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

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Abstract

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

Key Words

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

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

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

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

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

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

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

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

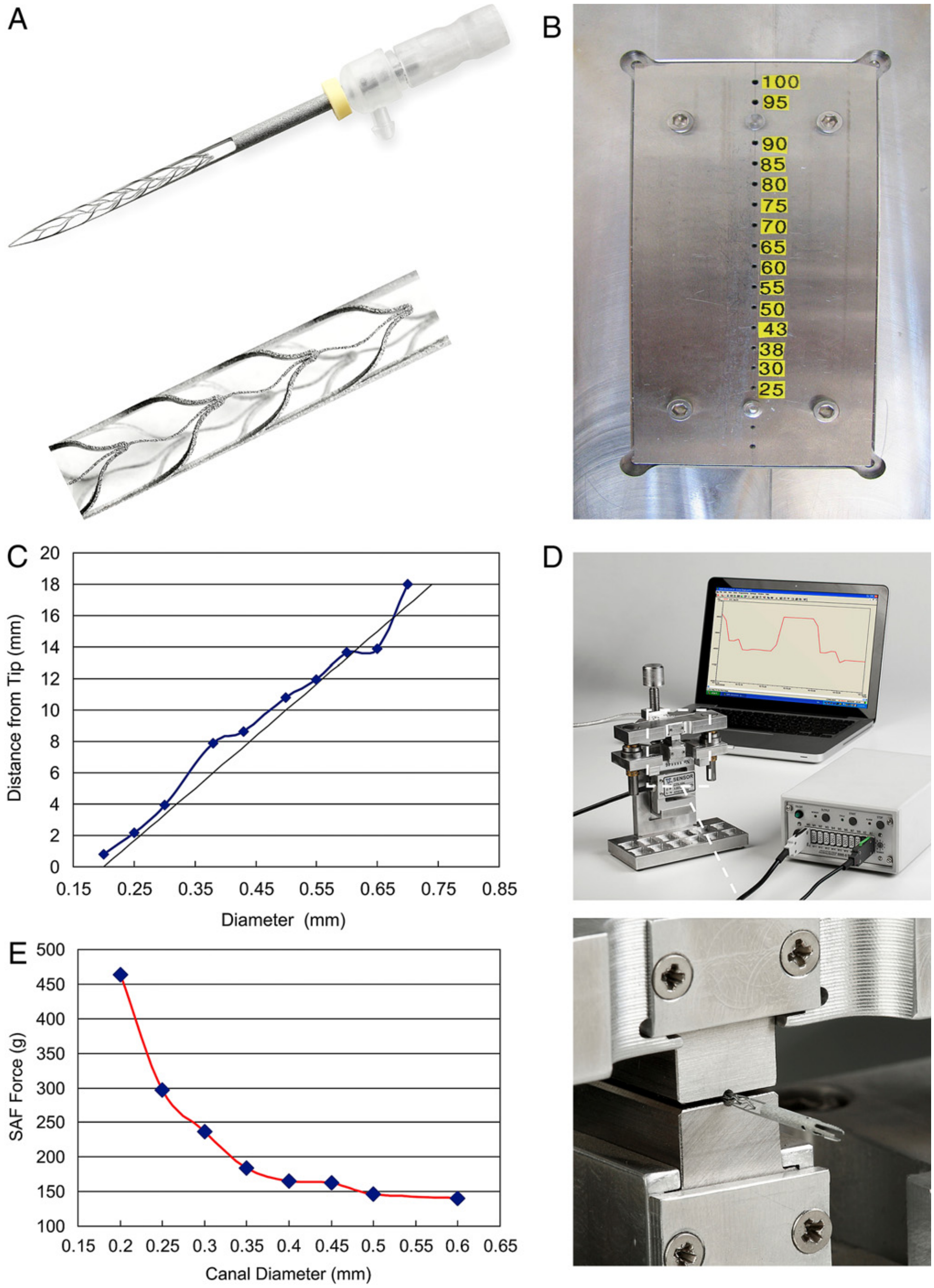

Figure 1. (*A*) The SAF file: longitudinal beams connected by arches, forming a pointed cylinder with a 1.5-mm diameter and wall thickness of 120 μm. The arches are stabilized by thin longitudinal struts. The surface is lightly abrasive. (*B*) Compressibility test: precision drill holes in a stainless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

Materials and Methods

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

Compressibility of the SAF

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

Force Applied as a Result of Compression

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

Surface Roughness

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

Abrasivity Test

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

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

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

Durability: Torque Test

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

Durability: ADA Cyclic Fatigue Test

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

Durability: Free Buckling Fatigue Test

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

Durability: Functional Fatigue-to-Failure Test

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

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

SAF Degradation as a Function of Working Time

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

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

Irrigation Experiments

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

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

Results

Compressibility of the SAF

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

Force Applied as a Result of Compression

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

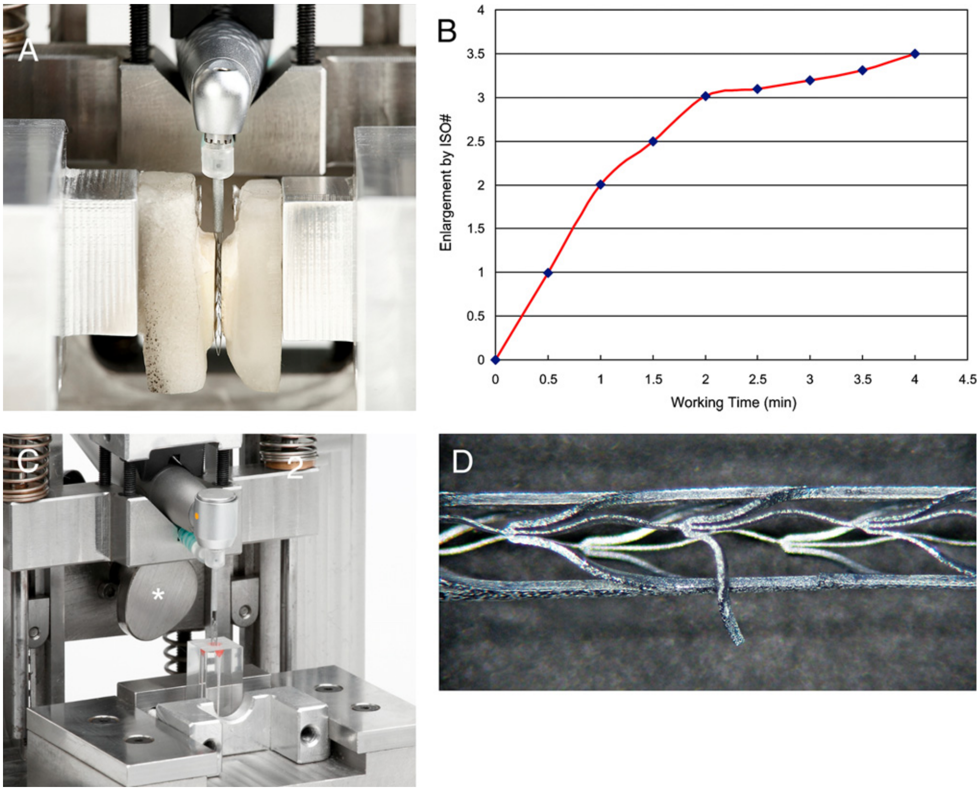

Figure 2. (*A*) Setup for testing abrasivity: two preweighed dentin slices are held in a precision device at a 0.2-mm distance from each other. An SAF file is operated while compressed between the plates. The amount of dentin removed is calculated by weighing the plates before and after the procedure.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

Surface Roughness

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

Abrasivity Test

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

Durability: Torque Test

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

Durability: ADA Cyclic Fatigue Test

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

Durability: Free Buckling Fatigue Test

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

Durability: Functional Fatigue-to-Failure Test

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

SAF Degradation as a Function of Working Time

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

Irrigation Experiments

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

TABLE 1. SAF Durability: Functional Fatigue to Failure

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

SAF, self-adjusting file.

*Each lot consisted of 10 SAF files.

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

Discussion

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

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

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

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

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

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

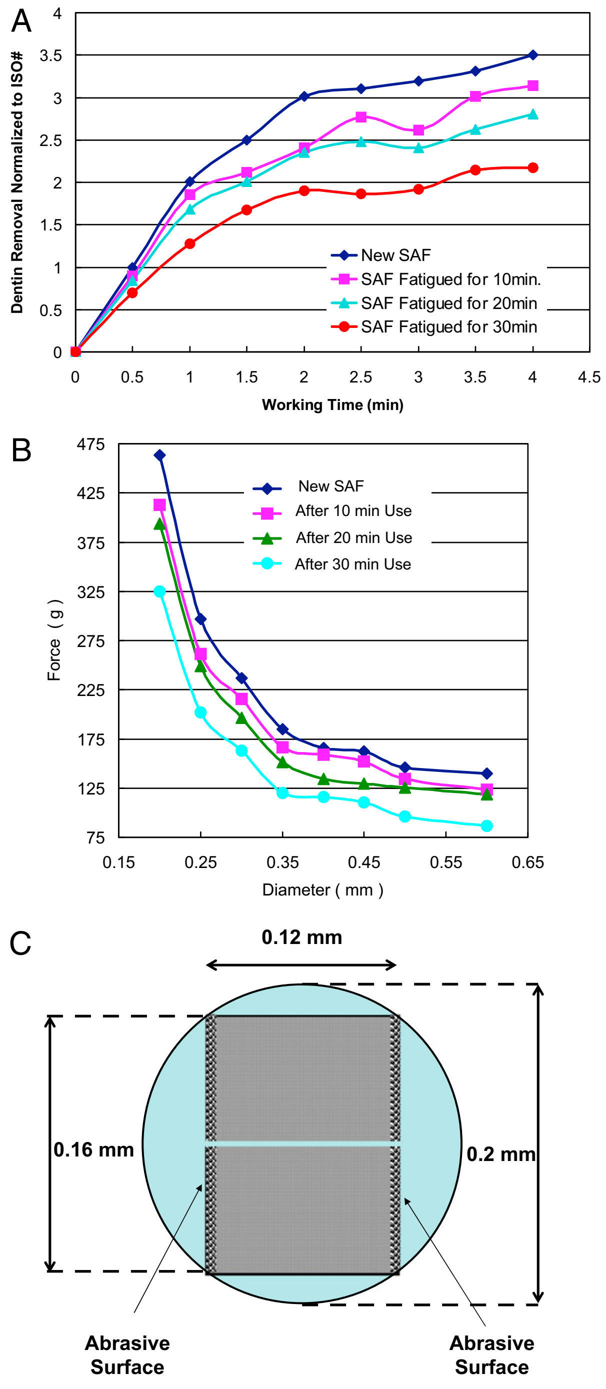

Figure 3. (*A*) SAF efficacy degradation as a function of working time. SAF files were used for 10, 20, or 30 minutes and their efficacy measured and compared with new SAF files. Each point represents the mean of 10 samples. The standard deviation was within $\pm$ 0.1%. (*B*) Degradation of the force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

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

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

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

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

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

Conclusions

The following conclusions were made:

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

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