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ORIGINAL RESEARCH

Cyclic fatigue resistance of two pediatric rotary files manufactured with different heat treatments: an *in-vitro* study

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Abstract

Nickel-titanium (NiTi) instruments offer many advantages during endodontic instrumentation; however, the fracture risk within the canal remains a concern. Manufacturers continuously develop and introduce instruments to the market with supposedly enhanced cyclic fatigue resistance and increased flexibility, achieved through different proprietary manufacturing processes, the details of which have not been made public. In recent years, two rotary systems specially designed for deciduous teeth have been commercially available, but information about their performance is lacking. This investigation aimed to identify which manufacturing process provides better cyclic fatigue resistance: the AF-H Wire technology used in the AF baby rotary files (AF-f) or the CM-Wire technology used in the i3 Gold deciduous teeth rotary files (i3G-f). Forty rotary International Organization for Standardization (ISO) 25/04 files were tested in artificial canals with a standard geometry of 60° angle and 2.5 mm radius until fracture. The number of cycles to fracture was calculated, and the length of the fragments was measured. A scanning electron microscope (SEM) was used to examine the fracture surfaces and fragments. Energy dispersive spectroscopy (EDS) was used to determine the percentage weight of NiTi in each file. The statistical analysis (Mann-Whitney test) showed that the cyclic fatigue resistance of the AF-f was significantly higher ($p < 0.0001$) than that of the i3G-f. Additionally, there was a significant difference ($p = 0.0419$) in the length of the fractured fragments. All instruments showed one or more types of manufacturing defects and presented similar NiTi percentages by weight. The manufacturing process is critical to cyclic fatigue resistance, and there seems to be responsible for the difference in cyclic fatigue resistance between these similar instruments.

Keywords

Cyclic fatigue; Nickel-Titanium; Pediatric rotary files; Deciduous teeth; Pulpectomy

1. Introduction

Despite advances in pediatric dentistry, the prevalence of dental caries and the occurrence of pulp disease in deciduous teeth and their premature loss continue to be common problems [1]. However, maintaining a tooth in the arch for as long as possible is a primary concern in pediatric dentistry, as this helps to prevent harmful habits and to promote the eruption of succeeding permanent teeth into an ideal position, besides contributing to mastication, phonation, and esthetics [2–6].

Pulpectomy is the primary treatment when the effects on pulp are irreversible and possesses several advantages over extraction. This procedure includes the removal of the irreversible inflamed or necrotic pulp tissue while the root canal system is chemical-mechanical cleaned and shaped; for this, the instrumentation plays an essential role [7]. To date, the most common method of instrumentation in deciduous teeth is by hand with stainless steel files; however, the use of these files is responsible in part for procedural errors such as canal transportation, zipping, elbowing, ledging and root perforations, all mainly associated with the straightening of curved canals because of the stiffness of the stainless steel files, which also increases with increasing size, hampering the procedure [8]. As if this were not enough, the root canal anatomy of deciduous teeth further aggravates the situation. They present shorter, thinner, and more curved geometry than permanent teeth, also undergo continuous reconfiguration because of the formation of secondary dentine and physiological root resorption [9]; rotary nickel-titanium (NiTi) instruments have been developed in an attempt to overcome these features [10].

NiTi files offer many advantages, such as maintaining the original shape of the root canal and decreasing the possibilities of zipping, ledge formation, and perforation risk. Thanks to their flexibility and efficiency, pediatric dentists are increasingly interested in mechanized instrumentation with NiTi files [10]. Besides, several investigators have reported the superiority of rotary over manual instrumentation [11]. Despite the various advantages and the superelasticity of these rotary files, the risk of a fracture within the root canal remains a concern, because an intracanal separation of the instrument may negatively affect the outcome of the treatment, especially when the instrument prevents optimal sealing in necrotic teeth [12]. An intracanal separation of a file could occur, especially in severely curved root canals where the instrument encounters high stress while rotating at the point of greatest curvature [13]. Fracture of rotary files occurs in two ways: by cyclic fatigue or by torsion load. A torsional fracture occurs when the tip or another part of the file is locked in a canal while the shank rotates. At this point the fracture becomes inevitable when the torque exerted by the handpiece exceeds the elastic limit of the metal [14].

On the other hand, fractures caused by cyclic fatigue occur when the instrument is held in a static position and continues to rotate; one-half of the instrument is in tension, whereas the other half is in compression. This repeated tension-compression cycle within curved canals increases the cyclic fatigue of the instrument over time and is a crucial factor contributing to fractures [14].

Cyclic fatigue is the main reason for rotary file fracture in curved canals; it has been reported that 70% of fractures are caused by cyclic fatigue, while the remainder are caused by torsional fatigue [15]. In an attempt to solve this problem, manufacturers worldwide have introduced to the market instruments with different alloys manufactured through several proprietary manufacturing procedures, including thermal, mechanical, and surface treatments, in order to improve their mechanical properties [16]. These new technologies can produce instruments capable of change from the martensitic to austenitic phase at different temperatures, which enables instruments to operate in the austenitic phase (strong and hard) when heated to their phase transition point, but in the martensitic phase (soft, ductile, and flexible) at room temperature. This increased flexibility allows instruments to rotate more centrally within the root canal, following the canal's anatomy and reducing issues such as canal and apical transportation [17] but also enhancing its cyclic fatigue resistance.

Nevertheless, most manufacturers' efforts have been centered on rotary systems designed for permanent teeth, with which pediatric dentists face difficulties when performing root canal therapy in children, mainly related to the limited mouth opening of these patients. Nowadays, very few rotary systems are designed explicitly for deciduous dentition, and there is very little information on these specific instruments, precluding their selection based on scientific knowledge about their properties [18].

In recent years, two Chinese trade brands have introduced to the market two rotary systems specifically for pediatric use: the AF baby rotary files (AF-f) (Fanta Dental, Shanghai, China) and the i3 Gold deciduous teeth rotary files (i3G-f) (Denjoy, Changsha, China).

AF-f are made with AF-H Wire technology; they present a triangular cross-section, non-cutting tip, and 4% or 6% taper [19]. i3G-f are made with CM-Wire heat treatment technology; they also present a triangular cross-section, non-cutting tip, and 4% or 6% taper [20]; both manufacturers claim that their manufacturing process decreases cyclic fatigue; however, to date, there have been no independent investigations to prove this, which is why this investigation aimed to identify the influence of the alloy and manufacturing process on the cyclic fatigue resistance of the AF-f (AF-H Wire technology) and i3G-f (CM-Wire technology). The null hypothesis was that there is no difference in cyclic fatigue resistance between these two systems.

2. Materials and methods

Two pediatric NiTi rotary systems were studied: the AF-f and the i3G-f. After sample size calculation (α = 0.03; β level of 0.20 (20%) (*i.e.*, power = 80% at a 5% significance level); σ = 20.0; δ = 20.0), 20 files were used in each group. All files were ISO 25/04 and 16 mm in length. Before the test, each new file was examined for defects under a stereomicroscope (Zeiss Stemi SV6; Carl Zeiss, Jena, Germany).

2.1 Cyclic fatigue resistance testing

The static cyclic fatigue resistance test was used with a stainless-steel device fixed to a main frame. This custom-made device was based on characteristics described by Pruett *et al.* [21]. The device was machined with a length of 17 mm, an angle of curvature of 60°, a radius of 2.5 mm (extremely curved canal), and a 1 mm depth. The device was covered with transparent acrylic plates fixed with screws, which allowed observation of the instrument rotating until the time of its fracture.

Each file was mounted in the handpiece of an electric motor (E-extreme micromotor, Eighteeth, Changzhou, Jiangsu, China) and positioned at the same point in the testing device, ensuring the transparent acrylic plate was not in contact. Both systems were used according to their manufacturer's instructions. The AF-f were rotated at a fixed speed of 350 rpm and a torque of 2 N.cm, while the i3G-f were set at 350 rpm with a torque of 1.6 N.cm. To reduce friction, the simulated canals were flooded with 3-IN-ONE mineral oil (WD-40 Company, California, USA). The working time was taken from when the file rotation was activated until its fracture was observed. The time was recorded with a digital 1:1000 s chronometer. The total number of cycles to fracture (NCF) for each file was calculated by multiplying the speed (rpm) by the time (in seconds)/60. Once the cyclic fatigue resistance testing had concluded, each file's apical and coronal fragments were recovered and measured using a digital caliper (Mitutoyo, Digimatic, Kawasaki, Japan).

2.2 Scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) analyses

In order to characterize the files and to match the conditions with those used in the cyclic fatigue resistance test, a new file from each rotary system was rotated inside an Eppendorf tube containing 1.5 mL of 3-IN-ONE mineral oil (WD-40 Company, California, USA) with the same rpm and torque indicated by each manufacturer for 5 min to cover the file with the mineral oil, taking care not to touch the walls of the tube at any time. These two files and three fractured ones from each system were randomly selected to characterize their topographic features. They were mounted on a holder and analyzed using a scanning electron microscope (SEM) (TM1000, Hitachi, Mito, Japan) operating at 15 kV. Images were obtained at different locations and magnifications (50×, 200×, 400×, 800×, 4000×) using a backscattering electron detector. In addition, elemental analysis was carried out with an energy-dispersive spectroscopy (EDS) Oxford detector coupled to the microscope. The mean of detected elements was obtained from 10 regions randomly selected in the analyzed instruments.

2.3 Statistical analysis

The total number of cycles to fracture and the length of the fragments were calculated in terms of means and standard deviations. The normality of the data was assessed using the Shapiro-Wilk test. The nonparametric Mann-Whitney test using GraphPad Prism version 9.5 (GraphPad Prism Software Inc., San Diego, CA, USA) was used for comparisons. The level of statistical significance was set at ($p < 0.05$).

3. Results

The number of cycles to fracture and the length of the apical fragments for each rotary file are shown in Table 1. The cyclic fatigue resistance of the AF-f was significantly higher than that of the i3G-f ($p < 0.0001$). In addition, there was a significant difference in the fractured length of the fragments ($p = 0.0419$).

SEM analysis of the new files demonstrated similar file designs (Fig. 1), as claimed by their manufacturers, with an inactive rounded tip (Fig. 1a,a',d,d') and triangular cross-section. However, the AF-f has a convex triangular cross-section and a different pitch (Fig. 1A,B,D,E). All instruments demonstrated one or more types of manufacturing defect, not only at the surface of the flutes but also on the cutting edges where blunting (rolling-over) was a constant feature and where debris particles appear to adhere tenaciously (Fig. 1b,c,e,f). At higher magnification, numerous superficial fissures were observed in the i3G-f (Fig. 1C), while in the AF-f, numerous rounded porosities were observed on the surface (Fig. 1F).

Following the cyclic fatigue resistance test (Fig. 2A–D), numerous surface cracks close to the fracture site were evident in i3G-f (Fig. 2a,b). In contrast, cracks in the AF-f were not visible close to the fracture (Fig. 2e,f), but both files had a fractured edge (Fig. 2c,d).

The cross-section images of both files revealed similar features in terms of the origin of the crack, the fatigue zone, and fracture striations (Fig. 2C,D). Both files presented crack initiation at the cutting edges and the fracture cross-sections had areas of microscopic dimples on the fracture surfaces (Fig. 2g–j). A similar pattern of voids was observed at higher magnification at the center of both files (Fig. 2k,l).

Concerning the elements in the alloy of each file, the EDS analysis indicated that the i3G-f consisted of 55.7 weight percent (wt%) of nickel and 44.3 wt% of titanium. Meanwhile, the AF-f consisted of 55.9 wt% of nickel and 44.1 wt% of titanium (Fig. 3). There was no significant difference in the composition ($p = 0.5436$), and no other element was detected.

4. Discussion

A successful pulpectomy on deciduous teeth is heavily dependent on factors such as deciduous dentition longevity, structural integrity, and root canal anatomy, making treatment challenging [22]. Disinfection, correct instrumentation, and obturation of a pulpectomy treatment are essential. Rotary systems efficiently create predetermined conical shapes with minimum risk, mainly because of the NiTi alloy [22]. The desirable mechanical properties of NiTi alloys facilitate the preparation of root canals within a shorter time, and with less canal transportation, higher dentin preservation, and a reduced risk of apical deformation or zipping in curved canals. They also allow the pulpectomy treatment to be completed in one appointment, preventing contamination or bacterial recolonization; the decreased working time aids in maintaining patient cooperation, is less stressful for the patient, and diminishes the operator's tiredness [23, 24]. However, the fracture of rotary NiTi files remains a significant drawback that must be considered in clinical practice [18]. Several factors are responsible for file fracture; however, cyclic fatigue has been reported as a significant cause [25]. Cyclic fatigue is affected by multiple factors, such as the instrument design, radius and angle of curvature, movement kinematics and temperature during use [26], but also by the alloys and their treatment.

In this study, the cyclic fatigue resistance of two pediatric rotary systems (manufactured using different technologies) was tested, and the results led to the rejection of the null hypothesis because there was a significant difference between the two rotary systems. The AF-f showed higher cyclic fatigue resistance. In addition, the length of separated fragments tended to be longer in the case of AF-f (although the difference was not significant), which is desirable as this facilitates their removal with an extractor system [27], with the coronal portion providing a longer protruding end for manipulation, thus resulting in higher success rates when removing fragments [28, 29].

These results must be attributed to the characteristics of each rotary file related to the manufacturing process, structure, and design of the files for each system. As expected, each manufacturer claims that their product has enhanced properties. The AF-f manufacturer claims "improved resistance to cyclic fatigue in its design and an advanced tip process that avoids forming ledges" [19]. In contrast, the i3G-f manufacturer claims "advanced thermal activation technology that makes the files more flexible" [20]. Nonetheless, it is crucial to carry out independent studies to prove these claims.

TABLE 1. Comparison of the number of cycles to fracture and apical fragment length of both rotary files.

Group	i3G-f (n = 20)	AF-f (n = 20)	*p*-value
	Mean ± SD		
NCF	379.45 ± 89.36	1516.66 ± 204.05	<0.0001
Fragment length (mm)	7.25 ± 2.79	9.12 ± 2.78	0.0419

i3G-f: i3 Gold deciduous teeth rotary files; AF-f: AF baby rotary files; NCF: Number of cycles to fracture; SD: standard deviation. Mann-Whitney test.

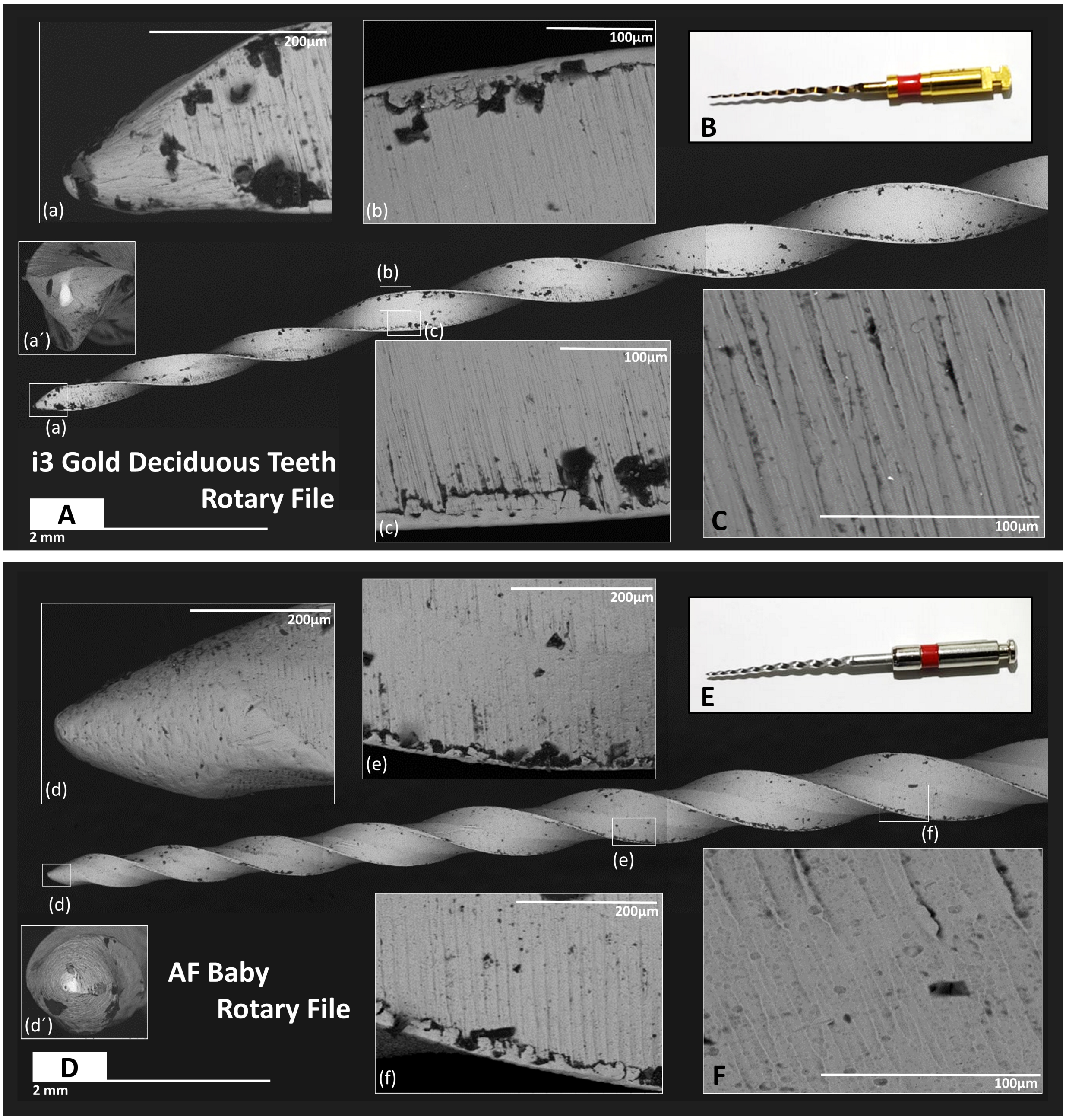

FIGURE 1. Scanning electron micrographs. (A) Approximately the first 8 mm of a new ISO 25/04 i3 Gold deciduous teeth rotary file; (a,a') Tip of the file (observe several surface irregularities, they retain many particles from the oil); (b,c) Surface flutes and cutting edges (observe "rolling over" of the cutting edges); (B) Photograph of the same instrument; (C) High magnification on a random central zone of the i3G-f (observe the presence of numerous superficial fissures). (D) Scanning electron micrographs of approximately the first 8 mm of a new ISO 25/04 AF baby rotary file; (d,d') Tip of the file (observe a smother surface with no irregularities, the surface prevented retention of particles from the oil); (e,f) Surface flutes and cutting edges (observe a lower "rolling over" of the cutting edges in comparison with i3 Gold deciduous teeth rotary file); (E) Photograph of the same instrument; (F) High magnification on a random central zone of the AF-f (observe the presence of rounded porosities on the surface).

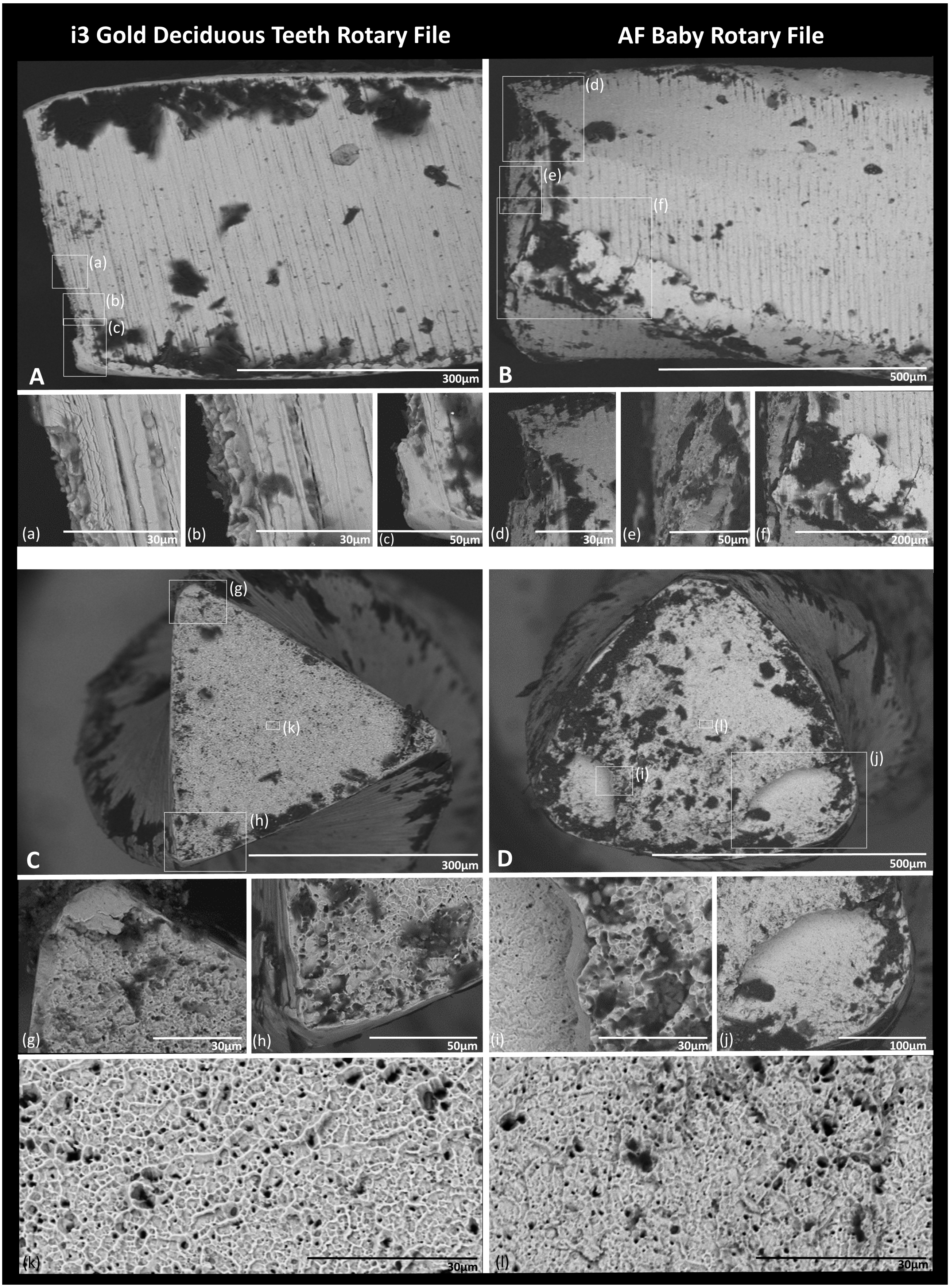

FIGURE 2. Scanning electron micrographs of the fractured files. (A,B) Horizontal view of the files showing the fracture in relation to the shaft. (a–f) Enlargement of the fractured zones (observe the numerous cracks close to the fracture site in a,b but not in e,f). (C,D) Cross-section view of the fractured files. (g–j) Enlargement of the fractured zones. (k,l) A high magnification of the center of the files.

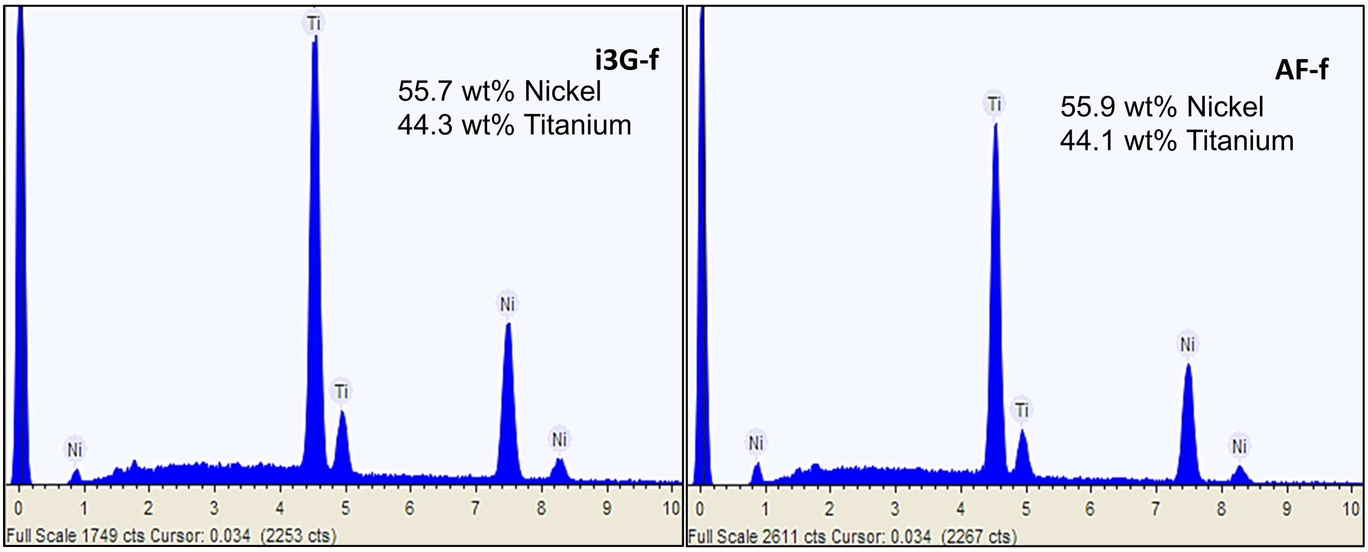

FIGURE 3. EDS representative spectrums of both files. Only nickel and titanium were detected. i3G-f: i3 Gold deciduous teeth rotary files; AF-f: AF baby rotary files.

In this study, to reduce variables that could have an effect on the cyclic fatigue resistance of the files and to test the impact of NiTi alloy and the proprietary manufacturing process, similar files were tested and compared. Both were 16 mm long, ISO 25 and 0.4 taper (in pediatric dentistry a minimally invasive approach that involves minimal root canal preparation with a taper strictly below 6% is generally preferred; this reduces the risk of root fracture, as extensive preparation could weaken the tooth structure and lead to microcrack formation. This also decreases the risk of perforation, ledges and canal transportation [30]). Both files were shape memory files with a triangular cross-section (convex cross-section in the AF-f) and heat-treated; the most important difference between files was the wire manufacturing technology. The AF-f is made using "advanced metallurgy of AF-H Wire technology", whereas the i3G-f is made using "CM-Wire heat-treatment NiTi technology" [19, 20].

There is currently some information available about the CM NiTi Wire technology, and instruments manufactured using this technology are considered an excellent option; it has been mentioned that instruments manufactured using this technology are 300 to 800% more resistant to fracture due to cyclic fatigue than instruments made with the conventional NiTi alloy [31]. On the other hand, there is a lack of information regarding the AF-H Wire technology. We found that the files manufactured using this technology presented a slightly higher nickel content (55.9 wt%) than those manufactured using the CM-Wire heat treatment (55.7 wt%). The NiTi alloy used in endodontic instruments is a simple binary mixture of nickel and titanium, about 56 wt% nickel and 44 wt% titanium. Common NiTi rotary files contain 54.5 to 57 wt% nickel [32]. Both systems evaluated in this study showed values within these ranges. Although there was no significant difference between their proportions, it is well known that subtle adjustments in the ratio of these two elements make the alloy unique and could result in significant differences in their final properties [33], including the flexibility of an instrument. Nevertheless, the exact role of different percentages of these elements' weight remains uncertain. On the other hand, it is also well known that manufacturing processes, including heat treatments with different temperatures and time intervals, produce instruments with different bending properties by varying their phase transition points [34]. However, as these are proprietary processes that the manufacturers do not discuss, their role in increasing flexibility and cyclic fatigue resistance cannot be known. Some transition temperatures from martensitic to austenitic phases have been reported for different current technologies, including the CM technology supposedly used to manufacture the i3G-f (55 °C) [17]. However, no information is available about the transition temperature of AF-H technology, and determining it is beyond our reach. This represents a limitation of this study since we cannot correlate our results with the phase transition points of each file.

On the other hand, it was notable that several manufacturing defects were observed in both files, mainly on the cutting edges where blunting (rolling-over) was constant and where debris particles appeared to have adhered, but also on the surface of the flutes. This is worrying because it is well known that fractures quickly initiate from defects. Besides, blunting (rolling-over) of the cutting edges favors the retention of debris during root canal instrumentation, as happened with the debris present in the oil.

In this investigation, the two tested instruments were manufactured using different heat treatments but presented a similar nickel-titanium ratio. The results of this investigation highlight higher values for the AF-f, which leads us to think that the newly manufactured heat-treated alloy (the AF-H Wire) enhances the metallurgical properties of the system, providing better cyclic fatigue resistance when compared with the i3G-f.

It is important to note that this study has some limitations. Firstly, the tests were conducted *in vitro* to evaluate a single characteristic of the instruments in a static mode. Although flexibility is one of the most important properties of NiTi rotary instruments, it is not the only one that needs to be investigated and tested. Secondly, the tests were performed at room temperature, so we cannot accurately determine the impact of temperature on cyclic fatigue resistance. It is possible that cyclic fatigue resistance could differ significantly when instruments are exposed to higher temperatures, such as those encountered during instrumentation in root canals.

Despite these limitations, this study represents a preliminary evaluation and an approximation of the expected performance of two types of files in the clinic. Further *in vitro* investigations should be done using different angulations on simulated curve canals, using a dynamic test and evaluating them at body temperature too. Finally, *ex vivo* and clinical evaluations must be done to fully understand the instrument's clinical behavior in detail.

5. Conclusions

The AF-f manufactured with AF-H Wire technology presents higher cyclic fatigue resistance in simulated curve canals and longer apical fragments when the file fractures, compared with the i3G-files (CM-Wire technology). The manufacturing process is one determinant of cyclic fatigue resistance.

AVAILABILITY OF DATA AND MATERIALS

The datasets used and analyzed during the current study are available from the corresponding author upon reasonable request.

AUTHOR CONTRIBUTIONS

KLSL and RADP—designed the research study; wrote the manuscript. KLSL, MVG and AISB—performed the research. LCHA and TAO—provided help and general advice. RADP, TAO and MVG—analyzed the data. All authors contributed to editorial changes in the manuscript. All authors read and approved the final manuscript.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

Not applicable.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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