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REVIEW

Prevention and management of fractured instruments in endodontic treatment

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Abstract

Intracanal instrument fracture is an unpredictable and problematic occurrence that can prevent adequate cleaning and shaping procedures and influence the prognosis of endodontic treatment. The prevalence of instrument fracture is reported to range between 0.28% and 16.2%. This article presents an overview of the prevention and management of instruments fractured during endodontic therapy on the basis of literature retrieved from PubMed and selected journal searches. Instrument fracture occurs because of reduced metal fatigue and/or torsional resistance. The reasons include canal morphology and curvature, manufacturing processes and instrument design, instrument use times and technique, rotational speeds and operator experience. With the development of various equipment and techniques, most of the retained instrument separations can be removed safely. However, in canals without associated periapical disease not every fractured separation should be removed from difficult locations because of the increased risk for root perforation and fracture. In difficult cases, either retain or bypass the fragment in the root canal and ensure regular follow-up reviews. Fractured instruments retained in the presence of periapical disease reduce significantly the prognosis of endodontically treated teeth, indicating a greater need to attempt the removal or bypass of the file separations. Apical surgery might be required in some instances, emphasizing the importance of preventing instrument fracture.

Key words: Endodontics; Instrument fracture; Root canal preparation; Prevention; Management

Core tip: It is important to prevent the potential adverse consequences that may follow the fracture of endodontic instruments during root canal preparation. Nickel-titanium engine-driven rotary instruments are more prone to fracture than stainless steel hand

instruments, but the risks may be reduced by avoiding multiple use of instruments, by careful operative techniques, in particular with small-sized instruments used in sharply curved root canals, by employing reciprocating hand-pieces and by selecting instruments having high torsional and fatigue resistance.

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INTRODUCTION

Intracanal instrument fracture with separation is often an unpredictable and problematic occurrence that can prevent adequate root canal cleaning and shaping and adversely affect the prognosis of endodontic treatment. The prevalence and incidence of such fractures vary widely among different studies, and fracture not uncommon in the mesiobuccal root canals of molar teeth. Decisions to remove or bypass fractured instrument separations from root canals should be weighed against the necessity to do so, the time involved and the possible adverse iatrogenic complications that might occur. Care taken in the prevention of instrument fracture is preferable to managing the consequences of fracture.

Publications in PubMed were initially searched for by using the key words "instrument separation", "instrument broken", "removal" and "prevention". Further articles were obtained from references listed in the publications and related articles and from hand searching selected journals.

PREVALENCE AND INCIDENCE OF INSTRUMENT FRACTURE

The occurrence of intracanal instrument fracture is reported to range widely between 0.28% and 16.20%[1-8]. In a 5-year retrospective study involving postgraduate students the overall prevalence of instrument fracture among 1367 patients (2180 endodontic cases, 4897 root canals) during root canal preparation was found to be 1.83% (40/2180 cases)[1]. Among 1682 instruments collected over 16 mo, the prevalence of fracture was 5% with the lowest fracture rate being 3% for K3 (SybronEndo, Orange, CA, United States) stainless steel (SS) hand instruments[2]. In a student clinic, during a 10-year period (1997-2006) the overall incidence of instrument fracture in 3854 root-filled teeth was 1.0% at the tooth level[3]. Over 1 year, among 1235 patients (1403 teeth, 3181 canals) from a clinical practice, the incidence of fracture for ProFile (Dentsply-Maillefer, Ballaigues, Switzerland), ProTaper (Dentsply Maillefer), GTRotary (Dentsply Tulsa Dental Specialities, Tulsa, OK, United States) and K3Endo (SybronEndo) nickel-titanium (NiTi) rotary files was 0.28%, 0.41%, 0.39% and 0.52%, respectively[4]. A 4-year retrospective study of 3706 ProFile instruments reported a fracture rate of 0.3%[5]. In a large retrospective study, the incidence of Mtwo (VDW GmbH, Munich, Germany) NiTi rotary instrument separation was 2.2% according to the number of teeth (11306), and 1.0% according to the number of root canals (24108)[6]. In another 1-year study, the fracture incidence was 16.02% among 593 discarded Mtwo instruments after clinical use[7]. Over a 2-year period, 3543 canals were treated during which 46 LightSpeed (LightSpeed Technology, Inc., San Antonio, TX, United States) NiTi rotary instruments separated and were found to be non-retrievable, resulting in a separation rate of 1.30%[8]. A survey from Tehran reported that the most prevalent NiTi instrument failure fault was "intra-canal file fracture" (88.5%) among all procedural faults[9].

The prevalence and incidence of intracanal instrument fractures is difficult to determine, being reported variously (Table 1) at the tooth and/or canal level in disparate studies having very different designs and populations. The determination is compounded by such factors as differences in tooth location and operative difficulties and experience of the operators. Hence, the very wide range reported in literature for the occurrence of intracanal instrument fracture.

PREVENTION OF INSTRUMENT FRACTURE

The endodontic management of intracanal instrument fracture is often difficult and risky, and not all canals and teeth can be managed successfully. Hence, prevention of such fractures is important, requiring an understanding of factors contributing to instrument fracture to reduce the likelihood of file separation within the root canal. Iatrogenic mishaps have been associated with factors such as canal curvature and patency, instrument design and manufacturing process, instrument use times and metal alloy fatigue, hand-piece torque and rotational speed, and operator technique and experience[21]. Prevention of instrument fracture will be investigated as follows.

Canal morphology

It is important to assess the many variations in root and root-canal morphology before initiating any endodontic treatment[22]. Plotino *et al*[23] stated that the shape of an artificial root canal influenced the trajectory of the intracanal instrument. Differences in shape were reflected by the number of cycles to failure (NCF) measured for the same instrument in different artificial root canals, and by the impact of the type of

Table 1 The prevalence and incidence of files separation at different studies

Year	Ref.	Instrument	*n*	Level	Location	Separation
1997	Ramirez-Salomon *et al*[10]	LightSpeed	162	Canals	Molars	3.7%
			52	Teeth	Molars	11.5%
2000	Sattapan *et al*[11]	Quantec Series 2000	378	Files	Tooth	21%
2003	Al-Fouzan *et al*[12]	Profile	1457	Canals	Molars	1.4%
			419	Teeth	Molars	5%
2003	Hülsmann *et al*[13]	Quantec Sc	50	Canals	Molars	6%
			25	Teeth	Molars	12%
		LightSpeed	50	Canals	Molars	10%
			25	Teeth	Molars	20%
2004	Ankrum *et al*[14]	Profile	59	Files	Molars	1.7%
		Protaper	84	Files	Molars	6.0%
		K3 Endo	48	Files	Molars	2.1%
2006	Troian *et al*[15]	RaCe	50	Canals	Artificial	12%
		K3	50	Canals	Artificial	0%
2006	Iqbal *et al*[16]	Hand and rotary instrument	10237	Canals	Tooth	0.09%
			4116	Teeth	Tooth	0.22%
		Hand only	1801	Canals	Tooth	0.17%
			749	Teeth	Tooth	0.40%
		Rotary instrument	10237	Canals	Tooth	0.67%
			4116	Teeth	Tooth	1.68%
2006	Di Fiore *et al*[4]	Profile	2476	Files	Tooth	0.28%
		Protaper	1689	Files	Tooth	0.41%
		GTRotary	771	Files	Tooth	0.39%
		K3Endo	1725	Files	Tooth	0.52%
2006	Knowles *et al*[8]	LightSpeed	3543	Canals	Tooth	1.30%
2009	Inan *et al*[7]	Mtwo	593	Files	Tooth	16.2%
2009	Shen *et al*[2,5]	Profile	3706	Files	Tooth	0.3%
		Protaper	1895	Files	Tooth	0.26%
		Protaper for hand use	280	Files	Tooth	2.9%
		K3	294	Files	Tooth	3%
2011	Wu *et al*[17]	Protaper	6154	Canals	Tooth	1.1%
			2654	Teeth	Tooth	2.6%
2013	Gu *et al*[18]	Protaper	2061	Files	Tooth	28.2%
2014	Plotino *et al*[19]	Reciproc	3780	Canals	Tooth	0.21%
			1696	Files	Tooth	0.47%
2014	Labaf *et al*[20]	Hero642	233	Canals	Simulated	4.75%
		FlexMaster	92	Canals	Simulated	3.92%
		Mtwo	152	Canals	Simulated	6.33%
2014	Wang *et al*[6]	Mtwo	24108	Canals	Tooth	1.0%
			11036	Teeth	Tooth	2.2%
2014	Ungerechts *et al*[3]	Hand instruments	3854	Teeth	Tooth	1.0%

canal on both the NCF and fragment length. Lopes *et al*[24] indicated that significantly lower NCF values were observed for instruments tested in canals with the smallest root curvature radius, the longest arc and the arc located in the middle portion of the canal. Tzanetakis *et al*[1] reported that the prevalence of instruments fractured in the apical third (52.5%) was significantly higher when compared with the middle (27.5%) and coronal (12.5%) thirds of the canals. Instrument fracture occurred significantly more often in molars and in teeth rated as difficult preoperatively[3,25]. Di Fiore *et al*[4] found that instruments fractured in anterior teeth was 0.28%, in premolars 1.56% and in molars 2.74%, which appeared to be related to the increasingly complexity of canal morphology. Some 39.5% of fractured instruments were located in the mesiobuccal canals of molars and 76.5% of the fragments were located apically, while a significantly high percentage of instruments of small apical diameters (sizes 006-015) fractured in relatively straight root canals[3].

In conclusion, premolar and molar teeth, and the apical third of small-diameter and curved canals in particular are prone to cause instrument fracture separation.

Root canal curvature angle: The *in vitro* time to failure significantly decreased and the cyclic fatigue life increased as the angles of root canal curvature increased[26,27]. The abruptness of root canal curvature negatively influenced the failure rate of ProFile rotary instruments[28]. Rotary FlexMaster instruments, with a cross-section similar to a triangle with convex sides, are suitable for preparing curved root canals with the balanced-force technique[29]. These instruments provided results similar to LightSpeed rotary instruments, featured a noncutting pilot tip, a small cutting head and a smooth non-tapering shaft with a minimal risk of instrument fracture, but an increased risk of root-canal transportation[29,30]. Kim *et al*[31] found that the "minimally invasive instrumentation" design of the Self-Adjusting File (ReDent-Nova, Ra'anana, Israel) may produce minimal stress concentrations in the apical root dentin during shaping of the curved canal. The calculated stress values from the ProTaper Universal F1 (Dentsply-Maillefer) and ProFile size 20/0.06 files were approximately 8 to 10 times larger than that of the Self-Adjusting File. Kitchens *et al*[32] reported that increasing the angle (25°, 28° and 33.5°) at which the ProFile instrument was rotated, decreased the number of rotations to fracture for the 0.04- and 0.06-tapers. The 0.04-taper ProFile was more affected by an increase in the angle than the 0.06-taper. Kramkowski *et al*[30] compared the torsional stress and cyclic fatigue characteristics of ProFile GT (Dentsply Tulsa Dental Specialities) and ProFile GT Series X (Dentsply Tulsa Dental Specialities) for root canals of 45° and 60° degree curvatures. For the 60° canal curvatures, ProFile GT was found to be significantly more resistant to cyclic fatigue fracture than ProFile GT Series X for file sizes 30/0.06, 20/0.06 and 30/0.04 ($P \leqslant 0.005$).

The greater the degree of root canal curvature, then the easier the instrument will fracture. Apart from possible root canal transportation, Rotary FlexMaster, LightSpeed and Self-Adjusting File instruments are suitable to prepare curved root canals. However, the risk of any instrument fracturing increases with the severity of canal curvature.

Root canal curvature radius: Haïkel *et al*[33] tested three engine-driven NiTi rotary instruments, using ProFile, Hero (Micro-Mega, Besancon, France) and Quantec (McSpadden, NT Co., Inc., Chattanooga, TN), in root canals with 5- and 10-mm radii of curvature. Radius of canal curvature was considered as the most significant factor in determining the fatigue resistance of the files. As the radius decreased, then the time to fracture also decreased. One other study compared the cyclic fatigue resistance of each size (S1, S2, F1, F2 and F3) of ProTaper NiTi rotary files in artificial canals also with 5- and 10-mm radii of curvature. The 5-mm radius group had significantly fewer cycles to fracture than the 10-mm radius group for all file sizes[34]. Azimi *et al*[35] investigated the fatigue and fracture modes of RaCe (FKG Dentaire, La-Chaux de Fonds, Switzerland) rotary instruments, which are designed to constantly switch the helix angles of the blades as they rotate inside root canals, and ProTaper instruments used by rotating the files 30° or 60°. Again, both file types exhibited significantly less resistance to fracture when the radius of canal curvature was reduced from 5 mm to 2 mm.

These *in vitro* studies all demonstrated that the risk of instrument fracture increases as the radius of canal curvature decreases.

Preparation instruments

The prevalence of SS hand and NiTi rotary instrument fractures by postgraduate students was reported as 0.55% and 1.33%, respectively[1]. SS instruments usually deform before they fracture, unlike NiTi instruments that do not show visual signs of deformation before fracture[36]. It was observed that SS files had a significantly greater occurrence of failure in clockwise rotation, whereas NiTi files had a significantly greater occurrence of failure in counterclockwise rotation[37]. Many studies have suggested that fatigue fracture and torsional fracture are two major reasons for instrument separation. Plotino *et al*[38] attributed the fracture of NiTi rotary instruments to cyclic flexural fatigue or torsional failure, or a combination.

Fatigue fracture: Instrument fractures often result from their cyclic fatigue. Plotino *et al*[39] evaluated the cyclic fatigue resistance of five NiTi rotary systems in an apical abrupt curvature using SS artificial canals with a 2-mm radius of curvature and a 90° angle of curvature. Ten each of FlexMaster, Mtwo, ProFile (Dentsply -Maillefer) and ProFile (Dentsply Tulsa Dental Specialities), all with tip size 25, taper 0.06, and 10 ProTaper Universal F2 (Dentsply-Maillefer) instruments were rotated passively at 300 rpm until fracture occurred. The survival times for the instruments tested in an apical abrupt curvature were Mtwo > ProFile (from Maillefer) > ProFile (from Tulsa) > FlexMaster > ProTaper. Bahia *et al*[40] found that the mechanical behavior of the NiTi wires was modified slightly by cyclic tensile loading in the superelastic plateau. Because the changes tended towards stabilization, the clinical use of ProFile rotary instruments did not compromise their superelastic properties until they fractured by fatigue or torsional overload, or were otherwise discarded. Lee *et al*[41] studied the cyclic fatigue resistance of various NiTi rotary files, using three root canal curvatures (25°, 35° and 45°), by correlating cyclic fatigue fracture test results with finite-element analysis. The NiTi rotary files investigated were ProTaper, ProFile (Dentsply-Maillefer), HeroShaper (Micro-Mega) and Mtwo. ProTaper showed the least cyclic fatigue resistance and the highest stress concentration for all tested curvatures, whereas Mtwo showed the most cyclic fatigue resistance. When the stresses increased, the number of instrument rotations to fracture decreased. Shen *et al*[42] found that most of the NiTi rotary instruments (78% of K3 and 66% of ProTaper) among 79 fractured instruments failed because of fatigue fracture, whereas 91% of NiTi hand instruments failed from shear fracture. In another (clinical) study, Shen *et al*[5] reported that 10 of 12 ProFile instruments failed because of shear stress, whereas only two failed because of fatigue fracture.

From these studies, most of the NiTi rotary instruments failed *in vitro* from fatigue fracture, but with different rates for different brands. However, the main reason for NiTi hand instrument failures *in vitro* was from shear fracture.

Torsional fracture: Haïkel *et al*[43] assessed the torsional moment (torque at failure) of four brands of NiTi endodontic files: Brasseler (triangular cross-section; Cms-dental, Paris, France), JS Dental (triangular cross-section; JS Dental, Inc., Ridgefield, CT, United States), McSpadden (H-file types 0.8 to 20, Unifile or S-file cross-section sizes 25 to 40), and Maillefer (concave triangular cross-section). The results suggested that JS Dental and McSpadden NiTi files were the most resistant to torsional fracture, but all NiTi files were inferior when compared with SS files from a previous study. A relationship was proposed between fatigue fracture and torsional fracture[44]. When the torsional resistance of ProFile 25/0.06 and ProTaper F1 were investigated, it was found that approximately 75% cyclic fatigue reduced the torsional resistance of the NiTi rotary instruments significantly. A repeated clinical "locking effect" was considered in a study that evaluated the torsional resistance of five brands of NiTi rotary instruments: Twisted File (TF; SybronEndo), RaCe systems, ProTaper, Helix (DiaDent, Chongju, South Korea) and FlexMaster[45]. TF had the lowest and FlexMaster the highest torsional resistance among the five brands. Braga *et al*[46] also found that TF had similar (TF 25/0.08 taper and RaCe 25/0.06 taper) or significantly higher (TF 25/0.06 taper and RaCe 25/0.04 taper) torsional resistance. Setzer *et al*[47] tested three rotary NiTi systems at 30° curvature under cyclic fatigue only or in combination with torsional stress (with an added 1-Ncm torsional load): Revo-S (Micro-Mega), ProFile Vortex (Dentsply, York, PA, United States) and ProFile with tip sizes 25 and 35. Regardless of fatigue alone or in combination with torsional stress, all fractures occurred within the area of the file curvature. But, with the addition of a torsional load the location of the fracture moved in the direction of the additionally applied torsional stress. One other study found that torsional resistance and angular deflection of instruments were reduced following clinical use when compared with new instruments[48]. Stock NiTi instruments had a torsional fracture resistance up to 10.3%, 8.0% and 7.4% lower for the Small, Primary and Large files, respectively than did M-Wire (Dentsply Tulsa Dental Specialities) instruments, when using finite element analysis simulations based on micro-computed tomography scans at 10 μm resolution[49]. Shen *et al*[50] suggested that the torque at fracture values of K3 and K3XF (SybronEndo) instruments increased significantly with increased diameter.

The torsional resistance of SS files was certified many years ago to be higher than NiTi instruments. The higher the torsional resistance is, the less an instrument is prone to fracture, but clinical use reduces such resistance. There is a relationship between torsional and fatigue resistance, which are two significant factors associated with file separation. Any instrument may fracture in root canals if the curvatures are severe, regardless of how much torsional or fatigue resistance it has.

Manufacturing methods: Intracanal instruments produced by twisting had significantly lower Vickers microhardness values, but presented greater resistance to cyclic fatigue and were more flexible than instruments produced by a grinding process[46,51]. Larsen *et al*[52] reported that the twisted TF was significantly more resistant to cyclic fatigue than traditionally ground EndoSequence (Brasseler, Savannah, GA, United States) instruments, but not significantly different from ProFile. Recently, thermal treatments of NiTi alloys, *e.g.,* Controlled Memory Wire (CM Wire; DS Dental, Johnson City, TN, United States), M-Wire, and R-phase wire (SybronEndo) have been used to modify their mechanical properties[53]. M-Wire has been thermomechanically processed to have greater flexibility at body temperature. The GT Series X (Dentsply Tulsa Dental Specialities) instruments made from M-Wire are more flexible and capable of stress relief than ProFile GT at the most critical curved canal sections[54]. M-Wire is nearly 400% more resistant to cyclic fatigue than stock ProFile 25/0.04 taper instruments[55]. Thermal treatment improved the resistance of NiTi rotary instruments against fatigue fracture. Treatment resulted in significant changes in the instrument bulk with the appearance of an R-phase and an improved fatigue resistance. Indeed, after treatment at 500 ℃, the number of revolutions to failure increased up to 829 and 474 for electropolished and non-electropolished instruments, respectively[56]. The shape-memory CM-wire manufacturing process produced NiTi rotary instruments more flexible and more resistant to cyclic fatigue than instruments produced by a traditional manufacturing process or by a thermally treated NiTi alloy (M-wire)[57]. CM Wire files also showed a high angle of rotation before fracture, but the results were not significantly different from some other files[58]. CM Wire files may have a combined advantage of greater torsional strength and high deformation before fracture[59]. In various environments, the CM Wire instruments yielded an improvement of more than 4 to 9 times for the number of revolutions before fracture than conventional NiTi files with the same design[60]. Electropolished instruments performed significantly better than non-electropolished instruments in cyclic fatigue testing. The benefits of electropolishing were possibly from a reduction in surface irregularities that served as points for stress concentration and crack initiation[61]. Although surface smoothness was enhanced by electropolishing, this did not protect the instruments from low-cycle fatigue failure. No electropolished instrument showed more than one crack origin, significantly fewer than for the non-electropolished instruments[62]. Gutmann *et* *al*[63] have reviewed the inherent metallic and surface properties of NiTi root canal instruments.

Many manufacturers have sought ways to enhance the performance, durability and safety of the many root canal instrument designs presently available, such as by modification of the alloy surface or the alloy microstructure with post-machining or post-twisting heat treatment.

Cross-section design: The resistance of NiTi rotary instruments to cyclic failure increased significantly with decreasing cross-sectional area[64]. The bending fatigue behavior was affected by the properties of the material and the cross-sectional configuration of the instrument. NiTi and triangular geometry profiles were associated with better fatigue resistance than SS and square cross-sections[65]. Yum *et al*[66] compared torsional strength, distortion angle and toughness of various NiTi rotary files with different cross-sectional geometries - TF and RaCe, ProTaper, ProFile, Mtwo (equilateral triangle, convex triangle, U-shape, and S-shape). TF and RaCe had significantly lowest yield strengths. TF had a significantly lowest ultimate strength, whereas Mtwo showed the highest. ProFile showed the highest distortion angle at break, followed by TF. ProFile also showed the highest toughness value, whereas TF and RaCe both showed a lowest toughness value[66]. Baek *et al*[67] also evaluated the effect of cross-sectional geometry on the torsional stiffness of NiTi instruments. Triangle, slender rectangle, rectangle and square were tested. The models with the rectangular cross section had higher torsional stiffness than models with the triangular cross section.

A larger cross-sectional area, a rectangular geometry and the S-shape of Mtwo instruments favored a higher fracture resistance.

Retreatment instruments: Inan *et al*[68] compared the cyclic fatigue resistance of three different rotary NiTi instruments designed for endodontic retreatments. The results showed that the R-Endo R3 (Micro-Mega) instruments were more resistant to fatigue failure than the ProTaper D3 and Mtwo R 25/0.05[68]. Hand and rotary instruments were compared for removing gutta-percha from previously treated curved root canals, where the NITi rotary FlexMaster, ProTaper Universal and D-RaCe (FKG Dentaire) retreatment files were associated with a higher risk of instrument fracture. No fractures occurred with the Hedström (Dentsply Maillefer) SS hand files[69,70].

Endodontic retreatments with NiTi rotary instruments resulted in a higher occurrence of instrument fracture than when using SS hand instruments.

Operator

In a 5-year retrospective study, the prevalence of fractured instruments was 7.41% for 2180 endodontic cases treated by postgraduate students[1]. A recent British survey showed that the main reasons for not adopting NiTi use included cost, a lack of training and the perceived risk of instrument fracture[71]. In another study, 88.8% of the respondents had experienced fractured endodontic instruments, with a significantly higher proportion of endodontists (94.8%) compared with general dental practitioners (85.1%)[72]. For ProTaper instruments used at two different clinics, defect rates (fracture and distortion combined) were observed of 7% (Clinic A) *vs* 13% (Clinic B) for shaping files, and 4% *vs* 10% for finishing files[2].

Dentists require more training and more comprehensive education regarding different endodontic instruments and techniques.

Use times: The main operator factors associated with the instrument fracture are "over-use" and "excessive pressure". Factors related to clinician experience, technique and competence have been shown to influence use times. In one study, 54.3% of the respondents re-used NiTi files more than 10 times[73]. The majority of defects (34/48) occurred in small (size 20) instruments, which should be considered as single-use, disposable instruments because of the higher possibility of torsional deformation[5]. The fracture rate of a single ProTaper rotary instrument was significantly increased after the number of prepared root canals exceeded 20 times[74]. Single-use of endodontic NiTi instruments has been recommended to reduce instrument fatigue and the possibility of cross-contamination[19]. The risk of NiTi rotary instrument fracture in the canal was low when a new instrument is used by experienced endodontists. A total of 1071 ProFile 0.04, 432 ProFile Series 29.04, and 1895 ProTaper files were discarded after single use. No fractures occurred in the ProFile, there were no fractures or deformations in the ProFile Series 29, and instrument separation was 0.26% in the ProTaper instruments[75]. Shen *et al*[53] reported that the risk of ProFile Vortex fracture is very low when the files were used once only by undergraduate students. Although multiple clinical use caused significant changes in the microstructural properties of HyFlex CM (Coltène Whaledent, Cuyahoga Falls, OH, United States) instruments, the risk of fracture in the root canal was very low when the instruments were discarded after three cases of clinical use[76]. ProTaper Universal rotary instruments used by an experienced endodontist allowed the cleaning and shaping of the root canal systems of five molar teeth without fracture[48]. The size of the rotary file, among other factors, will determine how many times a particular file should be used[77]. Root canal instrumentation following the manufacturer's instructions was performed with Reciproc (VDW GmbH) with a very low occurrence of instrument fracture and deformation[19].

The recommended use times for different files and for differently experienced operators, varied widely (Table 2). In narrow and/or sharply curved root canals

Table 2 The recommended use times of different studies

Year	Ref.	Instruments (rotary)	*n*	Used times	Operator	Deformation (files)	Separation (files)
2006	Wolcott *et al*[77]	ProTaper	4652 canals	1 tooth	Experienced		20
				2 teeth	Experienced		12
				3 teeth	Experienced		23
				4 teeth	Experienced		19
				5 teeth	Experienced		39
2009	Shen *et al*[75]	ProFile 0.04,	1071 files	1 visit	Experienced	8 (0.75%)	0
		ProFile Series 29 0.04	432 files	1 visit	Experienced	0	0
		ProTaper	1895 files	1 visit	Experienced	55 (2.9%)	5 (0.26%)
2009	Inan *et al*[7]	Mtwo	593 files	4 molar teeth or 2 molar teeth with curved canals	10 trained	58 (9.78%) (unwinding and curve/bend)	95 (16.02%)
2009	Vieira *et al*[48]	ProTaper Universal	10 sets files	5 molar teeth	Experienced	0	0
2010	Ma *et al*[74]	ProTaper	432 case	20 canals			27
2012	Shen *et al*[53]	ProFile Vortex	2023 files	1 visit	Undergraduate students	0	1 (0.04)
2013	Shen *et al*[76]	HyFlex CM	468 files	3 teeth	9 residents	16 (3.4%)	0
2015	Plotino *et al*[19]	Reciproc	1696 files	1 tooth		6 (0.35%)	8 (0.47%)

the number of times that an instrument is used should be as few as possible.

Rotational movements: Different rotational movements of endodontic instruments resulted in different cyclic fatigue survivals, and reciprocating movements were shown to increase the cyclic fatigue resistance of NiTi instruments[78]. When using the reciprocating Reciproc R25 (VDW GmbH) system, only 8 of 1580 instruments fractured during treatment, which represented 0.47% of the total number of instruments used and 0.21% of the root canals treated[19]. Compared with continuous rotation, the probability of a longer instrument survival was greater when using reciprocating motion for all file types tested (100% for K3, 87% for K3XF and 99% for Twisted File)[79]. Fatigue life was shown to increase with decreasing reciprocating amplitude in stationary reciprocation[80], and reciprocating movements resulted in a significantly longer cyclic fatigue life when compared with continuous rotation[81]. Kim *et al*[82] tested the cyclic fatigue of Reciproc and WaveOne (Dentsply-Maillefer) instruments using a simultaneous pecking motion performed with the instruments operating in the recommended reciprocation motion until fracture. Reciproc showed higher cycles to fracture and WaveOne higher torsional resistance. These two reciprocating files demonstrated significantly higher cyclic fatigue and torsional resistances than ProTaper. To simulate clinical conditions, Kiefner *et al*[78] employed a continuous up-and-down pecking motion along the vertical axes of Reciproc (R25 and R40) and Mtwo (M25 and M40) instruments when comparing reciprocating and continuous rotary motions. Reciproc files in reciprocating motion had a significantly higher number of cycles to fracture than Mtwo files used in continuous rotation[78]. Reciproc R25 instruments were associated with a significant increase in mean time to fracture when compared with primary (tip size 25 with a taper of 0.08) WaveOne instruments[83]. WaveOne Large (tip size 40 with a taper of 0.08) instruments presented significantly higher bending resistance than the Reciproc instruments, but Reciproc R40 resisted dynamic and static cyclic fatigue significantly better than WaveOne Large instruments[84]. [WaveOne NiTi files are available in three sizes: small (tip size 21 with a taper of 0.06), primary (tip size 25 with a taper of 0.08) and large (tip size 40 with a taper of 0.08)].

The likelihood of NiTi instrument fracture in root canals appeared to be reduced when using reciprocating rather than rotational motion with engine-driven instruments.

Rotational speeds: The time-to-failure for NiTi instruments decreased significantly as rotational speeds increased (200, 300 and 400 rpm), but the time-to-failure increased with increased pecking distances[26]. Pérez-Higueras *et al*[79] found that TF instruments were more resistant to cyclic fatigue when rotated at 300 rpm instead of 500 rpm. This result was supported by another study where ProTaper F2 instruments failed more rapidly at a rotational speed of 400 rpm (approximately 95 s) than those used at 250 rpm (approximately 25 s)[81]. Also, approximately a 30% reduction in the observed number of cycles to fracture occurred as rotational speeds were increased from 300 to 600 rmp[85]. By contrast, one study reported that the number of rotations to fracture was not related to the speed (350 or 600 rmp) at which the NiTi files were operated[32].

Appropriate rotational speeds and continuous pecking motions within the root canals are recommended. The rotational speed employed for any instrument should be considered in accordance with the manufacturer's recommendations, the clinical situation and the experience of the operator.

Lubricants: During root treatment, lubricants are mostly used to reduce the frictional resistance between the rotating instruments and float debris produced after mechanical instrumentation. Boessler *et al*[86] used ProFile 30/0.06 instruments in milled artificial root canals in human dentin and gauged the effects of sodium hypochlorite (1% NaOCl) and a chelator (18% etidronic acid) on maximum torque, full torsional load, and maximum force values using a torque testing platform. They found that the aqueous lubricants significantly reduced all outcome variables compared to dry conditions ($P < 0.05$), and that an aqueous lubricant was more beneficial than a gel-type counterpart. The findings were similar to those reported by Shantiaee *et al*[87] who investigated the rates of fracture, deformity and metal slivering of ProTaper rotary instrument with three different lubricants [1% NaOCl (Gorang, Pakshoo Co.,Tehran, Iran), RC-Prep (Premier Dental Produce, Philadelphia, PA, United States) and 17% EDTA (Asia Chemi Teb Co., Tehran, Iran)] in the root canals of extracted molars. The fracture rate of instruments in the RC-Prep group was significant higher compared with the other two groups, with the lowest fracture rate in the EDTA group.

Different forms of lubricant influence the fracture rates of endodontic instruments. Aqueous lubricants are better than dry conditions, and paste-like lubricants can mix with dentin debris in the canal to create increased friction between the instrument and dentin walls.

Hypochlorite solutions: Reciprocating dynamic immersion in NaOCl solution for 1 or 5 min did not reduce significantly the cyclic fatigue resistance of NiTi files[88]. For all properties tested (torsional moment, maximum angular deflection, maximum bending moment and permanent angular deflection), NaOCl immersion had no statistically significant effect[43]. While instruments completely immersed in 5% NaOCl at 50 ℃ for 5 min had a significantly lower resistance to fracture from cyclic fatigue than instruments not immersed or only partially immersed, SEM observations revealed evident signs of corrosion of the fractured instruments[89]. Galvanic corrosion may be induced when different metals are immersed in an electrolyte, where one metal acts as the cathode and one as the anode of a galvanic couple.

The prolonged use of NaOCl as an intracanal irrigating solution might result in the corrosion and enhanced fracture of NiTi instruments.

Other factors: The use of small size SS K-files in a reciprocating manner might be a rational choice for the creation of a mechanical endodontic glide path in curved root canals[90]. The fatigue life of NiTi rotary instruments of larger size could be increased by using them with a lateral brushing or pressing movement[91]. The most frequently fractured file was 10/0.04 (30.39%) among 597 Mtwo rotary instruments[7]. Although more instruments with visible signs of plastic deformation were identified for the novice operator, the novice operator did not significantly affect the cyclic fatigue resistance when compared with the experienced operator[92]. Autoclave cycles had no significant overall effect on file performance for the tested instrument systems, including Profile Vortex made from M-Wire, Twisted File, and 10 Series files made from CM Wire[59]. Unused and sterilized used Profile GTX (Dentsply, Tulsa Dental Specialities) files lasted significantly longer than similar ProFile GT files with a probability of 75% and 65%, respectively; while mean life was significantly longer for GT than for GTX used files with a probability of 68%. Sterilized GT files lasted longer than unused files with a probability of 66%[93].

MANAGEMENT OF INSTRUMENT FRACTURE

When a file fractures during root-canal therapy, there are several treatment options available to the clinician. The management of the problem should be based on the effect of the fractured instrument on immediate treatment outcome and its potential influence on the endodontic prognosis[94]. Before clinical decision-making on the management, some factors should be considered as follows: (1) the stage of endodontic treatment at which the instrument fractured; (2) the armamentaria available; (3) the potential complications of the treatment approach adopted; (4) the presence or absence of periapical pathosis; and (5) the location and the length of the fractured fragment in the canal[95]. It is important that the patient is informed (accompanied by appropriate record keeping) when instrument fracture occurs during treatment or if a fractured file is discovered during a routine radiographic examination[96].

With no apical disease

Retain in the canal as a metal obstruction: Endodontists and general dental practitioners both reported a conservative approach when the management of fractured instruments failed[97]. In certain clinical situations it may be better to leave the fractured file in the root canal. After 5 years, in 12 instances of irretrievable instrument separation (from 3216 endodontically treated root canals), attempts were made to contact the patients to assess healing and tooth retention. Eight contacted patients confirmed the presence of the root canal-treated tooth in question. Among 5 attending patients, 2 teeth were classified as having complete healing, 2 uncertain healing, and 1 no healing according to radiographic assessments (Figure 1)[98]. Retained, fractured endodontic instruments did not reduce the prognosis of endodontically treated teeth when apical disease was absent and any treatment was well-managed[96,99]. Leaving fractured instruments in the apical one-third of the canal also

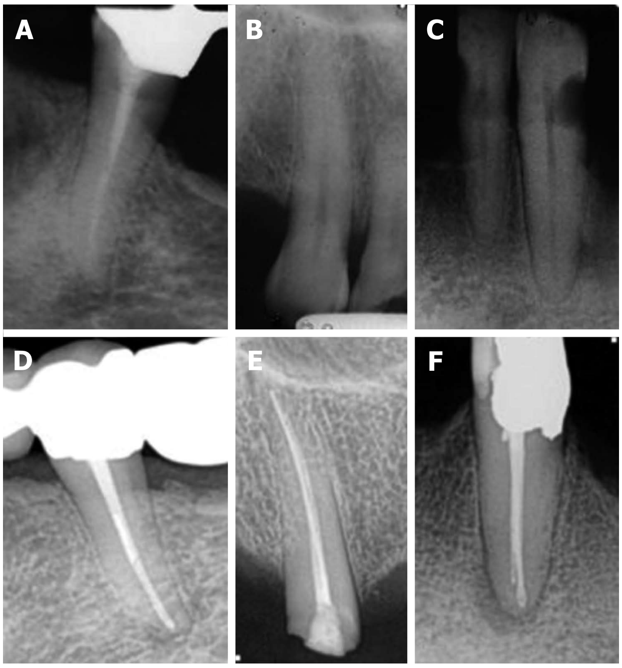

Figure 1 (A-C) preoperative and (D-E) 5-year follow-up radiographs: (D) complete healing, (E) uncertain healing, and (F) no healing.

did not appear to affect adversely the resistance of the root to vertical fracture[100].

Long-term tooth retention and functionality can occur after irretrievable instrument separation. However, clinicians are required to evaluate whether additional treatment is necessary.

Bypass: Bypassing a fractured instrument is often considered an acceptable treatment option to achieve clinical success. However, once bypassed, recent studies consider that the instrument could then be removed. Also, attempting to bypass a fractured instrument may result in perforation of the root canal wall[25].

With apical disease

If apical disease is present, healing is significantly reduced. Therefore, the treatment stage at which an instrument fractures in infected cases appears likely to be significant, as canal disinfection may be compromised[94]. At the earlier treatment stages, attempts must always be made to retrieve separated instruments and, if retrieval is not possible, a bypass should be attempted[101]. Ungerechts *et al*[3] reported that the success rate of removing fractured instruments was 72.7% for vital teeth, 58.3% for primary infected teeth and 42.9% in retreatment cases. The retrieval or bypass of fractured instruments was most successful in the coronal (100%) and middle (45.4%) thirds when compared with the apical third (37.5%) of the root canals[1]. Creating straight-line access and a ditched groove around the fractured instrument are two key steps for removal of fractured instruments. Then use ultrasonic files and/or bypass it with K-Files. Many fractured instruments can be vibrated ultrasonically and flushed out of the root canal. If not, the Tube-and-Hedstrőm file-Method or similar techniques, such as a microdebrider, a Hedstrőm file, a Masserann Kit trephine or with fine narrow-nosed pliers, can be used to remove the loosened instruments or bypass the instruments. When using these methods, 84 instruments (87%) were removed successfully[25]. Failure reasons might include ledge formation, excessive canal enlargement, perforation, limited visibility, dislocation, secondary fracture and incomplete removal, and apical extrusion of the fractured fragment. Several of these reasons may result in weakened root structure and predispose to vertical root fracture[99]. When used as canal filling materials, Resilon (Resilon Research, Madison, CT, United States) and mineral trioxide aggregate appeared to compensate for the root dentin loss that occurred as a result of attempts at retrieval of fractured instruments[100].

Microtube or trephine: When an attempt to bypass an instrument fragment becomes difficult, it should be retrieved by mechanical devices. A microtube or trephine creates a ditched groove around the coronal aspect of the retained instrument fragment. The Masserann Kit (Micro-Mega) is one such device, along with Gates-Glidden (Dentsply-Maillefer) drills, for the orthograde removal of intracanal fractured instruments[77,102]. The Masserann Kit is made up of hollow cutting-end trephine burs (ranging in diameter from 1.1-2.4 mm) and extractors (tubes into which a plunger can be advanced). The trephines are used to prepare a groove or trough around the coronal portion of the fragment. Then the extractor is inserted into the groove and locked the end of the fragment by the screw tightened between the plunger and the internal embossment (Figure 2)[95]. However, in the severely and moderately curved mesial root of mandibular molars, the Masserann Kit increased the risk of creating thin or perforated walls. Additionally, after 7.5 mm depth of drilling, the percentage of perforations increased[103].

Ultrasonics: The use of ultrasonic vibration is a favorite technique for the removal of fractured instruments, although it may result in some complications. The technique demonstrated a success rate of 80% in removing broken Hero 30/0.04 taper files within 70 extracted maxillary premolars[104]. Ultrasound, like above methods, creates a groove around the fractured instrument, but the used instruments are different. Diamond-coated zirconium ultrasonic tips (CPR 1-CPR 5; Obtura Spartan, Earth City, MO, United States) and titanium cutting tips (CPR 6-CPR 8; Obtura Spartan) were reported as the instruments. The former are selected according to the anatomy of the root canal to creat the groove. The later are placed in close contact with the fragment and worked in a circular counterclockwise motion to dislodge the fractured

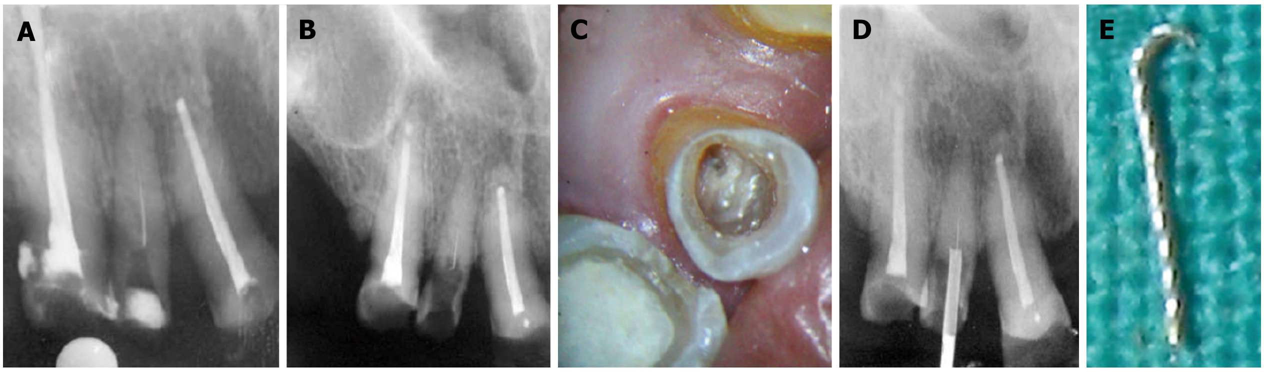

Figure 2 The extractor is inserted into the groove and locked the end of the fragment by the screw tightened between the plunger and the internal embossment. A: Periapical radiograph: Separated instrument is visible in middle 3rd of calcified root canal in maxillary right lateral incisor; B and C: Making a channel around the separated instrument to keep the broken instrument in the center of the tube of Masserann Kit; D and E: Engaging tube of Masserann Kit with the separated instrument and removal of the fragment from root canal.

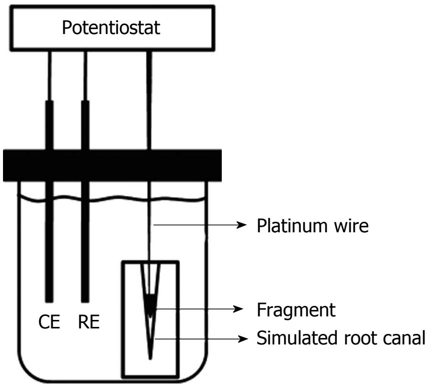

Figure 3 Schematic diagram of the intracanal fragment dissolution test. CE: Counter electrode; RE: Reference electrode.

instrument. All procedures are performed dry to ensure constant visualization, with the ultrasonic unit set at low power (20% to 30%)[96,105]. An ultrasonic technique was used to remove fractured NiTi rotary instruments from narrow, curved canals in both simulated (resin blocks) and mesiolingual canals of extracted mandibular first molars. However, when the fractured instrument segment was located entirely beyond the canal curvature, the success rate was significantly decreased and major canal wall damage often occurred[106]. Gencoglu *et al*[107] used ultrasonics with an operating microscope and reported that the success rate in removing fractured files in curved canals was 93.3%. This was significantly higher than the success rate of 66.6% when only conventional methods were used. The success rate was highest with ultrasonics (95.2%) in straight canals, followed by the conventional method (80.9%) and use of the Masserann Kit (47.6%)[107]. Visualization of fractured instruments with the aid of an operating microscope plays an important role in the success rates when removing or bypassing the fractured instruments. The success rate for the visible group was 85.3% (n = 58), and for the nonvisible group was 47.7% (n = 21)[105].

Electrochemical dissolution: Electrochemical dissolution has been proposed as a novel method to retrieve fractured instruments, especially for NiTi endodontic files. However, using NaF resulted in solutions that were cytotoxic to periodontal ligament fibroblasts, and artificial saliva may be a less toxic alternative for dissolving NiTi files[108]. A progressive consumption of K3 NiTi file tips was observed up to 30 min[109]. The anodic polarization of file fragments in simulated root canals for 60 min resulted in their partial dissolution and enabled the recovery of the original canal pathway with size 10 K-files[109]. The time taken by this procedure is clinically acceptable. K3 and ProTaper instruments had significantly greater weight loss than Mtwo instruments after 30 min of polarization in chloride- and fluoride-containing solutions, and 60 min anodic polarization of various NiTi instrument fragments in simulated root canals resulted in their partial dissolution (Figure 3)[110].

File removal system: Many different devices and techniques have been developed to retrieve fractured instruments from root canals, but iatrogenic accidents such as perforation, ledge formation, zipping, canal transportation or destruction, and fragments extruded beyond the root apex also occured during the removal procedures. The file removal process turns out to be more difficult when the fracture occurs in the apical third of the canal or in a sharply curved canal. Four separated files from the apical third of curved canals were successfully treated using the file removal system (FRS) (Figure 4)[111]. When compared with the Masserann Kit and an ultrasonic file-removal method, the FRS minimized both the root canal dentin removal and the time required to remove the fractured instruments[21].

Laser: Yu *et al*[112] found that a Nd:YAG laser successfully removed broken endodontic instruments from root canals in more than 55% of instances.

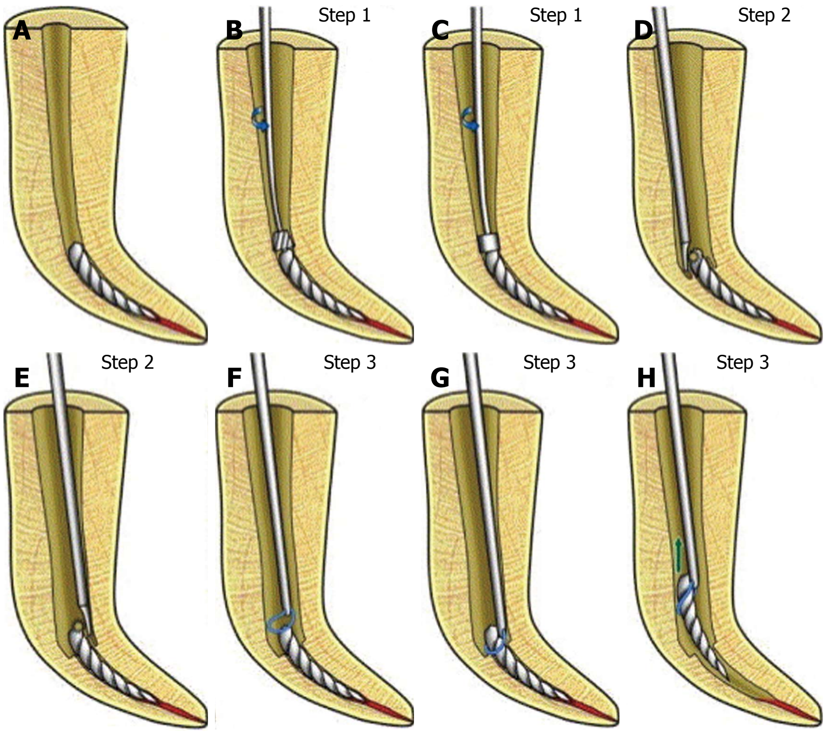

Figure 4 Procedures for removing a separated file from a root canal using the new file removal system. A: Initial canal with a separated file; B: Canal enlarged with CBA; C: Dentin removal around the separated file with CBB; D: Ultrasonic tip troughed semicircularly around the separated file to create space for the file-removal device; E: troughing semicircularly on the remaining half of the separated file for complete exposure; F: Placement of the loop over the separated file; G: Fastening the loop to grab the separated file; H: Removal of the separated file from the root canal.

However, temperature rises on root surfaces ranging from 17 ℃ to 27 ℃ might lead to periodontal tissue damage. Cvikl *et al*[113] also evaluated a Nd:YAG laser for the removal of fractured SS instruments. A narrow brass tube charged with solder was placed at the exposed coronal end of the fractured instrument and laser energy then used to melt the solder, fusing the fractured instrument to the brass tube. The laser technique requires the removal of a minimum amount of dentin, reducing the risk of root fracture.

Some other uncommon methods: Mini-forceps, broaches and cotton, and wire loops were historical methods used for the removal of instruments fractured and loosened in the more coronal portion of the root canal[114-116]. When the fractured instrument is positioned more deeply in the canal and is not visible or loose, and cannot be retrieved with other methods, then a Hedström or K-type file(s) can be inserted into the root canal where the clinician relies on tactile sense to withdraw the fractured instrument[25,116]. During the procedure, caution should be taken to avoid endodontic file separation. A modified 18-gauge needle and cyanoacrylate glue were used to retrieve a separated NiTi instrument from the mesiolingual canal of a mandibular first molar (Figure 5)[101]. As a safety feature during use, Gates-Glidden drills are designed to separate near the hub of the drill to allow for easier retrieval[117]. With the assistance of SS hand files and a chloroform-dipped gutta-percha cone, a fractured rotary NiTi instrument was successfully removed from the severely curved apical portion of the distobuccal canal of a mandibular molar[118]. However, chloroform is toxic and carcinogenic, and its extrusion through an existing root perforation resulted in subsequent necrosis in the supporting bone and periodontal tissues[119]. Chloroform used in the apical part of the root canal may also leak through the apical foramen and damage periapical tissues.

Factors influencing fractured instrument retrieval: Favorable factors for the removal of separated NiTi fragments are anterior teeth, straight root canals, localization before the canal curve, fragments longer than 5 mm, and NiTi hand K-files[116]. The success rate in roots with file fracture before the curve was 11.5 times more than that for file fracture beyond the curve[104]. Removal of a fractured instrument from the middle-third of the root canal decreased the force required to fracture the root vertically, regardless of the technique used for instrument removal[120]. There were statistically significant differences between experienced and less-experienced operators for the file-removal times and the root dentin removal rates[21].

Beyond the apical foramen

When the fractured instrument fragment is beyond the apical foramen, it is very difficult to retrieve the

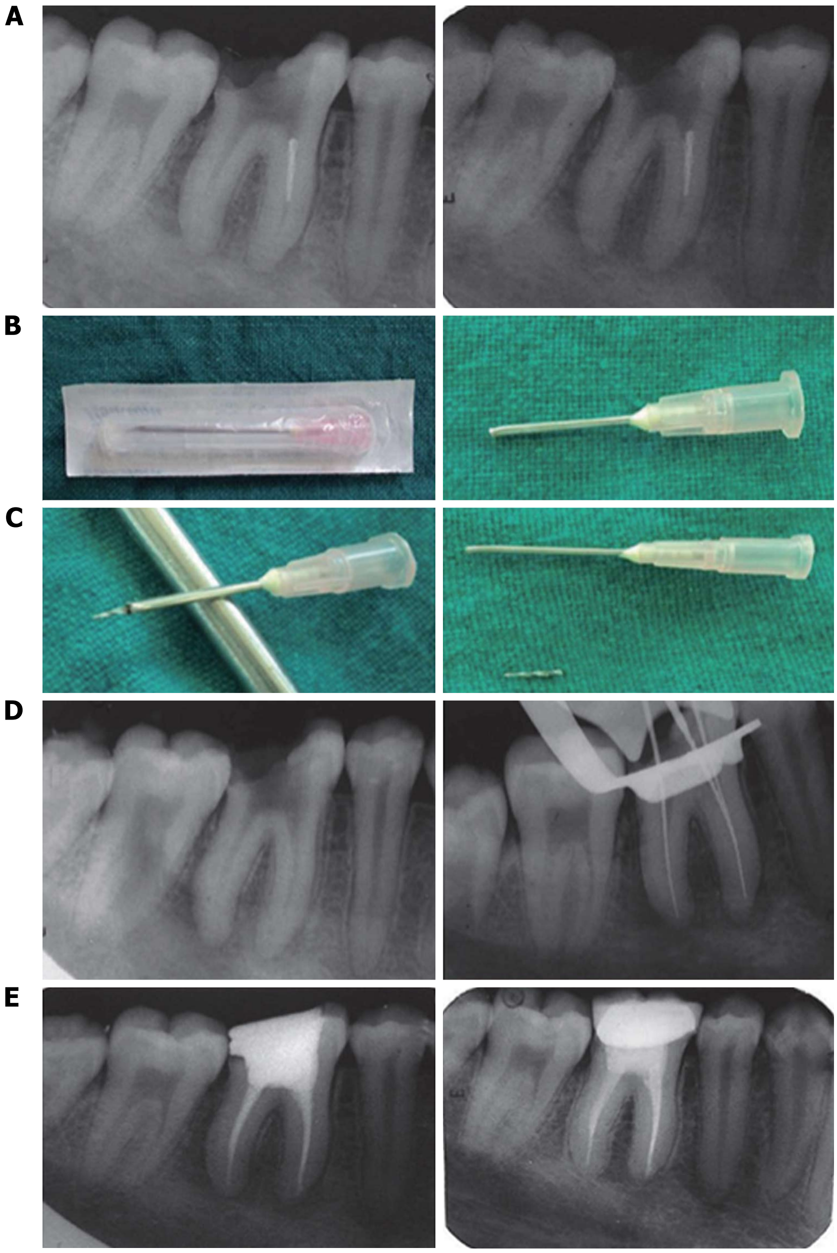

Figure 5 A modified 18-gauge needle and cyanoacrylate glue were used to retrieve a separated nickel-titanium instrument from the mesiolingual canal of a mandibular first molar. A: Radiograph showing separated instrument; Radiograph showing dentine surrounding the coronalend of the separated fragment removed with GG drill; B: An 18-guage needle, modified by cutting with a carborundum disc from the tip to transform it into a microtube; C: Separated instrument fragment removed adhered to the microtube; D: Radiograph confirming instrument removal; Working length reconfirmed; Post-obturation radiograph; E: Two-year follow up radiograph.

fragment using the previous approaches. In one report, two fragments beyond the apical foramen were removed by non-surgical approaches. A 3-mm fragment was pushed out of the root apex while the removal of a 7-mm fragment resulted in root perforation[25]. Surgical approaches may be better for these cases. However, the microsurgical procedure relies on considerable surgical skill and may reduce the crown-root ratio[96]. A separated hand instrument in a second molar was retrieved from the mesiobuccal root, which was close to the mandibular canal, using tooth replantation (Figure 6). After atraumatic tooth extraction, the separated instrument protruding 3 mm beyond the root apex was removed and the entrance to the mesiobuccal canal was cleaned, shaped and obturated. The tooth was re-implanted and orthodontic bands placed on both first and second molars. Periodic evaluations over 1 year showed progressive reductions in periapical radiolucency[121].

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We are very sad to declare that Professor Roger J Smales, as the second author of this article, was

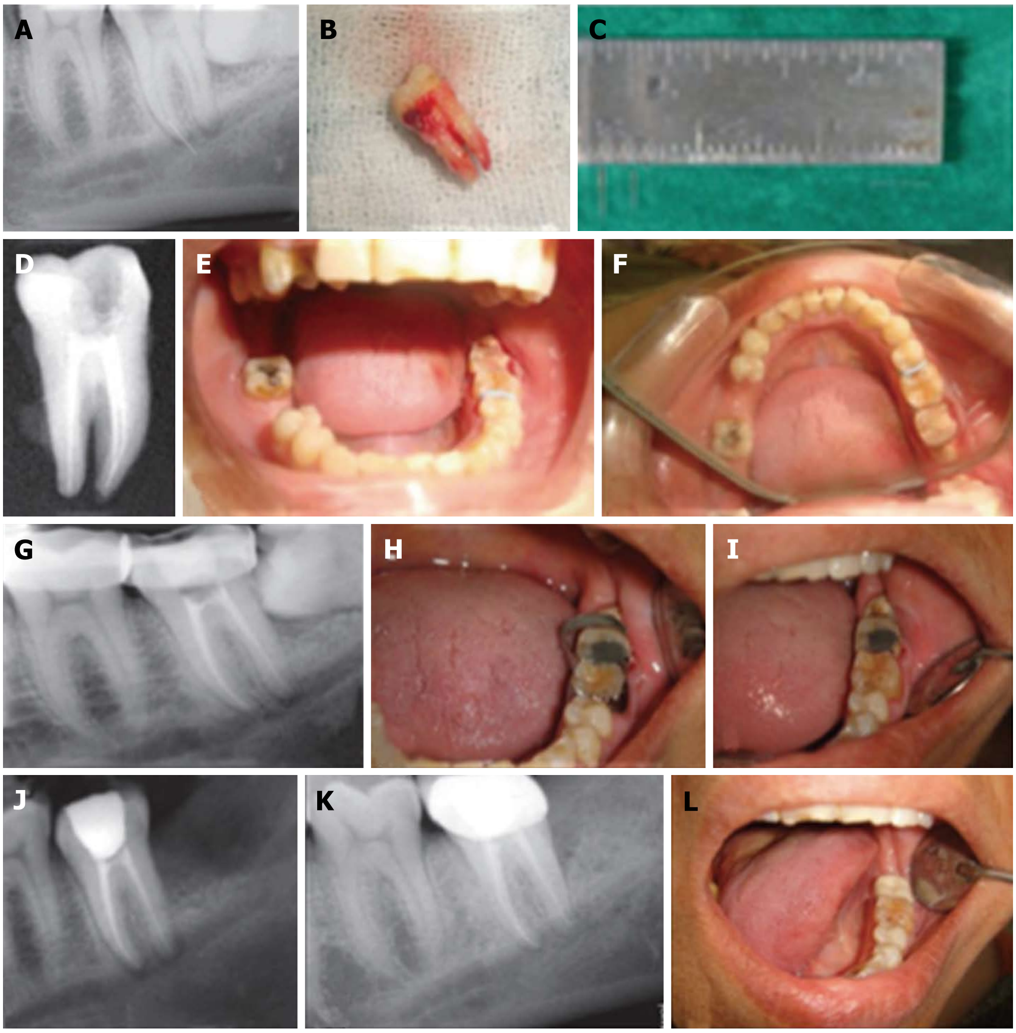

Figure 6 A separated hand instrument in a second molar was retrieved from the mesiobuccal root, which was close to the mandibular canal, using tooth replantation. A: Broken instrument near to the mandibular canal; B: After extraction; C: Measured broken instrument of 7 mm; D: After obturation; E: After separators were placed; F: Extra coronal splinting with orthodontic wires were prepared; G: Post operative Radiograph; H and I: Four weeks after Band removal; J: Three months follow-up Radiograph; K: One year follow-up radiograph; L: One year clinical radiograph.

sudden to die on Sunday November 9th. We dedicate this article to commemorate him.

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