by all tapered rotary files.[6,7,14,15,18,19,91] Until recently, both these damaging effects were either ignored or accepted, as there was no other effective way to clean the root canal thoroughly.

The minimally invasive concept aims to achieve effective cleaning of the root canal by (a) removing a thin uniform layer of dentin from around the entire root canal without the unnecessary excessive removal of sound dentin and without causing micro-cracks, and (b) providing a continuous flow of fresh, fully active irrigant applied with a scrubbing motion all the way to the apical part of the canal.

Conventional shaping procedures involve machining the root canal into a desired shape, using either a sequence of rotary instruments or one reciprocating tool. This process is used to enable irrigation in the apical part of the canal and to facilitate and simplify obturation by using a master cone with the shape of the machined canal.

As long as the canal is straight, narrow and has a round cross-section, this method works well, as it allows for removal of the entire inner layer of dentin along with anything that was attached to it, be it pulp tissue or bacterial biofilm. The debris are then carried coronally by the flutes or compacted into the flutes; subsequent irrigation may be carried out to remove what is left in the canal.

Nevertheless, if this simplistic view of the process is applied to all canals, it may be considered, in many cases, to be treating an imaginary canal while ignoring the 3D reality of that individual root canal. Micro-CT studies have shown that in oval and curved canals, the use of rotary files fails to remove the inner layer of dentin from around the entire canal.[5,12,20] Furthermore, the discrepancy between the size of the tip of many of these files (i.e., #25) and the known dimensions and shape of the apical part of root canals led to the suggestion that a larger apical preparation should be used in order to include all of the apical canal surface within the perimeter of the round instrumented canal.[88,89] Such larger apical preparations may lead to further unnecessary removal of sound dentin as well as the creation of micro-cracks in the dentin of the apical part of the root.[14] Such large apical preparations are no longer required as the SAF technology can achieve the same goals with a minimally invasive approach.

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How to cite this article: Metzger Z. The self-adjusting file (SAF) system: An evidence-based update. J Conserv Dent 2014;17:401-19.

Source of Support: Nil, **Conflict of Interest:** None declared.