Endodontic instrument fracture: causes and prevention

M. B. McGuigan,[1] C. Louca[1] and H. F. Duncan*[2]

IN BRIEF

- Reveals incidence of stainless steel and nickel-titanium file fracture.
- Considers the instrument, patient and operator factors which can increase the likelihood of file fracture.
- Discusses the range of manufacturer modifications aimed at reducing the fracture incidence.
- Evaluates the benefits of a file prevention protocol.

PRACTICE

Endodontic file fracture has traditionally been considered an uncommon event; however, a recent perception of increased fracture incidence with rotary nickel-titanium (NiTi) instruments has emerged. It is essential for the clinician to understand the likelihood of instrument fracture and the reasons for this unfortunate occurrence. Removal of fractured files is both technically difficult and time consuming and therefore it is of key importance to limit the probability of fracture. Over the last ten years, a range of NiTi alloy modifications have been made by instrument manufacturers, with varying reports of success, in an attempt to reduce the likelihood of file separation. The aim of this review was to investigate the incidence and aetiology of file fracture as well as analysing recommended prevention protocols. Additionally, the effectiveness of alloy modifications in reducing the incidence of file fracture was considered. Analysis demonstrated that the bulk of the literature relating to instrument fracture is *in vitro* evidence, which limits its clinical relevance. The reported incidence of NiTi instrument fracture is similar to stainless-steel (SS) files; however, inconsistent methodologies hamper accurate comparison. NiTi instruments are reported to fail by torsional overload and/or flexural fatigue, with file fracture occurring principally in the apical third of the canal or with inappropriate use. Finally, operator skill, manufacturer modifications and limiting file reuse have been demonstrated to be significant in reducing fracture incidence indicating the importance of a prevention strategy.

AIM

The aim of this review was to investigate the incidence and aetiology of file fracture as well as analysing suggested prevention protocols. In addition, the effectiveness of manufacturer alloy modifications in reducing the incidence and aetiology of file fracture was considered.

WHEN AND WHAT TYPE OF ROOT CANAL INSTRUMENTS FRACTURE?

Although root canal instruments can fracture at any stage of treatment, several studies have demonstrated that smaller instruments are more prone to fracture.[1–4] This is attributed to a smaller instrument cross section, which is mechanically more susceptible to torsional failure, in addition to the clinical challenge of initial instrumentation which enhances instrument stress. This may have implications for chemo-mechanical cleansing as it suggests that fracture would be more common earlier in the procedure. However, other studies have contradicted this demonstrating that larger, stiffer files exhibited the greatest rate of fracture.[5,6] This suggests that fracture is more prevalent in the later stages of treatment. These conflicting reports may reflect different operator/instrumentation technique or variations in canal morphology rather than the specific file dimensions. Nevertheless, no study has conclusively answered the question of when root canal instruments are more likely to fracture.

A wide range of instruments has been reported to fracture within the root canal system including Gates-Glidden burs, carbon steel or stainless steel (SS) endodontic files (K-files, Hedström files, barbed broaches, reamers), nickel-titanium (NiTi) rotary instruments, lateral spreaders, peeso reamers, spiral fillers and irrigation needles.[7–10] However, the bulk of the literature reports on the fracture of SS K-files[11–13] and rotary NiTi files,[3,9,14] with other instruments such as barbed broaches, spiral fillers or Gates-Gliddens only referred to anecdotally in the literature. This is disappointing as it is not readily possible to extrapolate the data regarding fracture incidence or even mode of failure from stainless steel files to rotary Gate-Glidden or lentulo spiral fillers.

HOW COMMON IS FRACTURE?

Ascertaining the incidence of file fracture can be difficult as it is reported in several ways, some studies examining instruments discarded after clinical use[3,15] while others report specifically on radiographic evidence of fractured instrument retention.[5–16] There are drawbacks with both methods of reporting, the first, not necessarily being clinically relevant and the second, an underestimate as it does not account for those instruments that have successfully been removed.

[1]Eastman CPD, UCL Eastman Dental Institute, 123 Grey's Inn Road, London, WC1X 8WD; [2]Division of Restorative Dentistry and Periodontology, Dublin Dental University Hospital, Trinity College Dublin, University of Dublin, Dublin, Ireland
*Correspondence to: Henry F. Duncan
Tel: +353 161 27356; Fax: +353 161 27312;
E-mail: Hal.Duncan@dental.tcd.ie

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The prevalence of retained endodontic SS hand instruments has been reported to be in the range of 0.7–7.4%.[9,11,14,17,18] Notably, prevalence is measured both per tooth and per canal, which alters the range considerably and makes comparison meaningless. The common perception is that NiTi rotary instruments have a higher fracture incidence than SS hand instruments.[5–19] However, the incidence of retained fractured NiTi rotary instruments is similar to SS hand instruments, being reported in a range of 0.4–5%.[18,20–22] In general it has been speculated that the reports of higher prevalence reflect selective inclusion criteria[21] with one study reporting on fractures only in molar teeth.[5] Conversely, the lower end of the spectrum may be as a result of a predetermined single-use policy or use in straight 'unchallenging' canals. Interestingly, it was reported that 0.9% of previously unused NiTi instruments fractured during their first use,[23] perhaps due to misuse or a manufacturing defect.[4]

Although initial comparison suggests that rotary NiTi instruments have a similar fracture rate to hand instruments, it must be stressed that fracture of both materials is seldom compared equally in the same study, as hand instruments are used initially to create a glide path only, with the remainder of instrumentation completed with rotary instruments. The aforementioned protocol is likely to influence the fracture rate of rotary NiTi instruments as the preparation of a manual glide path before rotary instrumentation decreases the likelihood of rotary NiTi instrument fracture.[5,24]

In vitro studies analysing the performance and fracture rate of SS hand and rotary NiTi files when carrying out identical procedures in retreatment, generally report a higher fracture incidence for NiTi files than SS hand instruments.[25,26] However, the variability of fracture prevalence is wide for both materials, which has been attributed to the number of uses of the instrument[3] and/or the operators skill/experience level.[1,3,27]

CAUSES OF FRACTURE

The bulk of recent literature reporting instrument fracture has investigated specifically rotary NiTi instrument fracture with a relatively small number of studies reporting on the fracture of SS hand instruments.[22–28,29] For this reason a greater emphasis is placed on the fracture of rotary NiTi instruments in this review.

MODE OF FRACTURE

NiTi is a versatile alloy with properties such as memory, super-elasticity, corrosion resistance and biocompatibility creating a range of dental applications.[30] NiTi files were first introduced in endodontics over twenty years ago, being reported to have two to three times more elastic flexibility and superior resistance to torsional fracture than SS files.[30] However, the low yield and tensile strength of NiTi compared to SS resulted in an increased susceptibility to fracture at lower loads.[31] Fracture of SS files and reamers is generally associated with overuse and is preceded by distortion.[32] Visible warning signs of permanent deformation and potential fracture are more often evident in manually operated SS files rather than NiTi rotary instruments,[33] and as a result, rotary NiTi instruments have been associated with fracture without warning.[23,34] It appears that distortion of rotary NiTi instruments is often not visible without magnification[3,35] and this may be related to the shape-memory properties of the alloy. Rotary NiTi instruments are described as failing either as a result of cyclical flexural fatigue and torsional failure or a combination of both.[36]

Torsional fracture

Torsional fracture occurs when the instrument (generally the tip) becomes locked in the canal while the file shank continues to rotate. Subsequently fracture of the file occurs when the elastic limit of the alloy is exceeded. Instruments that fracture as a result of torsional overload, reveal evidence of plastic deformation such as unwinding, straightening and twisting (Fig. 1).[3]

Flexural fatigue

Flexural fatigue occurs when the instrument continuously rotates freely in a curved canal generating tension/compression cycles at the point of maximum flexure, which eventually results in fracture. It is proposed that repeated tension-compression cycles caused by the rotation within curved canals increases cyclic fatigue of the instrument over time.[3,37] Flexural fatigue fracture occurs essentially due to overuse of the metal alloy, other factors potentially contributing to metal fatigue include corrosion and changes caused by thermal expansion and contraction.

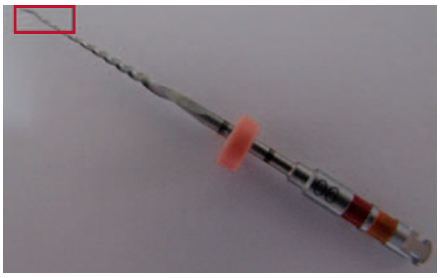

Fig. 1 Rotary NiTi file demonstrating unwinding of the flutes and separation of the tip as a result of torsional failure (damage highlighted)

The literature is inconsistent as to the relative importance of torsional or/and flexural fatigue in the aetiology of rotary NiTi instrument fracture. Certain studies[3,38–40] reported that the majority of instruments fractured due to flexural fatigue thereby implying that overuse was the most significant mechanism of failure. It was theorised that once a microcrack was initiated (fatigue-crack growth rates are higher in NiTi alloys than in other metals of similar strength) it can propagate quickly causing catastrophic failure.[38] Conversely other studies[41] classified torsional fracture as the dominant mode of fracture suggesting that torsional failure was the result of using excessive apical force during instrumentation or excessive curvature of the canal. Generally, torsional failure of instruments decreases and flexural failure increases as the size of the instrument increases.[15,42]

INSTRUMENT FAILURE INVESTIGATION TECHNIQUES

Fracture studies are generally based on a low powered lateral microscopic examination of the fractured file.[36,41] Reliability of this technique has been questioned[4,38] as, although it enables detection of plastic deformation, it does not reveal the actual mechanism involved in the fracture process. It has been suggested that a fractographic examination[4,38] is necessary to identify features on the fracture surface that would indicate the origin and propagation of the crack which ultimately leads to a fracture. Additionally, scanning electron microscopy (SEM) of fracture surfaces has been employed experimentally *in vitro*; however, the application of SEM analysis may be limited after *in vivo* file use, due to excessive distortion of the fractured file surface.[10]

In conclusion, the clinical relevance of *in vitro* investigations is generally undermined by the lack of standardisation of testing methods.[4,15] Indeed, it was concluded in a recent review of cyclic fatigue testing that methodological variation altered the fatigue behaviour of the tested instruments, thereby influencing the study results.[43] The authors further suggested that it was difficult to assess clinical relevance of studies which test one factor in isolation for example, cyclic fatigue, as this differs from the *in vivo* fracture situation where a series of factors act simultaneously.

FACTORS CONTRIBUTING TO FRACTURE

Numerous factors have been implicated in the fracture of NiTi instruments including operator skill/experience, instrumentation technique, dynamics of instrument use, number of uses, instrument design, anatomic configuration of the canals, metallurgy and number of sterilisation cycles. Attempts have been made to ascertain the relative importance of these factors with regards to their contribution to fracture.[9,10]

Operator skill/experience

Operator experience is a consistently reported factor in relation to the incidence of clinical instrument fracture.[1,44] When other factors (instrument speed and sequence, canal morphology) remained constant, the ability of the operator was the key factor in instrument failure.[45] The importance of the operator has been corroborated in other studies.[3,28,46] However, no significant difference in fracture rate was also reported between experienced and inexperienced operators, a finding that was attributed to the allocation of complex cases to the more proficient operator.[5] Each rotary NiTi system has a 'learning curve', highlighting the importance of proper training and initial supervision in the use of NiTi endodontic systems as these instruments will fracture if used incorrectly or excessively.[41,47]

Significance of instrumentation technique

A crown-down instrumentation technique (enlarging the coronal aspect of the canal before apical preparation) and creation of a manual glide path (preparing the canals manually with a SS file to working length before rotary NiTi instrumentation) has been proposed to reduce the frequency of instrument fracture.[24,48] These techniques aid in reducing instrument 'taper lock' or 'instrument jamming' which is associated with torsional fracture. Crown-down instrumentation reduces torsional stresses generated particularly in the smaller instruments[49] and a glide path limits the level of torque on the instrument thereby protecting against shear fracture.[24]

Dynamics of instrument use

Torque

Torque-controlled electric motors are generally recommended for use with rotary NiTi systems. An *in vitro* study has demonstrated that torque controlled motors, which perform below the elastic limit of the file, reduce instrument fracture due to torsional overload.[47] However, clinical studies did not demonstrate any significant difference in failure of Profile NiTi instruments used with high or low torque motors.[5,50] Another clinical study investigated three torque control levels (high, moderate and low) during NiTi canal preparation and reported that if the operator was inexperienced fracture rates decreased with a low torque-controlled motor.[51] Nevertheless, this study observed no difference when experienced operators used a high or moderate torque-controlled motor. The use of torque control has been questioned by one study[52] which suggested that rotary NiTi instruments function better at higher torque and that frequent engagement of the auto-reverse function carries a risk of torsional fatigue and failure.

Rotational speed

The effect of rotational speed on fracture remains to be elucidated, with some studies reporting rotational speed to have no influence on fracture incidence[1,53] while others reported the opposite.[54,55] Difficulties arise when comparing these studies as different methods of testing, instrument types and operator experience were employed in each study. However, manufacturers generally recommend a specific number of rotations per minute (rpm) for the safe use of rotary NiTi instruments, which is usually in the region of 250-600 rpm.

Electric versus *air driven handpieces*

Interestingly when comparing air-driven and electric handpieces, no difference in instrument fracture rate was reported.[56] However, clinical logic dictates that an electric motor would ensure delivery of a constant speed; whereas air driven instruments would subject the instrument to surges in pressure and lack of speed and control, creating a more fracture-prone situation. It is worth noting that all manufacturers of NiTi instruments currently recommend that the rotary files are used in a speed controlled electric motor.

CANAL GEOMETRY AND TOOTH TYPE

Cyclic fatigue testing of rotary NiTi files has demonstrated that fracture occurs at the point of maximum flexure, which corresponds to the point of greatest curvature within simulated root canals. Specifically these tests have shown that as the angle of curvature increases and the radius of curvature decreases there is a reduced number of cycles to file fracture.[37,53,56,57] This is supported by clinical research which identified that the majority of instruments fractured in the apical third of the canal, as this is the area of maximum curvature and smallest diameter.[5] Iqbal and co-workers[5] rationalised this by concluding that the probability of separating a file in the apical regions was thirty-three times greater than in the coronal-third and six times greater than the middle-third of the root. The observed increase in file fracture in the apical third of root canals was corroborated in other studies,[58,59] this is clinically relevant as, the greater the degree of flexing that a rotary NiTi instrument is subjected to when used in curved canals, the shorter the instruments life expectancy.

Furthermore, the more complex the root canal anatomy, the greater the torsional failure.[60] The radius of canal curvature is generally decreased in molar teeth, which also decreases the instrument's ability to resist torsional forces.[61] This has been observed clinically where instrument fracture was significantly greater (up to 3 ×) in molars than in premolars.[5] The relative increase in fracture of files in molar teeth has been reported elsewhere.[4,59] Additionally, the probability of fracturing an instrument in the mesiobuccal canal of a maxillary molar was three times greater than the distobuccal canal; similarly the probability of fracturing a file in the mesiobuccal canal of a mandibular molar (known for their greater curvature) was greater than the mesiolingual canal.[5]

EFFECT OF CLEANING AND STERILISATION

The literature, regarding the impact of sterilisation on NiTi instruments, appears contradictory. A number of studies report that subsequent to multiple sterilisation/autoclave cycles, NiTi instruments exhibit evidence of crack initiation and propagation and an increase in depth of surface irregularities, furthermore, a decrease in cutting efficiency has been demonstrated.[62–64] However, the deleterious effects of heat sterilisation on the mechanical properties of NiTi files have been disputed with other studies concluding that it does not significantly affect the fracture incidence of NiTi instruments.[27,58,65] Nonetheless, the evidence appears clearer in relation to recently developed files that are twisted rather than machined, with a recent study reporting a decreased cyclic fatigue resistance subsequent to multiple heat sterilisation cycles.[66] Interestingly, the sterilisation process has been reported to have positive effects on the fatigue life of NiTi files by reversing the stress-induced martensite state back to the parent austenite phase.[53] However, generally the temperatures required to achieve these positive characteristics are unlikely to be achieved in practice.[10]

It has been postulated that the corrosive effect of the root canal irrigant sodium hypochlorite (NaOCl) may have a negative impact on the mechanical properties of NiTi instruments.[67] However, it has also been argued that NaOCl is unlikely to result in pitting or cause crevice corrosion of NiTi instruments[68] and therefore its use did not increase the prevalence of fracture or the number of revolutions to cause flexural fatigue of NiTi instruments.[69]

NUMBER OF USES

Since 2007, 'The Department of Health' in the United Kingdom has dictated that for reasons relating to cross infection and theoretical prion transmission, all endodontic files are single use.[70,71] Within other European jurisdictions no such regulation exists and the number of file uses is at the discretion of the operator. File manufacturers have recently advocated that files should be single use only and have introduced features into new files which distort when autoclaving, hence preventing reuse (WaveOne™, Dentsply Maillefer, Ballaigues, Switzerland) (Fig. 2). The literature is unclear in providing guidance on the issue of the number of uses, particularly in relation to NiTi instruments where damage to the files is often not evident clinically before fracture.[58] Several studies state that NiTi instrument failure is influenced more by the manner in which they are used rather than how many times they are used.[4–46] However, regardless of the manner in which files are used, NiTi rotary files undergo a reduced flexural fatigue resistance with repeated usage and the torque necessary to induce failure of a previously used instrument is significantly lower when compared with new instruments.[72–75] Surprisingly, no correlation has been established clinically between the number of uses and the frequency of file fracture.[46]

Advocates of single use files suggest that even brand-new instruments fracture (0.9%) and as files become progressively fatigued with repeated use, recurrent use cannot be justified.[23] It has been postulated that the reason for fracture of new files may be due to a combination of manufacturing defects, operator error and/or complex canal anatomy.[4] Others have recommended discarding instruments, SS or NiTi, after a predetermined number of clinical uses.[16,41] A large cohort study demonstrated that reusing ProTaper rotary NiTi files up to four times did not significantly increase the incidence of fracture, but no details were provided as to the prevalence of severely curved canals included in the study.[6] Another study concluded similarly, that rotary instruments could be used clinically to complete endodontic treatment in up to four molars,[58] however this study excluded teeth with complex root canal anatomy that is, sclerosed canals and/or canals with severe curvatures. Most deformations and fractures appeared to occur after multiple use in complex anatomical configurations with almost 75% of NiTi deformations occurring after use in molar teeth.[4] Signs of deterioration in rotary NiTi instruments have been reported to be visible under SEM even after one use, but this may not be clinically relevant.[72] Since visible inspection is not a reliable method for evaluating used NiTi instruments,[6] employing a prudent approach of instrument disposal is sensible. At present it is not possible to provide a definitive guideline as to a safe number of uses of rotary NiTi files as use varies depending on the tooth, operator and root canal anatomy. What is clear, however, is that there is a trend towards the single use of rotary NiTi files during root canal treatment.

Fig. 2 The shank of a WaveOne™ rotary file NiTi file (Dentsply Maillefer, Ballaigues, Switzerland) demonstrating the colour-coded plastic sheath which expands after sterilisation preventing reuse

INSTRUMENT DESIGN

It has been shown that when instruments are subjected to flexural and torsional load their cross-sectional area and design may affect their resistance to fracture.[2,77]

Cross-sectional dimensions and design

It has been demonstrated that enhancing the diameter and cross-section of a file provides increased resistance to torsional failure,[73,78] but conversely reduces resistance to flexural fatigue failure.[53] Cross-sectional design may also be an important factor with regards to fracture incidence. Triangular ProTaper files were compared to U-fluted ProFile instruments and it

Table 1 Summary of recent manufacturer alterations to NiTi alloy to improve mechanical properties and reduce fracture incidence	
Type of metallurgy advancement	Commercial file system
Electropolishing	BioRace (FKG Dentaire, La Chaux-de-fonds, Switzerland)
Ion implantation	None
File twisting (R-phase)	Twisted files (SybronEndo, Orange, CA, USA)
Control memory	HyFLEX (Coltène/Whaledent, Cuyahoga Falls, OH, US)
M-phase	WaveOne (Dentsply Maillefer, Ballaigues, Switzerland) ProFile Vortex (Tulsa Dental Specialities, Tulsa, OK, USA)

was demonstrated that stress distribution was lower and more evenly distributed in the ProTaper instruments.[2] However, this result may be confounded by taper differences between the files; the ProTaper file being of variable taper and the ProFile of fixed taper. Furthermore, it was also suggested that although the U-flute design and resulting smaller cross-sectional area of ProFile conferred more flexibility than the triangular design, it was weaker when exposed to torsional stress.[2,78] In terms of landed and non-landed instruments, the cutting flute does not seem to affect the fatigue resistance of instruments of the same size.[79,80] Interestingly, while it has been suggested that cross-sectional configuration has little influence on the fatigue resistance of NiTi instruments made from conventional wire[80] a study has reported that a triangular and square design of NiTi instrument made from 'controlled memory wire' demonstrated significantly differing fatigue lives.[81]

Brands of rotary NiTi instruments

Ex vivo studies have compared ProFile, ProTaper and K3 instruments after use in human extracted teeth reporting the lowest defect rate for K3 instruments but concluded that there was no difference in frequency of fracture of the different instrument designs.[34] This conclusion was further supported by a clinical study of incidence of instrument fracture in an endodontic graduate programme,[5] which concluded that an increased incidence of instrument fracture could not be attributed to a particular rotary system. Perhaps, what may be more relevant than the respective fracture resistance of each system is the operator's proficiency and expertise with a chosen system, experience enabling an awareness of the limits of the file in clinical use.

Instrument size

A higher incidence of fracture and distortion in smaller NiTi instruments has been recorded in a number of *in vitro* studies.[1,40,50] Certain investigators[1,2] have concluded that smaller instruments are more susceptible to torsional failure than larger instruments and have recommended that small files (eg 0.04 taper ProFile size 20) should be considered as a single use instrument, such is the likelihood of distortion. Conversely, a large clinical cohort study[6] reported the greatest number of instrument failures occurred when using the larger diameter files, suggesting that larger stiffer files experienced greater stress during use.[42,53] Clinically, logic would suggest that smaller files are more susceptible to distortion as they are the principal files involved in negotiation and initial instrumentation of the root canal system.

MANUFACTURING PROCESS

Traditionally, NiTi endodontic files are 'machined' from a blank NiTi alloy wire during manufacture. The process has been shown to create an irregular surface characterised by grooves, pits, multiple cracks and metal rollover[15–82] with the frequency of such irregularities increasing proportionally with the taper of the instrument.[64] The manufacturing process itself leads to work hardening of rotary NiTi instruments, creating brittle areas.[82] These surface imperfections may act as a centre of stress concentration, initiating crack formation during clinical use.[82] In general, surface defects affect the ultimate strength of the material and have a major bearing on the fatigue resistance of the instrument. As a result manufacturers have endeavoured to improve the mechanical properties of the files by modifying the surface or alloy microstructure during the manufacturing process. These modifications are discussed in detail within the following section.

FUTURE DEVELOPMENT OF NITI – ALTERATION OF ALLOY SURFACE OR MICROSTRUCTURE

A range of strategies, including electropolishing, ion implantation and file twisting have been investigated in an attempt to enhance the characteristics of NiTi instruments, thereby improving their flexibility, fatigue resistance and cutting efficiency (Table 1).

Electropolishing

Electropolishing alters the surface composition of the NiTi file creating a homogeneous oxide layer, with an associated reduction in surface defects and stress, which it is claimed results in enhanced NiTi corrosion resistance and fracture resistance.[83] Commercially available file systems include BioRace™ and RaCe™ (FKG Dentaire, La Chaux-de-fonds, Switzerland). Certain studies specifically reported a significantly improved resistance to flexural fatigue and improved torsional properties after electropolishing;[84,85]however, this has not been universally demonstrated.[86] Interestingly, it was also shown that the improved surface composition of NiTi after electropolishing rendered the instrument more resistant to the effects of sodium hypochlorite solution (NaOCl).[85] However, the positive effects of electropolishing are inconsistent and appear to alter in magnitude with factors such as instrument design, type and particularly cross-sectional area.[41,87]

Ion implantation

The implantation of argon,[88] boron[89] or nitrogen[90] into manufactured files has been investigated in an attempt to improve surface characteristics of NiTi instruments and thereby enhance mechanical properties such as flexibility, surface hardness, and cyclic fatigue resistance.[83] Ion implantation has demonstrated promise in improving the mechanical characteristics of certain NiTi files *in vitro*,[90,91] however, these techniques are experimental, not cost effective and currently not implemented by file manufacturers.[83]

Twisting of files

Originally, due to the shape-memory characteristics of NiTi rotary instruments, it was deemed necessary to machine these instruments to create the desired taper, flute design and cutting edge and other features. Recent technological advancements have enabled twisting of NiTi alloys (Twisted file™ [TF] SybronEndo, Orange, CA, USA) by a process of heating and cooling raw NiTi wire in the austenite crystalline structure and then modifying it into a different phase of crystalline structure (R-phase).[92] It has been reported that the properties and structure of R-phase NiTi are superior to traditional machined NiTi files due to optimisation of the grain structure, as grinding is believed to create microfractures on the metal surface. In an attempt to further enhance the mechanical features of the file, TFs undergo a proprietary process (Deox) in which surface impurities and the oxidation layer is removed.[92,93] Ground and twisted files have been compared *in vitro* where it was reported that TFs exhibited increased torsional resisitance, flexibility and strength compared to ground files.[92,94,95] A separate study corroborated the significantly higher resistance of TFs compared with selected, but not all ground files.[96] Other evidence contradicts the reported mechanical benefits of twisting NiTi alloys demonstrating that TF files actually had the lowest resistance to torsional fracture when compared with several other commercially available ground files.[97]

Advancements in machined files

Recent developments in alloy technology include M-Wire (Dentsply-Tulsa Dental Specialities, Tulsa, OK, USA). M-Wire is a variant of NiTi, composed of SE508 Nitinol, that has undergone heat treatments and drawing of the wire under a specified tension producing a material described as 'partially in the martensitic and the premartensitic R-phase while still maintaining a pseudoelastic state.'[98] WaveOne™ (Dentsply Maillefer, Ballaigues, Switzerland) (Fig. 2) is an example of a new file system availing of this technology. Several studies have reported a significantly increased resistance to cyclic fatigue with M-Wire compared with conventionally ground NiTi rotary files.[96,98,99,100] However, one study reported that files manufactured from M-Wire showed no difference in cyclic fatigue resistance when compared with those produced from conventional grinding while also finding that TFs (SybronEndo, Orange, CA, USA) demonstrated significantly more resistance to cyclic fatigue than ground files.[92] However, it is perhaps worth noting that several of these studies were undertaken by commercial representatives of companies and this highlights the need for investigation of new technologies to be carried out by independent groups.

Table 2 Evidence-based summary of measures demonstrated to prevent or reduce the likelihood of fracture

Preventative measure	Reference(s)
Training courses and practice	Sattapan *et al.*, 2000[36]
Instrumentation technique	Patiño *et al.*, 2005[24] Schrader and Peters, 2005[49]
Use of speed and torque control motors	Gambarini *et al.*, 2001[47] Cheung, 2009[10]
Single use or limited use policy	Arens *et al.*, 2003[23] Sotokawa, 1990[16]
Case selection (dilacerated roots, abrupt bifurcations)	Parashos and Messer, 2006[9]

Heat treatment (post-machining/post-twisting)

This process has recently been heralded as potentially offering the most promising technological developments in NiTi alloy metallurgy.[83] It is theorised that the use of appropriate heat treatment – transforming the alloy into a slightly altered crystalline phase structure – to achieve microstructure control, may be used as a cost effective method of creating rotary NiTi instruments with superior flexibility and fatigue resistance.[15,101,102] Heat treatment strongly affects superelasticity and shape memory characteristics[82] resulting in the development of instruments that have no memory or a 'controlled memory' (for example, HyFLEX™ CM; Coltène/Whaledent, Inc., Cuyahoga Falls, OH, USA) with claims of increased fatig ue resistance.[81]

RECOMMENDATIONS FOR THE PREVENTION OF FILE FRACTURE

Several of the factors which contribute to file fracture particularly of NiTi files can be minimised by the implementation of prevention guidelines.[9,10] Preventative measures not only reduce the probability of fracture, but also obviate the need for difficult management decisions and awkward patient conversations. The following recommendations have been suggested for the use of NiTi file systems (Table 2);

- Ensure adequate training and proficiency in the NiTi system of choice before clinical use by practicing on extracted teeth or resin blocks[36]
- Create a manual glide path (K-file, size 10–15° or NiTi pathfiles™ (Dentsply Maillefer, Ballaigues) to ensure unimpeded access to the root canal, before use of greater taper NiTi files[24]
- Employ a crown-down instrumentation technique to ensure straight-line access to the root canal[49]
- Use an electric speed and torque-controlled motor at the manufacturer's recommended settings[47]
- The NiTi files should be used in constant motion using gentle pressure to avoid placing excessive torsional forces on the instrument
- Avoid triggering or disable the auto-reverse mode or disable the auto-reverse feature on the motor, as it increases the risk of torsional fatigue[10]
- If not obligated to adopt a single-use file policy[71] consider adopting a personal policy to prevent overuse of files. Files used in particular challenging root morphology should be considered for early replacement or discard
- Use of rotary files in abruptly curved or dilacerated canals should be avoided.

CONCLUSIONS

- Although, it is generally perceived that NiTi files fracture more commonly than their SS counterparts, providing NiTi files are used judiciously, the fracture incidence appears to be comparable
- Preventative measures including clinician's experience of a system, case selection, limiting file re-use, the

technique of the operator have all been reported to decrease the incidence of fracture

- Although the reported impact of heat sterilisation on NiTi file fracture is contradictory, it appears that repeated usage can reduce flexural fatigue resistance and the torque necessary to induce failure. Therefore in an ideal situation, single or limited usage of files is advocated
- Modifying the surface of the NiTi wire by electropolishing has resulted in studies reporting improved cyclic fatigue resistance and an increased threshold to torsional failure. Other surface modifications such as ion implantation have been proposed as future techniques to enhance the mechanical properties of the file further. At present, the reported benefits associated with these modifications are not universal
- Manufacturer modifications during NiTi file construction including heat treatment and twisting rather than lathe cutting the alloy wire have produced reports of improved flexibility, cutting efficiency and increased fatigue resistance, while reducing torsional failure
- The bulk of the current literature regarding fractured files is *in vitro* in nature, displaying a wide range of methodologies with conflicting results. This makes comparison between studies and clear conclusions difficult
- At present there is a lack of international standardisation for certain mechanical property tests such as cyclic fatigue tests. This needs to be remedied to improve the homogeneity of data and facilitate ready comparison between studies
- A conflict of interest appears common in some studies with commercial representatives of certain systems also reporting on their benefits within the literature.

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