REVIEW

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Causes and prevention of endodontic file fractures: a review of the literature.

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Abstract
Endodontic file fracture has traditionally been viewed as an undesirable event. However, recent evidence suggests that the incidence of fracture may be higher with rotary nickel-titanium (NiTi) files. Therefore, it is crucial for clinicians to be aware of the prevalence of file fracture and the underlying causes of this unfortunate occurrence. The removal of fractured files is technically challenging and time-consuming, making it essential to implement measures to prevent fracture whenever possible. Over the past decade, file manufacturers have introduced various modifications such as mechanical and heat processes to NiTi alloys to reduce the likelihood of file separation, though with varying degrees of success. The aim of this review is to explore the prevalence and causes of file fracture, and to assess the efficacy of the recommended prevention protocols. Furthermore, the review evaluates the effectiveness of alloy modifications in reducing the incidence of file fracture. The analysis reveals that much of the literature on file fracture is based on in vitro studies, which limits its clinical relevance. The reported incidence of NiTi file fracture is similar to that of stainless steel (SS) files; however, inconsistent methodologies make accurate comparison difficult. NiTi files are reported to fail primarily due to torsional overload and/or flexural fatigue, with fractures occurring most often in the apical third of the canal or due to improper use. Finally, factors such as operator skill, manufacturer modifications, and limiting file reuse have been shown to significantly reduce the incidence of fracture, highlighting the importance of a robust prevention strategy.
Keywords: root canal treatment, file fracture, endodontics, nickel-titanium, review.

Introduction

Intracanal file fracture is one of the most common procedural errors that occur during routine clinical endodontic practice [1]. Fractured root canal files may include endodontic files, Gates Glidden (GG) burs, spreaders, lentulos, and ultrasonic tips. Endodontic files can be made from nickel-titanium (NiTi), stainless steel (SS) or carbon steel [2].

While the prevalence of fractured endodontic SS hand files has been reported to be in the range of 0.7-7.4% the incidence for NiTi rotary files is reported in a range of 0.4-5% [3]. A study by Iqbal et al. [4] investigated the incidence of hand and rotary file fracture at the University of Pennsylvania between 2000 and 2004. In 4,865 endodontic resident cases the incidence of hand and rotary file fracture rate was 0.25% and 1.68%, respectively. They found that rotary file fractures were seven times higher than hand file fractures. Some of the studies that have investigated the incidence of file fractures are shown in Table 1.

Author(s)	Study design	Year	Kinematics	Used system	Teeth group	Operator	Prevalance
Eskibağlar et al. [1]	Prospective	2023	Reciprocating	Endoart Expert Gold	All	Undergraduate Postgraduate	2.7%
Iqbal et al. [4]	Retrospective	2006	Rotary	No brand specified	All	Postgraduate	1.68%
Wu et al. [58]	Prospective	2011	Rotary	ProTaper Universal	All	Endodontists	2.6%

Di Fiore et al. [102]	Prospective	2006	Rotary	ProFile, ProTaper GT Rotary	All	Postgraduate	0.39%
Caballero-Flores et al. [103]	Retrospective	2019	Reciprocating	WaveOne Reciproc	All	Postgraduate	0.91% 5.79%
Plotino et al. [104]	Prospective	2015	Reciprocating	Reciproc	All	Endodontists	0.47%
Algarni et al. [105]	Retrospective	2024	Reciprocating	Premium Blue	All	Endodontists	0.43%
Haug et al. [106]	Prospective	2018	Reciprocating	WaveOne	All	Undergraduate	4.31%
Sattapan et al. [107]	Prospective	2000	Rotary	Quantec	Not reported	Endodontists	20.90%
Shen et al. [108]	Prospective	2015	Rotary	ProFile Vortex ProFile Vortex Blue	Molar s	Postgraduate	0.00% 0.14%

This review aims to examine the prevalence, etiological factors, and preventive strategies related to file fractures, with a particular focus on rotary NiTi files. Additionally, it explores alloy modifications designed to minimize these risks. A comprehensive understanding of the metallurgical properties of NiTi alloys is crucial for identifying potential failure points and optimizing manufacturing processes to minimize the risk of fracture.

Historical Development of NiTi Files

In 1963, Buehler et al. developed an intermetallic alloy called NiTi, which was to be used extensively in medicine and dentistry [5]. NiTi alloy is also known as "nitinol", which is a combination of the words nickel (Ni), titanium (Ti), and Naval Ordinance Laboratory. Due to its superelasticity, shape memory effect and biocompatibility, NiTi alloy was used in the production of orthodontic wires in 1971 [6]. The concept of producing endodontic files using NiTi was first proposed by Civjan et al. [7] in 1975. A hand file (#15), produced using NiTi, was first introduced to the market in 1988 [8]. However, it was not until the 1990s that commercial rotary NiTi files were produced and became available. John McSpadden & Johnson known as the founders of rotary NiTi files, developed a file with a taper of 0.02 in 1992 and the ProFile Orifice Shaper (Dentsply Sirona, York, LA, USA) with tapers of 0.04 and 0.06, respectively, in 1994 [9]. Unlike SS files, which follow a unified international standard, no unified standard has been established for the design of rotary NiTi systems and therefore many different NiTi files have been developed to date (Figure 1).

Figure 1. Current new technology several NiTi file systems.

Metallurgy of NiTi Alloy

The NiTi alloy used in the production of endodontic files contains approximately 55% Ni and 45% Ti by weight. In some NiTi alloys, cobalt element may be present instead of Ni at less than 2% by weight [10]. Equiatomic NiTi alloy can exist in 3 microstructural phases: austenite, martensite, and the R-phase (Figure 2). Austenite and martensite phases are the main crystal structures of the NiTi alloy.

These crystal structures can alter depending on temperature and stress [10]. Austenite phase can transform to martensite phase at temperature 16-31°C. Austenite phase can be also called R-phase.

There is also a Pseudomartensite phase that can be formed in a very small temperature range and whose Young's modulus is lower than the austenite phase. The NiTi alloy in austenic phase is relatively stiff and has shape memory, and in the martensitic phase is flexible and ductile and can be easily deformed [9].

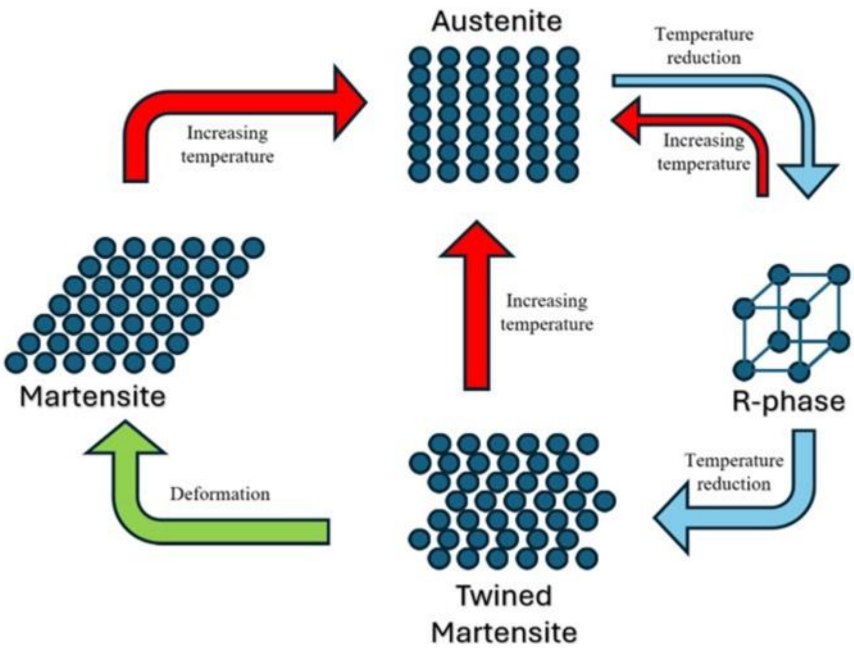

Figure 2. NiTi alloy microstructural phases.

Since the first production of NiTi files, many different file systems have been developed to increase both fracture resistance and cutting efficiency. In addition, it was aimed to increase the flexural and cyclic fatigue resistances of the files by applying different thermomechanical processes to NiTi files [11]. The developments in the mechanical and heat treatment processes in the alloy of NiTi files are explained below (Figure 3).

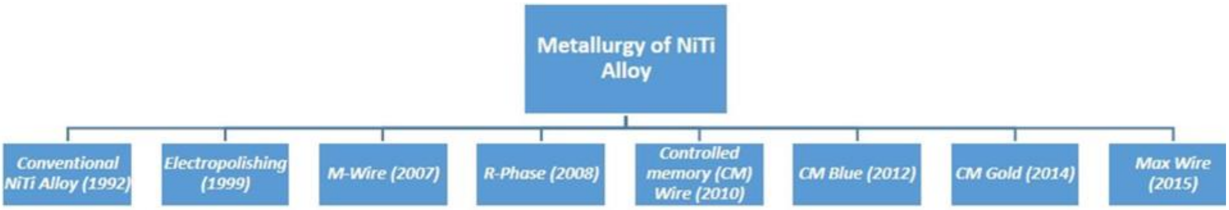

Figure 3. Developments in the mechanical and heat treatment processes in the alloy of NiTi files.

Conventional NiTi Alloy (1992): Conventional NiTi alloy mainly exists in the form of austenite at room and body temperatures [9]. Conventional NiTi endodontic files possess superelastic properties. Since these NiTi files are produced by the grinding process, they may cause defects on the surface of the files, which can cause negative effects on fracture resistance, cutting efficiency, and corrosion resistance [12]. Examples of these NiTi files are Mtwo (VDW, Munich, Germany), ProTaper Universal (Dentsply Maillefer, Ballaigues, Switzerland), and OneShape (Micro Mega, Besancon, France).

Electropolishing (1999): Electropolishing is a surface finishing process for metal files that allows for a controlled electrochemical removal of surface material, resulting in a brighter, smoother surface. Thus, it is used to remove surface irregularities that are caused by the previous processes [12]. Electropolishing was first used by FKG (La Chaux-de-Fonds, Switzerland) in 1999 [13]. A study by Lopes et al. [14] revealed that electropolished files have finer irregular zigzag crack patterns than non-polished files. RaCe systems (FKG) such as BioRaCe and iRaCe are examples of files produced in this way. F360 (Komet, Brasseler, Lemgo, Germany) and F6 Skytaper (Komet) are also produced using electropolishing techniques.

M-Wire (2007): Tulsa Dental created a new type of NiTi alloy by thermal treatment with composition consisting of 55.8 ± 1.5% Ni, 44.2 ± 1.5% Ti and trace elements less than 1% by weight [1]. M-Wire exhibits greater flexibility because its elastic moduli of martensite and R-phase are lower than that of austenite. Thus, the M-wire files can shape the inclined root canal more easily, and these files can reduce the deviations that may occur along the canal as a result [9]. Some studies [15-17] showed that M-wire files showed more resistant to cyclic fatigue. Examples of these files include ProTaper Next (Dentsply Maillefer) ProFile Vortex (Dentsply Sirona), Reciproc (VDW), and WaveOne (Dentsply Sirona).

R-Phase (2008): R-phase NiTi systems produced after multiple heat treatments. For more elasticity and fatigue resistance of the file The Young's modulus of the R-phase NiTi alloy is lower than those of alloys in the martensite and austenite phases. To protect the crystal structure of the NiTi alloy from damage and avoid fractures, heated R-phase NiTi wire is twisted [9]. Examples of these files include Twisted File (SybronEndo, Orange, CA, USA) and Twisted File Adaptive (TFA; SybronEndo).

Controlled Memory (CM) Wire (2010): CM Wire files are flexible and have shape memory. Compared with the conventional NiTi alloy, CM NiTi wire contains less than 52% Ni which improves the mechanical properties. CM wires have qualities such as improved fracture resistance, good flexibility, controlled shape memory and resistance to cyclic fatigue [9]. Neither room nor body temperature CM Wire alloy possesses superelastic properties. To austenitic NiTi files, CM Wire files do not tend to entirely straighten during the preparation of curved root canals [12]. Hyflex CM (Coltene/Whaledent, Altstätten, Switzerland), Typhoon CM (TYP CM; Clinician's Choice Dental Products, New Milford, CT, USA) are some examples of CM wire files. CM wire alloy forms a titanium oxide layer by continuous heating and cooling, and the color of the alloy surface varies depending on the thickness of the titanium oxide layer.

CM Blue (2012): When the titanium oxide layer thickness is 60-80 nm, the surface of alloy becomes blue colored. CM Blue files are softer and more ductile [12]. It has been shown in some studies that in blue wire files cyclic fatigue is increased [5]. Some examples are ProFile Vortex Blue (Dentsply Tulsa, Johnson City, TN, USA) and Reciproc Blue (RB; VDW).

CM Gold (2014): When the titanium oxide layer thickness is 100-140 nm, the surface color is golden. One example of gold wire is ProTaper Gold (Dentsply Maillefer) which has the same design as the ProTaper Universal (Dentsply Maillefer), but has greater flexibility and better resistance to cyclic fatigue [5]. WaveOne Gold (Dentsply Sirona) is another example of gold wire technology.

Max Wire (2015): Max Wire alloy was developed because of heat treatment applied to NiTi alloy [9]. Max Wire is a NiTi alloy that combines shape memory and super flexibility in clinical applications [12]. The Max Wire alloy transitions from martensite to austenite after insertion into the root canal, at temperatures higher than 35°C, and the file changes from a flat shape to a semicircular shape due to the shape memory function [9]. FKG produced the XP-Endo Shaper, which revealed significantly increased cyclic fatigue [12].

Although NiTi files are more durable and flexible compared to SS files, breaking of these files in the canal during use is a major problem [18]. Fractured files can prevent the cleaning, shaping, and filling of the root canals and prevent the treatment from a successful outcome [18]. SS file fractures usually occur due to excessive use and show deformation before fracturing. The bending of the file and its deformation by opening its grooves indicate that the elastic limit has been exceeded. In this case, the files should be discarded and reuse should be avoided [20]. The situation is different with NiTi rotary files, and it is known that they can break without showing any signs of permanent deformation. Therefore, visually evaluating NiTi files is an unreliable method [18].

A retrospective study by Alamoudi et al. [19] analyzed a total of 3,150 cases with 108 instances of identified fractured files. The overall incidence of file fracture was 3.4%, with 53.7% of these fractures occurring in mandibular molars and 42.6% in maxillary molars. The mesiobuccal canal exhibited the highest frequency of file fracture at 35.2%. Moreover, the level of fracture demonstrated a statistically significant correlation with the management approach.

Fracture in NiTi rotary files occurs in 2 ways [20].

Torsional (Shear) Fracture: Torsional fracture occurs when the tip or any part of the files gets stuck in the root canal system while the handpiece continues to turn [21]. This type of fracture occurs when excessive apical force is applied during instrumentation, exceeding the elastic limit of the metal, and breaking the file becomes inevitable [21].

Fatigue Failure: The term 'cyclic fatigue' describes the breakage of NiTi files after continuous rotation in a curved canal [18]. The file is exposed to repeated tension and compression during movement and, eventually, fracture occurs [20].

While fractures due to cyclic fatigue are more common in inclined root canals, fractures due to torsional stress can be seen even in straight root canals [22]. Cyclic fatigue is shown to be the primary cause of file fractures [20]. Wei et al. [23], in addition to this type of breaks, described a type of combined fracture in which fracture marks due to both cyclic and torsional fatigue are observed.

Although modifications have been made to the metallurgy of alloys and file designs to reduce file fractures, complete prevention of file separation has not been achieved in endodontic practice.

Predisposing Factors for NiTi Files Fracture

Design of Files

The design and horizontal cross-sectional areas of the files affect the stress distribution under mechanical influence; it can affect the fracture resistance under cyclic stress or torsional load. It is known that larger files encounter cyclic fatigue earlier than those with smaller diameters [24]. However, increasing the radii and cross-sectional areas of the files can increase the fracture resistance against torsional fatigue [25].

Taper angle may determine the amount of force that can cause NiTi files to break. NiTi rotary files with the same taper angle but smaller tip diameter have a higher tendency to jam and screw in the root canal. This causes the tip of the files to be exposed to excessive torsional load [26]. NiTi rotary file systems with variable taper angles have less contact with the root canal walls than files with fixed taper angle, which increases their resistance to cyclic and torsional fracture [27].

It has been confirmed that there is a relationship between the cross-sectional design of the tools and the bending force. Tools with a rhombus-shaped cross-section design have been reported to be less resistant to bending force compared to files with a square cross-section [28]. S-shaped files and Hedstrom (H-type) cross-section were found to be less resistant to fracture compared to the triangular cross-section shape [29]. Additionally, files with triangular triple-helix design, although they are not flexible compared to files with a U-shaped cross-section and smaller cross-sectional area, are more resistant to torsional fatigue [30].

Production Errors

During the manufacturing process of NiTi files, surface irregularities such as cracks and grooves may occur in the file. Oxide particles released during the production phase of NiTi files can cause weakening of the grain boundaries inside the file and can lead to the onset of microcracks. Micro voids form on the surface of NiTi rotary tools due to the inclusion of hydrogen, carbon, nitrogen, and oxygen on the surface of the file [31].

Surface irregularities are more common in wide taper angle files whose production process is more complex. Whether or not the surface on the working parts of the files is rough affects the resistance to cyclic fatigue. Files with smoother surfaces have been shown to have higher resistance to fracture [32].

Production methods that can increase the durability of files include electropolishing method, titanium nitride deposition via chemical steam and physical steam, cryogenic processes, and ion implantation [33].

Although ion implantation increases the resistance of the surface of the file to wear, it has been stated that the surfaces to which boron implantation is applied are harder than the SS alloy [34].

Vapor accumulation increases the cutting efficiency of NiTi files by increasing their surface hardness. However, this type of implantation techniques is not widely used by manufacturers due to their high costs [2].

It has been shown that the cyclic fatigue resistance of files treated with electropolishing, another method used by manufacturers, is 117% higher than tools of the same size and width without the application [32].

However, in terms of torsional resistance, no significant difference was observed between files with and without electropolishing. After the electropolishing procedure, defects and metal folds can be seen on the surface [35].

Effect of Disinfection and Sterilization

There is conflicting information in the literature about the effect of sterilization on the fracture resistance of NiTi files. While some studies [36,37] show that sterilization has no effect, other studies say that it causes significant changes. It has been found that multiple autoclave series increase the irregularities on the surface of NiTi rotary files and reduce cutting efficiency [38].

A single or repeated autoclave cycle beats the files until they break. There are also studies [39,40] showing that it does not cause any negative change in the number of turns and does not increase the possibility of fracture. It has also been reported [22] that the sterilization procedure can have a positive effect on the fatigue life of NiTi files by returning the file in the martensitic phase to the austenite phase under stress.

In disinfection of endodontic files, the use of sodium hypochlorite (SH), which is preferred in the irrigation of root canals, causes corrosion on the surface of the file, affecting its mechanical properties and causing fracture [41]. A study by Berutti et al. [42] showed that files immersed in 5.25% SH had significantly less resistance to fracture when subjected to cyclic fatigue. However, Peters et al. [43] showed that low concentration 1% SH did not reduce the cyclic fatigue and torsional resistance of NiTi files after 2.5 h, but immersion for 18 h caused clear signs of corrosion on the files.

Number of Uses

There are studies [2,11] reporting that the way a tool is used is more important than how many times it is used. It has also been reported that the fatigue resistance of files decreases due to repeated use, and the torque value that can cause fracture is significantly lower for used files than for an unused file [44].

Although it has been reported that all NiTi files have surface defects and changes in their mechanical properties after a single use, there are also studies showing that they can be used repeatedly without any problems [45]. There is no relationship between the incidence of file fracture and the number of uses of the files, and there are also studies where files were observed to break during the first use [46,47].

The different results reported in studies show that there is no direct relationship between tool fracture and the number of uses [2].

Rotation Speed

The optimum speed for NiTi rotary files varies between manufacturers. For safety, files should be used at optimum speed in accordance with the manufacturer's recommendations. Since there is an average number of cycles that files can resist fatigue, which is determined by different factors such as cross-sectional design, alloy, tip design and angle, high rotation speed can reduce this clinical life of the files much faster [22]. However, there are some studies [48,49] stating that fracture and deformation of files are less likely to occur at low rotation speeds and that rotation speed is one of the important parameters in NiTi file fracture.

Use of Torque Controlled Motors

When a torque value is applied to the file below the maximum strength of the material, it can be ensured that the file is not exposed to excessive torsional load and its fracture is prevented. This has enabled the production and development of endodontic motors with torque control [50]. When torque-controlled motors are run in programs adapted to different file types, they stop the rotation of the file or reverse the rotation when the torque value is reached. Thanks to the motors designed in this way, file fracture may be prevented [51].

Preparation Technique

It has been stated that the preparation method used during shaping of root canals is an important factor in the fracture of the files. To reduce the torsional stress on the file before preparation with NiTi rotary files, it is recommended to create an entry route with hand files numbered 15-20 or specially designed rotary NiTi files [52].

It has been suggested that reciprocal NiTi files can reach the working length in the canal without creating an entry route beforehand, and that this will not lead to any increase in the incidence of fracture of the file [53].

It has been shown that the friction of the files decreases and the prevalence of fractures due to torsional fatigue decreases significantly with the crown-down preparation technique, which is based on the principle of widening the coronal section before widening the apex [50].

If files are used with minimal apical pressure and pecking motion during preparation, stress can be prevented from accumulating in a certain part of the file and the resulting load can be spread over the entire length. Thus, the fatigue life of the file increases and the possibility of fracture decreases [54,55].

Experience of Clinician

Studies have shown that NiTi rotary tool fractures are more likely to occur in inexperienced clinicians than in experienced ones [56]. The ability of the physician to manage the situation well by detecting the file getting stuck and locked in the canal wall while working is a skill that can only be gained with experience [57].

Curvature of Root Canal and Type of Tooth

The risk of fracture of NiTi files varies depending on variables such as whether the root canal is straight or curved, curvature angle, and radius. The use of NiTi rotary files in inclined canals increases the compressive and tensile stresses applied to the file and shortens the useful life of the files [58].

It was determined that the fracture point seen in the files was seen at the maximum bending point in the canal, which corresponds to the place where the curvature is observed the most [43]. The decrease in the curvature radius indicates a sudden change in direction of the canal structure. Increasing the curvature angle and decreasing the curvature radius reduces the torsional fatigue resistance by reducing the number of rotations of the file until it breaks [59].

The complexity of the root canal anatomy increases the risk of fracture of NiTi rotary files, leading to torsional failure [43].

The low curvature radius in molars reduces the resistance of the tool used against torsional loads [60]. This explains why there are significantly more fractures in molars than in anterior and premolars. It has been reported that the probability of file fracture in the mesiobuccal (MB) canal of the maxillary molar tooth is 3 times higher than in the distobuccal (DB) canal. Similarly, in mandibular molars, the probability of file fracture in the MB canal is higher than in the mesiolingual (ML) canal [4]. Although these reported results can be explained by the complex anatomy of root canals, the primary reason is that the root canals are curved [22].

It was determined that many of the files broke in this region because the area where the curvature was maximum and the radius was lowest was the apical third. It has been determined by many different studies that the probability of file fracture in the apical third region is 6 times higher than in the middle third of the root and 33 times higher than in the coronal third [4].

Considering the fracture mechanisms of NiTi rotary files, the precautions to be taken to prevent fracture are as follows [20]:

To reduce the risk of fracture by reducing torsional stress.

- Before using NiTi rotary files with larger taper angles, an entry path should be created at working length with a #15 and #20 K type hand file.
- Files should be used with endomotors at appropriate torque settings, considering the manufacturer's recommendations.
- The file should be advanced gradually within the canal with a pushing-pulling motion.
- Files with different taper angles should be used to reduce the shear stress on the file by reducing the contact area with the canal.

To reduce the risk of fractures due to cyclic fatigue.

- Files should not be used in the canal for a long time and the apical pressure should not be increased when resistance is felt.
- The rotation speed of the file should be reduced to postpone the onset of fatigue.
- Straight access should be provided to the apical half of the canal to reduce stress on the file and extend the radius of curvature.
- The use of a rotary file with a large taper angle (0.06 or more) should be avoided in canals with a medial root slope.
- Rotary files should not be used in sharply curved canals (with a very low radius of curvature).
- To reduce the risk of fracture due to torsional fatigue, work should be done without triggering the automatic return mode. This can be achieved by advancing the file slowly at the high torque setting.

Treatment Options for File Fractures in Root Canals

Removing a broken file from the root canal is a complex process that requires training, experience, and knowledge of broken file removal methods. Before starting to remove the broken file, the location of the broken file in the root canal, root canal anatomy, length and type of the broken piece, the condition of the periapical and periodontal tissues, and the patient's wishes should be considered [3].

Currently, there is no standard procedure in the dental literature for the safe, consistent, and successful removal of file fractures. In any case, the chances of success must be balanced against possible complications.

Treatment options for broken files include:

- Leaving the broken file in place or bypassing
- Orthograde removal of the broken tool
- Surgical removal of the broken file
- Tooth extraction

As a rule, an initial effort should be made to remove the broken file and if this is not possible, to bypass it [62]. If the fractured file in the root canal is in a position that cannot be removed or if the periodontal condition of the tooth does not require intervention, bypass is attempted, but if unsuccessful, the file is left. In a tooth where there is no clinical or radiographic evidence of infection, the tool fracture that occurs in the last stage of the treatment can be left without removal. In this case, the fractured file is left in the canal, the root canal treatment of the coronal part is completed, and the patient is called for regular check-ups [2, 63]. When the conservative approach fails or is thought to have led to failure from the beginning, surgical treatment can be performed with apicectomy, hemisection, root amputation or intentional reimplantation. Otherwise, tooth extraction is recommended [3] (Figure 4).

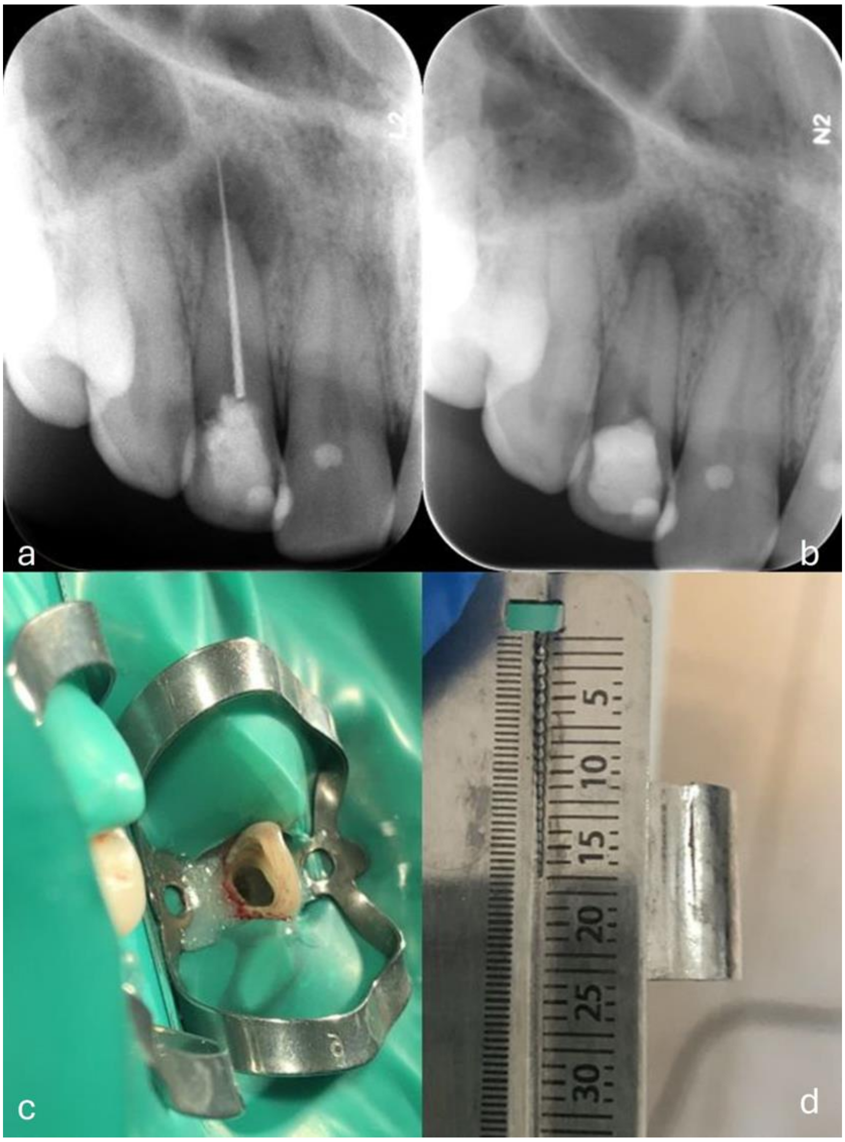

Figure 4. A sample fractured file. (a) Preoperative periapical radiograph of the patient, (b) Periapical radiograph of the patient after removal of broken file, (c) Intraoral photography of fractured file, (d) Photography of broken file after removal.

Factors Affecting the Success of Removing Fractured Files

Studies [64,65] have shown that the increase in time required to remove broken files in the root canal may increase the likelihood of complications and can cause treatment failure. Some of the factors that affect the success of removing a broken file include:

- Dental factors
- Location of the broken file
- Broken file factors (length, type)
- Operator factors
- Selected technique for treatment
- Patient factors

Dental factors

The type of tooth, root canal morphology, dentin thickness, presence of root canal curvature, radius and degree of root canal curvature, presence of isthmus are among the tooth-related factors that affect decision-making in removing fractured files. The success rate in retrieving file fractures in straight and wide canals is higher than in curved and narrow canals. The success rate of removing file fractures in canals with severe curvature was found to be quite low, in contrast to the success rate in canals with moderate or mild curvature [3,66,67].

The presence of isthmus, which is most seen between the mesial roots of mandibular molars, facilitates the removal of tool fractures in these teeth and reduces the possibility of perforation. Because it is easier and safer to remove dentin in the presence of isthmus.

Therefore, CBCT imaging can be used to obtain comprehensive information about tooth and root morphology [68-70].

Localization of the Fractured File

As a rule, successful removal of a file that cannot be seen is extremely difficult. Fragments in the coronal third of the root can be removed more successfully than fragments in the middle or apical third [63,66]. Successful removal of a fractured file in a curved canal cannot be expected unless straight access is achieved to its most coronal portion [71].

Fractured Files Related Factors

The type of alloy from which the fractured file is made one of the factors affecting its removal from the root canal. Compared to SS files, NiTi-based rotary files that fracture in the root canal become smaller and tend to break repeatedly when ultrasonic energy is applied, and the difficulty of exposing the coronal third due to their increased taper may make it difficult to remove the files from the root canal [3].

It has been found that the type of file does not affect the success rate of root canal extraction, but does affect the extraction potential [65].

A study also stated that lentulo spirals are easier to remove than reamers or Hedstrom files [67].

There are different opinions regarding the length of the broken files. Hülsmann et al. [68] stated that since the ends of long broken pieces (>5 mm) that fractured in the root canal were stuck in the dentin, there was a space left for bypass in the coronal part, and this facilitated the removal of the fractured file. On the contrary, some researchers [65,66] have argued that there is no correlation between fragment length and the success of file extraction. Shen et al. [72] stated that the rate of successful removal of longer pieces from the root canal was higher, but the difference was not statistically significant. Therefore, there is insufficient evidence-based data regarding the effect of the length of the broken piece on the success of removal.

Operator Related Factors

Ruddle [71] stated the importance of magnification, illumination, and linear space creation to be successful in removing broken files. When these factors are met, it becomes easier to see, reach and remove the broken piece. In cases where the broken file cannot be seen, the possibility of complications increases. During all these operations, the operator's knowledge, skill, experience, creativity, and patience are very important for success [71-73].

Patient Related Factors

Situations that affect the successful progress of the treatment process, such as difficulties in accessing broken equipment, should be carefully evaluated before starting any intervention. The patients' level of anxiety and pain tolerance and their attitude towards dentistry and especially the retention of the tooth in question can also affect the operator's manipulations and efforts. The patient's age, general health status, and current medical history should be effective in deciding on treatment options [74].

Dental Operating Microscope

During the removal of broken files from root canals, illumination and magnification with an operating microscope are very important to see the broken file [64]. A good field of view allows the amount of dentin removed during broken file removal to be controlled, to remain in the center of the canal during operation, and to place the ultrasonic tip next to the broken file. When the operator uses an operating microscope, the possibility of complications and failures is minimized [75].

Methods Used for Removing Fractured Files

Removal of broken files from root canals should be carried out in a way that causes minimal damage to the teeth and surrounding tissues. To date, many tools and techniques have been described to remove broken files from the root canal system, but a standard procedure has not yet been found because each requires a long working time, there is a large amount of dentin loss from the tooth, and the success rates are uncertain [76].

Various mechanical and chemical methods have been tried to remove fractured files from the root canal.

Bypass Technique

This is a technique that allows access to the apical foramen by bypassing the broken piece and can also be released by placing the broken piece in the grooves of the file and can be performed using endodontic hand tools available in all dental clinics, without requiring special or complex files. This technique is a challenging procedure that depends on tactile sensitivity and patient effort on the part of the practitioner [77].

A fine K-type hand file (ISO 6, 8 or 10) is given a sharp pre-bending. The bent file is then placed in the root canal and, with very light apical pressure, is advanced in quarter-turns until its tip is occluded in the narrow space between the fragment and the root canal wall. The advancement of the file is checked radiographically, and the procedure is continued until the file reaches the apical foramen [78].

Studies [29,63], especially in cases where access to the trailer is limited, suggest that bypassing the fractured file (beyond the apical third of the canal or canal curvature) is more conservative and that its removal may lead to excessive dentin loss. Studies [63,79] have reported that if the fractured file is omitted, the piece remaining in the canal does not reduce the obturation quality.

Fracture of a second file during application is very likely to create another iatrogenic error such as step formation, perforation, or transportation, and therefore the entire procedure should be performed with great care [77].

Ultrasonic Technique

Ultrasound is sound energy with a frequency of 20 kHz, a frequency above the range of human hearing. The ultrasonic technique transmits ultrasonic energy to the fractured file, allowing the fractured file to break free and come out of the canal. It is currently the most widely used method for removing fractured files from the root canals [80]. File fractures, silver cones or intracanal posts can be removed by loosening them ultrasonically [81].

First, the ultrasound was used to remove the fractured file by delivering energy through the largest handpiece that reaches the fractured file, such as an endodontic probe or spreader. Later, to enable the use of ultrasonic tips in various parts of the root canals, tips at different angles and different lengths were specially designed by various companies and coated with abrasives such as diamond or zirconium nitride to increase cutting efficiency [82].

Ultrasonic units currently available in dentistry are of 2 basic types with different mechanisms of action:

- Magnetostrictive: Magnetostriction converts electromagnetic energy into mechanical energy.
- Piezoelectric: These are based on the piezoelectric principle, in which a crystal changes size when an electric charge is applied. This deformation of the crystal is

converted into mechanical oscillation without generating heat [83].

Both types are clinically accepted in dentistry, but piezoelectric type ultrasonics are more suitable for endodontic applications. The tips of these units operate in a linear, reciprocating, "piston-like" motion that is ideal for endodontics [84]. As a rule, the deeper the part is in the canal, the longer and thinner the ultrasonic tip should be used. These long, thin ultrasonic tips should be used at very low power settings to avoid tip breakage [85].

Ruddle [71] reported that it is important to be able to see the broken piece to be successful in removing fractured files from the canal with the ultrasonic. In the study, to make the coronal part of the broken piece visible under direct microscopic vision, the staging platform at the coronal part of the broken piece is prepared with modified number 2-4 Gates Glidden burs used in a crown-down manner as described by Ruddle.

The maximum cross-sectional diameter of the pre-selected GG bur should be slightly larger than the diameter of the broken piece in the coronal direction. The modified GG bur with its tip cut off is placed in the pre-widened canal, rotated clockwise at a low speed of approximately 300 rpm, and guided apically until it makes light contact with the most coronal of the broken file. To allow better visualization, the platform is kept at the center of the fragment and the surrounding dentine root canal walls; therefore, an equal amount of dentin around the fragment is preserved, minimizing the risk of root perforation. Similarly modified LightSpeed NiTi rotary files (Lightspeed Technology, San Antonio, TX, USA) can also be used. In a comparative study, the extraction platform created by NiTi rotary files was found to be more central than that created by Gates Glidden burs, especially in inclined canals [4,71].

To reach the fragment, an ultrasonic tip of appropriate length and diameter is passively inserted into the preformed canal in close contact between the exposed coronal end of the fragment and the canal wall. The ultrasonic device is then activated at low power settings to trephinate the dentin around the part in a counterclockwise motion. This continues until the coronal end of the fragment is released by 1-1.5 mm or until some movement of the fragment is noticed [71].

At this point, care should be taken to touch the fragment as little as possible and to avoid removing too much dentin from the less thick inner canal wall. Sometimes, the loosening force created in this way can displace the part and throw it out of the channel. Diamond-coated tips should be avoided for this trephine stage as they are very aggressive and can remove too much of the dentinal wall. Titanium ultrasonic tips can be used in case of fragments in long roots with limited access and thin root morphology. These are longer and more flexible at smaller diameters than abrasive diamond-coated bits, they can only cut at the tip [85].

It is very important to avoid unnecessary pressure on the ultrasonic tip to prevent it from breaking. Blind trephining of dentin may lead to undesirable complications. For this reason, all ultrasonic studies inside the root canal are carried out in a dry environment, so that the clinician can constantly see the area around the broken file with the ultrasonic tip and the microscope [71].

Masserann Technique

The Masserann kit (Micro Mega) is a system that has been used for many years to remove fractured files inside the canal. It has also been used to remove metallic objects such as silver cones and posts from the root canal [86,87]. The Masserann kit consists of trephine burs and extractor tubes. Trephine burs consist of 14 drills with diameters ranging from 1.1 mm to 2.4 mm. Trephine burs are hollow tubes with edges designed to peripherally cut the dentin around the fractured file. It is designed to be used by turning it counterclockwise. Trephine burs can be operated using the special hand tool provided or manually with a reverse angle contra-angle handpiece (300-600 rpm). Manual use is preferred as it prevents temperature rise and provides better tactile sensation [88]. After the trephine bur, the extractor is used to extract the broken piece. It consists of 2 sizes of tubular extractor (1.2 and 1.5 mm). The smaller size tubular extractor (1.2 mm) is used for broken pieces up to size 40, while the larger size (1.5 mm) is used for larger tool sizes or hides [86-88].

The most important advantage of the Masserann kit is that it can grasp the fractured file strongly, thanks to the locking system of the extractor tube. In the research conducted, it has been reported that file removal attempts using the Masserann technique remove excessive amounts of dentin from the tooth, resulting in an increased risk of perforation and a decrease in root fracture resistance [88]. It has been recommended to be applied in straight root canals, not in difficult areas such as the apical third region of inclined, narrow, and calcified canals [71,88].

Meitrac Endo Safety System

The Meitrac Endo Safety System (Hager & Meisinger, Neuss, Germany) is a trephine bur system similar to the Masserann technique developed to reduce dentin loss in the removal of fractured files and posts. It is available in 3 different diameter types designed for the extraction of broken pieces (Meitrac I, II and III) and each consists of a trephine bur and 2 extractor tubes. Meitrac I 0.15 to 0.50 mm; Meitrac II 0.55 to 0.9 mm; Meitrac III is used to remove fractured files with diameters between 0.95 and 1.5 mm. All Meitrac Endo systems are made of stainless steel. Therefore, they can be sterilized and reused.

The trephine bur is like a typical reverse-angle low-speed round bur, but is hollow along its length. It exposes the coronal end of the broken piece by removing the dentin around the fractured file to a depth of 1-2 mm, then an extractor tube is placed in the opened space and squeezes the broken piece into it, allowing it to be removed [77].

Instrument Removal System (IRS)

The IRS (Dentsply Tulsa) was specifically designed by Ruddle for the removal of fractured files from the root canal [71]. IRS is used to remove the fractured file, the coronal part of which is exposed, from the canal with an ultrasonic. The system consists of 4 extraction devices made of titanium and stainless steel with tubes with a 45° inclination at the end and a truncated side window. The system consists of a microtube, and a screw placed inside it. The 45° inclined cut side opening at the end of the microtube is designed to catch the fractured file. The microtube is placed in the canal to contain the fractured file, the coronal part of which is exposed 1.5-3 mm by ultrasonic, and a tight contact is created by placing the screw inside the microtube. The microtube along with the stuck fractured file is removed from the canal [71,89].

Terauchi File Retrieval Kit (TFRK)

TFRK (Dental Care, Santa Barbara, CA, USA) is a system consisting of the combined application of loop technique and ultrasonic system. It has been stated that this system enables the removal of fractured files in the apical and inclined canals of root canals and inclined canals, where it is difficult to remove fractured files, and where there is a lot of material loss, by removing the minimum amount of dentin [75].

In the 3-stage fracture file extraction system, a staging platform is first created coronally. After this, the entrance path is created up to the fractured file with the CBA (Cutting Bur A) bur. With CBB (Cutting Bur B), a groove is created around the fractured file. In the canal filled with EDTA, the ultrasonic tip is placed in this groove and vibration is given to the broken piece. The fractured file is moved out of the canal by compressing it with a ring made of NiTi wire [75,90].

Micro-Retrieve & Repair System (Trepan Bur)

It is a small-diameter trephine bur technique developed to reduce dentin loss during fractured file removal (Superline NIC Dental, Shenzhen, China). The system consists of trephine burs of 5 different sizes (varying between outer diameters: 0.70-1.26 mm and inner diameters: 0.40-0.86 mm) and microtube tips with side oval windows in the working length of the relevant sizes [91,92].

Under direct microscopic vision to increase straight-line access and visualization, an extraction platform is prepared in the most coronal aspect of the part using modified Gates Glidden burs preselected based on the diameter of the fractured file [71].

A trephine bur, operated counterclockwise (500 rpm) by an endodontic motor, is used to expose the 1-1.5 mm long coronal part of the piece. The broken piece may get stuck in the trephine mill and come out spontaneously. In case it does not come out, a microtube with dimensions corresponding to the trephine bur used is inserted into the canal and placed over the exposed part. By pushing the sliding button on the handle, the part is gripped and locked by a wedge effect at the end of the microtube with the side oval window. Once the broken part is mechanically held, the entire assembly is slowly removed from the canal [91,92].

Other Instrument Removal Techniques

Separated Instrument Removal System (SIR)

After the coronal end of the fractured file is exposed by 1.5-2 mm with trephine drills or an ultrasonic system, the bendable soft tube with adhesive is placed on the fractured file to ensure its adhesion. After the adhesive material has hardened, the fractured file is moved coronally [93].

Endo Extractor System

It (Roydent Dental Products, Johnson City, USA) consists of SS sterilizable hollow trephine burs with an inner diameter of 0.80 mm and an outer diameter of 1.6 mm and 3 different sizes extractor tubes of 0.30, 0.50 and 0.70 mm with an outer diameter of 1.5 mm in white, yellow, and red colors [94]. After exposing the coronal segment of the fragment with the trephine bur, the 6 claws on the pre-selected extractor grip the trephined coronal segment of the fractured fragment with equal force all the way around and extract it back by applying tight tensile force during extraction. The main disadvantages of the Endo Extractor system are the limited number of tool sizes and the possibility of breaking the tabs on the extractor when a twist rather than solid pulling force is applied during extraction [93].

Cancelier Extractor Kit

It consists of a handle and 4 different diameter extractor tubes with outer diameters of 0.50, 0.60, 0.70, and 0.80 mm. Since there is no trephine bur in the Cancellier kit, the 2-3 mm coronal segment of the fragment is opened with ultrasonic, and the extractor tube is placed on the coronal end of the broken fragment and removed by gluing it with cyanoacrylate adhesive [78].

Wire Loop Technique

It aims to remove the fractured file by circling it with a wire loop. Disposable 25 G dental injection needle with outer diameter 0.46 mm; 12-15 cm piece of steel wire with a diameter of 0.14 mm; and a small hemostatic forceps are used. The effectiveness of this technique may be increased if the tips stated by the inventor of the technique obtained from the clinical experience of the technique are considered [95].

Knitting technique

It is a technique for removing fractured files using many Hedström files. In this technique, Hedström files are placed to bypass the fractured file, rotated to grasp the broken piece, and removed by withdrawing 1 unit [78,90].

Softened gutta percha technique

It is a simple technique that uses softened gutta percha to remove loosely attached fragments located in hard-to-reach areas that obstruct straight line access and thus do not allow direct vision. Rahimi & Parashos [96] applied this technique as follows; The apical 2-3 mm part of a gutta percha cone was immersed in chloroform for approximately 30 sec, then placed in the canal and allowed to harden for roughly 3 min. The gutta percha thread and broken fragment were then successfully removed using a careful clockwise and counterclockwise pulling motion [96].

Hypodermic surgical needle

It is a simple, cost-effective method that can be successful in removing fractured files from the root canal without the need for special complex equipment. This technique uses cut hypodermic surgical needles converted into microtubes. There are modifications used with adhesive and Hedström files [97,98].

Multisonic Ultracleaning System (GentleWave System)

It (Sonendo, Orange County, CA, USA) aims to remove the file by creating negative pressure in the root canal with continuous irrigation throughout the root canal system through the hand piece placed on the occlusal tooth surface. Its effectiveness has been described in studies evaluating the removal of fractured files from the root canal [99].

Electrolytic technique

It partially or even completely dissolves the broken piece through electrolysis, allowing the original canal path to the apex to be restored. For this purpose, an electrode system is placed in the root canal so that the anode encounters the instrument part. The major disadvantages of this technique are the need for special equipment, the use of acid in the electrolyte, and its limited effectiveness with SS files. Ormiga et al. [100] tested the concept of electrolytic technique on NiTi tools in fluoride environment, but stated that 6 h were required for effectiveness. It does not seem clinically possible to use such a long-term method.

Laser-assisted removal of fractured files

Neodymium-Doped Yttrium Aluminum Garnet lasers (Nd:YAG lasers) tested in laboratory studies have been claimed to successfully remove file parts in less than 5 min [101].

Conclusions

In summary, the NiTi alloy used in endodontic files, composed of approximately 55% Ni and 45% Ti, exhibits unique properties due to its ability to exist in multiple microstructural phases: austenite, martensite, and the R-phase. These phases can shift in response to temperature and stress, influencing the mechanical behavior of the alloy. The austenite phase is characterized by stiffness and shape memory, while the martensite phase offers flexibility and ductility. Over time, advancements in NiTi file systems have focused on enhancing fracture resistance and cutting efficiency through various thermomechanical processes. This continuous evolution aims to improve both flexural and cyclic fatigue resistance, ensuring better performance in endodontic procedures.

The fracture of NiTi files is influenced by a range of factors, including their design, production quality, disinfection methods, usage frequency, rotation speed, torque control, preparation techniques, clinician experience, and the anatomical characteristics of the root canal. Understanding these factors is essential for optimizing the use of NiTi files in endodontic procedures. By addressing design improvements, adhering to proper sterilization protocols, and employing effective preparation techniques, practitioners can significantly reduce the risk of file fractures, thereby enhancing treatment outcomes.

In conclusion, successfully removing fractured files from the root canal depends on several factors. These include the dental situation, where the file is located, the length and type of the file, the skill of the operator, the treatment method chosen, and individual patient factors. Understanding and managing these elements is important to reduce complications and improve the chances of successful treatment. In the process of removing fractured files from the root canal, systems that will cause the least damage to the tooth and surrounding tissues and preserve the original shape of the root canal as much as possible should be chosen. The primary treatment option for file fractures is non-surgical, aimed at retrieving the fragment. If this attempt fails, bypass is the option to follow. If this also fails, instrumentation and obturation of the canal down to the fragment is performed. When the conservative approach fails or is thought to have led to failure from the beginning, surgical treatment is preferred. Further, more clinical studies are essential to substantiate the efficacy of these modifications in reducing fracture rates during routine endodontic procedures.

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