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2.1 Introduction

Root canal treatment (RCT) may require the use of a variety of instruments including files and reamers, ultrasonic tips, explorers, irrigation needles, Lentulo spirals, spreaders and pluggers, heat-conducting tips, and filling material injection tips; any of these instruments may fracture inside the root canal during use, but the fracture of files and reamers is considered to be a more frequent problem. Furthermore, despite the longevity of stainless steel (SS) instruments, only a small number of studies have dealt with the factors leading to their fracture; most of the available information concerns nickel-titanium (NiTi) instruments. As a result, this chapter will discuss the parameters influencing the fracture of files and reamers with a particular focus on NiTi instruments that have dominated the interest of both clinicians and researchers for almost two decades.

Several factors have been implicated in the failure of root canal instruments, and many studies have attempted to elucidate their individual contributions. In order to facilitate the description and analysis of the relevant factors, they have been grouped together in four main categories, namely, *operator related*, *anatomy related*, *instrument related*, and *technique/use related* (Table 2.1). However, it is likely that some of these factors may actually fit in more than one category. Moreover, in accordance with the principles of evidence-based dentistry, the description and analysis of these factors have been based only on higher quality in vitro and clinical studies, while

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Table 2.1 Outline of the factors affecting intracanal instrument fracture

Factors affecting intracanal instrument fracture	
Operator related	Skill, proficiency, judgment
Anatomy related	Access cavity
	Root canal anatomy
Instrument related	Material
	Design
	Manufacturing process and errors
Technique/use related	Motors operating parameters
	Instrumentation technique
	Reuse and sterilization
	Irrigants

unreliable in vitro models clearly deviating from in vivo conditions have been excluded (Hülsmann 2013).

2.2 Operator-Related Factors

Just like many other dental procedures, RCT involves a series of delicate and meticulous manipulations requiring adequate training and dexterity; preparation of root canals is perhaps one of the most technically demanding phases, so it doesn't come as a surprise that factors pertaining to the operator's skill and proficiency have been ranked as the most important among those contributing to instrument fracture (Parashos et al. 2004; Cheung 2009).

Practitioners need to choose from a constantly expanding variety of instruments, each one having its own design and mechanical properties and being accompanied by its own guidelines for use; this process can already create some confusion. Once the choice has been made, the clinician needs to become familiar with the instruments, their specific mode of use, and the manufacturer's recommendations. For example, switching from hand instrumentation by SS files to rotary instrumentation by NiTi files can be rather challenging; NiTi files provide less tactile feedback regarding the morphology of the canal, so a different kind of awareness is required.

Proper in vitro training is necessary in order to bridge this gap (Yared et al. 2001, 2002; McGuigan et al. 2013). Despite wide variability among clinicians, it appears that the handling of instruments is characteristic for each clinician (Regan et al. 2000) so it could be modified through training. Avoiding aggressive penetration in the root canal by applying too much apically directed force on the instrument (Saber 2008), sensing when a rotary instrument is about to bind inside a root canal so that it is withdrawn before torsional overload occurs, and recognizing the stress applied to the instruments during preparation of very curved root canals that could lead to a fatigue failure are skills that can be developed through practicing on extracted teeth and fine-tuned through the gradual accumulation of clinical experience. Even so, a clinician's performance may still vary to some extent over time depending on workload and physical fatigue (Briseno et al. 1993). Finally, the operator has to develop his/her judgment in order to discard an instrument that shows a dubious defect or that has been used in a difficult-to-prepare root canal.

2.3 Anatomy-Related Factors

2.3.1 Access Cavity

The definition of an “adequate” access cavity has undergone several changes throughout the years. A completed access cavity should still allow unobstructed visual access to all root canals and act as a funnel to guide the instruments into the canal, straight to the apex, or to the point of first curvature (Peters 2008). Interference by the cavity walls or by unremoved dentin shoulders in the coronal third of the root canal can increase the stress imposed on the instruments during preparation by increasing the number and severity of curvatures that must be negotiated (iatrogenic S curve) (Roda and Gettleman 2016); this could lead to instrument failure (Figs. 2.1, 2.2, and 2.3). Conversely, expanding the access cavity beyond the confines of the pulp chamber could also hinder the entrance of files into the root canals and lead to accidental bending of the tips.

Nowadays, the extensive use of the dental operating microscope that provides superior magnification and illumination has facilitated more conservative access cavities specifically designed for each case according to the pulp chamber morphology in an effort to conserve as much tooth structure as possible. The extensive occlusal tapering of the cavity wall circumferentially has been replaced by selective tapering of the cavity walls only where necessary, depending on the location of the root canal orifices and the direction and shape of the canals (Peters 2008). Taken to

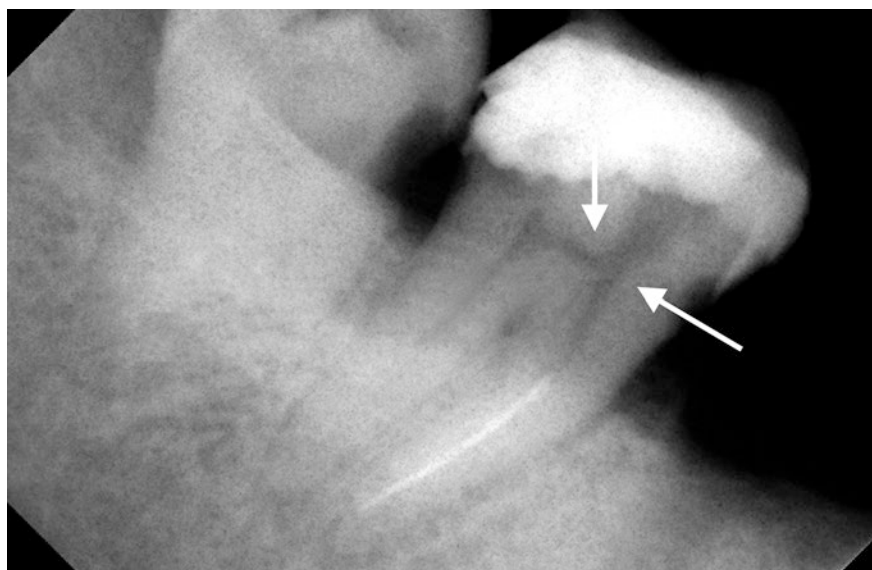


Fig. 2.1 Fractured instrument in the mesial root of a mandibular molar due to inadequate access cavity preparation. Note the presence of pulp chamber roof (*short arrow*) and insufficient shoulder removal (*long arrow*) that impeded straight-line access to the coronal third of the canal

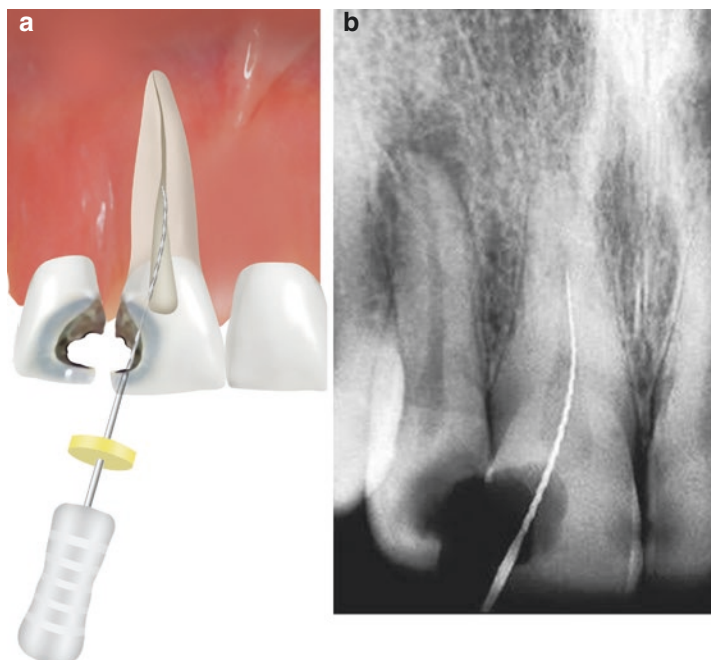


Fig. 2.2 Improper access cavity through a mesial or distal carious lesion. Instruments penetrating through such lesions cannot follow a straight-line path to the apex, which may eventually result in a variety of iatrogenic errors, including instrument fracture

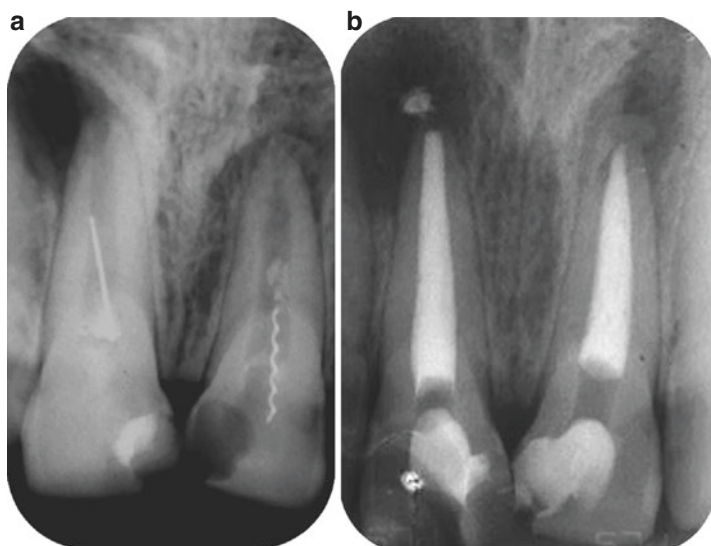


Fig. 2.3 (a) Two fractured instruments, one in each maxillary central incisor, were identified in the preoperative radiograph. The instruments fractured possibly due to incorrect access cavity preparation through existing carious lesions. (b) Following conventional access cavity preparation, the fragments were retrieved and RCT was completed. (c, d) Three- and twelve-month recall radiographs revealed uneventful healing

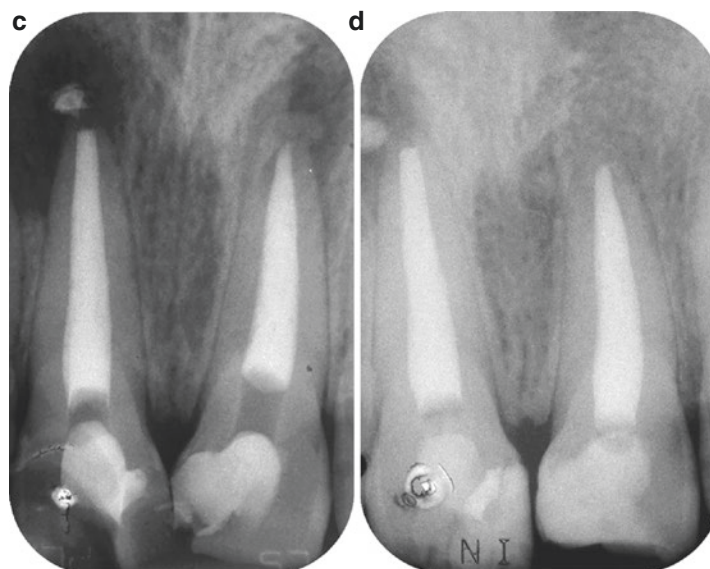


Fig. 2.3 (continued)

its extremes, this trend has led to the concept of *minimally invasive access cavities* which advocates removal of only a minimum amount of hard dental tissue (Gluskin et al. 2014; Krishan et al. 2014; Eaton et al. 2015; Moore et al. 2016), even if subsequent treatment procedures become far more challenging. Nevertheless, anecdotal evidence indicates that such miniature access cavities do not seem to increase the chance of instrument fracture, at least when treatments are performed under the microscope by experienced and skillful clinicians.

SS instruments possess several advantages regarding their placement in the root canal as compared to NiTi files that require considerably more attention to gaining straight-line access. SS files can be pre-bent enabling their introduction into difficult-to-access canals; with the exception of controlled-memory files (Coltene Endo 2014), NiTi instruments are very difficult to pre-bent accurately. In addition, stiff hand-operated SS files also provide superior tactile feedback regarding obstacles as opposed to the flexible NiTi files that are usually attached to a handpiece.

2.3.2 Root Canal Anatomy

The risk of instrument failure seems to increase in cases with complex root canal anatomy (Peters et al. 2003). Fractures appear more often in molars than premolars or anterior teeth (Iqbal et al. 2006; Wu et al. 2011; Ungerechts et al. 2014; Wang et al. 2014) and also in the mesiobuccal root canal of maxillary and mandibular molars (Iqbal et al. 2006; Wu et al. 2011) than in other root canals. These findings could be explained by the overall morphological complexity of the molar root canal system and the existence of multiple canals within each tooth, but the primary reason is most likely the curvature of these root canals.

The curvature of a root canal is described by its angle and radius (Pruett et al. 1997); the wider the angle and the smaller the radius, the more abrupt the curvature. These two parameters can vary independently of each other, so it is possible that two root canals may have the same angle but very different radii of curvature or the opposite (Fig. 2.4). In addition to the shear stress applied to the instrument during preparation of any root canal, a bending stress is concurrently applied inside a curved root canal. As the file rotates, it undergoes repeated cycles of tension and compression, with tension occurring near the outer curved surface and compression near the inner. This repeated cyclic loading may result in crack initiation and eventually in fracture (Pruett et al. 1997; Cheung 2009).

Ex vivo studies have suggested that root canal curvature may increase the failure rate of rotary NiTi instruments (Li et al. 2002, Zelada et al. 2002, Martin et al. 2003, Di Fiore et al. 2006, Kosti et al. 2011) due to both torsional overload and cyclic fatigue (Pruett et al. 1997; Zelada et al. 2002; Kosti et al. 2011), and clinical studies have corroborated these findings (Wu et al. 2011; Wang et al. 2014). The risk of fracture seems to increase as the angle increases, especially beyond 30° (Zelada et al. 2002, Martin et al. 2003, Kitchens et al. 2007), and also as the radius decreases (Haikel et al. 1999; Booth et al. 2003; Patino et al. 2005), and it appears that the radius has a more pronounced effect on this process.

Moreover, an early curvature in the coronal or middle third of the root canal is more likely to lead to failure compared to an apical curvature (Peters and Paque 2010; Lopes et al. 2013) because the diameter of the instrument at the area where

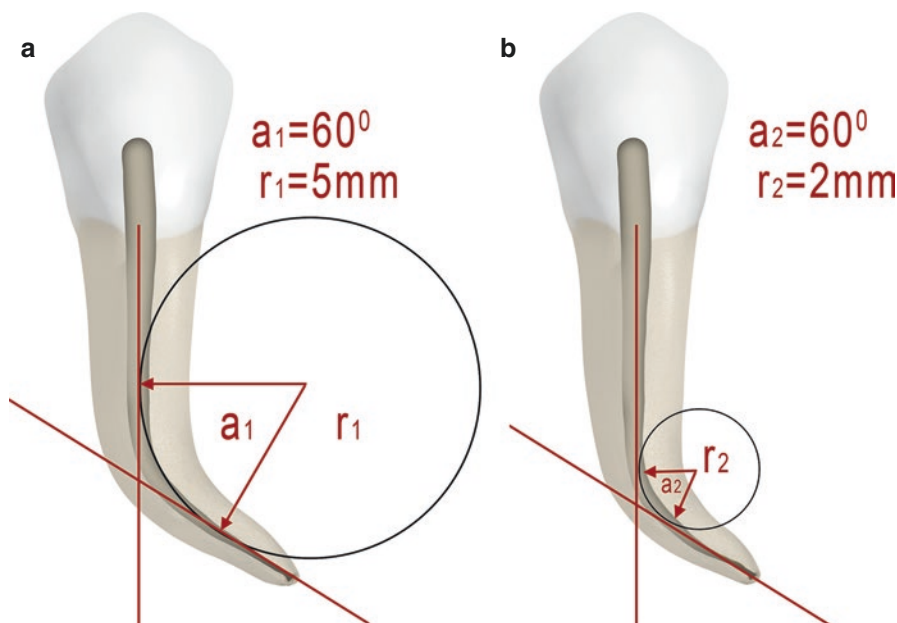


Fig. 2.4 Angle and radius of curvature measured according to Pruett et al. (1997). The two root canals have the same angle ($a_1 = a_2 = 60^\circ$) but different radii of curvature ($r_1 = 5\text{ mm}$, $r_2 = 2\text{ mm}$)

flexural fatigue is concentrated (point of maximum flexure) is larger in the former two cases. This is consistent with the authors' anecdotal observation that NiTi instruments seem to fracture more easily when the tip binds in an acutely curved root canal compared to a straight one. Therefore, it is widely recommended that instruments should not be held at a static position inside a curved root canal but should rather be moved continuously in an axial direction in order to avoid concentrating the flexural fatigue on a specific part of the instrument (Gambarra-Soares et al. 2013). Furthermore, instruments should be discarded after a single use in very complex, calcified, or sharply curved canals.

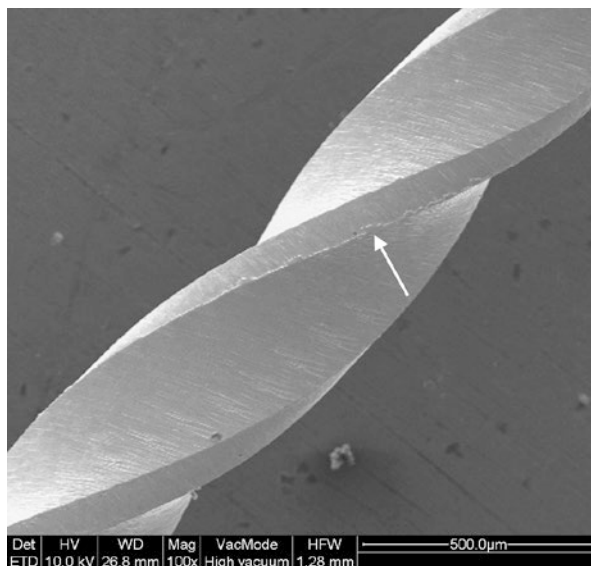
2.4 Instrument-Related Factors

Raw materials, design, and manufacturing process can have a significant impact on instrument fracture (Alapati et al. 2005; McSpadden 2007). A noteworthy example was described several decades ago when a large number of alarmed dentists complained about fracturing of SS reamers of a certain size manufactured by a single company. These incidents were attributed to manufacturing errors (Lilley and Smith 1966) that were subsequently corrected.

Early studies have provided some support to the widespread notion that rotary NiTi instruments seem to fracture more often than hand SS instruments during clinical use (Iqbal et al. 2006). Arguably, manufacturing of NiTi instruments is much more complicated compared to that of SS instruments (Thompson 2000), and manufacturers continuously explore metallurgical modifications to the NiTi alloy, new instrument designs and additional treatments in an ongoing effort to improve the material properties, minimize inherent defects, and increase the instrument resistance to permanent distortion or fracture; still, details about proprietary manufacturing methods are rarely revealed.

Owing to the shape memory of the NiTi alloy, most such instruments are milled rather than twisted (Shen et al. 2013a), a process that allows creation of complex shapes through computer-aided design and manufacturing (CAD-CAM) technology (Thompson 2000) but that can also result in surface imperfections such as milling grooves, cracks, pits, and regions of metal rollover (Fig. 2.5) (Marsicovetere et al. 1996; Eggert et al. 1999; Kuhn et al. 2001; Tripi et al. 2001; Martins et al. 2002; Alapati et al. 2003, 2004, 2005; Valois et al. 2005; Alexandrou et al. 2006a, b; Chianello et al. 2008). It has been hypothesized that these irregularities may render the instruments more prone to fracture (Alapati et al. 2003) because they could act as stress concentration points and enable the initiation of cracks; propagation of these cracks requires less stress and could eventually lead to failure (Sawaguchi et al. 2003; McSpadden 2007). Several methods, such as implantation of argon, boron, or nitrogen ions, thermal nitridation, plasma immersion, deep dry cryogenic treatment, and electropolishing, have been applied to reduce these surface imperfections and consequently improve the resistance of instruments to failure (Anderson et al. 2007; Cheung et al. 2007a; Condorelli et al. 2010; Praisarnti et al. 2010), but the results are inconclusive in most cases [for an extensive review, see Gutmann and Gao (2012)].

Fig. 2.5 Metal rollover at the edge of an unused Profile NiTi instrument (Dentsply Maillefer, Ballaigues, Switzerland). (Magnification $\times 100$) (Courtesy Dr. S. Zinelis)



Rather than applying surface modifications on the milled instruments, additional thermomechanical processing of either the raw NiTi alloy or the completed instruments (Gambarini et al. 2008; Johnson et al. 2008; Larsen et al. 2009; Gao et al. 2012; Shen et al. 2013a, b; Zhao et al. 2013, 2016; Plotino et al. 2014; Capar et al. 2015) seems to be more effective and appears to increase the flexibility of the files and their fatigue resistance (Zinelis et al. 2007; Plotino et al. 2014, 2017; Kaval et al. 2016). However, it should be noted that, in general, more flexible NiTi files are also considered less resistant to torsional loading (Peters and Paque 2010; Shen et al. 2013a).

Some issues may also arise from the quality of the raw material (NiTi alloy). Oxide particles may be incorporated into the alloy during production, and later, during stress application, they could serve as nucleating sites for micro-voids that may be related to the failure process (Alapati et al. 2005). The relative concentration of these particles may indicate the metallurgical quality of the alloy (Alapati et al. 2005).

The cross-sectional area of an instrument could also affect instrument fracture (McSpadden 2007). This area is determined by a number of other parameters, including the size and taper of the instrument and its specific design (Schäfer et al. 2003; Parashos et al. 2004). Increasing the cross-sectional area by either increasing the size or the taper will increase the resistance to torsional failure (Yared et al. 2003, Guilford et al. 2005, Ullmann and Peters 2005), but it will concurrently decrease the resistance to cyclic fatigue (Haikel et al. 1999, Gambarini 2001c, Hübscher et al. 2003, Ullmann and Peters 2005, Plotino et al. 2006, Kitchens et al. 2007, Peters and Paque 2010), although indications to the contrary have also been reported (Hilfer et al. 2011). In the absence of definite evidence about the primary cause of instrument fracture in vivo (torsional overload, flexural fatigue, or a combination of both), it is noteworthy that smaller files seem to fracture more frequently during clinical use (Inan and Gonulol 2009).

The instrument design can further reduce the cross-sectional area of an instrument by increasing the number or depth of the flutes (Schäfer and Tepel 2001,

McSpadden 2007); deeper flutes seem to facilitate stress concentration (Xu et al. 2006), but the shank-to-flute ratio (Fig. 2.6) does not seem to be a contributing factor in the occurrence of fractures (Biz and Figueiredo 2004). Abrupt variations in the cross-sectional shape could also serve as stress concentration points and may promote crack initiation (Xu et al. 2006, McSpadden 2007). Finally, wide metal areas coming in contact with the dentinal wall (e.g., radial lands) (Fig. 2.7) increase

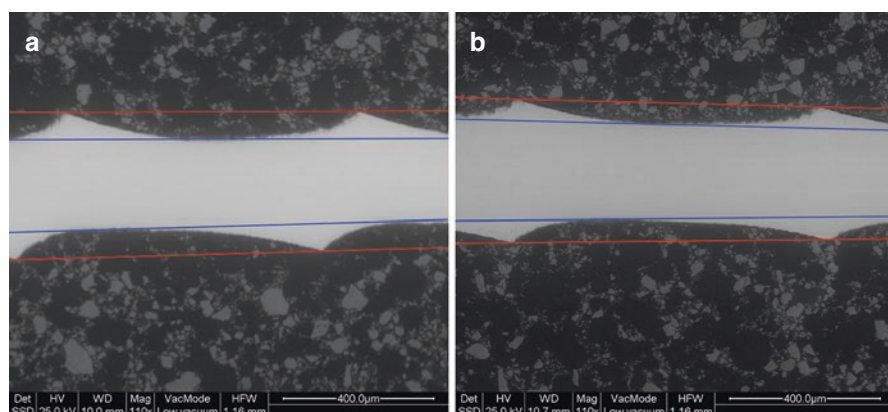


Fig. 2.6 Longitudinal sections of different files depicting the width of the shank (between the *blue lines*) in comparison with the flute depth (between the *blue and red line* on either side). **(a)** Smaller shank-to-flute ratio. **(b)** Larger shank-to-flute ratio (magnification $\times 110$) (Courtesy Dr. S. Zinelis)

Fig. 2.7 Cross section of a rotary NiTi file depicting wide metal areas that come in contact with the dentinal wall during instrumentation (radial lands)

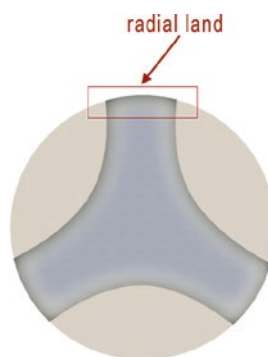


Fig. 2.8 Unused counterfeit (*top*) and original Protaper Universal F3 files (Dentsply Maillefer, Ballaigues, Switzerland) (*bottom*). Despite resemblance, differences in the design and diameter of the cutting part are noticeable (Courtesy Dr. G. Tsakiris)

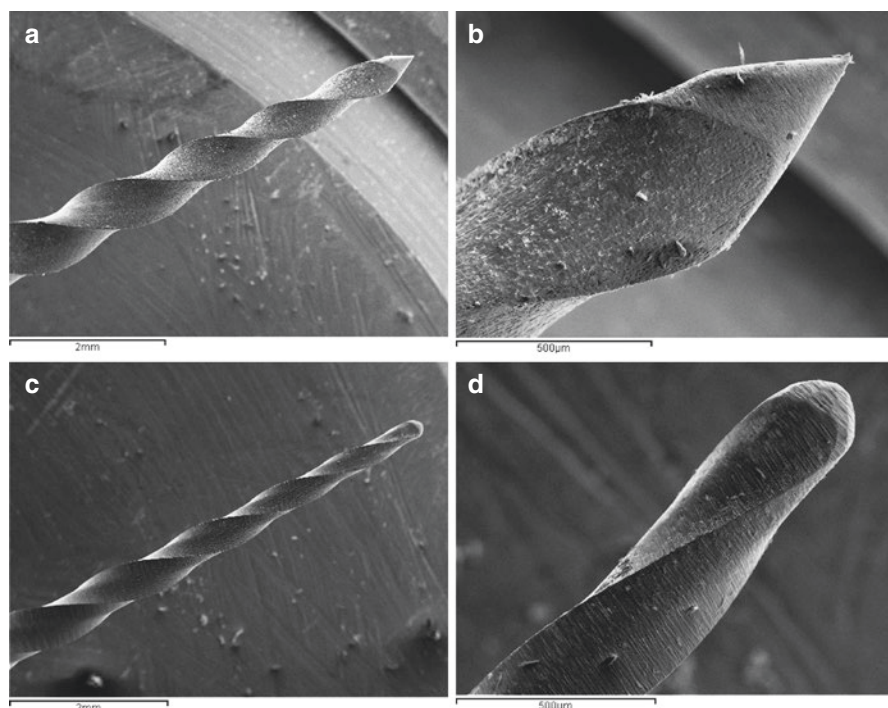


Fig. 2.9 Differences in design and surface smoothness between unused counterfeit (*top row, a, b*) and original Protaper Universal F2 files (Dentsply Maillefer, Ballaigues, Switzerland) (*bottom row, c, d*). A large amount of debris is visible on the counterfeit instrument. Its tip is larger and incorrectly manufactured as active (**b**), contrary to the original instrument's tip which is smaller and non-cutting (**d**) (magnification $\times 20$, $\times 100$) (Courtesy Dr. G. Tsakiris)

the friction during use (Haikel et al. 1999, Xu et al. 2006) and could also increase the risk of failure.

Even if original files are manufactured according to the highest quality standards by well-established companies, it is prudent to examine all new instruments under magnification for gross manufacturing defects prior to the first use. This precaution is also required due to the circulation of counterfeit instruments resembling the original files only in macroscopic appearance (Figs. 2.8 and 2.9). Counterfeit instruments seem to have more variations in their design and shape and also more surface imperfections than original ones (Tsakiris 2016), and their use should be avoided.

2.5 Technique/Use-Related Factors

2.5.1 Motors-Operating Parameters

Nowadays electric motors are almost unanimously recommended over air-driven motors for rotary instrumentation mainly because they can maintain a constant rotational speed and also limit the maximum torque applied to the instruments; both

parameters can be easily adjusted by the operator (Fig. 2.10). Air-driven motors lack such precise controls and may be also affected by air-pressure differences. Nevertheless, the instrument fracture rate may be similar for both types of motors (Bortnick et al. 2001).

The widespread adoption of electric motors has occurred in parallel with the prevalence of the low-speed low-torque instrumentation concept (Gambarini 2001b). Manufacturers of rotary NiTi files recommend a specific rotational speed, usually in the range from 250 to 600 revolutions per minute (rpm), but its effect on instrument failure is controversial; several studies have found no influence on instrument fracture (Pruett et al. 1997, Yared et al. 2002, Zelada et al. 2002, Herold et al. 2007, Kitchens et al. 2007), while others have reported an increase in fractures with increasing speed (Li et al. 2002, Martin et al. 2003). In addition, fatigue failure seems to occur more often with motor-driven NiTi files compared with the same files used by hand, possibly because handheld files rotate at a much lower speed (Cheung et al. 2007b). Interestingly, even studies that found that cyclic fatigue is unaffected by rotational speed recognize that, since an instrument has a finite fatigue life (number of revolutions to failure), a higher rotational speed should consume this life span in a shorter time (Pruett et al. 1997), although it may also accelerate the preparation of the root canal. The rotational speed may also alter the tactile feedback provided by the instruments. Many canal irregularities can be felt through the instrument at low speed, but higher speed may result in almost total loss of any sensation, at least in vitro (Poulsen et al. 1995). In general, it is advisable to adhere to the manufacturer's recommendations regarding the rotational speed.

Torque is a less straight forward parameter than rotational speed. It is a measure of the turning force applied to the instrument in order for the instrument to overcome friction and continue rotating. Since electric motors strive to maintain a



Fig. 2.10 (a) Electric motor featuring speed and torque control (X-Smart Plus, Courtesy Dentsply Maillefer, Ballaigues, Switzerland). (b) Gear-reduction contra-angle handpiece with predefined torque levels which can be attached to a conventional electric or air-driven motor (Mtwo Direct, VDW, Munich, Germany)

constant rotational speed, the torque applied to the instrument can vary continuously depending on friction, which is, in turn, determined by the contact area between the instrument blades and dentin (Fig. 2.11) and the handling of the instrument. The contact area is mainly affected by the size, taper, and cross-sectional shape of both the instrument and the root canal; a wider contact area increases friction, so higher torque is necessary in order for a larger instrument to rotate inside a narrow root canal (Kobayashi et al. 1997, Sattapan et al. 2000a). For instance, the contact area increases considerably when instruments of the same taper but of progressively larger size are used consecutively in the same root canal; every subsequent instrument after the first one is subjected to excessive friction and requires much higher driving torque to rotate (a situation called “taper lock”) (Fig. 2.12) that could lead to a torsional failure. Erroneous handling of instruments such as aggressive insertion of the instrument inside the root canal also increases friction and the required torque. The maximum torque that can be applied is limited by the instrument’s ability to withstand the applied stress without undergoing plastic deformation or fracture (Gambarini 2000, 2001a, b).

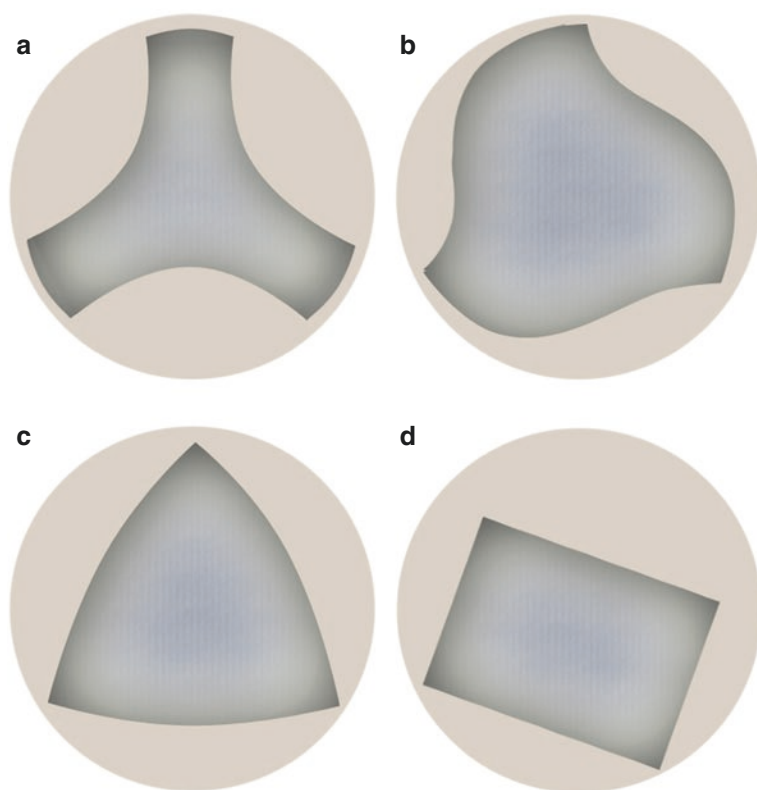
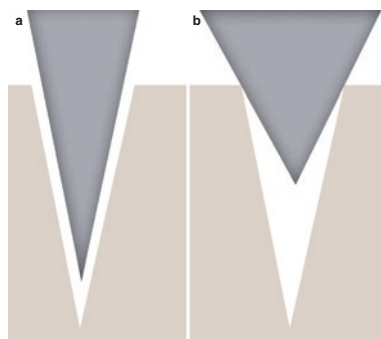


Fig. 2.11 Cross section of rotary NiTi files having a large (a, b) or small (c, d) contact area with the root canal wall, which affects friction and the torque needed to drive the instrument

Fig. 2.12 (a) Using instruments of the same taper but of progressively larger size to prepare a root canal results in excessive friction due to the wider contact area with the dentinal wall (“taper lock”) and requires higher driving torque that could lead to a torsional failure. (b) Taper lock can be prevented when sequentially used instruments have different tapers



The maximum torque at failure differs among instruments (Kobayashi et al. 1997, Gambarini 2001a, b), and it increases together with the cross-sectional area of the instrument (Yared et al. 2003; Guilford et al. 2005; Ullmann and Peters 2005); larger files can withstand higher torque without fracturing. Therefore, the applied torque should be always maintained within the narrow range that allows the instrument to rotate and cut dentin without exceeding its own plastic deformation or fracture limit (Gambarini 2000); this range is difficult to determine clinically. Manufacturers typically provide the proper maximum torque value for each instrument (Gambarini 2001a). This value is usually lower for the smaller and less tapered instruments and higher for the bigger and more tapered ones (Gambarini 2001a), which means that smaller instruments should be used taking special care not to force them aggressively inside the root canal. In addition, the recommended values refer to unused instruments and may need to be reduced for reused instruments (Gambarini 2001a).

Torque control electric motors allow the operator to determine a maximum torque value to be applied to the instrument during rotation; upon exceeding this value, the motor stops and usually reverses the rotation (auto-reverse) to disengage the instrument from dentin. Obviously, different torque limits should be used for each instrument, according to the manufacturer's recommendations (Kobayashi et al. 1997, Gambarini 2001a, b). Nevertheless, it remains unclear whether low-torque motors are able to prevent or even reduce instrument fractures. Some studies have reported benefits for both experienced (Gambarini 2001b) and inexperienced operators such as students and dentists at their initial learning phase (Yared and Kulkarni 2002), while others found no improvement compared to high-torque air-driven motors (Bortnick et al. 2001). Just like lowering the speed, low-torque instrumentation may also improve the tactile feedback, but it could also reduce the instrument's cutting efficiency to some extent and hinder its advance in the root canal; this might occasionally mislead an inexperienced operator to force the instrument which could result in locking, deformation, or even fracture (Yared et al. 2002).

Motor-driven NiTi instruments were initially used only in continuous rotation, contrary to the earlier reciprocating SS instruments that were introduced more than 60 years ago (Frank 1967, Klayman and Brilliant 1975, Hülsmann et al. 2005). The idea of reciprocation was reintroduced by Yared (2008) who proposed root canal

preparation using only a very small hand instrument and a single reciprocating NiTi file. Evidently, reciprocation has evolved a lot since its reintroduction. Nowadays, elaborate electric motors allow for precise and independent setting of the clockwise and counterclockwise angles of reciprocation, and, contrary to the earlier reciprocating SS files, the rotation angle of modern NiTi files in the cutting direction is larger than in the opposite direction, enabling the so-called partial or asymmetrical reciprocation with a rotary effect (Plotino et al. 2015). This motion is believed to prolong the life span of NiTi instruments and their resistance to cyclic fatigue compared to continuous rotation (De-Deus et al. 2010, Varela-Patino et al. 2010, Gavini et al. 2012, Pedulla et al. 2013, Ahn et al. 2016), although the method used to quantify the resistance to cyclic fatigue is markedly different in continuous rotation and in reciprocation and the results may not be directly comparable. The difference between the nominal and actual rotation speed could also affect these results (Fidler 2014).

2.5.2 Instrumentation Technique

The instrumentation technique has an influence on instrument failure (Roland et al. 2002). For instance, hand-operated NiTi files used clinically in a modified balanced force movement seem to fail mainly due to torsional overload, while motor-driven files of the same type appear to fracture mostly because of cyclic fatigue (Cheung et al. 2007b). The crown-down approach has been recommended for the vast majority of rotary NiTi instruments in order to reduce friction and minimize the fracture risk (Peters 2004), even though this may not be necessary for other types of NiTi files that are advocated as “single-length” instruments and should be advanced to working length irrespective of size (Plotino et al. 2007; Ehrhardt et al. 2012). Most currently available reciprocating files are also used in a single-file single-length manner (De-Deus et al. 2013; Rodrigues et al. 2016).

Regarding the technique, light apical pressure, continuous axial movement (pecking motion), and brief use inside the root canal are almost unanimously recommended (Parashos and Messer 2006) in order to prevent torsional overload and prolong the fatigue life (Sattapan et al. 2000a; Li et al. 2002; Rodrigues et al. 2011; Gambarra-Soares et al. 2013). Moreover, the handpiece should not be tilted away from the root canal axis at the orifice in order to avoid increasing friction. In general it is advisable for inexperienced users of a particular system to adhere to the recommended instrument sequence, but files from different systems can be combined in hybrid protocols to cope with individual clinical needs; the latter requires a certain level of expertise.

Due to the non-cutting tip of most NiTi files, it is of particular importance to ensure that the root canal will allow free rotation of the tip even at its narrowest point in order to avoid locking and eventual torsional failure (Sattapan et al. 2000b; Peters 2004). This almost uniform requirement can be met by creating a continuous smooth pathway to the apical terminus of the root canal (glide path) before using the main series of rotary NiTi instruments. A glide path can be prepared by small-size hand SS instruments (Blum et al. 1999; Patino et al. 2005; Lopes et al. 2011) or by specially designed rotary NiTi instruments (Fig. 2.13) (Alves et al. 2012; Lopes



Fig. 2.13 Specially-designed rotary NiTi files for preparation of a glide path (Pathfiles, Dentsply Maillefer, Ballaigues, Switzerland) (Courtesy Dentsply Maillefer)

et al. 2012; De-Deus et al. 2016; Alovisei et al. 2017). The latter may present some advantages according to some studies (Paleker and van der Vyver 2016; Alovisei et al. 2017) but not according to others (Alves et al. 2012) and still suffer from the typical limitations of NiTi instruments. It has been claimed that reciprocating NiTi files are able to reach working length safely without a previously established glide path and without increasing the instrument failure rate during both in vitro (De-Deus et al. 2013) and clinical use (Rodrigues et al. 2016). However, operators are advised to follow the manufacturers' recommendations regarding the need for a glide path.

2.5.3 Reuse and Sterilization

Due to the increased cost of root canal instruments and especially of NiTi files, the question of whether they can be reused is always pertinent. The number of times that a file can be safely used is still a topic of ongoing debate. Manufacturers claim that the only predictable way to prevent failure is by discarding rotary instruments on a regular basis; in some cases, special features are embedded in the NiTi instrument handle to prevent their reuse after sterilization and enforce a single-use policy. However, these recommendations and policies may be influenced to some extent by the commercial interest involved.

Grossman (1981) recommended using small hand SS instruments no more than twice. More recently, single use of all rotary NiTi instruments has been suggested as a precaution (Pruett et al. 1997; Arens et al. 2003), while others advocate this strict rule only concerning the smaller files (Haapasalo and Shen 2013), possibly because any defects may be more difficult to detect. A survey found that discarding after a certain number of uses is a common practice among both general dentists and endodontists (Madarati et al. 2008), and the type of alloy, the design and size of the instrument, and the case difficulty are parameters frequently taken into account in order to decide when to discard an instrument (Cheung et al. 2005).

The evidence behind these recommendations is conflicting. Prolonged clinical use of NiTi rotary files seems to reduce their resistance to cyclic fatigue during subsequent in vitro tests (Gambarini 2001b, c; Bahia and Buono 2005; Plotino et al. 2006), so larger files should be discarded earlier than smaller ones when preparing curved root canals because their resistance to cyclic fatigue is lower (Bahia and

Buono 2005). However, instrument failure is a complex and multifactorial problem, and it seems impossible to predict when an instrument will fracture during clinical use based on simplified *in vitro* tests. The number of uses before failure varies widely (Parashos et al. 2004; Kosti et al. 2011), and fracture can occur even during the first use in the hands of experienced clinicians (Arens et al. 2003). In addition, instruments may fracture following clinical use for fewer times than identical instruments that present no defects or fracture. Therefore, it appears that other variables such as the operator proficiency and the root canal anatomy may be far more significant determinants of the instrument fracture rate (Parashos et al. 2004).

This apparent discrepancy could be explained by the fact that NiTi instrument failure during clinical use seems to occur because of a single overloading event (e.g., inadvertent locking in the root canal) rather than a fatigue accumulation process (Spanaki-Voreadi et al. 2006); *in vitro* failures during preparation of root canals seem to occur by a similar mechanism (Kosti et al. 2011). Interestingly, even authors concluding that files should not be reused because their resistance to cyclic fatigue is reduced actually managed to prepare up to ten clinical cases using the same set of instruments without any intracanal fracture (Gambarini 2001c). Furthermore, contrary to earlier views about the effect of repetitive loading on the NiTi instrument fatigue life (Sattapan et al. 2000b), more recent studies found that mild torsional preloading (not causing permanent deformation) can actually improve both the torsional strength (Oh et al. 2017) and the resistance to cyclic fatigue during subsequent loading (Cheung et al. 2013); this effect could reduce the fracture risk during clinical use, but the result may differ among various types of files (Ha et al. 2015). Therefore, taking all evidence into account, multiple uses of NiTi instruments are clinically acceptable from a mechanical point of view (Parashos et al. 2004), but it is impossible to recommend a safe number of uses. These findings are at variance to the failure of SS instruments that seems to occur mostly because of fatigue accumulation, during both *in vitro* (Kosti et al. 2004) and clinical use (Zinelis and Margelos 2002), and justifies frequent discarding.

All endodontic instruments should be carefully examined under magnification prior to reuse for signs of wear. Regarding SS instruments, any shiny marks, uneven spacing between the flutes, areas of unwinding, sharp bending, or any other kind of permanent distortion or corrosion (Fig. 2.14) are indications of excessive fatigue and should serve as warnings of impending fracture; any such instruments should be discarded.

Similar deformations of NiTi instruments should also be regarded as a signal to discard them (Fig. 2.15). However, their original shape can be more complex or asymmetric and may include flutes with reverse direction combined with straight areas, varying helical angles or pitch, and off-center cross section (Peters et al. 2016); these features should not be confused with indications of impending fracture. In addition, instruments made of the so-called “controlled memory” alloy may normally undergo some unwinding during use, and this should only be considered an indication to discard the instrument if rewinding in the opposite direction appears or the file does not regain its original shape upon heat treatment (Fig. 2.16) (Coltene Endo 2014). Therefore, the clinician must bear in mind the original shape of the

Fig. 2.14 Hand SS instruments with permanent distortion, sharp bend, or damage of the cutting part that needs to be discarded

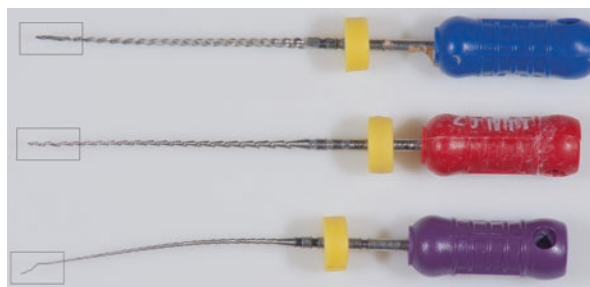


Fig. 2.15 Defects of rotary NiTi instruments signaling impending fracture; these instruments need to be discarded

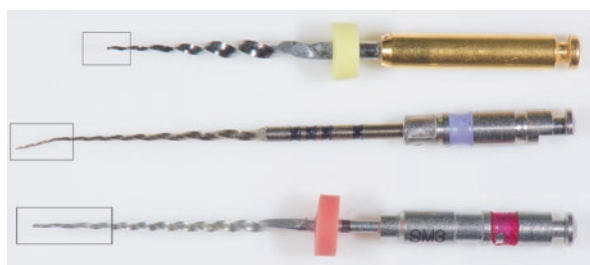


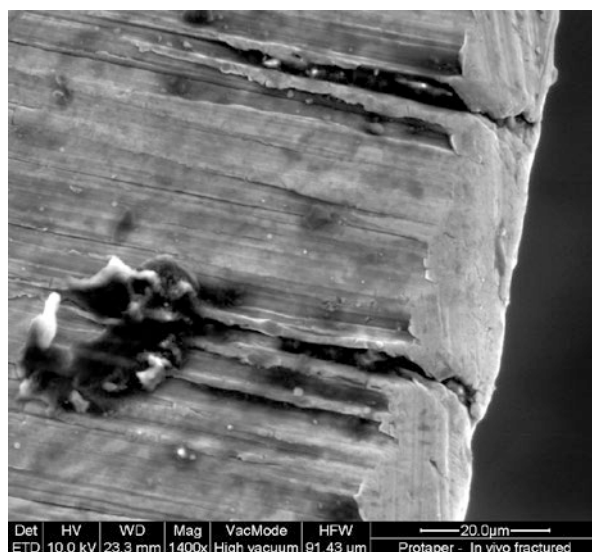
Fig. 2.16 Controlled-memory rotary NiTi files (Hyflex CM, Coltene, Altstätten, Switzerland) before (a) and after use (b, c). Despite unwinding (b), such instruments don't need to be discarded and can regain their original shape upon heat treatment. On the contrary, instruments showing rewinding in the opposite direction (c) should be discarded (Courtesy COLTENE Group)

instrument and any specific guidelines by the manufacturer in order to identify correctly which instruments should be discarded. Still, NiTi instruments may commonly fracture even without any visible deformation (Sattapan et al. 2000b; Martin et al. 2003; Peng et al. 2005; Shen et al. 2006, 2009).

Examination under high magnification has also revealed dentin debris embedded into machining grooves or surface cracks of used instruments (Fig. 2.17) (Zinelis and Margelos 2002; Alapati et al. 2004), and it has been hypothesized that this debris may accelerate crack propagation (Alapati et al. 2004). However, the presence of debris could also be a random observation without any involvement in the fracture process since there is no proven cause-effect relationship (Parashos and Messer 2006).

Instruments need to be cleaned and sterilized before their first use (unless they are delivered by the manufacturer in sealed presterilized packages) and also before every reuse; the effect of this process on instrument failure is still controversial.

Fig. 2.17 Dentin debris embedded into surface cracks of a rotary NiTi file (magnification $\times 1400$) (Courtesy Dr. S. Zinelis)



Regarding SS instruments, a small reduction in the torsional strength has been reported after 10 cycles of immersion in 5% sodium hypochlorite followed by autoclave sterilization, especially for larger files (Mitchell et al. 1983); a similar small effect was found after 10–40 autoclave sterilization cycles without immersion in sodium hypochlorite (Hilt et al. 2000), but in both cases the difference may not be clinically significant. Other studies did not find any such difference (Iverson et al. 1985).

Multiple sterilization cycles may induce surface alterations on NiTi files, including corrosion and defects (Valois et al. 2008; Spagnuolo et al. 2012), and may also increase their surface roughness (Alexandrou et al. 2006a, b) possibly because of changes in the passive titanium oxide layer that covers the surfaces (Rapisarda et al. 1999, Thierry et al. 2000). However, these surface alterations have not been clearly linked to instrument fracture, so they may not be clinically relevant (Eggert et al. 1999).

Both dry heat and autoclave sterilization don't seem to have a negative effect on the cyclic fatigue resistance of several types of NiTi files (Yared et al. 1999, 2000; Hilfer et al. 2011; Plotino et al. 2012; Elbatal et al. 2016; Zhao et al. 2016), but this is not true for all types (Plotino et al. 2006; Hilfer et al. 2011; Elbatal et al. 2016). Inconsistent results have been also published regarding the torsional strength, with some files showing no effect (Svec and Powers 1999; Casper et al. 2011; King et al. 2012) and others showing a decrease (Canalda-Sahli et al. 1998; King et al. 2012).

Although its clinical relevance has been questioned (Mize et al. 1998), a possible beneficial effect of sterilization on instruments has also been reported; both resistance to cyclic fatigue and torsional strength of certain types of files were found to increase following sterilization (Silvaggio and Hicks 1997; Craveiro de Melo et al. 2002; Viana et al. 2006; Plotino et al. 2012; Zhao et al. 2016), especially after

repeated cycles (Casper et al. 2011), so dry heat or autoclave sterilization could act as a form of heat treatment.

One additional parameter that should be considered before deciding to reuse root canal instruments is the cleaning and sterilization efficacy of the available methods (Sonntag and Peters 2007; Walker et al. 2007; Hartwell et al. 2011), but this parameter is beyond the scope of the present chapter.

2.5.4 Irrigants

Instruments may come in contact with irrigants in two different occasions, namely, inside the root canal during use and, afterward, during reprocessing. Although the same solutions may be used for both purposes, the exposure conditions can be different. First of all, instrumentation should never be performed in a dry root canal; excessive friction could lead to instrument failure. Manufacturers still recommend the use of gel-based lubricants in conjunction with NiTi files in order to reduce the stress applied to the instrument (Anderson et al. 2006); these gels are advised to be repeatedly applied either directly on the cutting part of the instrument or in the pulp chamber, and in addition to lubrication, they could also soften root dentin to facilitate instrumentation (Zehnder 2006). It is noteworthy that several of these gel-based lubricants are also produced by the instrument manufacturers advocating their routine use.

Experimental evidence does not support the use of these gels. They fail to reduce the friction between the instrument and the root canal wall, and in some cases friction may even be increased compared to a dry root canal (Peters et al. 2005; Boessler et al. 2007). Aqueous solutions or distilled water are much more effective for this purpose (Peters et al. 2005; Boessler et al. 2007), and they may also flush away dentin debris from the cutting flutes of the instruments (Zehnder 2006), a function unlikely to be performed by gels.

In addition, most of the gel-type lubricants contain various chelators, and similarly to aqueous chelator solutions, they can interact strongly with sodium hypochlorite and consume its free available chlorine very rapidly (Grawehr et al. 2003; Zehnder et al. 2005). Since chelator solutions are only marginally better than water as lubricants (Peters et al. 2005; Boessler et al. 2007), the effect may occur primarily due to mechanical lubrication and not due to chemical softening of dentin, so any liquid should suffice (Peters et al. 2005; Boessler et al. 2007). Thus, during instrumentation root canals and the pulp chamber should be flooded with irrigant and preferably with sodium hypochlorite, which can serve multiple purposes like killing bacteria and dissolving tissue remnants in addition to providing lubrication (Zehnder 2006).

The possible corrosive effect of sodium hypochlorite and of other irrigants on root canal instruments is an additional concern (Sonntag and Peters 2007). During instrumentation only the cutting part of the file is likely to contact the irrigant. Partial immersion (only the cutting part) of either SS or NiTi files in 5% sodium hypochlorite or 17% EDTA solution in vitro even for extended periods of time

(1–24 h) did not result in any detectable corrosion (Darabara et al. 2004; de Castro Martins et al. 2006) and did not reduce the fatigue resistance of the files (Smith 2007). Similar findings were reported after partial immersion in preheated (50 °C) 5% sodium hypochlorite for 5 min (Berutti et al. 2006) or repeated 5-min immersion in a 2.5% solution at room temperature (Bulem et al. 2013). In addition no signs of surface corrosion were found on hand SS files used clinically in combination with 2.5% sodium hypochlorite irrigation (Zinelis and Margelos 2002).

Total immersion of the instruments in sodium hypochlorite, which may occur during post-use cleaning prior to sterilization, seems to have a more pronounced effect, but there is a considerable discrepancy among studies. Corrosion begins to appear after immersion of NiTi instruments in 5% NaOCl either at room temperature or preheated (50 °C) for 5 min (Berutti et al. 2006; Smith 2007) or 30 min (Busslinger et al. 1998) and may increase with immersion time (Peters et al. 2007). Corrosion seems to be accompanied by a reduction in the resistance to cyclic fatigue, at least for some types of NiTi files (Berutti et al. 2006; Peters et al. 2007; Smith 2007). A lower concentration (1%) solution doesn't seem to corrode NiTi files or reduce their torsional strength or cyclic fatigue resistance after a cumulative exposure of 2.5 h, but overnight immersion (18 h) produces clear signs of corrosion (Fig. 2.18), although there are differences between various types of files (O'Hoy et al. 2003). Finally, very brief immersion in a 5% sodium hypochlorite solution at body temperature (37 °C) during a cyclic fatigue test does not seem to affect the results (Elnaghy and Elsaka 2017).

The main difference between partial and total immersion in sodium hypochlorite is whether the instrument shank is also immersed or not (O'Hoy et al. 2003; Berutti et al. 2006; Novoa et al. 2007). The shank of some types of instruments is made of a different metal than the cutting part (Peters et al. 2007; Bonaccorso et al. 2008a), and the concurrent presence of two metals in a sodium hypochlorite solution can affect the ion release and generate galvanic reactions that may accelerate the corrosion process (Berutti et al. 2006; Novoa et al. 2007; Smith 2007). This parameter could partially explain the wide range of results reported in corrosion studies.

Parameters related to the sodium hypochlorite solution may also modify its effect on instruments. Lower-pH solutions seem to be less aggressive in terms of corrosion (Novoa et al. 2007), and preheated solutions (60 °C) seem to decrease the fatigue resistance even though only minor corrosion may be found on the instruments (Peters et al. 2007). The clinical relevance of preheated solutions used as irrigants is very limited (de Hemptinne et al. 2015), but they may still be employed for post-use



Fig. 2.18 Corrosion of rotary NiTi files immersed overnight in 3% NaOCl

disinfection of the instruments. Finally, the corrosive effect of Milton's solution (1% NaOCl, 19% NaCl) may be more pronounced than that of a normal sodium hypochlorite solution at the same concentration (O'Hoy et al. 2003).

Efforts to improve the corrosion resistance of NiTi files have been undertaken by the manufacturers, but the results are inconclusive. Surface treatment by electropolishing or physical vapor deposition may reduce corrosion during contact with normal saline (Bonaccorso et al. 2008b) but not in the presence of sodium hypochlorite (Peters et al. 2007). Nevertheless, it should be kept in mind that variations may exist in the extent of corrosion between different brands and also between individual files of the same brand (O'Hoy et al. 2003), and that, despite impressive *in vitro* results, there are no confirmed reports of file fracture during clinical use that can be attributed to corrosion alone.

2.6 Concluding Remarks

Contradictory findings have been reported regarding several of the parameters analyzed in this chapter. Apart from inevitable experimental errors, these discrepancies may be largely attributed to the wide variation in the testing protocols and conditions among studies; different types of instruments, evaluation of used or unused instruments, the precise conditions during use, contact with sodium hypochlorite, different cleaning and sterilization methods, varying cyclic fatigue tests, and corrosion detection methods are only a few of the parameters that differ. The possibility of interactions between different parameters cannot be excluded either. Thus, efforts should be undertaken to standardize the testing methods and conditions in order to facilitate comparisons among future studies. It has been suggested that standard testing of all types of instruments should be conducted prior to their introduction into the market by the manufacturers and should accompany the instrument as essential documentation (Hülsmann 2013).

Information about the behavior of the instruments during clinical use is limited, and it is possible that *in vitro* models may not mimic *in vivo* conditions closely. For instance, instruments are normally used inside root canals filled with an irrigant (usually sodium hypochlorite) very close to body temperature (~35 °C) (de Hemptinne et al. 2015), but several *in vitro* studies have ignored this fact and have conducted the tests at room temperature (20 °C). Recently it was shown that temperature is an important confounder, and an increase from 20 to 35 °C may decrease the fatigue resistance considerably (up to 85%) at least for some types of instruments (de Vasconcelos et al. 2016; Elnaghy and Elsaka 2017; Plotino et al. 2017). Thus, choosing clinically realistic conditions during *in vitro* testing is of paramount importance in order to obtain clinically relevant information.

Despite *in vitro* evidence that some of the abovementioned parameters may affect the fracture resistance of root canal instruments, it is worth noticing that

results obtained with one type of instrument cannot be directly extrapolated to other types due to considerable differences in the material, the design, and the mode of use. Several instruments are currently available, and new “improved” versions are constantly being introduced, so detailed evaluation of all possible combinations is not feasible. Simple comparisons of randomly selected, popular, or new instruments to each other are manufacturer-oriented and make little scientific sense because of the large number of confounders. Instead, it would be more reasonable for future studies to isolate and study the effect of specific material-, design-, or technique-related parameters that may be significant across brands.

References

- Ahn SY, Kim HC, Kim E. Kinematic effects of nickel-titanium instruments with reciprocating or continuous rotation motion: a systematic review of in vitro studies. *J Endod.* 2016;42(7):1009–17.
- Alapati SB, Brantley WA, Svec TA, Powers JM, Mitchell JC. Scanning electron microscope observations of new and used nickel-titanium rotary files. *J Endod.* 2003;29(10):667–9.
- Alapati SB, Brantley WA, Svec TA, Powers JM, Nusstein JM, Daehn GS. Proposed role of embedded dentin chips for the clinical failure of nickel titanium rotary instruments. *J Endod.* 2004;30(5):339–41.
- Alapati SB, Brantley WA, Svec TA, Powers JM, Nusstein JM, Daehn GS. SEM observations of nickel-titanium rotary endodontic instruments that fractured during clinical use. *J Endod.* 2005;31(1):40–3.
- Alexandrou G, Chrissafis K, Vasiliadis L, Pavlidou E, Polychroniadis EK. SEM observations and differential scanning calorimetric studies of new and sterilized nickel-titanium rotary endodontic instruments. *J Endod.* 2006a;32(7):675–9.
- Alexandrou G, Chrissafis K, Vasiliadis L, Pavlidou E, Polychroniadis EK. Effect of heat sterilization on surface characteristics and microstructure of Mani NRT rotary nickel-titanium instruments. *Int Endod J.* 2006b;39(10):770–8.
- Alovisi M, Cemenasco A, Mancini L, Paolino D, Scotti N, Bianchi CC, Pasqualini D. Micro-CT evaluation of several glide path techniques and ProTaper Next shaping outcomes in maxillary first molar curved canals. *Int Endod J.* 2017;50(4):387–97.
- Alves O, Bueno CE, Cunha RS, Pinheiro SL, Fontana CE, de Martin AS. Comparison among manual instruments and PathFile and Mtwo rotary instruments to create a glide path in the root canal preparation of curved canals. *J Endod.* 2012;38(1):117–20.
- Anderson DN, Joyce AP, Roberts S, Runner R. A comparative photoelastic stress analysis of internal root stresses between RC Prep and saline when applied to the Profile/GT rotary instrumentation system. *J Endod.* 2006;32(3):222–4.
- Anderson ME, John WH, Price JWH, Parashos P. Fracture resistance of electropolished rotary nickel–titanium endodontic instruments. *J Endod.* 2007;33(10):1212–6.
- Arens FC, Hoen MM, Steiman HR, Dietz GC Jr. Evaluation of single-use rotary nickel-titanium instruments. *J Endod.* 2003;29(10):664–6.
- Bahia MG, Buono VT. Decrease in the fatigue resistance of nickel-titanium rotary instruments after clinical use in curved root canals. *Oral Surg Oral Med Oral Path Oral Radiol Endod.* 2005;100(2):249–55.
- Berutti E, Angelini E, Rigolone M, Migliaretti G, Pasqualini D. Influence of sodium hypochlorite on fracture properties and corrosion of ProTaper rotary instruments. *Int Endod J.* 2006;39(9):693–9.
- Biz MT, Figueiredo JA. Morphometric analysis of shank-to-flute ratio in rotary nickel titanium files. *Int Endod J.* 2004;37(6):353–8.

- Blum JY, Cohen A, Machtou P, Micallef JP. Analysis of forces developed during mechanical preparation of extracted teeth using Profile NiTi rotary instruments. *Int Endod J*. 1999;32(1):24–31.
- Boessler C, Peters OA, Zehnder M. Impact of lubricant parameters on rotary instrument torque and force. *J Endod*. 2007;33(3):280–3.
- Bonaccorso A, Schäfer E, Condorelli GG, Cantatore G, Tripi TR. Chemical analysis of nickel-titanium rotary instruments with and without electropolishing after cleaning procedures with sodium hypochlorite. *J Endod*. 2008a;34(11):1391–5.
- Bonaccorso A, Tripi TR, Rondelli G, Condorelli GG, Cantatore G, Schäfer E. Pitting corrosion resistance of nickel-titanium rotary instruments with different surface treatments in seventeen percent ethylenediaminetetraacetic acid and sodium chloride solutions. *J Endod*. 2008b;34(2):208–11.
- Booth JR, Scheetz JP, Lemons JE, Eleazer PD. A comparison of torque required to fracture three different nickel-titanium rotary instruments around curves of the same angle but of different radius when bound at the tip. *J Endod*. 2003;29(1):55–7.
- Bortnick KL, Steiman HR, Ruskin A. Comparison of nickel-titanium file distortion using electric and air-driven handpieces. *J Endod*. 2001;27(1):57–9.
- Briseno B, Kremers L, Hamm G, Nitsch C. Comparison by means of a computer supported device of the enlarging characteristics of two different instruments. *J Endod*. 1993;19(6):281–7.
- Bülem ÜK, Kececi AD, Guldaz HE. Experimental evaluation of cyclic fatigue resistance of four different nickel-titanium instruments after immersion in sodium hypochlorite and/or sterilization. *J Appl Oral Sci*. 2013;21(6):505–10.
- Busslinger A, Sener B, Barbakow F. Effects of sodium hypochlorite on nickel-titanium Lightspeed instruments. *Int Endod J*. 1998;31(4):290–4.
- Canalda-Sahli C, Brau-Aguadé E, Sentis-Vilalta J. The effect of sterilization on bending and torsional properties of K-files manufactured with different metallic alloys. *Int Endod J*. 1998;31(1):48–52.
- Capar ID, Kaval ME, Ertas H, Sen BH. Comparison of the cyclic fatigue resistance of 5 different rotary pathfinding instruments made of conventional nickel-titanium wire, M-wire, and controlled memory wire. *J Endod*. 2015;41(4):535–8.
- Casper RB, Roberts HW, Roberts MD, Himel VT, Bergeron BE. Comparison of autoclaving effects on torsional deformation and fracture resistance of three innovative endodontic file systems. *J Endod*. 2011;37(11):1572–5.
- Cheung GS, Peng B, Bian Z, Shen Y, Darvell BW. Defects in ProTaper S1 instruments after clinical use: fractographic examination. *Int Endod J*. 2005;38(11):802–9.
- Cheung GS, Peng B, Bian Z, Shen Y, Darvell BW. *Int Endod J*. 2005;38(11):802–9.
- Cheung GS, Shen Y, Darvell BW. Does electropolishing improve the low-cycle fatigue behavior of nickel-titanium rotary instrument in hypochlorite? *J Endod*. 2007a;33(10):1217–21.
- Cheung GS, Bian Z, Shen Y, Peng B, Darvell BW. Comparison of defects in ProTaper hand-operated and engine-driven instruments after clinical use. *Int Endod J*. 2007b;40(3):169–78.
- Cheung GS, Oh SH, Ha JH, Kim SK, Park SH, Kim HC. Effect of torsional loading of nickel-titanium instruments on cyclic fatigue resistance. *J Endod*. 2013;39(12):1593–7.
- Chianello G, Specian VL, Hardt LCF, Raldi DP, Lage-Marques JL, Habitate SM. Surface finishing of unused rotary endodontic instruments: a SEM study. *Braz Dent J*. 2008;19(2):109–13.
- Coltene Endo. HyFlex® CM – Controlled memory NiTi files. File sequence step by step card. 2014. Available at: http://www.hyflex.info/fileadmin/dam/DATEN/HyFlex-CM/downloads/allgemein/30001993_03-14_StepByStep_HyflexCM_DB.pdf Accessed on 27 Dec 2016.
- Condorelli GG, Bonaccorso A, Smecca E, Schäfer E, Cantatore G, Tripi TR. Improvement of the fatigue resistance of NiTi endodontic files by surface and bulk modifications. *Int Endod J*. 2010;43(10):866–73.
- Craveiro de Melo MC, Bahia MGA, Buono VTL. Fatigue resistance of engine driven rotary nickel-titanium endodontic instruments. *J Endod*. 2002;28(11):765–9.
- Darabara M, Bourithis L, Zinelis S, Papadimitriou GD. Susceptibility to localized corrosion of stainless steel and NiTi endodontic instruments in irrigating solutions. *Int Endod J*. 2004;37(10):705–10.

- de Castro Martins R, Bahia MG, Buono VT, Horizonte B. The effect of sodium hypochlorite on the surface characteristics and fatigue resistance of ProFile nickel-titanium instruments. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod.* 2006;102(4):e99–105.
- de Hemptinne F, Slaus G, Vandendael M, Jacquet W, De Moor RJ, Bottenberg P. In vivo intracanal temperature evolution during endodontic treatment after the injection of room temperature or preheated sodium hypochlorite. *J Endod.* 2015;41(7):1112–5.
- de Vasconcelos RA, Murphy S, Carvalho CA, Govindjee RG, Govindjee S, Peters OA. Evidence for reduced fatigue resistance of contemporary rotary instruments exposed to body temperature. *J Endod.* 2016;42(5):782–7.
- De-Deus G, Moreira EJ, Lopes HP, Elias CN. Extended cyclic fatigue life of F2 ProTaper instruments used in reciprocating movement. *Int Endod J.* 2010;43(2):1063–8.
- De-Deus G, Arruda TEP, Souza EM, Neves A, Magalhaes K, Thuanne E, Fidel RAS. The ability of the Reciproc R25 instrument to reach the full root canal working length without a glide path. *Int Endod J.* 2013;46(10):993–8.
- De-Deus G, Belladonna FG, Souza EM, Alves Vde O, Silva EJ, Rodrigues E, Versiani MA, Bueno CE. Scouting ability of 4 pathfinding instruments in moderately curved molar canals. *J Endod.* 2016;42(10):1540–4.
- Di Fiore PM, Genov KA, Komaroff E, Li Y, Lin L. Nickel-titanium rotary instrument fracture: a clinical practice assessment. *Int Endod J.* 2006;39(9):700–8.
- Eaton JA, Clement DJ, Lloyd A, Marchesan MA. Micro-computed tomographic evaluation of the influence of root canal system landmarks on access outline forms and canal curvatures in mandibular molars. *J Endod.* 2015;41(11):1888–91.
- Eggert C, Peters O, Barbakow F. Wear of nickel-titanium Lightspeed instruments evaluated by scanning electron microscopy. *J Endod.* 1999;25(7):494–7.
- Ehrhardt IC, Zuolo ML, Cunha RS, De Martin AS, Kherlakian D, Carvalho MC, Bueno CE. Assessment of the separation incidence of Mtwo files used with preflaring: prospective clinical study. *J Endod.* 2012;38(8):1078–81.
- Elbatal LM, El Batouty KM, Obeid MM. Effect of repeated autoclaving on cyclic fatigue of three nickel-titanium rotary instruments. *ENDO (Lond Engl).* 2016;10(1):15–22.
- Elnaghy AM, Elsaka SE. Effect of sodium hypochlorite and saline on cyclic fatigue resistance of WaveOne Gold and Reciproc reciprocating instruments. *Int Endod J.* 2017; In press: 1–8. (doi: 10.1111/iej.12712).
- Fidler A. Kinematics of 2 reciprocating endodontic motors: the difference between actual and set values. *J Endod.* 2014;40(7):990–4.
- Frank AL. An evaluation of the Giromatic endodontic handpiece. *Oral Surg Oral Med Oral Path.* 1967;24(3):419–21.
- Gambarini G. Rationale for the use of low-torque endodontic motors in root canal instrumentation. *Endod Dent Traumatol.* 2000;16(3):95–100.
- Gambarini G. Advantages and disadvantages of new torque-controlled endodontic motors and low-torque NiTi rotary instrumentation. *Aust Endod J.* 2001a;27(3):99–104.
- Gambarini G. Cyclic fatigue of nickel-titanium rotary instruments after clinical use with low- and high-torque endodontic motors. *J Endod.* 2001b;27(12):772–4.
- Gambarini G. Cyclic fatigue of ProFile rotary instruments after prolonged clinical use. *Int Endod J.* 2001c;34(5):386–9.
- Gambarini G, Grande NM, Plotino G, Somma F, Garala M, DeLuca M, Teslarelli L. Fatigue resistance of engine-driven rotary Nickel-Titanium instruments produced by new manufacturing methods. *J Endod.* 2008;34(8):1003–5.
- Gambarra-Soares T, Lopes HP, Machado Oliveira JC, Chaves Souza L, Leal Vieira VT, Elias CN. Dynamic or static cyclic fatigue tests: which best determines the lifespan of endodontic files? *ENDO (Lond Engl).* 2013;7(2):101–4.
- Gao Y, Gutmann JL, Wilkinson K, Maxwell R, Ammon D. Evaluation of the impact of raw materials on the fatigue and mechanical properties of ProFile Vortex rotary instruments. *J Endod.* 2012;38(3):398–401.

- Gambarini G, Grande NM, Plotino G, Somma F, Garala M, De Luca M, Testarelli L. Fatigue resistance of engine-driven rotary nickel-titanium instruments produced by new manufacturing methods. *J Endod.* 2008;34(8):1003–5.
- Gluskin AH, Peters CI, Peters OA. Minimally invasive endodontics: challenging prevailing paradigms. *Br Dent J.* 2014;216(6):347–53.
- Grawehr M, Sener B, Waltimo T, Zehnder M. Interactions of ethylenediaminetetraacetic acid with sodium hypochlorite in aqueous solutions. *Int Endod J.* 2003;36(6):411–7.
- Grossman LI. Endodontic practice. 10th ed. Philadelphia: Lea & Febiger; 1981. p. 200–36.
- Guilford WL, Lemons JE, Eleazer PD. A comparison of torque required to fracture rotary files with tips bound in simulated curved canal. *J Endod.* 2005;31(6):468–70.
- Gutmann JL, Gao Y. Alteration in the inherent metallic and surface properties of nickel-titanium root canal instruments to enhance performance, durability and safety: a focused review. *Int Endod J.* 2012;45(2):113–28.
- Ha JH, Kim SK, Cheung GS, Jeong SH, Bae YC, Kim HC. Effect of alloy type on the life-time of torsion-preloaded nickel-titanium endodontic instruments. *Scanning.* 2015;37(3):172–8.
- Haapasalo M, Shen Y. Evolution of nickel-titanium instruments: from past to future. *Endod Top.* 2013;29(1):3–17.
- Haikel Y, Serfaty R, Bateman G, Senger B, Allemann C. Dynamic and cyclic fatigue of engine-driven rotary nickel-titanium endodontic instruments. *J Endod.* 1999;25(6):434–40.
- Hartwell G, Bowles W, Peters O, Peikoff M, Torneck C. Joint AAE/CAE special committee on single use endodontic instruments. Final report. 2011. p. 1–5.
- Herold KS, Johnson BR, Wenckus CS. A scanning electron microscopy evaluation of microfractures, deformation and separation in EndoSequence and Profile nickel-titanium rotary files using an extracted molar tooth model. *J Endod.* 2007;33(6):712–4.
- Hilfer PB, Bergeron BE, Mayerchak MJ, Roberts HW, Jeansonne BG. Multiple autoclave cycle effects on cyclic fatigue of nickel titanium rotary files produced by new manufacturing methods. *J Endod.* 2011;37(1):72–4.
- Hilt BR, Cunningham CJ, Shen C, Richards N. Torsional properties of stainless-steel and nickel-titanium files after multiple autoclave sterilizations. *J Endod.* 2000;26(2):76–80.
- Hübscher W, Barbakow F, Peters OA. Root canal preparation with FlexMaster: assessment of torque and force in relation to canal anatomy. *Int Endod J.* 2003;36(12):883–90.
- Hülsmann M. Research that matters – canal preparation, retreatment and working length studies. *Int Endod J.* 2013;46(4):293–5.
- Hülsmann M, Peters OA, Dummer PM. Mechanical preparation of root canals: shaping goals, techniques and means. *Endod Top.* 2005;10(1):30–76.
- Inan U, Gonulol N. Deformation and fracture of Mtwo rotary nickel-titanium instruments after clinical use. *J Endod.* 2009;35(10):1396–9.
- Iqbal MK, Kohli MR, Kim JS. A retrospective clinical study of incidence of root canal instrument separation in an endodontics graduate program: a PennEndo database study. *J Endod.* 2006;32(11):1048–52.
- Iverson GW, von Fraunhofer JA, Herrmann JW. The effects of various sterilization methods on the torsional strength of endodontic files. *J Endod.* 1985;11(6):266–8.
- Johnson E, Lloyd A, Kuttler S, Namerow K. Comparison between a novel nickel titanium alloy and 508 nitinol on the cyclic fatigue life of ProFile 25/04 rotary instruments. *J Endod.* 2008;34(11):1406–9.
- Kaval ME, Capar IC, Ertas H. Evaluation of the cyclic fatigue and torsional resistance of novel nickel-titanium rotary files with various alloy properties. *J Endod.* 2016;42(12):1840–3.
- King JB, Roberts HW, Bergeron BE, Mayerchak MJ. The effect of autoclaving on torsional moment of two nickel-titanium endodontic files. *Int Endod J.* 2012;45(2):156–61.
- Kitchens GG, Lieweh FR, Moon PC. The effect of operational speed on the fracture of nickel-titanium rotary instruments. *J Endod.* 2007;33(1):52–4.
- Klayman SM, Brilliant JD. A comparison of the efficacy of serial preparation versus Giromatic preparation. *J Endod.* 1975;1(10):334–7.

- Kobayashi C, Yoshioka T, Suda H. A new engine-driven canal preparation system with electronic canal measuring capability. *J Endod.* 1997;23(12):751–4.
- Kosti E, Zinelis S, Lambrianidis T, Margelos J. A comparative study of crack development in stainless-steel hedstrom files used with step-back or crown-down techniques. *J Endod.* 2004;30(1):38–41.
- Kosti E, Zinelis S, Molyvdas I, Lambrianidis T. Effect of root canal curvature on the failure incidence of ProFile rotary Ni–Ti endodontic instruments. *Int Endod J.* 2011;44(10):917–25.
- Krishan R, Paqué F, Ossareh A, Kishen A, Dao T, Friedman S. Impacts of conservative endodontic cavity on root canal instrumentation efficacy and resistance to fracture assessed in incisors, premolars, and molars. *J Endod.* 2014;40(8):1160–6.
- Kuhn G, Tavernier B, Jordan L. Influence of structure on nickel-titanium endodontic instruments failure. *J Endod.* 2001;27(8):516–20.
- Larsen CM, Watanabe I, Glickman G, He J. Cyclic fatigue analysis of a new generation of nickel titanium rotary instruments. *J Endod.* 2009;35(3):401–3.
- Li U, Lee B, Shih C, Lan W, Lin C. Cyclic fatigue of endodontic nickel-titanium rotary instruments: static and dynamic tests. *J Endod.* 2002;28(6):448–51.
- Lilley JD, Smith DC. An investigation of the fracture of root canal reamers. *Br Dent J.* 1966;120(8):364–72.
- Lopes HP, Elias CN, Amaral G, Vieira VT, Moreira EJJ, Mangelli M, Siqueira JF. Torsional properties of pathfinding instruments. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod.* 2011;112(5):667–70.
- Lopes HP, Elias CN, Siqueira JF Jr, Soares RG, Souza LC, Oliveira JCM, Lopes WSP, Mangelli M. Mechanical behavior of pathfinding endodontic instruments. *J Endod.* 2012;38(10):1417–21.
- Lopes HP, Vieira MVB, Elias CN, Siqueira JF Jr, Gonçalves LS, Vieira TLV. Location of the canal curvature and its influence on the resistance to fatigue fracture of two rotary nickel-titanium endodontic instruments. *ENDO (Lond Engl).* 2013;7(1):53–8.
- Madarati AA, Watts DC, Qualtrough AJ. Opinions and attitudes of endodontists and general dental practitioners in the UK towards the intracanal fracture of endodontic instruments: part 1. *Int Endod J.* 2008;41(8):693–701.
- Marsicovetere ES, Clement DJ, Del Rio CE. Morphometric video analysis of the engine-driven nickel-titanium Lightspeed instrument system. *J Endod.* 1996;22(5):231–5.
- Martin B, Zelada G, Varela P, Bahillo JG, Magan F, Ahn S, Rodriguez C. Factors influencing the fracture of nickel-titanium rotary instruments. *Int Endod J.* 2003;36(4):262–6.
- Martins RC, Bahia MGA, Buono VTL. Surface analysis of ProFile instruments by scanning electron microscopy and X-ray energy-dispersive spectroscopy: a preliminary study. *Int Endod J.* 2002;35(10):848–53.
- McGuigan MB, Louca C, Duncan HF. Endodontic instrument fracture: causes and prevention. *Br Dent J.* 2013;214(7):341–8.
- McSpadden J. Mastering endodontic instrumentation. Chattanooga: Cloudland Institute; 2007. p. 1–197.
- Mitchell BF, James GA, Nelson RC. The effect of autoclave sterilization on endodontic files. *Oral Surg Oral Med Oral Pathol.* 1983;55(2):204–7.
- Mize SB, Clement DJ, Pruett JP, Carnes DL. Effect of sterilization on cyclic fatigue of rotary nickel-titanium endodontic instruments. *J Endod.* 1998;24(12):843–7.
- Moore B, Verdelis K, Kishen A, Dao T, Friedman S. Impacts of contracted endodontic cavities on instrumentation efficacy and biomechanical responses in maxillary molars. *J Endod.* 2016;42(12):1779–83.
- Novoa XR, Martin-Biedma B, Varela-Patino P, Collazo A, Macías-Luaces A, Cantatore G, Pérez MC, Magán-Muñoz F. The corrosion of nickeltitanium rotary endodontic instruments in sodium hypochlorite. *Int Endod J.* 2007;40(1):36–44.
- O’Hoy PY, Messer HH, Palamara JE. The effect of cleaning procedures on fracture properties and corrosion of NiTi files. *Int Endod J.* 2003;36(11):724–32.
- Oh SH, Ha JH, Kwak SW, Ahn SW, Lee WC, Kim HC. The effects of torsional preloading on the torsional resistance of nickel-titanium instruments. *J Endod.* 2017;43(1):157–62.

- Paleker F, van der Vyver PJ. Comparison of canal transportation and centering ability of K-files, Proglider file, and G-files: a micro-computed tomography study of curved root canals. *J Endod.* 2016;42(7):1105–9.
- Parashos P, Gordon I, Messer HH. Factors influencing defects of rotary nickel-titanium endodontic instruments after clinical use. *J Endod.* 2004;30(10):722–5.
- Parashos P, Gordon I, Messer HH. Factors influencing defects of rotary Nickel-Titanium endodontic instruments after clinical use. *J Endod.* 2004;30(10):722–5.
- Patino PV, Biedma BM, Liebana CR, Cantatore G, Bahillo JG. The influence of a manual glide path on the separation rate of NiTi rotary instruments. *J Endod.* 2005;31(2):114–6.
- Pedulla E, Grande NM, Plotino G, Gambarini G, Rapisarda E. Influence of continuous or reciprocating motion on cyclic fatigue resistance of different nickel-titanium rotary instruments. *J Endod.* 2013;39(2):258–61.
- Peng B, Shen Y, Cheung GSP, Xia TJ. Defects in ProTaper S1 instruments after clinical use: longitudinal examination. *Int Endod J.* 2005;38(8):550–7.
- Peters OA. Current challenges and concepts in the preparation of root canal systems: a review. *J Endod.* 2004;30(8):559–65.
- Peters OA. Accessing root canal systems: knowledge base and clinical techniques. *ENDO (Lond Engl).* 2008;2(2):87–104.
- Peters OA, Paque F. Current developments in rotary root canal instrument technology and clinical use: a review. *Quintessence Int.* 2010;41(6):479–88.
- Peters OA, Peters CI, Schonenberger K, Barbakow F. ProTaper rotary root canal preparation: assessment of torque and force in relation to canal anatomy. *Int Endod J.* 2003;36(2):93–9.
- Peters OA, Boessler C, Zehnder M. Effect of liquid and paste type lubricants on torque values during simulated rotary root canal instrumentation. *Int Endod J.* 2005;38(4):223–9.
- Peters OA, Roehlike JO, Baumann MA. Effect of immersion in sodium hypochlorite on torque and fatigue resistance of nickel-titanium instruments. *J Endod.* 2007;33(5):589–93.
- Peters OA, Peters CI, Basrani B. Cleaning and shaping the root canal system. In: Hargreaves K, Berman LH, editors. *Cohen's pathways of the pulp*. 11th ed. St. Louis: Elsevier; 2016. p. 209–79.
- Plotino G, Grande NM, Sorci E, Malagnino VA, Somma F. A comparison of cyclic fatigue between used and new Mtwo Ni-Ti rotary instruments. *Int Endod J.* 2006;39(9):716–23.
- Plotino G, Grande NM, Falanga A, Di Giuseppe IL, Lamorgese V, Somma F. Dentine removal in the coronal portion of root canals following two preparation techniques. *Int Endod J.* 2007;40(11):852–8.
- Plotino G, Costanzo A, Grande NM, Petrovic R, Testarelli L, Gambarini G. Experimental evaluation on the influence of autoclave sterilization on the cyclic fatigue of new nickel-titanium rotary instruments. *J Endod.* 2012;38(2):222–5.
- Plotino G, Testarelli L, Al-Sudani D, Pongione G, Grande NM, Gambarini G. Fatigue resistance of rotary instruments manufactured using different nickel-titanium alloys: a comparative study. *Odontology.* 2014;102(1):31–5.
- Plotino G, Grande NM, Porciani PF. Deformation and fracture incidence of Reciproc instruments: a clinical evaluation. *Int Endod J.* 2015;48(2):199–205.
- Plotino G, Grande NM, Mercadé M, Testarelli L, Gambarini G. Influence of temperature on cyclic fatigue resistance of ProTaper Gold and ProTaper Universal rotary files. *J Endod.* 2017;43(2):200–2.
- Poulsen WB, Dove SB, del Rio CE. Effect of nickel-titanium engine-driven instrument rotational speed on root canal morphology. *J Endod.* 1995;21(12):609–12.
- Praisarnit C, Chang JW, Cheung GS. Electropolishing enhances the resistance of nickel-titanium rotary files to corrosion-fatigue failure in hypochlorite. *J Endod.* 2010;36(8):1354–7.
- Pruett JP, Clement DJ, Carnes DL Jr. Cyclic fatigue testing of nickel-titanium endodontic instruments. *J Endod.* 1997;23(2):77–85.
- Rapisarda E, Bonaccorso A, Tripi TR, Condorelli GG. Effect of sterilization on the cutting efficiency of rotary nickel-titanium endodontic files. *Oral Surg Oral Med Oral Path Oral Radiol Endod.* 1999;88(3):343–7.

- Regan JD, Sherriff M, Meredith N, Gulabivala K. A survey of interfacial forces used during filing of root canals. *Endod Dent Traumatol*. 2000;16(3):101–6.
- Roda SR, Gettleman BH. Nonsurgical retreatment. In: Hargreaves K, Berman LH, editors. *Cohen's pathways of the pulp*. 11th ed. St. Louis: Elsevier; 2016. p. 324–86.
- Rodrigues RC, Lopes HP, Elias CN, Amaral G, Vieira VT, De Martin AS. Influence of different manufacturing methods on the cyclic fatigue of rotary nickel-titanium endodontic instruments. *J Endod*. 2011;37(11):1553–7.
- Rodrigues E, De-Deus G, Souza E, Silva EJ. Safe mechanical preparation with reciprocation movement without glide path creation: result from a pool of 673 root canals. *Braz Dent J*. 2016;27(1):22–7.
- Roland DD, Andelin WE, Browning DF, Hsu GH, Torabinejad M. The effect of preflaring on the rates of separation for 0.04 taper nickel titanium rotary instruments. *J Endod*. 2002;28(7):543–5.
- Saber SEDM. Factors influencing the fracture of rotary nickel titanium instruments. *ENDO (Lond Engl)*. 2008;2(4):273–83.
- Sattapan B, Palamara J, Messer H. Torque during canal instrumentation using rotary nickel-titanium files. *J Endod*. 2000a;26(3):156–60.
- Sattapan B, Nervo GJ, Palamara JE, Messer HH. Defects in rotary nickel-titanium files after clinical use. *J Endod*. 2000b;26(3):161–5.
- Sawaguchi T, Kausträter G, Yawny A, Wagner M, Eggeler G. Crack initiation and propagation in 50.9 at. pct Ni-Ti pseudoelastic shape-memory wires in bending-rotation fatigue. *Metall Mater Trans A*. 2003;34(12):2847–60.
- Schäfer E, Tepel J. Relationship between design features of endodontic instruments and their properties. Part 3. Resistance to bending and fracture. *J Endod*. 2001;27(4):299–303.
- Schäfer E, Dzepina A, Danesh G. Bending properties of rotary nickel-titanium instruments. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod*. 2003;96(6):757–63.
- Shen Y, Cheung GS, Bian Z, Pang B. Comparison of defects in ProFile and ProTaper systems after clinical use. *J Endod*. 2006;32(1):61–5.
- Shen Y, Haapasalo M, Cheung GS, Peng B. Defects in nickel-titanium instruments after clinical use. Part 1: Relationship between observed imperfections and factors leading to such defects in a cohort study. *J Endod*. 2009;35(1):129–32.
- Shen Y, Zhou HM, Zheng YF, Peng B, Haapasalo M. Current challenges and concepts of the thermomechanical treatment of nickel-titanium instruments. *J Endod*. 2013a;39(2):163–72.
- Shen Y, Zhou HM, Wang Z, Campbell L, Zheng YF, Haapasalo M. Phase transformation behavior and mechanical properties of thermomechanically treated K3XF nickel-titanium instruments. *J Endod*. 2013b;39(7):919–23.
- Silvaggio J, Hicks ML. Effect of heat sterilization on the torsional properties of rotary nickel-titanium endodontic files. *J Endod*. 1997;23(12):731–4.
- Smith MS. Sodium hypochlorite's effect on nickel-titanium rotary instruments and its effect on resistance to fracture. Master Thesis. Richmond: Virginia Commonwealth University; 2007. p. 1–34.
- Sonntag D, Peters OA. Effect of decontamination protocols on nickel titanium rotary surfaces. *J Endod*. 2007;33(4):442–6.
- Spagnuolo G, Ametrano G, D'Antò V, Rengo C, Simeone M, Riccitiello F, Amato M. Effect of autoclaving on the surfaces of TiN-coated and conventional nickel-titanium rotary instruments. *Int Endod J*. 2012;45(12):1148–55.
- Spanaki-Voreadi AP, Kerezoudis NP, Zinelis S. Failure mechanism of ProTaper Ni-Ti rotary instruments during clinical use: fractographic analysis. *Int Endod J*. 2006;39(3):171–8.
- Svec TA, Powers JM. Effects of simulated conditions on NiTi rotary files. *J Endod*. 1999;25(11):759–60.
- Thierry B, Tabrizian M, Savadogo O, Yahia LH. Effects of sterilization processes on NiTi alloy: surface characterization. *J Biomed Mater Res*. 2000;49(1):88–98.
- Thompson SA. An overview of nickel-titanium alloys used in dentistry. *Int Endod J*. 2000;33(4):297–310.

- Tripi TR, Bonaccorso A, Tripi V, Condorelli GG, Rapisarda E. Defects in GT rotary instruments after use: an SEM study. *J Endod.* 2001;27(12):782–5.
- Tsakiris G. Surface analysis of original and counterfeit rotary instruments by scanning electron microscopy and x-ray energy dispersive spectroscopy. Postgraduate dissertation. Thessaloniki, Greece: Dental School, Aristotle University of Thessaloniki; 2016. p. 1–50 (in Greek).
- Ullmann CJ, Peters OA. Effect of cyclic fatigue on static fracture loads in ProTaper nickel-titanium rotary instruments. *J Endod.* 2005;31(3):183–6.
- Ungerechts C, Bårdsen A, Frisstad I. Instrument fracture in root canals - where, why, when and what? A study from a student clinic. *Int Endod J.* 2014;47(2):183–90.
- Valois CRA, Silva LP, Azevedo RB. Atomic force microscopy study of stainless steel and nickel-titanium files. *J Endod.* 2005;31(12):882–5.
- Valois CR, Silva LP, Azevedo RB. Multiple autoclave cycles affect the surface of rotary nickel-titanium files: an atomic force microscopy study. *J Endod.* 2008;34(7):859–62.
- Varela-Patino P, Ibanez-Parraga A, Rivas-Mundina B, Cantatore G, Otero XL, Martin-Biedma B. Alternating versus continuous rotation: a comparative study of the effect on instrument life. *J Endod.* 2010;36(1):157–9.
- Viana ACD, Gonzalez BM, Buono VTL, Bahia MGA. Influence of sterilization on mechanical properties and fatigue resistance of nickel-titanium rotary endodontic instruments. *Int Endod J.* 2006;39(9):709–15.
- Walker JT, Dickinson J, Sutton JM, Raven NDH, Marsh PD. Cleanability of dental instruments – implications of residual protein and risks from Creutzfeldt-Jakob disease. *Br Dent J.* 2007;203(7):395–401.
- Wang NN, Ge JY, Xie SJ, Chen G, Zhu M. Analysis of Mtwo rotary instrument separation during endodontic therapy: a retrospective clinical study. *Cell Biochem Biophys.* 2014;70(2):1091–5.
- Wu J, Lei G, Yan M, Yu Y, Yu J, Zhang G. Instrument separation analysis of multi-used ProTaper Universal rotary system during root canal therapy. *J Endod.* 2011;37(6):758–63.
- Xu X, Eng M, Zheng Y, Eng D. Comparative study of torsional and bending properties for six models of nickel-titanium root canal instruments with different cross-sections. *J Endod.* 2006;32(4):372–5.
- Yared G. Canal preparation using only one Ni-Ti rotary instrument: preliminary observations. *Int Endod J.* 2008;41(4):339–44.
- Yared GM, Kulkarni GK. Failure of ProFile Ni-Ti instruments used by an inexperienced operator under access limitations. *Int Endod J.* 2002;35(6):536–41.
- Yared G, Bou Dagher FEB, Matchou P. Cyclic fatigue of profile rotary instruments after simulated clinical use. *Int Endod J.* 1999;32(2):115–9.
- Yared GM, Bou Dagher FE, Machtou P. Cyclic fatigue of ProFile rotary instruments after clinical use. *Int Endod J.* 2000;33(3):204–7.
- Yared G, Bou Dagher FE, Machtou P. Influence of rotational speed, torque, and operator's proficiency on ProFile failures. *Int Endod J.* 2001;34(1):47–53.
- Yared GM, Bou Dagher FE, Machtou P, Kulkarni GK. Influence of rotational speed, torque and operator proficiency on failure of Greater Taper files. *Int Endod J.* 2002;35(1):7–12.
- Yared G, Kulkarni GK, Ghossayn F. An in vitro study of the torsional properties of new and used K3 instruments. *Int Endod J.* 2003;36(11):764–9.
- Zehnder M. Root canal irrigants. *J Endod.* 2006;32(5):389–98.
- Zehnder M, Schmidlin P, Sener B, Waltimo T. Chelation in root canal therapy reconsidered. *J Endod.* 2005;31(11):817–20.
- Zelada G, Varela P, Martín B, Bahillo JG, Magán F, Ahn S. The effect of rotational speed and the curvature of root canals on the breakage of rotary endodontic instruments. *J Endod.* 2002;28(7):540–54.
- Zhao D, Shen Y, Peng B, Haapasalo M. Micro-computed tomography evaluation of the preparation of mesiobuccal root canals in maxillary first molars with Hyflex CM, Twisted Files, and K3 instruments. *J Endod.* 2013;39(3):385–8.
- Zhao D, Shen Y, Peng B, Haapasalo M. Effect of autoclave sterilization on the cyclic fatigue resistance of thermally treated nickel-titanium instruments. *Int Endod J.* 2016;49(10):990–5.

- Zinelis S, Margelos J. Failure mechanism of Hedstroem endodontic files in vivo. *J Endod.* 2002;28(6):471–3.
- Zinelis S, Darabara M, Takase T, Ogane K, Papadimitriou GD. The effect of thermal treatment on the resistance of nickel-titanium rotary files in cyclic fatigue. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod.* 2007;103(6):843–7.

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