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The Self-Adjusting File system

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Great progress has been made over the years in the technology of rotary nickel-titanium file systems. Nevertheless, both the oldest and the newest systems all use the same principle of a rotating blade with flutes, designed to carry off or contain the cut material and/or debris. While this concept may provide adequate results in narrow, straight canals with round cross sections, it has substantial limitations when oval or curved canals are concerned. Such canals are very common.
The Self-Adjusting File (SAF) system is based on a new and different concept that is aimed at overcoming the limitations of current rotary file technology. This review aims to familiarise the reader with the new concept and technology of the SAF system and to individually discuss the major endodontic challenges that are yet to be conquered by rotary file technology. The ways by which the new SAF system overcomes these challenges will be explained, based on 32 research papers that were published over the past 3 years. A new concept for root canal cleaning and shaping will be presented and justified: the concept of 'minimally invasive endodontics', which has been made possible by the new SAF technology.

SAF – a new concept

Do we need a new concept?

The introduction of rotary nickel-titanium (NiTi) files in 1993 represented a real paradigm shift in endodontics[1,2]. Over the years great advancement has occurred, with attempts to make these instruments more flexible and safer in terms of file separation[3]. Recently, innovative metallurgy combined with reciprocating movement allowed for a reduction in the number of instruments required and the formation of 'single file' systems, such as WaveOne (Dentsply Maillefer, Ballaigues, Switzerland) and Reciproc (VDW, Munich, Germany)[4].

Both new and traditional rotary file systems utilise the same basic concept, in as far as the files consist of a solid central metal core with a rotating blade and flutes to carry off or contain the cut material. As long as the canals are straight, narrow and round, such instruments are likely to adequately achieve the goals of root canal instrumentation/shaping. Nevertheless, when either oval or curved canals are concerned, rotary instruments, both new and old, may fail to meet the challenge[5-18]. This yet unmet challenge consists mainly of: the three-dimensional (3D) cleaning and shaping of oval and curved canals[5,8,9,12]; the microbiological challenge of infected oval canals[10]; the challenge of three-dimensional obturation of oval canals[11,13]; and the challenge of maintaining the integrity of the remaining radicular dentine[6,7,14,15,18].

With each and every one of these challenging targets, operators are expected to do as complete a

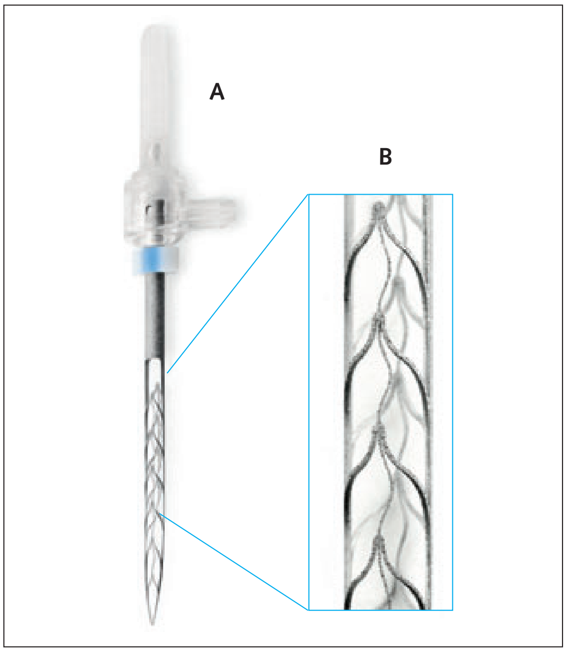


Fig 1 The Self-Adjusting File. (a) The SAF file has a hollow cylindrical shape and is made of a thin nickel-titanium lattice. (b) The lattice is constructed from two longitudinal beams, connected by specially designed arches that enable extreme compression: a file of 1.5 mm diameter can be compressed to dimensions similar to those of size 20 K-file. The arches are harnessed together by thin struts, to prevent the arch being pulled out of the cylinder wall.

job as possible to ensure endodontic success. Unfortunately, the result achieved with old or new rotary instruments is far from complete[5-19]. This incompleteness is due to a basic conceptual fault: ignoring the natural 3D shape of many of the root canals and cleaning and shaping all canals as if they were narrow, straight canals with round cross sections[20,21].

With the introduction of the Self-Adjusting file (SAF) system, the definition of 'possible' in 'as complete a job as possible' has substantially changed[10-12,15-20,22-26]. Although the treatment results that can be achieved with the help of this new system are not perfect, they are much closer to what the operator has in mind when performing a root canal treatment.

The aim of this review is to introduce the reader to the SAF system and to its mode of operation. The challenges that remain unmet by the current rotary file systems will be discussed one by one. The manner by which the SAF system can overcome each of these challenges will be presented, based on more than 32 studies by a variety of research teams that were published over the past 3 years. Furthermore, a new concept of minimally invasive 3D endodontics will be introduced, which achieves all of the basic aims of root canal treatment without causing unnecessary damage to the radicular dentine, as is often observed in the root after the use of traditional rotary instrumentation[6,7,14,15,18,19].

The SAF system

The SAF system is a cleaning-shaping-irrigation system[10,27]. The Self-Adjusting File (SAF file; ReDent, Raanana, Israel) is part of a system that allows its unique and effective operation[20,21,28]. The file is operated with a special handpiece head (RDT, ReDent) that turns the rotation of the micromotor into in-and-out vibration. The file is used with continuous irrigation, which is provided by the VATEA pump (ReDent), and enters the root canal through the hollow file. Together, these three components constitute the Self-Adjusting File system[20,21,28].

The Self-Adjusting File

The Self-Adjusting File is a hollow, thin-walled cylinder (Fig 1) with an asymmetrical tip (Fig 2a). It is the first endodontic file that does not have a central solid metal core. The walls of the cylinder are made of a nickel-titanium lattice that was specially designed to enable extreme compression of the file[20,21,28]. The lattice is constructed of two longitudinal beams that are connected to each other by two uniquely designed series of arches (Fig 1). The arches are connected and harnessed to each other by thin struts designed to prevent the arches from being pulled out of the cylinder's wall (Fig 1)[20,21,28]. The tip of the file is asymmetrical and is constructed from the longitudinal arches that meet each other at one of the walls of the cylinder (Fig 2a).

The SAF file is available in two diameters: 1.5 and 2.0 mm. Both are extremely compressible. The 1.5 mm-diameter file may be compressed to dimensions similar to those of a size 20 K-file[21,28]. The 2.0-mm diameter file can be compressed to dimensions similar to those of a size 35 K-file[21].

The metallic surface of the SAF file is rough (Fig 2b)[21,28]. When inserted into a root canal, the SAF file is compressed and adapts itself to the cross section of the canal[20,21,28]. Consequently, the file is adapted to the canal walls with light pressure[20,21,28]. Removal of dentine by this file is performed with the back-and-forth motion caused by the combination of the vibrations of the file (see below) and the pecking motion that is applied by the operator[20,21,28]. Thus, the removal of dentine is completed in a manner similar to the use of sandpaper: uniform removal

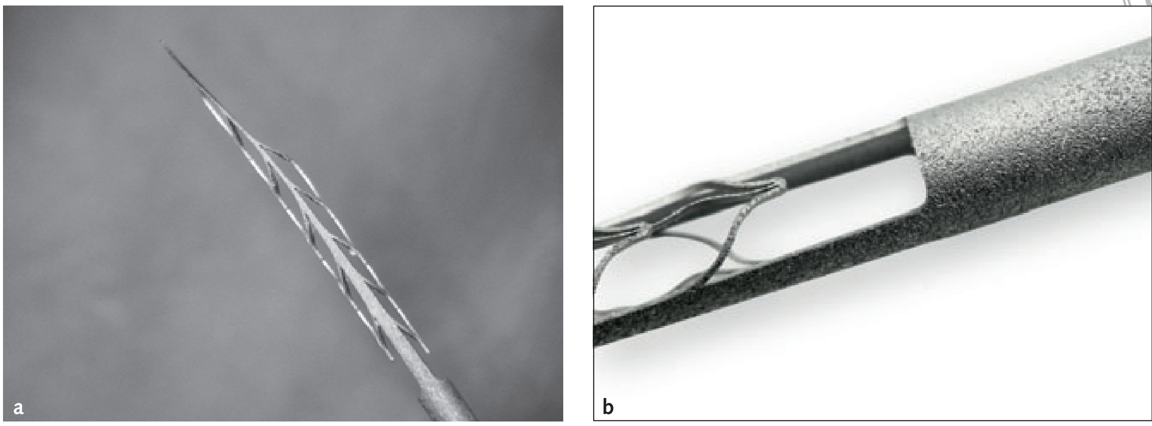


Fig 2 Surface and tip of the SAF file. (a) The tip of the SAF file is asymmetrical to allow negotiation of curves. (b) The metal surface of the file is rough with a top-to-bottom dimension of 3 µm.

of a layer of dentine from all around the surface of the canal, resulting in a clean and smooth dentine surface[20,21,28,29].

The SAF file is equipped with a freely rotating irrigation connector that allows for the attachment of an irrigation tube (Fig 3). The irrigation solution provided through the tube continuously flows through the connector, the hollow file and into the root canal[20,21].

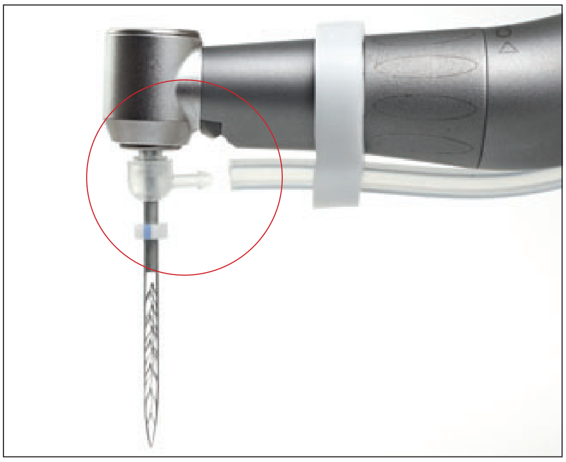


Fig 3 Irrigation hub on the SAF. A polyethylene tube is connected on one end to the VATEA pump, which delivers a continuous flow of the irrigant. The other end of the tube is connected to a rotating hub on the SAF file (circled), which allows the irrigant to enter the hollow SAF file and continuously flow through it into the root canal.

The RDT handpiece head

The RDT handpiece head has two functions: vibration and rotation. The RDT heads are available for use with a variety of handpieces and micromotors. They may be used with handpieces that have a KaVo-type connector (RDT3; ReDent – Fig 4a), such as micromotors and handpieces made by KaVo (Biberach an der Riss, Germany), Osada (Tokyo, Japan), MK-Dent (Bargteheide, Germany) or Chirana (Stará Turá, Slovakia). RDT heads can also be used with those handpieces that have an NSK-type connector (RDTNX, ReDent – Fig 4b), such as X-Smart (Dentsply Maillefer), EndoMate (NSK, Tochigi, Japan) or EndoTouch (Sybron, Orange, CA, USA). Furthermore, they can be also be used with motors that are designed exclusively for the new reciprocating files, such as WaveOne, X-Smart Plus (Dentsply Maillefer) or Reciproc (VDW).

The RDT head is operated at 5000 rpm, and its main function is to turn the rotation into an in-and-out vibration of 5000 vibrations per minute[20,21,28]. The SAF file is attached to the RDT head via a special friction-grip mechanism. When the SAF file is free to move, it is slowly rotated at 80 rpm. When inserted into the canal, the engagement of the SAF file with the dentine walls activates a clutch mechanism in the head, which stops all rotation of the file, allowing only the vibrations to occur[20,21,28]. The RDT head is made of titanium, to resist corrosion that may occur with exposure to sodium hypochlorite[21].

The VATEA irrigation pump

The VATEA irrigation pump is a peristaltic pump that has a 500 ml reservoir tank and a control panel (Fig 5a)[20,21]. The pump is operated by a rechargeable battery and its flow rate can be adjusted from 1–10 ml per minute. A Luer-type connector allows for the attachment of a polyethylene tube (Fig 5b) that is connected at its other end to the irrigation connector of the SAF file (Fig 4a)[20,21]. The control panel permits the adjustment of the flow rate and indicates the passing of operation time[20,21]. The pump is operated by a foot pedal (Fig 5c).

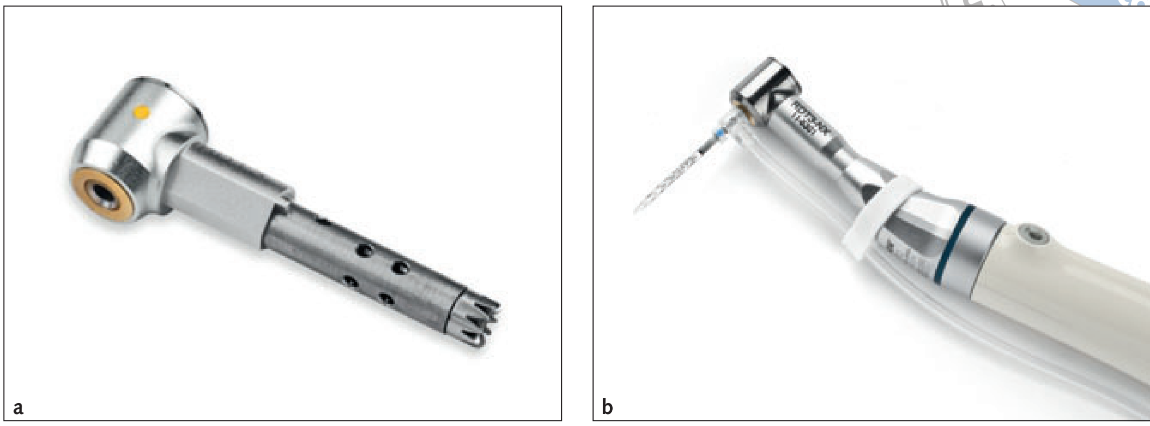


Fig 4 RDT handpiece heads. The RDT handpiece head is used to turn the rotation of the micromotor into in-and-out vibrations. It also contains a special clutch mechanism. Such heads are available for connection to a KaVo type handpiece: RDT3 (a) or RDTNX (b), which can be used with any NSK-type connector, such as those used by the X-smart machine (Dentsply Maillefer).

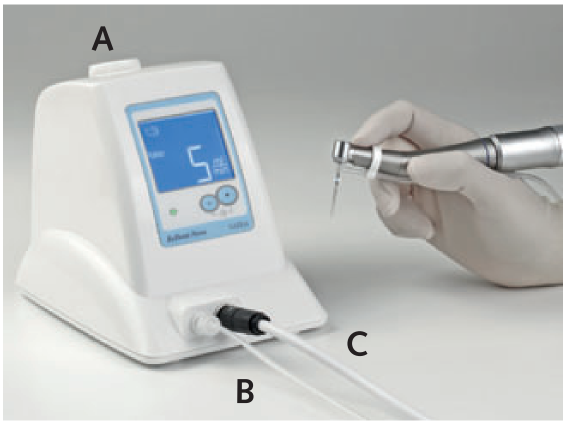


Fig 5 VATEA irrigation pump. A rechargeable battery-operated peristaltic pump. A 500 ml container (A) is filled with irrigant. The irrigant is delivered through a polyethylene tube (B) at a rate of 1–10 ml/min, and is operated by a foot switch cable connector (C).

The SAF system: mode of operation

Funnelling of the canal orifice

As with most shaping methods, negotiating the canal with hand files and preliminary slight funnelling of its coronal orifice are mandatory with the SAF system[20,21,28,29].

Glide path

Preparing or verifying an initial glide path so that a size 20 K-file can be freely inserted to working length is an essential preparatory stage for the use of the SAF system[20,21,28,29]. A similar stage is also recommended with most rotary file systems[30], including the recently introduced WaveOne (Dentsply Maillefer)[31-34]. Initial negotiation of the canal with hand files allows the operator to decide on the next stage and to select the right size of SAF file[29]. If the canal is large enough to allow a size 35 K-file to be inserted to working length, a 2.0-mm SAF file should be selected. If the canal allows a size 20 or 25 file to be inserted, a 1.5-mm SAF file will be chosen. In both the above cases, preliminary preparation will be limited to slight funnelling of the canal's coronal orifice and negotiating it to ensure the lack of obstructions[20,21,28,29]. If the canal is narrower than the above, a glide path should be prepared. This initial glide path can be prepared with any instrument(s) that the operator is familiar and comfortable with, such as K-files, PathFile system 13.02,16.02,19.02 (Dentsply Maillefer); ProFile 20.04 (Dentsply Maillefer); Mtwo 10.04, 15.05 (VDW); RaCe 10.02, 15.02, 20.02 (FKG, La Chaux-de-Fonds, Switzerland)[29]; or G1 12.03 and G2 17.03 instruments (Micro Méga, Besançon, France). In these cases, after glide path preparation, the 1.5-mm SAF file will be used[29].

It is important to keep in mind that the SAF is not a penetrating instrument. While reaching working length is the target with many rotary file systems, when the SAF is utilised, reaching working length is the beginning of the procedure. The SAF should be able to reach working length before starting the SAF procedure. The best way to verify whether the glide path is ready and satisfactory is to take the selected SAF file by hand, dip it in a viscous chelator/lubricant, such as an EDTA gel, and insert it into the canal with quarter circle rotations at a time, if required, to working length. If it reaches working length, the glide path is acceptable for the use of the SAF system. If not, the glide path should be improved[29].

Canal instrumentation

The SAF file is then connected to the RDT head, and the irrigation tube is connected to the hub on

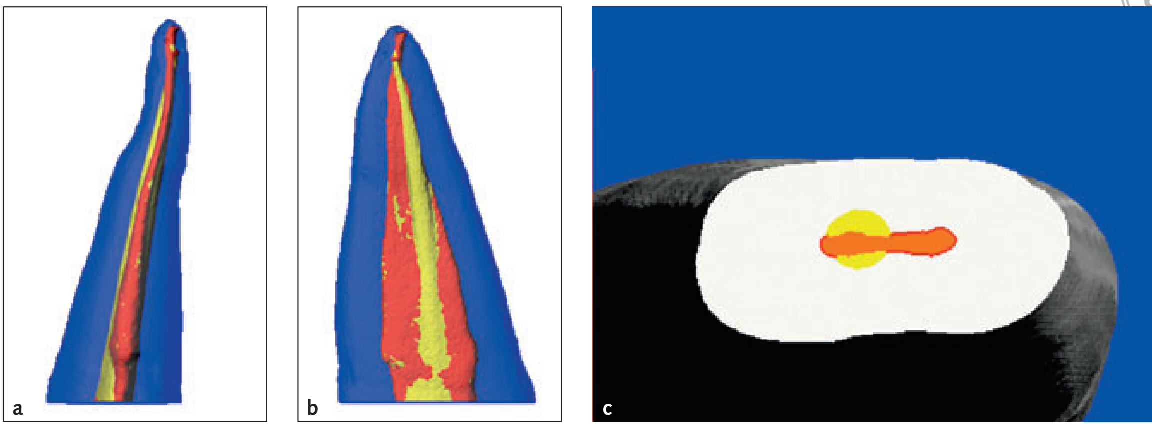


Fig 6 Rotary canal preparation of a flat-oval canal. Reconstruction from micro CT scans: (a) buccal view; (b) mesial view; (c) cross section. Red: canal before treatment. Yellow: the preparation by a rotary file. Note that a circular 'bore' was generated, while a large buccal area of the canal was unaffected by the procedure. (Please also compare to Fig 20d.)

the file (Figs 3 and 4b). The micromotor is operated at a constant speed of 5000 rpm, and the SAF file will start vibrating and should rotate slowly. When inserted into the canal, the file rotation will stop immediately, and the file will only vibrate[21,26,29]. The file should be used in the canal with a pecking motion. It is essential that the outbound movement of the file reaches far enough to allow for the rotation of the file in every outbound movement. This rotation will allow the file to be inserted in a different circular position with every inbound stroke[21]. This aspect of operation is important as it allows for: (i) uniform instrumentation of the walls all around the canal; and (ii) in the case of a curved canal, it will allow the asymmetrical tip of the file to negotiate the curvature and pass it. In the latter case, during the first few seconds of SAF operation, the file will sometimes extend and sometimes not extend beyond the curvature and may feel as if it were being blocked, depending on the circular position of the asymmetrical tip in relation to the curvature. After 20–30 s, the file will extend beyond the curvature with every inbound movement.

The irrigation system should be operated at 4 ml/min throughout the operation[20-22,25]. The irrigant flows through the tube and the hub into the hollow file and then into the canal[20-22,25]. The lattice shape of the file walls does not allow any hydraulic pressure to be generated in the canal, but effective cleaning occurs all the way to the apical part of the canal (see below)[17,21,22,25,35]. The fresh, fully active irrigant is continuously mixed and activated by the vibrations of the file and by the pecking movement. Even at the apical, cul-de-sac part of the canal, the irrigant is fully exchanged every 30 s[21]. The excess irrigant flows coronally and should be effectively and continually aspirated.

Most of the mechanical action of dentine removal by the SAF file is accomplished within the first 2 min of operation[20,21,28]. Nevertheless, it is recommended to use the SAF for a total of 4 min per canal to allow the full cleaning-irrigation action, with its important antimicrobial effect (see below), to take place[10,16].

The 3D cleaning and shaping challenge

The challenge of oval canals

In most cases, rotary file systems will result in adequate instrumentation, as far as straight, narrow canals with round cross sections are concerned. Nevertheless, in regard to the instrumentation of oval or flat-oval canals, the results are less satisfactory[8-10,12,13,17,20,27]. In such canals, the rotary file will prepare a circular 'bore', leaving uninstrumented buccal and/or lingual 'fin(s)' (Fig 6)[8-10,12,13,20,27]. This may result in the unnecessary removal of sound dentine while failing to reach the goals of cleaning and removal of the dentine layer all around the canal surface. Attempts to overcome this limitation by using either brushing or circumferential movements have failed[9], most likely due to the great flexibility of nickel-titanium instruments, which does not allow the operator to effectively control the middle and apical parts of the file or move the file in the desired direction.

When the oval canals of distal roots of mandibular molars were studied, rotary files left 69%

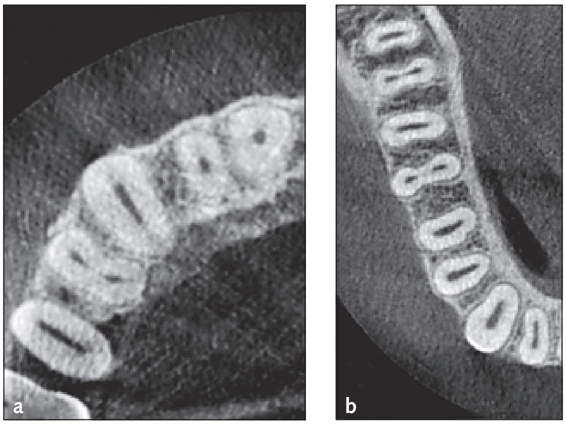


Fig 7 Flat-oval canals as seen in an axial view of CBCT. (a) Axial plane of a CBCT revealing flat-oval canals in a maxillary canine and second bicuspid; (b) Axial plane of a CBCT revealing flat-oval canals in the mandibular incisors, canine, bicuspids and distal roots of the mandibular molars.

of the canal wall unaffected by the procedure, even when circumferential movements were applied[9].

Flat-oval canals are rather common[36]. Nevertheless, a set of conventional, planar periapical radiographs will not usually reveal the oval nature of the canals because the flatness of the canal is normally in a plane parallel to the beam. However, in axial views of CBCT (cone beam computerised tomography) scans, this flatness is frequently observed (Fig 7). Oval canals are present in at least 25% of teeth, and in certain types of teeth, such anatomy may be found in up to 91%[36].

When an SAF file is inserted into an oval canal, it is compressed so that it assumes the cross section of that particular canal (Fig 8d)[20,21,28]. In an extreme case of a flat-oval canal with a mesiodistal dimension of 0.2 mm, the 1.5-mm file will assume a ribbon shape and can spread buccolingually as far as 2.4 mm (Figs 8c and 8d)[21,28]. This spreading occurs even if the operator is unaware that the canal is flat, hence the name Self-Adjusting File[21,28].

Contrary to rotary files that impose a cylindroconical preparation on any canal, round or oval, the SAF does not impose a given cross section[12,20,24,26]. The SAF file will adapt itself to the walls of the canal and gradually remove a thin, uniform layer of dentine all around the circumference of the canal (Figs 9 and 10)[12,20,24,26]. Consequently, a round canal will stay round with larger dimensions and an oval canal or one with a teardrop-like cross section will maintain that shape but with larger dimensions (Figs 9 and 10)[12,20,24,26]. The removal of such a uniform layer of dentine, as evident from micro computed tomography (micro CT) scans, is currently the only way to three-dimensionally demonstrate that anything that was attached to this inner layer of the dentine (pulp tissue or bacterial biofilm) was also removed.

Paqué and Peters[12] had found that when the SAF system was used in the oval canals of mandibular molars' distal roots, the area unaffected by the procedure dropped from 69% that they had previously reported for rotary files to 23% for the SAF[12]. While not being a perfect result, it is much closer to what a clinician has in mind when performing root canal treatment in such canals.

The challenge of curved canals

Rotary nickel-titanium instruments are commonly considered to be the best tools for the instrumentation of curved root canals[37]. Nevertheless, studies using micro CT indicate that these instruments, when operated in curved canals, also leave much to be desired[5,23,38]. In a series of studies on the curved roots of maxillary molars, Peters, Paqué and others have shown that a high percentage (45–53%) of the canal wall remains unaffected by the rotary instruments[5,38,23].

Canal straightening and canal transportation are two other procedural errors that may occur when using rotary instrumentation[5,20,23]. The thinner NiTi rotary instruments are extremely flexible, but when reaching the larger sizes that are used for the final stages of the procedure, the instruments having a more massive central metal core are much more rigid.

In both canal straightening and canal transportation, vast areas of the canal wall are left uninstrumented, while excessive dentine removal occurs in some other areas[5]. Such excessive removal of dentine may endanger the root at areas that may be termed 'danger zones'[39]. It may lead to actual strip perforation or result in a thin remaining dentine layer, in which strain concentration may occur thus predisposing the root to vertical root fracture, either during the process of obturation or later under the repeated loads of mastication[40].

The SAF file, which has no central metal core, is extremely flexible (Figs 8a and 8b), which minimises the risk for both canal straightening and canal transportation[20,21,23]. It adapts well to both longitudinal curvatures, as well as to the cross section of the canals and causes less canal transportation and canal straightening. Consequently, the area of the canal

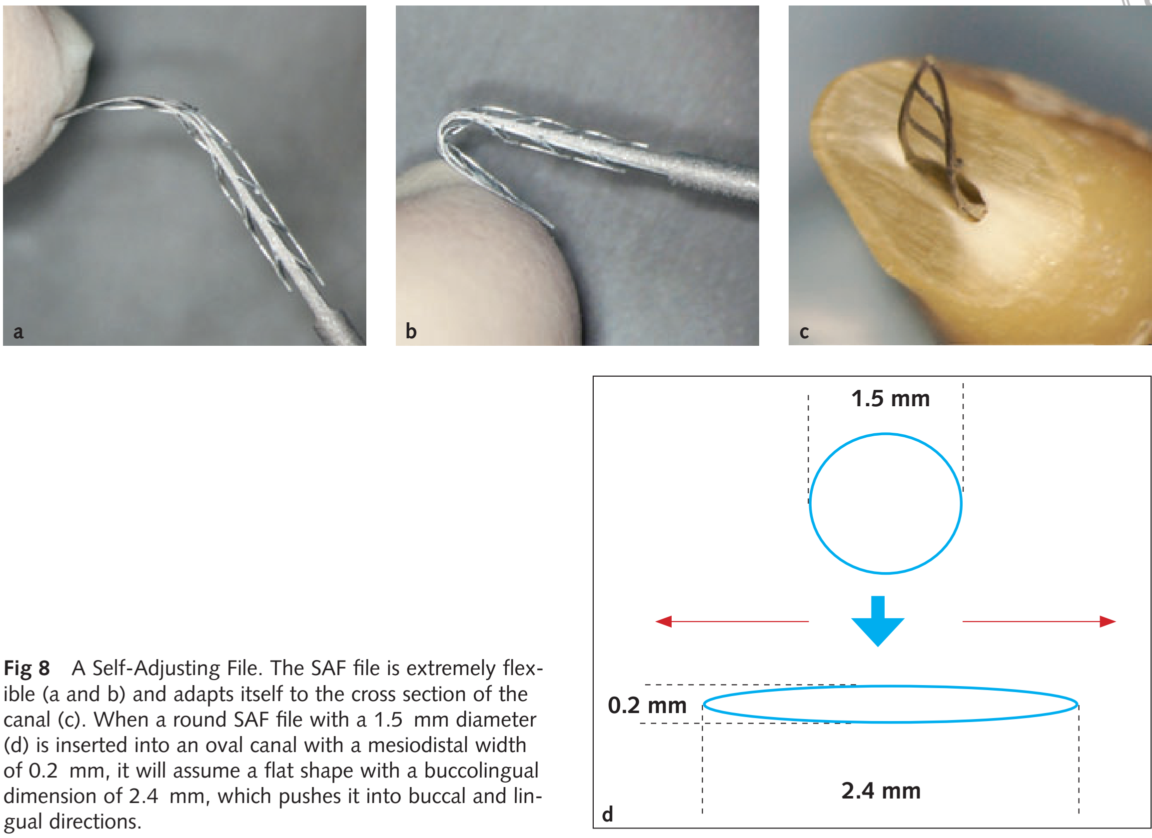


Fig 8 A Self-Adjusting File. The SAF file is extremely flexible (a and b) and adapts itself to the cross section of the canal (c). When a round SAF file with a 1.5 mm diameter (d) is inserted into an oval canal with a mesiodistal width of 0.2 mm, it will assume a flat shape with a buccolingual dimension of 2.4 mm, which pushes it into buccal and lingual directions.

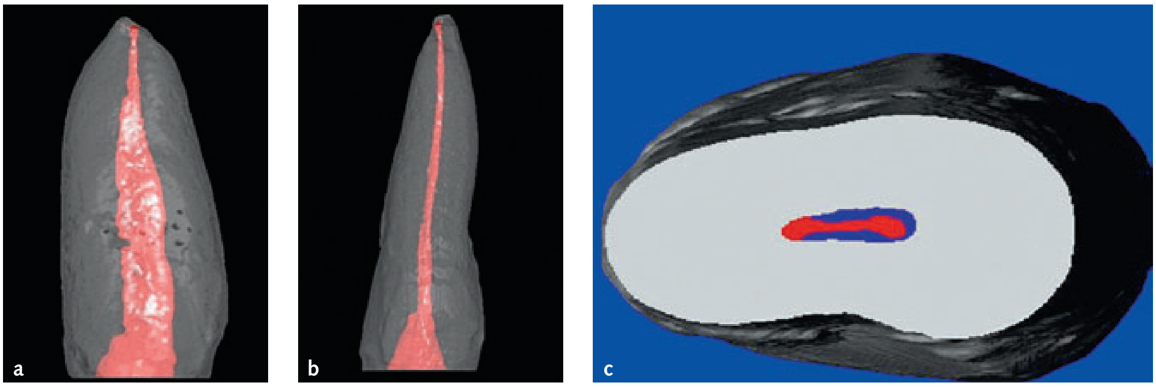


Fig 9 SAF preparation of a flat-oval canal. Reconstruction from a micro CT scan: (a) mesial view of the flat-oval canal before treatment; (b) buccal view of the canal before treatment; (c) cross section after treatment, at 6 mm from the apex. Red: the canal before treatment. Blue: the canal after treatment. Note that the oval shape of the canal was maintained with larger dimensions.

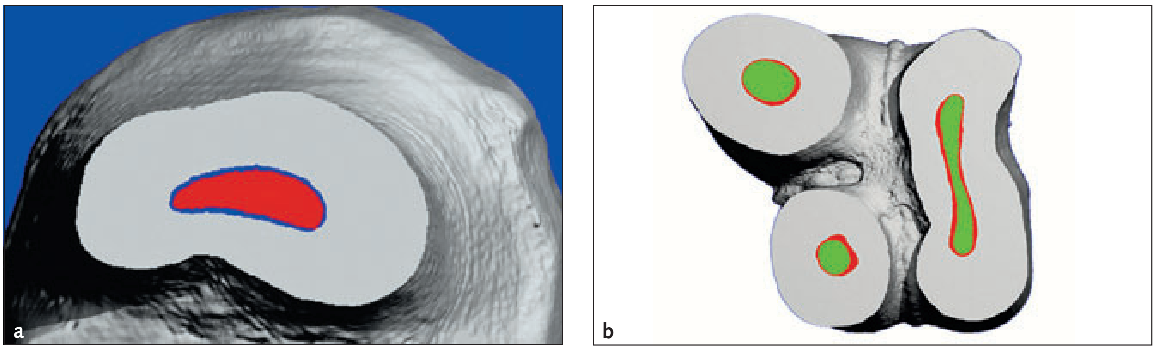


Fig 10 SAF preparation of flat-oval canals showing cross sections of reconstructions from micro CT scans. (a) Distal root of a mandibular molar. Red: before treatment. Blue: the effect of treatment. (b) Roots of a maxillary molar with extremely flat-oval palatal canal. Green: before treatment. Red: the effect of treatment. Note that round canals were prepared as per round canals with larger dimensions. While the flat anatomy of the palatal canal was preserved, a uniform layer of dentine was removed all around its periphery.

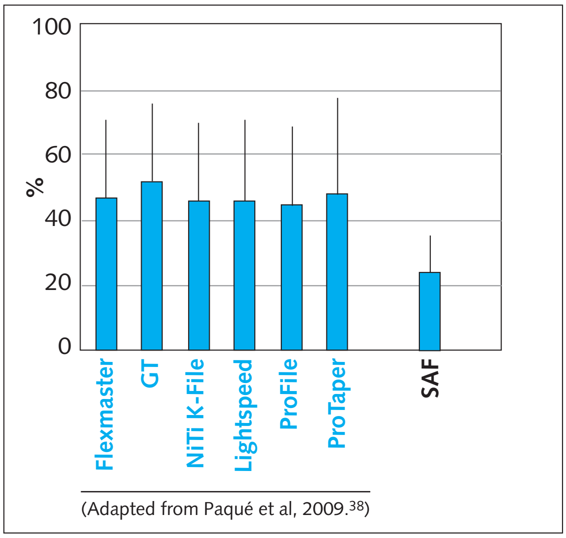


Fig 11 Area unaffected by instrumentation. When maxillary molars with curved root canals were instrumented with various hand or rotary files, a large percentage of the canal wall was unaffected by the procedure: 45–52% of the canal wall with a large standard deviations (adapted from Paqué et al, 2009[38]). The area unaffected by the SAF procedure is substantially smaller: 23% with a smaller standard deviation.

wall that is unaffected by the procedure is greatly reduced. Peters and Paqué have found it to be 24% for the SAF[23], compared to 45–53% for rotary and hand files in their previous reports[38] (Fig 11). Even though this result with the SAF system is not perfect, it is substantially better than that achieved with any of other methods of instrumentation.

The challenge of isthmuses

Roots that contain two canals in a single root may often contain an isthmus connecting the two canals[41]. Such anatomy may be encountered in the mesial roots of mandibular molars, in maxillary and mandibular premolars, in mesiobuccal roots of maxillary molars, and in mandibular incisors[42]. Cleaning and obturating such isthmuses has been a major challenge that does not yet have a satisfactory solution[42,43].

Recently, the challenge presented by the isthmus has been further complicated[44-46]. A study by Paqué et al indicated that rotary instruments tend to actively pack the isthmus with dentine chips (Fig 12)[44,45]. This phenomenon may be easily understood: when a rotating instrument removes dentine chips and tissue debris, it is much easier to push them sidewise into a non-resisting isthmus than to carry them coronally or pack them tightly within the instrument flutes. One should keep in mind that the isthmus is usually not empty: it may contain either pulp tissue or a bacterial biofilm. Pushing dentine chips into either of these soft substances is likely to form a composite of dentine chips embedded in pulp tissue or bacterial biofilm. Such composites were indeed found by Nair et al[43] in isthmuses of mesial roots of mandibular molars that were root canal treated with rotary files and resulted in clinically satisfactory radiographic results (Fig 13)[43].

With this in mind, it is easy to understand the results showing that attempts to remove the material packed into such isthmuses is of limited efficacy[45,46].

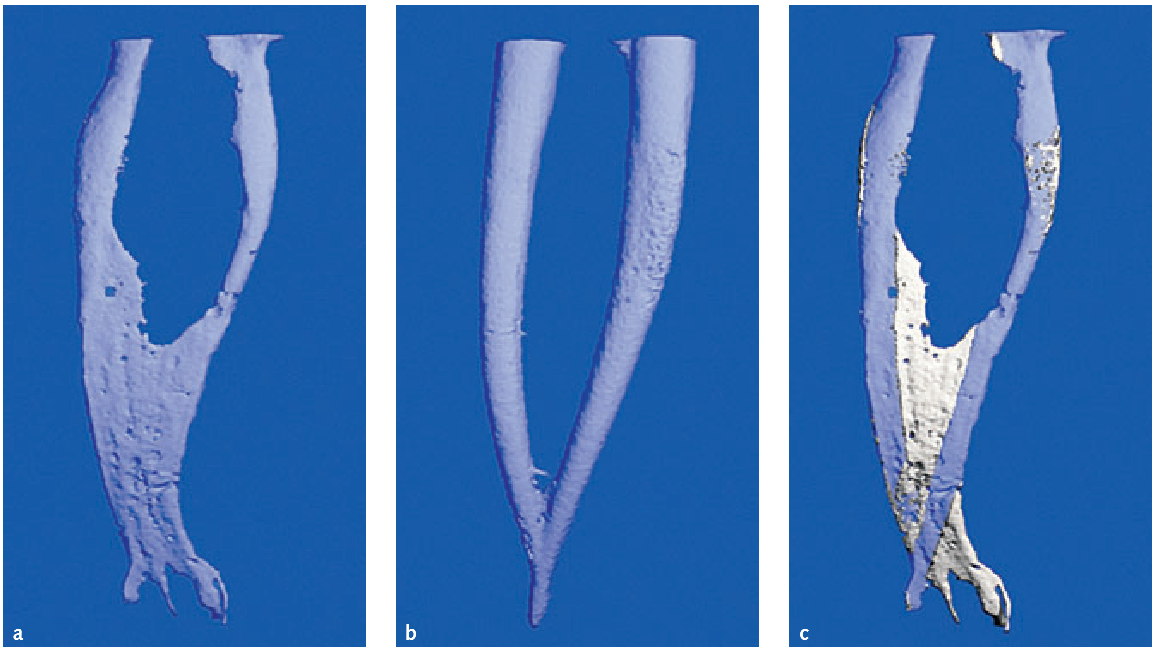


Fig 12 Packing of an isthmus with dentine chips. When an isthmus-containing root canal system in mesial roots of mandibular molars (a) was instrumented with rotary files, a nice preparation of the canals is evident (b). Nevertheless, large parts of the isthmus turned from radiolucent to radiopaque and the difference is presented in white in (c). This occurred due to active packing of radiopaque dentine chips into the isthmus by the rotary file. (Adapted from Paqué et al, 2009[44])

Paqué et al[45] found that neither conventional irrigation methods nor passive ultrasonic irrigation could remove all of the radiopaque material that was packed into the isthmus by the action of rotary nickel-titanium files[45]. A similar effect is likely to occur in long oval canals, in which the untreated longitudinal 'fins' may present with a similar effect. Consequently, such lateral packing of debris may explain the limited efficiency of the obturation of such flat-oval canals that were treated using rotary files (see below)[11,27,47,48].

It is also conceivable that in the case of infected canals, the packed composite of dentine chips and biofilm will protect 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 (see below)[10]. In the case of vital teeth, such a composite of dentine chips and pulp tissue may prevent the root canal filling from entering these occluded areas and also later serve as a potential place for bacterial growth and proliferation once some leakage has occurred.

The SAF file works in a totally different manner than rotary instruments[20,21,28]. It does not rotate in the canal and does not cut the dentine. The gentle abrasive action of the SAF file removes a dentine layer by converting it into thin powder that is continuously suspended and carried coronally by the flow of the irrigant. The SAF system produces no cut dentine chips, nor does it have the tendency to pack them into the isthmus. A recent study has shown that the packing of the isthmus with dentine particles by the SAF is negligible: 1.7% of the isthmus volume vs. 10.1% that occurred with rotary files (Fig 14)[46].

The challenge of C-shaped root canals

C-shaped canals represent a most complicated and challenging case of flat-oval canals[49]. Such canals may be found in 5–7% of second mandibular molars in populations of Caucasian origin[50]. However, in populations of Chinese origin, the incidence may be as high as 52%[51]. Rotary instrumentation has great limitations in these challenging root canal systems[26]. However, the SAF system may handle such extreme cases of flat-oval canals with greater efficacy (Fig 15)[26].

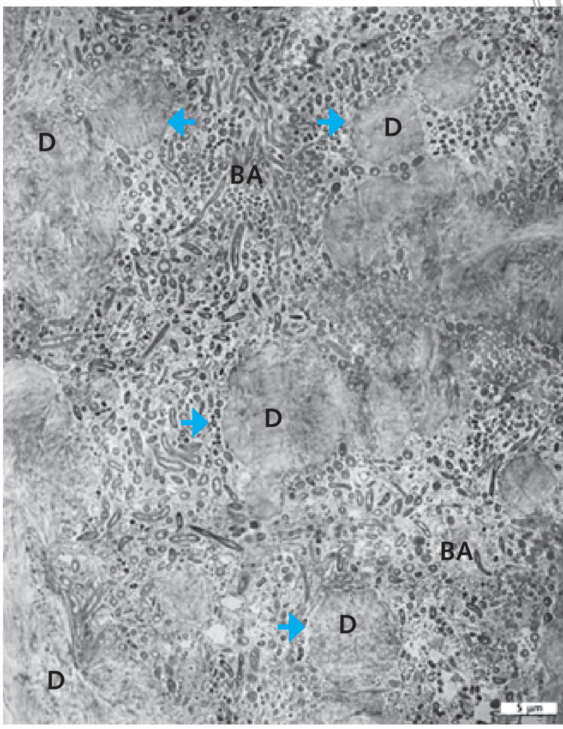


Fig 13 Dentine particles packed into a bacterial biofilm in an isthmus. Mandibular molars were clinically treated with rotary files and syringe and needle irrigation. The apical tip of the root was then immediately resected during apical surgery. Arrows: (D) Dentine particles packed into an intact bacterial biofilm (BA) that was left in the isthmus after complete cleaning and shaping with rotary files. (Adapted from Nair et al, 2005[43])

The challenge of retreatment

When retreatment is performed, the operator attempts to remove the previous root canal filling material completely[52]. Complete removal is important to allow for an effective disinfection of the canal[52]. Hand and rotary instruments are effective in removing the bulk of the root canal filling material, but after their use, the canal wall is often far from being clean[52-55]. Larger diameter instruments may be used to complete the cleaning process, but one must consider the risks of damaging the root by either canal transportation[56] or by the increased creation of microcracks and full thickness fractures[14,57] (see below), which may be caused by the thicker rotary instruments.

The SAF file cannot remove the bulk of the root canal filling material. Nevertheless, Abramovitz et al[58] showed that once this bulk is removed with rotary instruments, the material remaining on the canal walls can be effectively removed with the SAF system[58]. In their study, after the bulk of the root canal filling material had been removed, the canal was dried and a drop of chloroform was inserted. The SAF file was then used in the canal for 1 min without irrigation, followed by 2 min of operation with continuous irrigation, resulting in a much cleaner canal than when rotary instruments alone were used:

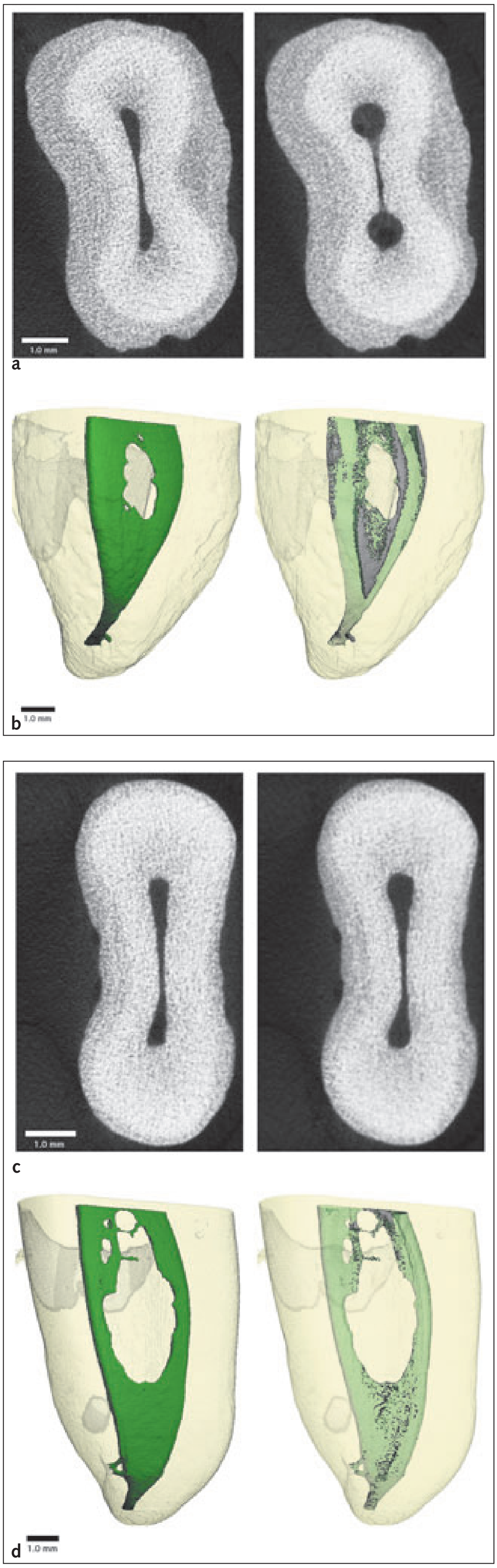


Fig 14 Packing of the isthmus with dentine particles: rotary file vs. SAF. Isthmus-containing root canal systems of mesial roots of mandibular molars were instrumented with either rotary files (a and b) or the SAF system (c and d). (a and c) Micro CT derived cross-sections. (b and d) Micro CT reconstructed images. Green: the volume of the isthmus before treatment. Light green: the volume of the isthmus after treatment. Grey: areas of the isthmus that turned radiopaque due to packing with dentine particles. (Adapted from Paqué et al, 2009[46])

32% of the area of the apical third of the canal was still covered with radiopaque residues after ProTaper retreatment files (Dentsply Maillefer) were used. The supplementary use of the SAF system reduced this residue to 7% (Fig 16)[58].

Because the canal has been previously instrumented and is likely to be a diameter of size 35 or larger, the 2.0-mm SAF file should be selected[59]. Solomonov et al[59] reported that when ProTaper retreatment files were used followed by an F2 file in the distal roots of mandibular molars, 5.4% of the volume of the root canal filling material was retained in the canal. On the other hand, when a ProFile size 25.06 was used, followed by a 2.0-mm SAF, the residue was reduced to 0.4%, and in 57% of the cases, the amount of residue was less than 0.5% (Fig 17)[59]. Additionally, the risks associated with using larger diameter rotary instruments[56] were avoided[59].

When straight, round canals are concerned, the use of a SAF file as a supplementary retreatment tool had no substantial benefit over the use of larger instruments[16]. Nevertheless, in both flat-oval canals[59] and curved canals[58], the supplementary use of the SAF system resulted in cleaner canals than those possible with rotary files[58,59].

■ The microbiological challenge

Reducing the bacterial content of an infected root canal as much as possible has always been one of the major objectives of root canal treatment[60-63]. This task is easily achieved when the canal is straight, narrow and with a round cross section[64]. Nevertheless, many canals do not fit the above description. Long oval canals are rather common[36], and the challenge of reducing bacterial counts as much as possible is quite different in such canals[10,16]. Siqueira et al[10] recently studied the elimination of microorganisms from oval canals *ex vivo*. When rotary files were used with copious irrigation with 2.5% sodium hypochlorite, 55% of the canals still contained viable bacteria after the procedure was complete[10]. When the SAF system was used in similar canals with the same amount and concentration of sodium hypochlorite, viable bacteria were recovered from only 20% of the canals (Fig 18)[10]. Areas of the canal that were not instrumented could serve as sanctuaries for viable bacteria. It is likely that such areas were blocked with dentine chips, as in the case of the isthmus in the studies by Paqué et al[44,45] (see above), which would protect the inner layers of the bacterial biofilm in these areas from the action of sodium hypochlorite.

Further studies from the same laboratory indicated that when similar oval canals were treated with the SAF system using full-strength (6%) sodium hypochlorite, the disinfection was even more effective, and that extending the operation time to 6 min gave better results than 2 min (Fig 19)[16]. The reduction of viable bacteria counts in this study[16] was equivalent to the result achieved using a two-visit procedure with calcium hydroxide dressing[16].

Some of these findings may be attributed to the bactericidal effect of the continuous replacement of fresh, fully active sodium hypochlorite. Nevertheless, Lin and Hapassalo[65] recently demonstrated that the SAF system is also more effective than either rotary or hand files in the removal of biofilm located in recesses (grooves) of the root canal, thus providing additional explanation for the antibacterial efficacy of the SAF system[65]. Therefore, it seems that the introduction of the SAF system may have advanced the above definition of the elimination of bacteria as much as possible one notch farther, at least in oval and irregular canals.

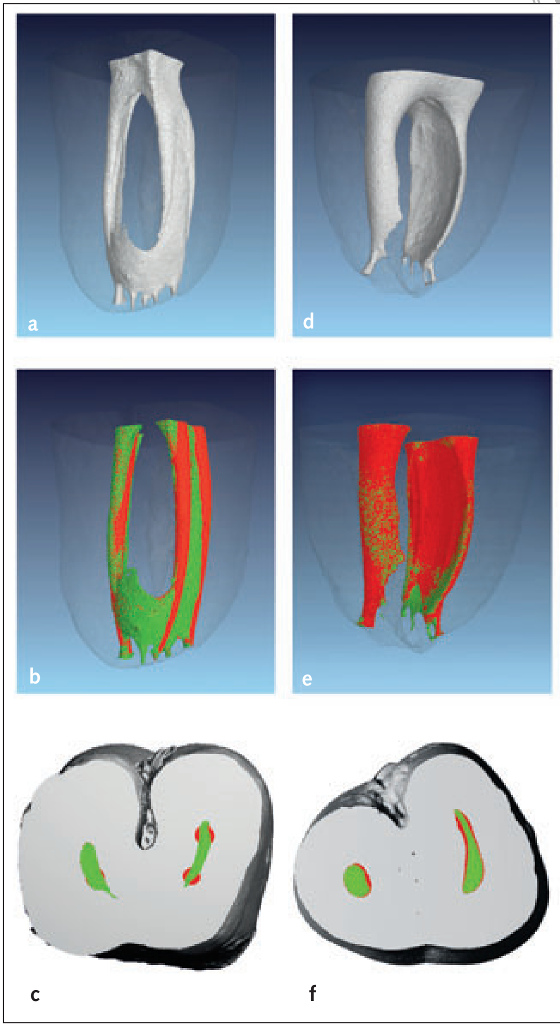


Fig 15 C-shaped canals were instrumented with either rotary files (b and c) or with the SAF system (e and f). Reconstruction from micro CT scans. (a and d) The C-shaped root canal systems before treatment. (b) After instrumentation with rotary files. (c) Cross section of (b). (e) After instrumentation with the SAF. (f) Cross section of (e). Green: the root canal system before treatment, Red: canal walls affected by the procedure. (Adapted from Solomonov et al, 2012[26])

The challenge of 3D obturation

Effective three-dimensional obturation is expected to provide an adequate sealing of the root canal, which has always been a major target in root canal treatment[66]. However, Schilder stated long ago that if the canal is not clean, it cannot be adequately obturated[66].

The quality of root canal fillings is usually clinically evaluated by their radiographic images. Never-

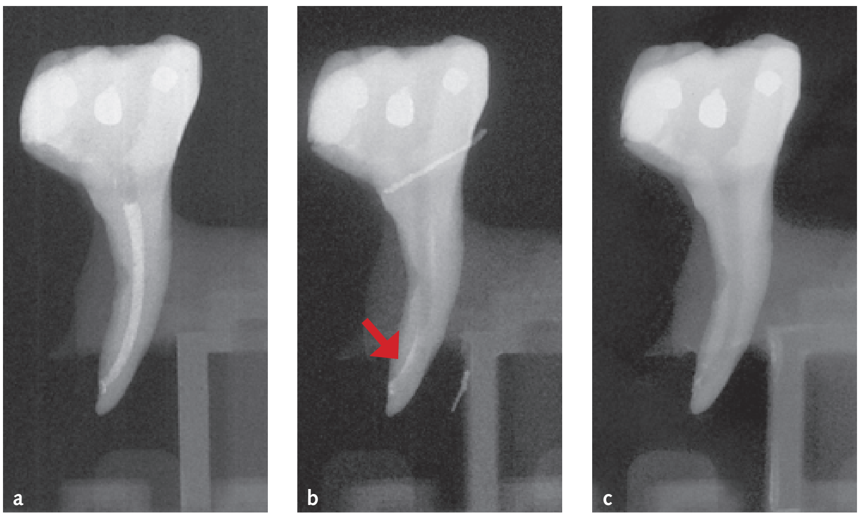
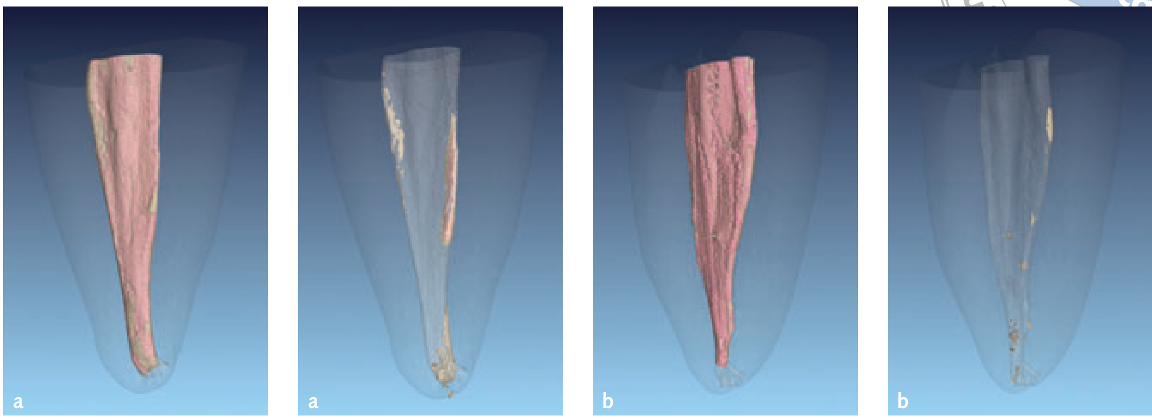


Fig 16 SAF-assisted retreatment: radiographic study. The root canal filling in the curved canals of a mandibular molar's mesial root (a) was initially removed using ProTaper retreatment files. Radiopaque material was left in the apical part of the canal (b, arrow). Supplementary use of the SAF system reduced the radiopaque residue in the apical part of the canal from 32% of the canal area to 7% (c). (Adapted from Abramovitz et al, 2012[58])



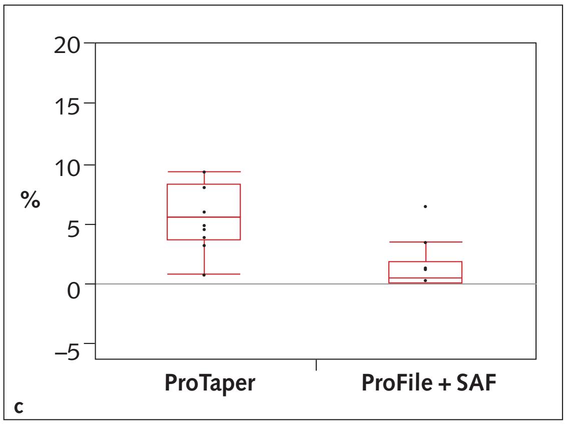


Fig 17 SAF-assisted retreatment: micro CT evaluation. The root canal filling in an oval canal of a distal root of a mandibular molar was removed with either ProTaper retreatment files followed by F2 (a) or by ProFile size 25.06, followed by supplementary use of the SAF system (b). The total volume of the root canal filling (left on a and b) was first measured. The root canal filling residue (Right in a and b) was measured and expressed as a percentage of the initial volume of the root canal fillings (c). The rotary instruments left 5.4% of the root canal filling, while the SAF-supplemented procedure left only 0.4% (c). (Adapted from Solomonov et al, 2012[59])

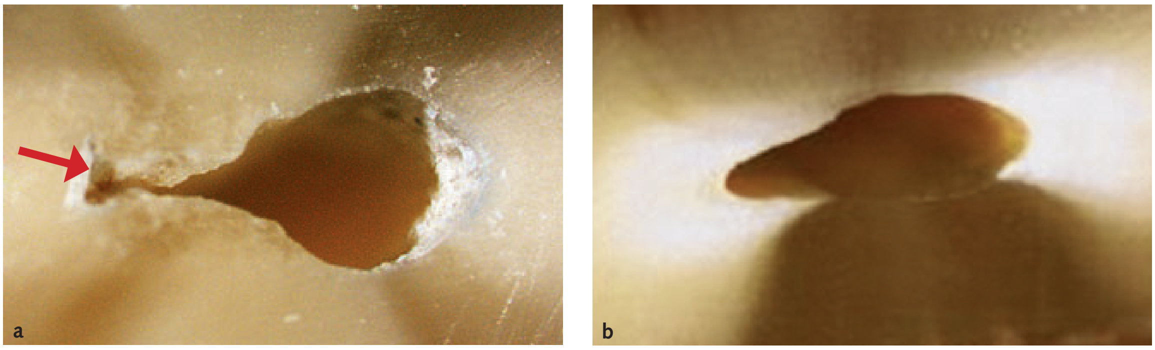


Fig 18 Cross sections of flat-oval canals of mandibular incisors, which were treated with either rotary files or the SAF system. (a) Canal treated with rotary files. Note the uninstrumented area (arrow). (b) Canal treated with the SAF system. (Adapted from Siqueira et al, 2010[10])

theless, limiting the scientific evaluation of root canal fillings to only their appearance on a 2D radiograph ignores the above, basic principle because a planar 2D periapical radiograph reveals only limited information[67] (Fig 20).
Rotary file systems have made it faster and easier to finish a case and produce an acceptable final radiograph of a root canal filling.

However, in a series of studies, De-Deus and coworkers demonstrated that where oval canals are concerned, rotary file systems that produced a satisfactory final radiograph often failed to result in a real 3D obturation of the canal[27,47,48] (Fig 21). The frequent presence of remaining pulp tissue or debris in the un-reached parts of oval canals that were instrumented with rotary files and irrigated with copious amounts of sodium hypochlorite led De-Deus et al to conclude 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"[13].

Debris that remains or is packed into uninstrumented buccal and/or lingual recesses or 'fins' often prevents the root canal filling from achieving 3D contact with the canal wall[27,47,48]. This finding is true even when the most flowable warm gutta-

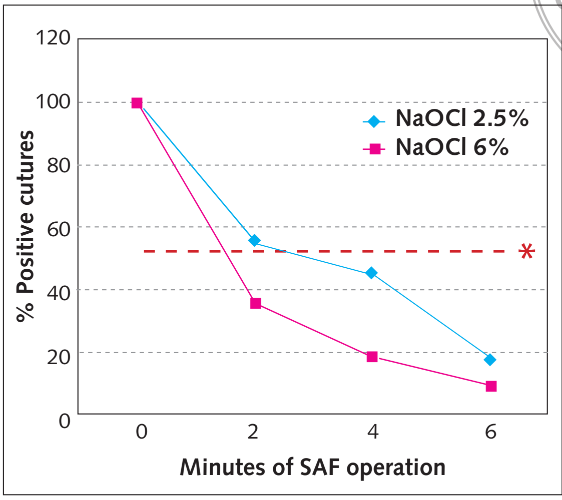


Fig 19 Antibacterial efficacy of the SAF system. Flat-oval canals were infected *ex vivo* with *E. faecalis*, and then treated with the SAF system using either 2.5% or 6% sodium hypochlorite. Percentage of positive cultures after treatment for 2–6 min: the red asterisk and red dashed line represent the percentage of positive cultures that were reported by Siqueira et al[10], when using the same model and treating the canals with rotary files and syringe and needle irrigation with 2.5 % sodium hypochlorite. (Adapted from Alves et al, 2011[16] and from Siqueira et al, 2010[10])

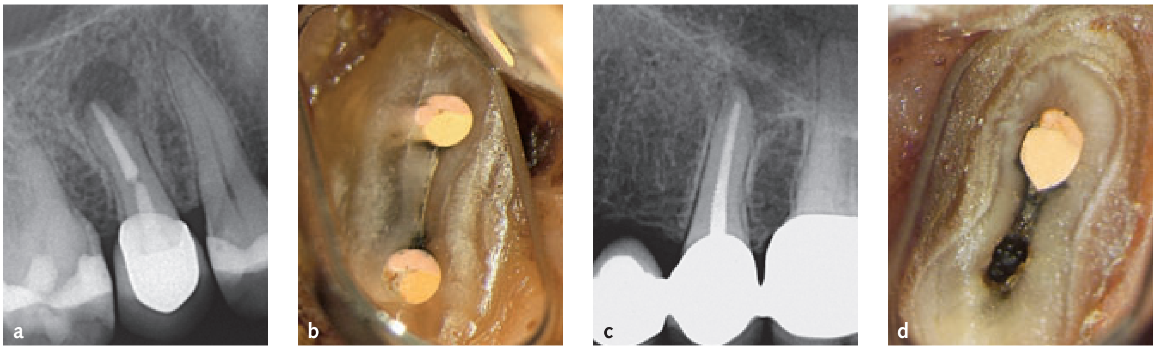


Fig 20 Misleading planar radiography: radiographic image vs. reality in root canal treatment. (a) Radiograph of a failing root canal treatment in a right second maxillary bicuspid. The radiographic image of the root canal filling reveals no reason for failure. (b) An uninstrumented isthmus between the two canals that were treated with rotary files, as seen during apical surgery. (c) Radiograph of failing root canal treatment in a left second maxillary bicuspid. The radiographic image fails to reveal the reason for failure. (d) The reason for failure as observed during apical surgery. The palatal part of the flat canal was excessively prepared with rotary files, but the buccal part of the canal was not instrumented or cleaned.

percha is used[27,47,48], and it is also true when a sealer is used with lateral compaction procedures[11]. Such unfilled recesses, full of debris, may eventually serve as passages and/or places of growth for intracanal bacteria, thus leading to endodontic failure[68]. Such obturation failures, despite the acceptable radiographs they produce, may later be discovered during periapical surgery[69] (Fig 20) or during a microscope-assisted retreatment procedure.

Such cleaning failures in oval canals were most likely the cause of the adaptation failure of the root canal filling in the study by Metzger et al[11], which demonstrated a positive correlation between the parameters of an area unaffected by instrumentation and an area untouched by the root canal filling[11].

The SAF system effectively addresses the oval cross section of the canal[12,20,21,24,29], and provides effective cleaning, even of areas that were not effectively reached by the metal mesh of the file[27,65]; therefore, it may avoid the above-mentioned problem (Fig 21). A recent comparative study in oval canals showed that the SAF system-treated canals were better obturated than those treated with rotary files with syringe and needle irrigation (Fig 21)[27]. The clear reason for that finding was the debris present in untreated longitudinal recesses in the group treated with rotary files, and the absence of such debris in the canals treated with the SAF system[27].

Furthermore, the scrubbing action of the SAF file, combined with the activation of the irrigant by the vibration, also resulted in a smooth and uniform clean surface that allowed for better adaptation of the root canal filling. This resulted in the significantly higher bond strength of the root canal fillings to the canal walls[70].

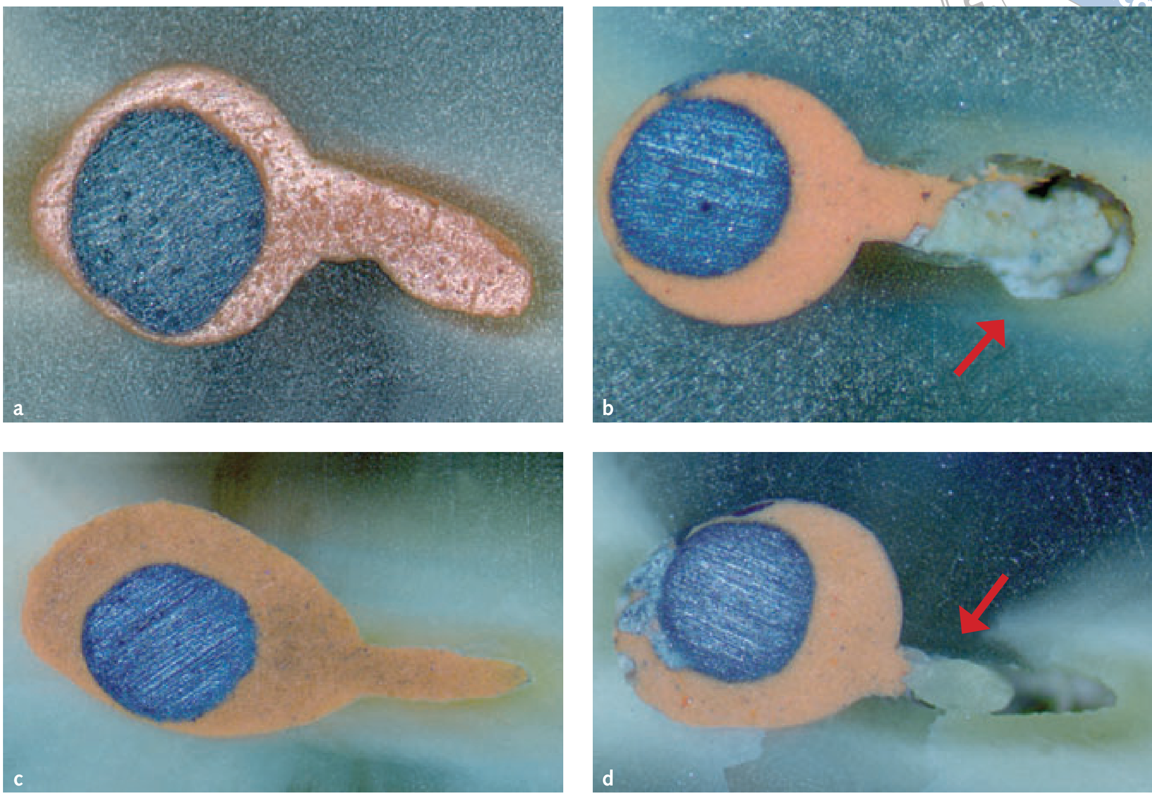


Fig 21 Obturation in flat-oval canals. Pairs of flat-oval canals of mandibular incisors with similar shape and dimensions (a and b, c and d) were cleaned and shaped using either the SAF system with continuous irrigation (a and c) or rotary files with syringe and needle irrigation with 6% sodium hypochlorite. Obturation was done with Thermafill obturators. No sealer was used in order to facilitate visual analysis of the results. The clean SAF-treated canals allowed an unobstructed flow of the thermoplasticised gutta-percha even into the less instrumented 'fins' (a and c), while debris in the uninstrumented 'fins' prevented the flow of the material resulting in poor adaptation of the root filling. (Adapted from De-Deus et al, 2012[27])

The challenge of file separation

File separation is one of the major drawbacks of nickel-titanium rotary files[71]. It is estimated to occur in 5% of cases, even in the hands of experienced operators[72]. The separated fragment is usually screwed-in in the canal and may block access to its apical portion. In such cases, it may be a cause of failed treatment[73]. Removal of the fragment requires expertise, is time consuming, and may lead to the loss of sound dentine with the danger of perforation or predisposing the tooth to vertical root fracture[74]. Furthermore, if the fragment is located beyond a curvature, it is often not retrievable[74]. Recent improvements in file design and nickel-titanium metallurgy have potentially reduced this risk[75-77], but the risk of file separation still exists.

The SAF file is extremely flexible, to the extent of bending upon itself (Fig 8b). It looks delicate, but it is rather resistant to mechanical damage[20,28]. SAF files were reported to operate in a simulated canal for 29 min before any mechanical damage occurred[20,28]. When mechanical failure did occur, it took the form of detachment of one of the arches or struts at one or both of their connecting points (Fig 22)[28]. Even when an arch is completely detached, it is usually easily washed out of the canal[78,79] because, contrary to a separated rotary file fragment, the detached arch is not screwed-in in the canal, and the canal is much larger than the arch or strut, as the whole SAF file was initially inserted into this same canal. These factors may explain why the arches are easily washed out, either simply by the action of the SAF system itself[78,79], by irrigation, or by irrigation assisted by ultrasonic application.

SAF file separation, namely the detachment of the apical part of the file that remains in the canal, is very rare. A recent international survey indicates that such file separation occurred in 0.6% of cases (Solomonov et al, manuscript submitted). In 13 of the 15 reported cases of SAF separation (out of 2517 files used), the separated part could be easily retrieved using a Hedström file. In the other two cases, root canal filling was completed through the hollow file, which enabled a bypass procedure (Solomonov et al, manuscript submitted).

Extensive SAF file damage or even file separation may occur when the SAF is allowed (wrongly) to rotate in a curved root canal[80]. The SAF instrument is designed to rotate only when disengaged, and the clutch mechanism in the RDT head should

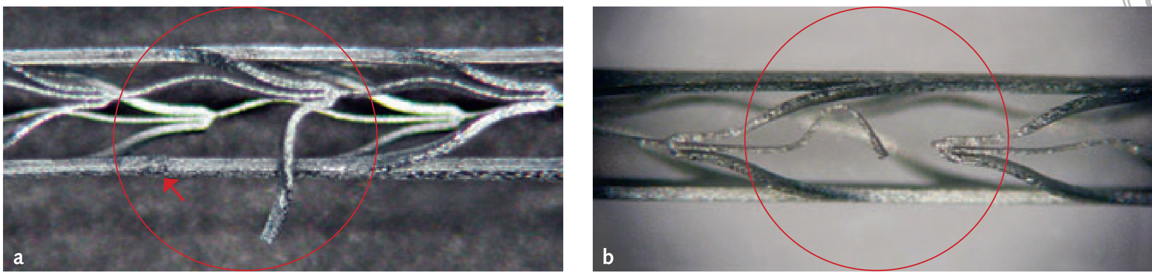


Fig 22 SAF mechanical failure. As opposed to file separation that is the common mechanical failure of rotary files, when mechanical failure occurs with the SAF file, it consists usually of a partial detachment of an arch (a) or a strut (b).

stop the rotation once it encounters the resistance of dentine engagement[21]. When artificial curved metal canals larger than the SAF were used by Akçay et al[80], major mechanical damage to the files was demonstrated due to the rotation that inevitably occurred in such a large curved canal[80]. This damage is the reason that the SAF manufacturers' instructions indicate that the operator should monitor the SAF during operation, and if it rotates when engaged in the canal, remove it immediately. A likely cause for such rotation is selecting a SAF file that is too small for a given canal. The canal diameter should be initially gauged using hand files. If the initial size of the canal is a size 35 or larger, a 2.0-mm SAF file should be used, as opposed to the 1.5-mm file that is routinely used in canals that are smaller than size 35. Using a 1.5-mm SAF file in a large canal will be ineffective[78] and may allow the undesired rotation of the file in the canal, which may lead to extensive damage to the file[80] or even file separation in curved canals.

With proper handling, a SAF file can be used for the instrumentation of three or more canals without significant loss of efficacy[28]. Nevertheless, it is recommended as a single-patient-use instrument, as is the case with other NiTi endodontic files.

The challenge of maintaining the integrity of the radicular dentine

The aim of root canal treatment is to preserve a functional tooth for many years to come. Vertical root fractures (VRF) are the reason for extraction of many root canal treated teeth[81,82]. Among the root canal treated teeth that were extracted, 10–20% were extracted because of such fractures[83,84]. Over time, occlusal repeated forces are believed to cause such fractures in teeth with predisposing factors, among which iatrogenic factors are of great importance[81].

Recent studies by Shemesh and others revealed a new potential iatrogenic factor: microcracks that are created in radicular dentine by rotary nickel-titanium instrumentation[6,7,14,15,18,19,85].

Nickel-titanium rotary files that were used for canal instrumentation caused microcracks in the remaining radicular dentine of single rooted teeth[6,7,18,19,85]. In hand instrumented teeth and in untreated controls, no such microcracks were found (Fig 23). In a recent study, it was shown that the new reciprocating instruments WaveOne and Reciproc caused significantly more microcracks than a full sequence of ProTaper or Mtwo files[85].

Yoldas et al[15] extended these studies to the mesial roots of mandibular molars and reported that all rotary files examined created microcracks in the radicular dentine. Up to 60% of the roots that were instrumented with rotary nickel-titanium files had such microcracks[15]. In all of these studies, some of the microcracks extended through the full thickness of the radicular dentine. However, the SAF, which was also used in the study by Yoldas et al, caused no microcracks (Fig 24)[15]. In a recent study by Hin et al[18], ProTaper and Mtwo produced microcracks in 35% and 25% of cases, respectively, while the creation of such defects by the SAF was limited to 10% of the premolars that were used in this study[18].

Generating such microcracks can be explained by the finite element analysis performed by Kim et al[86]. This analysis revealed that when a rotary file such as ProTaper is operated in a curved canal, it generates stress in the outer dentine layer of the root that exceed the elasticity of dentine, which are likely to result in cracks[86]. A recent similar analysis by the

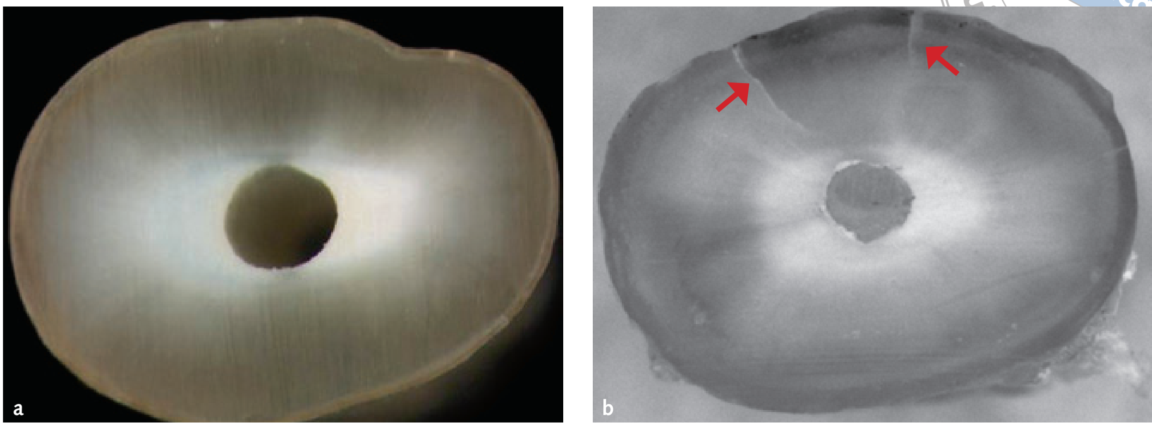


Fig 23 Microcracks in radicular dentine caused by rotary files. Rotary files cause microcracks in the radicular dentine in a large percentage of the teeth. (a) Control: instrumentation with hand instruments: no cracks. (b) Instrumentation with rotary files: microcracks in the radicular dentine (arrows) (Adapted from: Shemesh et al, 2009[6])

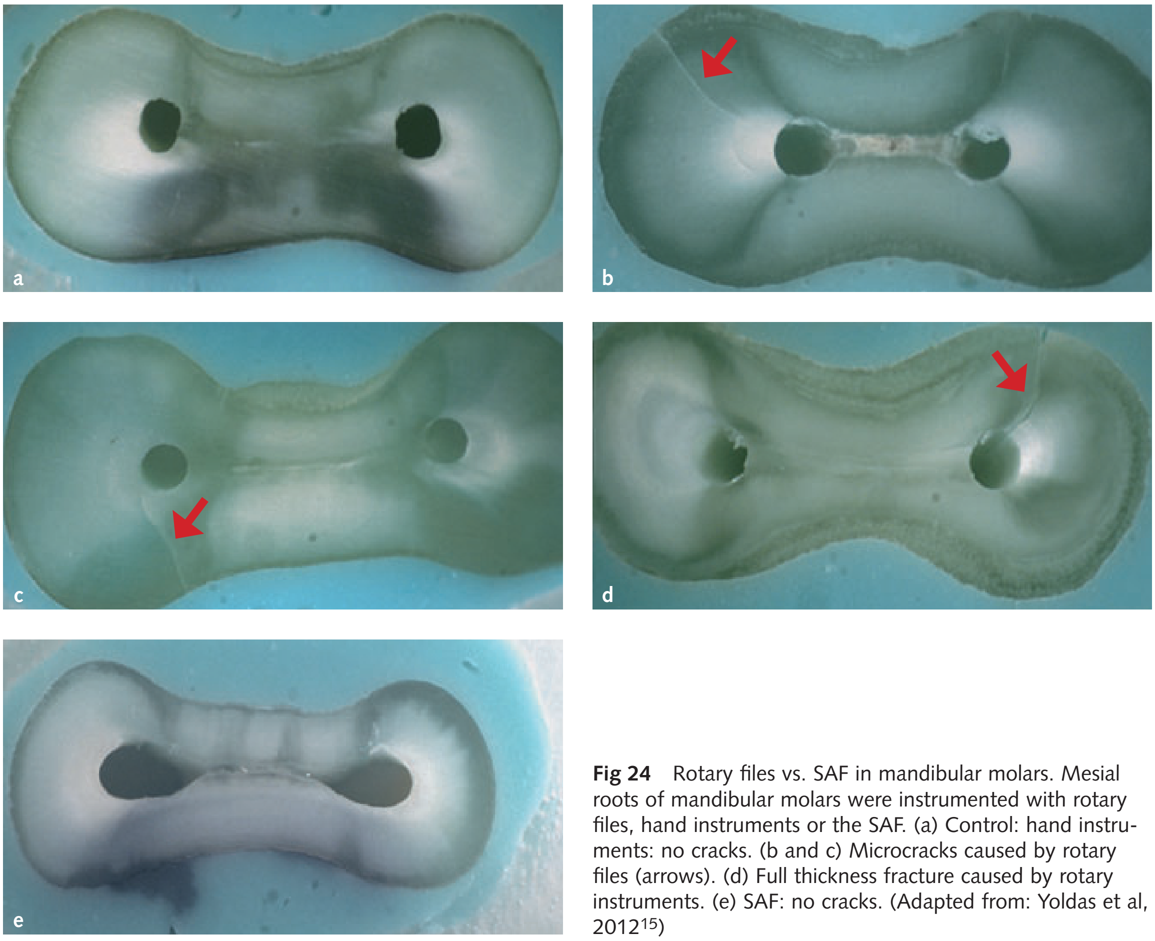


Fig 24 Rotary files vs. SAF in mandibular molars. Mesial roots of mandibular molars were instrumented with rotary files, hand instruments or the SAF. (a) Control: hand instruments: no cracks. (b and c) Microcracks caused by rotary files (arrows). (d) Full thickness fracture caused by rotary instruments. (e) SAF: no cracks. (Adapted from: Yoldas et al, 2012[15])

same group revealed that the operation of the SAF produced no such stress (Kim et al, personal communication – manuscript submitted).

When root canal filling was performed in canals treated with rotary instruments, the incidence of full, through and through dentinal fractures was increased[6]. Similarly, retreatment performed in these canals further increased the incidence of such damage[57]. Therefore, there is a reason to assume that such dentinal microcracks may eventually lead to VRFs.

A direct study connecting the use of rotary files to clinically occurring VRFs has not yet been conducted.

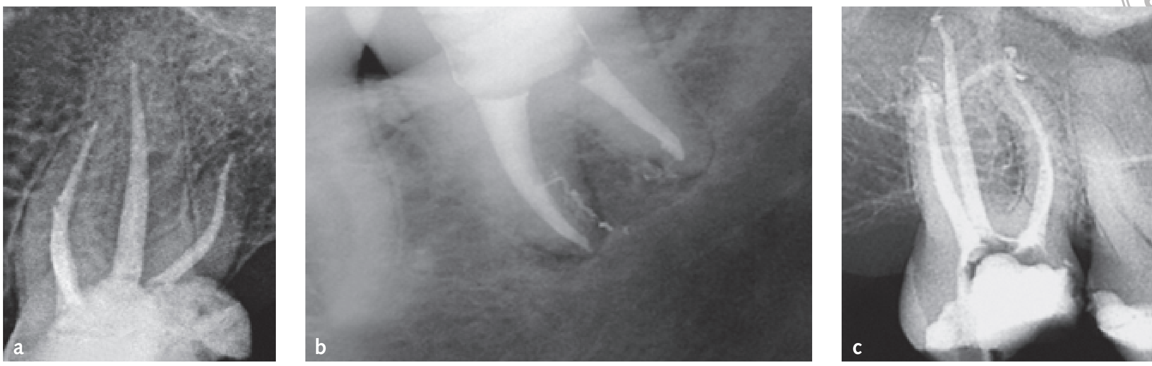


Fig 25 Clinical cases treated with the SAF system. (a) Left first maxillary molar. Note the preservation of the S-shaped curvature of the distobuccal canal. (b) Second left mandibular molar. Note the filled lateral canal in the mesial root. (a and b adapted from Solomonov 2011[29].) (c) Right second maxillary molar. Note the preserved curvatures of the mesiobuccal and the palatal canals (courtesy of Dr M. Levine, Chevy Chase, MD, USA).

Nevertheless, the basic principles of biomechanics indicate the likelihood of crack propagation in dentine under repeated loads until fracture occurs[87]. The SAF file has no blades and has a less aggressive mode of action, which does not cause[15] or produces fewer dentinal microcracks[18].

Clinical implementation of the SAF system

The SAF system is substantially different from all current rotary file systems. Consequently, when starting to use this system the operator has to change certain habits and should expect a certain learning curve. This is first of all because the SAF file is not a penetrating instrument, as per all current rotary files. Furthermore, the endpoint of treatment is defined by operating time rather than by reaching a working length with a given size of instrument.

The clinical radiographic results show some unique features (Fig 25) but they are not much different than those resulting from treatment with other files. Nevertheless the SAF system enables a new endodontic concept that requires some conceptual adaptation.

The concept of minimally invasive endodontics

It is widely accepted that 'cleaning and shaping' is a critical stage in root canal treatment[31,62,66]. The shaping part of this process is performed with endodontic files. This shaping will eventually dictate the 'look' of the root canal filling, which is clinically evaluated using planar, two-dimensional radiographs. Recent advances for root canal preparation have focused on the concept of 'less is more'[88,89]. The adequate 'look' has changed over the years from root canal fillings that had a large flare requiring rather extensive coronal enlargement, to one with a more moderate enlargement[37,88-90]. This change was due to the recognition of the damage to the root and the potential risk of VRFs associated with such generous preparations.

Controversy remains regarding the adequate apical enlargement of the canals. Some believe that a size 25 apical preparation is adequate, while others argue that in many cases, such an apical preparation will not even touch the canal walls, especially in slightly oval canals[91,92].

Why substantial shaping and/or large apical preparations are currently required

Obturation

Initially, shaping was adapted to and served the subsequent obturation method. This was the case in the era of standardised master cones fitted into a canal prepared with a 0.02 taper standardised file, and is still the case when fitting a master cone with the size and taper fitting the last rotary nickel-titanium instrument used. In a way, this is also the norm for when preparing a canal with a size 25 apical preparation to allow for, and facilitate, the use of various thermoplasticised gutta-percha obturation methods[93] without a large periapical extrusion of obturation materials.

Irrigation

It is well established that unless the canal is properly enlarged in its apical portion, effective irrigation of this part of the canal is precluded[94,95]. This is the case when hand instruments were used[94,95] and is still the case when rotary files are the primary endodontic tools[96-98]. Furthermore, even a negative pressure system, such as the EndoVac (SybronEndo, Orange, CA, USA), requires a minimal apical preparation of size 35.02 to be effective[99] and for better irrigation, size 40.06 enlargement is recommended[100].

With these data, the dispute over the adequate apical enlargement of the canals, in which some believe that a size 25 apical preparation is adequate, seems anachronistic, at least as far as the effective irrigation of the apical part of the canal is concerned.

Inclusion of all canal walls

As the removal of the inner infected dentine layer is desired in infected cases, and because the removal of all tissue remnants and biofilm is strongly recommended, larger apical preparations have been advocated[92,101,102]. Such preparations were expected to include the whole perimeter of the canal within the preparation in a larger percentage of the cases than possible, with preparations limited to a size 25 apical enlargement. Nevertheless, even with such larger preparations, it was often impossible to completely clean the apical area[97,102,103].

The price tag

The above requirements of effective irrigation, convenient obturation and/or attempts to include the whole apical canal cross section within the preparation have a price tag attached. They all require substantial, yet unnecessary, removal of sound dentine, which in turn may predispose the root to VRF[6,7,15,57]. Although the strength of a root canal treated tooth is directly proportional to the amount of remaining sound tooth structure[104], this price is commonly accepted, as the goals of root canal treatment must be met.

The alternative

The SAF system operates with a totally different mode of action than rotary instrumentation. With the SAF system, there is no need to increase the size of the preparation to include the whole canal. The SAF file removes a uniform layer from all dentine walls of the canal and affects a substantially higher percentage of the canal wall[11,12,17,20,21,23]. These results are accomplished while maintaining the natural shape of the canal and without imposing a circular 'bore' in oval canals[20].

Furthermore, there is no need for excessive dentine removal at the apical part of the canal or to create excessive artificial taper to enable effective irrigation and cleaning of that portion. The continuous flow of fresh, fully active irrigant combined with continuous activation by vibration and the scrubbing effect of the metal mesh of the SAF file enable better cleaning of the apical part of the canal, with no need for the excessive removal of dentine[17,22,25,35]. The obturation of oval canals has been also shown to be more effective after the SAF system was used due to the cleaner canal and the absence of remaining and/or packed debris, which may compromise the seal in oval canals treated with rotary files[27].

Minimally invasive endodontics

The SAF technology allows for a new concept in endodontics: minimally invasive endodontics. Minimally invasive procedures in medicine at large are procedures designed to achieve all of the goals of the traditional, more invasive procedures, while causing only minimal damage to the patient. Such procedures do not represent a compromise but, rather, attempts to reduce the destructive 'price tag' attached to the more invasive traditional approach[6,7,14,15].

The SAF system allows for such a change in endodontics; it allows for: (i) more complete instrumentation of the canal walls[11,12,17,20,21,23,24]; (ii) cleaner oval canals[12,13,20,27]; (iii) cleaner apical portion of the canal[17,22,25,35]; and (iv) better adaptation of the root canal filling to the canal walls, especially in oval canals[11,27].

All of these results are achieved: (i) without the excessive removal of dentine in all parts of the canal[11,12,20,21,23,24]; (ii) without straightening and/or transportation of the canal[20,23] or the risks associated with these phenomena; and (iii) without the inherent risk of creating microcracks in the radicular dentine[15,18].

Conclusion

What is the current success rate of endodontics? Some will quote 76–80% for infected teeth and higher than 90% for vital ones[1,105-107]. These figures represent the highest possible success rates. However, the real-life success rate in general practice is much lower[107]. Cross-sectional studies indicate relatively high failure rates up to 50%[108,109]. These high failure rates may be due to the many unmet challenges detailed above.

The following question may be asked: if so many unmet challenges exist, how have we achieved the good results in the cases in which we do succeed? Might this success be potentially attributed to the great tolerance that nature allows us? After all, we do often succeed with current technology in challenging 3D cases with oval or curved canals. Could it be that we succeed not *because* of what we did, but *in spite* of what we did?

No proof yet exists that the improved cleaning, shaping and obturation that have been made possible by the SAF system will affect the success rate. However, the basic concepts and principles of endodontics indicate that to allow success, the canal should be clean of debris, free of bacteria and sealed adequately by the root canal filling[66,98].

All of these basic demands are better achieved, at least in oval and/or curved canals, with the SAF system[10-13,17,20-25,27,35]. In this context, one has to keep in mind that oval canals are not rare; rather, planar radiography does not show them to be oval.

The SAF system opens up a new era and new horizons for those practitioners who are not content with just faster and easier root canal treatment, but who additionally strive for the best 3D root canal treatment. The new concept of 'minimally invasive endodontics' that has been made possible by the new SAF technology represents a potential paradigm shift. As such, it requires an open mind for new ways of thinking about endodontics.

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