



Minimally Invasive Root Canal Instrumentation

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Contents

4.1	Minimally Invasive Shaping: A Matter of Size	67
4.2	Limitations of the Current Technology for Mechanical Shaping	68
4.3	Preservation of Pericervical Dentin—Is Coronal Pre-flaring Still Necessary?	70
4.3.1	The Role of the Danger Zone.....	71
4.4	Evolution of NiTi-Based Preparations	72
4.4.1	NiTi Alloys.....	72
4.4.2	Shaping Kinematics.....	77
4.5	Apical Size and the Limits of Shaping	82
4.6	Taper of Root Canal Instrumentation	85
4.7	Concluding Remarks	86
	References	87

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4.1 Minimally Invasive Shaping: A Matter of Size

Vertical root fractures (VRFs) are defined as longitudinal fractures that follow the vertical axis of the root [1]. VRFs can occur in both endodontically and non-endodontically treated teeth; however, the root canal treatment has been associated with the incidence of this phenomenon since 1931 [2]. Even after almost a century, it is still a clinical complication of utmost importance, as it often leads to tooth extraction [3]. The current understanding points out a multifactorial basis for the causes of fractures in endodontically treated teeth [1]. Unfavourable occlusal load,

steep cuspal incline, deep fissures on the crown, overflared canals and supraosseous post and dowel placement have been traditionally related to VRFs [1]. In a broader sense, these factors can be considered as iatrogenic and non-iatrogenic causes, but the weakening of the teeth by dentin mass loss is supported by logical reasoning and by the weak scientific evidence that is currently available. The logical reasoning on this topic is plain and says that overall dentin mass loss, mitigates the ability of the tooth to resist intermittent masticatory forces in the long term. There is laboratory evidence showing a direct correlation between the amount of dentin removed and root strength [4–6]. Disease processes or clinical procedures that lead to dentinal loss or eccentric canal shaping result in more stress in the apical direction and in the bucco-lingual plane of the root, which may impact the overall resistance to root flexure. Rundquist and Versluis [7] called attention to the influence of the taper on the root stress during masticatory loading. They concluded that, in a tooth under compressive force, the maximum stress resulting from bending is predominantly observed at the cervical aspect of the root (cervical dentin), which may be related to coronal pre-flaring procedures. While it is undeniable that unnecessary loss of dentin tissue should be avoided, other factors such as root canal geometry and volume also impact on the resistance to fracture [8]. Therefore, it is understandable why the resistance of the root to flexion depends upon the distribution of dentin tissue around the canal wall.

Despite the passionate way that some defend that conventional canal mechanical instrumentation decreases the resistance of teeth to fracture, the current literature is composed by a limited amount of laboratory studies [9, 10], which means low-quality evidence to shape and guide the clinical decision-making process. Therefore, the idea of providing optimum dimensions for root canal mechanical preparation is one current ongoing concern in endodontic practice and science.

The degree of mechanical shaping is determined by the pre-operative dimensions of the root canal, the obturation technique, and the

restorative treatment plan. However, the greatest focus today is being able to clean the root canal space while preserving maximum strength of the tooth. Within this framework, one may argue that current mechanical preparations should keep the canal dimensions as small as possible, since instrumentation per se is ineffective in cleaning and disinfecting the inner dentinal walls in irregular and hard-to-reach areas, such as fins and isthmuses of oval-shaped canals [11–16]. On the other hand, mechanical preparation needs to suffice for creating an operational pathway to irrigate the root canal space. For that, a minimal but optimal size/taper is necessary to be set, which was not currently supported by reliable documented formal evidence.

Considering the as yet unclear situation of the minimal invasive approaches and rationales proposed to render an endodontically treated tooth predictably functional, the present text focuses on the optimal size/taper relationship necessary to avoid unnecessary overflared canals and, at the same time, to allow the turbulence and solution exchange indispensable for the minimal cleaning and disinfection conditions to assure healing. The big picture is to address and discuss the close-to-optimum operative conditions to maximize tooth strength and longevity. Moreover, advances and developments in nickel-titanium (NiTi) technology have allowed endodontics to move towards the minimally invasive dentistry paradigm.

4.2 Limitations of the Current Technology for Mechanical Shaping

The ongoing debate around the so-called minimally invasive canal shaping is indeed a matter of physical size, and it can be summarized into a single question: What's the optimal minimal canal size preparation?

The problem emerges with the limitations of current technology for canal shaping. Ideally, adequate mechanical instrumentation should uniformly plane the entire perimeter of the root canal—a kind of scrubbing action on the canal walls—thus completely removing the inner lay-

ers of heavily contaminated dentinal tissue. This, in turn, will ensure an effective removal of as much of the remaining soft tissue and bacterial biofilm as possible, which may predispose to cause or perpetuate disease, influencing the outcome of treatment [17–19]. However, current rotary and reciprocating NiTi systems are only able to prepare the main root canal space into a circular final shape, because the instrument cannot adapt to the irregular cross-section area of the canal; thus, they leave most buccal and lingual extensions unprepared [11–16, 20]. It is of note that this phenomenon cannot be observed in two-dimensional clinical periapical radiographs, which represent only the bucco-lingual projection. On the other hand, it can be easily observed in histological cross-sections and in the results from high-definition microtomography (micro-CT) studies [11–16, 20], which have underlined the suboptimal standard of mechanical preparation by the current NiTi systems. Using non-destructive micro-CT technology, it has been systematically shown that the amount of mechanically prepared root canal surface is frequently below 60% [11–16, 20–22].

In short, available NiTi systems leave a substantial amount of untreated dentin areas; therefore, it is possible to say that the current technology for canal shaping is satisfactory from a mechanical point of view, but way limited from a biological standpoint. This situation is illustrated in the sequence of Fig. 4.1. The first image (a) shows a histological cross-section of a given oval-shaped canal and the black line in the second image (b) roughly shows what the original anatomy of this canal should be—the canal before mechanical preparation. The green circle shows what is possible to obtain with the available NiTi preparation systems. The debried area always follows this very same pattern, because, as far as the NiTi instrument penetrates towards the apex, the resulting force pushes the instrument towards a single direction, where circular cutting occurs. This means that a lot of sound dentinal tissue is cut (as shown in blue in [c]) and, at the same time, a lot of contaminated

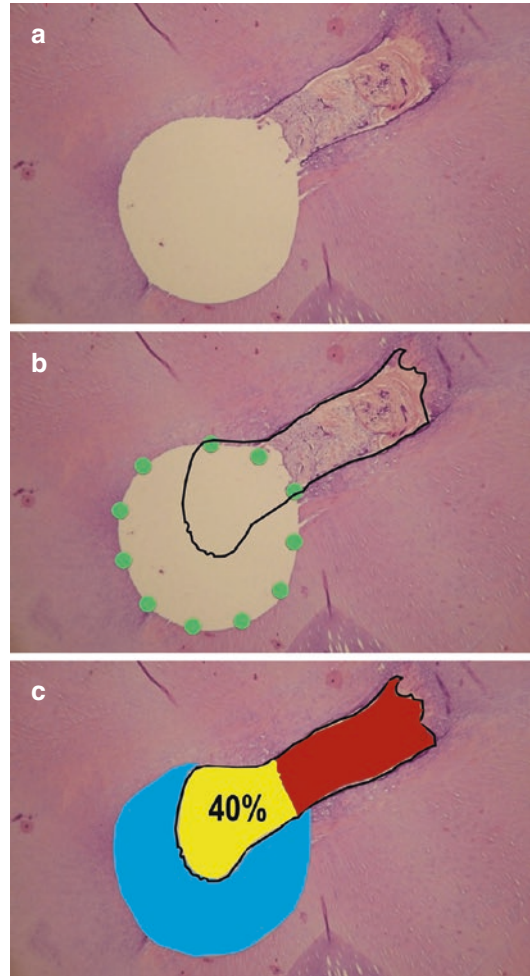


Fig. 4.1 Graphic illustration that exemplifies the dynamics that affect all mechanized systems currently available in the preparation of oval-shaped canal. In (a), we have a histological section of the canal with oval section. In (b), the black line illustrates what the original canal anatomy looked like. The green area shows the region of dentin that the mechanized system has cut. Any commercially available rotary or reciprocating system penetrates into the root space, following the same pattern as the resulting forces of this process require the instrument to settle and press on one side of the canal and only touching a fraction of the original root space (c). This process reveals that much healthy dentin tissue is eliminated (c, blue area), while a considerable area that should be mechanically debried is not removed due to the limitation of NiTi instrument technology (c, red area). Thus, the so-called real efficiency area of the mechanical debriedment process is only 40%, in a hypothetical situation of an oval canal like this example (c, yellow area)

dentin is left behind, as shown in the red area in (c). Only the yellow area is the effective cutting promoted by the NiTi preparation, which typically means that only around 40% of the effectiveness of mechanical debridement is possible in a typical oval-shaped canal like the current example.

Accordingly, the messages are crystal clear:

1. NiTi instruments only act on the central body of the canal, leaving almost all irregular areas untouched and undebrided. As such, the bacteria biofilm cannot be scrubbed out from most dentinal walls in a normal oval-shaped canal.
 2. This background puts too much responsibility on the shoulders of irrigation, which has its own limitations.
 3. Sound dentinal tissue is unnecessarily lost during shaping procedures. Future developments on mechanical shaping should be strictly focused on improving the scrubbing action and being able to uniformly plane the entire perimeter of the canal as much as possible.
- Mechanical canal preparation is invasive in nature and different degrees of dentin removal may occur as different instrumentation techniques and systems are used, which may alter the biomechanical response of teeth [23]. So, future work should focus on the quest for a balance in the ratio of canal enlargement to close-to-optimal irrigation.
1. Improving tactile sensation and control by removing cervical calcifications and dentin overhangs, which allows unimpeded access for the apical third stream, canal scouting and apical patency procedures.
 2. Facilitating larger instruments to reach the apical critical zone more loosely.
 3. Reducing procedural errors such as loss of working length and canal transportation.
 4. Optimization of infection control for twofold reasons: (a) most of bacteria is located in cervical and middle thirds of the root canal. Thus, coronal pre-flaring removes most of bacteria present in the root canal space early in treatment, contributing to the optimization of infection control and (b) coronal pre-flaring also allows deeper insertion of the irrigation needle in the earlier stages of cleaning and shaping procedures, which optimizes the irrigation. The enlarged area created by coronal pre-flaring acts as an escape space for the irrigating solution, enabling a better flow and reflux of the irrigating solution [24–26].
 5. Better control of the incidence of post-operative pain due to less bacterial extrusion through the apical foramen.
 6. Better control of instrument fracture. Ehrhardt et al. [27] performed 556 treatments and demonstrated that the use of MTwo system (VDW, Munich, Germany) after coronal pre-flaring revealed a low fracture rate, even reusing the instrument five times.
 7. Coronal pre-flaring leads to more accurate apical sizing [28], and this information can be useful to define an appropriate final diameter for apical shaping.

4.3 Preservation of Pericervical Dentin—Is Coronal Pre-flaring Still Necessary?

Coronal pre-flaring, canal scouting and glide path are early steps in mechanical canal preparation. Coronal pre-flaring can be defined as an extension of the access cavity into the cervical-most third of the canal space. Flaring the coronal portion of a narrow, calcified or difficult-to-access root canal affords several benefits by the relocation of the canal pathway, such as:

Independently of all aforesaid advantages of the pre-flaring procedure, overflaring of canals by unbalanced enlargement of its coronal region through overusing large instruments can weaken the root. Ultimately, it can compromise the outcome of the root canal treatment due to the amount of dentinal tissue removed in this key and strategic structural region, the so-called pericervical dentin (PCD). The preservation of this region can be even more important to maintain strength of endodontically treated teeth as compared to very

reduced occlusal access preparations [29]. Overall, logical reasoning claims that the loss of PCD implies in the weakening of root structure and decreased resistance to VRF. Actually, the more a canal is tapered and flared in the coronal region, the weaker the root tends to be. PCD was defined by Clark and Khademi [30] as “the dentin near the alveolar crest. This critical zone, roughly 4 mm coronal to the crestal bone and extending 4 mm apical to it, is crucial to transferring load from the occlusal table to the root, and much of the PCD is irreplaceable”. The authors move ahead saying that no man-made material can compensate the tooth structure lost in key areas of the PCD.

With all exposed plus the popularization of NiTi rotary files, it is easy to understand the rapid influx of new instruments specifically designed to perform a better-balanced coronal pre-flaring procedure. The introduction of superelastic alloys associated with variable taper instruments (not following the international ISO standardization system) and an improved cutting ability by an S-shape design has opened up a new technical possibility for the coronal pre-flaring procedure. Besides being specially designed to perform coronal pre-flaring procedures, some NiTi rotary instruments—defined as orifice shapers such as ProFile (Dentsply Tulsa Dental; Tulsa, OK, United States) or Vortex orifice openers (Dentsply Tulsa Dental)—have never really become popular, and none of them has become the archetypal instrument for the coronal pre-flaring procedure.

The introduction of reciprocating systems in late 2010 brought the possibility of a new approach for the coronal pre-flaring procedure, as a single variable regressive taper reciprocating NiTi instrument is able to enlarge the main root canal space into a minimum acceptable taper size. This approach is able to perform a significantly more conservative coronal pre-flaring procedure.

Coronal pre-flaring performed with a single reciprocating instrument is done synchronously with the canal glide path. This way, it is possible to didactically list four advantages of coronal pre-flaring directly performed with a single reciprocating instrument:

1. More conservative coronal preparation due to the regressive taper of the single reciprocating instrument.
2. Better technical workflow as a function of less transoperative stages and few instruments used.
3. Shorter learning curve.
4. Improved safety by the use of the reciprocating movement per se.

Thus, it is not erroneous to consider the coronal pre-flaring done with a single regressive taper reciprocating instrument as an efficient technical approach, aligning the most up-to-date concepts of mechanical shaping and also valuing preservation of unreplaceable dental tissues.

4.3.1 The Role of the Danger Zone

One of the critical points of the mechanical damage normally caused by over-instrumentation on an already thin dentinal wall is that it may seriously compromise the outcome of root canal treatment [31]. This kind of damage is essentially mid-root perforations or excessive loss of dentin, which have been historically related to the distal area of mesial roots of mandibular molars and, based on that, Abou-Rass et al. [32] introduced the concept of the “danger zone” (DZ) in the early 1980s. In fact, these authors formally reported what experienced clinicians already knew-often: mesial canals of mandibular molars do not assume a central position in the root with the distal area between the canal and root bifurcation being relatively thin, the so-called DZ, which is more vulnerable to strip perforations. On the other hand, the safety zone was described as the mesial area of the mesial root with a thicker dentine layer, which is often minimally instrumented by endodontic instruments.

In short, Abou-Rass et al. [32] pointed out the importance of this anatomical area during canal shaping. Nowadays, the concerns around the DZ have moved towards dentinal preservation of the critical cervical region since this over-weakening of the root seems to mitigate the overall fracture resistance standard of teeth. This topic is addressed

further where the taper of the mechanical preparation is discussed.

4.4 Evolution of NiTi-Based Preparations

4.4.1 NiTi Alloys

The use of NiTi alloy to produce instruments for root canal mechanical preparation has raised endodontic practice to a new level, revolutionizing it conceptually, practically and also economically. The NiTi technology made it possible to relate the geometric configuration of the instrument with the main anatomical features of the root canals, such as the angle and radius of curvature. Moreover, canal shaping became more centralized, giving a more precise adjustment to the canal anatomy and adequate modelling [33, 34] (Fig. 4.2). In addition, the mechanical properties and intrinsic characteristics presented by the NiTi alloy made it possible to use safety-mechanized canal shaping in a reduced treatment time with shorter learning curve [35, 36].

The NiTi alloy was developed by William Buehler in the United States in 1960, and it was firstly named NiTiNOL, an acronym for nickel (Ni), titanium (Ti) and Naval Ordnance Laboratory (NOL) [37]. In dentistry, Andreasen and Morrow [38] performed its initial application in orthodontics due to its low modulus of elasticity, shape memory effect and super flexibility. In 1975, Civjan and colleagues [39] published a manuscript containing suggestions for applying this new alloy in different dentistry specialties, including endodontics. The authors concluded that, due to the low modulus of elasticity, the construction of instruments with this alloy would allow the mechanical preparation of curved canals more efficiency and with less iatrogenic risks than using conventional manual stainless-steel instruments. The first experimental endodontic instruments made from NiTi orthodontic wires were found to have two to three times more elastic flexibility in bending, as well as superior resistance to torsional fracture, when compared to similar instruments manufactured using stainless-steel [40].

The NiTi alloys used in the manufacturing of endodontic instruments have near-equiatomic nickel and titanium proportions [40]. NiTi alloys contain three microstructural phases named austenite, martensite and R-phase, and the amounts of these phases determine the overall mechanical properties of the alloy [41]. The transformation of austenite into martensite (classic martensitic transformation) is caused by the alloy's ability to modify its atomic arrangement. The alteration of its crystalline microstructure and transformation characteristics directly influence the mechanical properties. Martensite, the low-temperature phase, is relatively soft and ductile, can be easily deformed and possesses the shape memory effect (SME) [41, 42]. In contrast, austenite, the high-temperature phase, is relatively stiff and hard, and possesses superior superelasticity (SE) [41–43]. The phase composition of the NiTi alloy is dependent on the ambient temperature and whether the alloy is cooled or heated to this temperature (Fig. 4.3). If the temperature is above the austenite finish temperature (A_f), the NiTi alloy is in the austenitic state. If the temperature is below the martensite finish temperature (M_f), the NiTi is in the martensitic state [41–43].

Among the main characteristic properties of the NiTi alloy used to manufacture endodontic instruments are the SME and SE [43–45]. SME is characterized as a property that, after relatively high deformations at temperatures below the full formation of martensite, instruments use to regain their original shape and size through subsequent heating at temperatures where austenite formation occurs (Figs. 4.4 and 4.5). In other words, SME is the ability of the NiTi alloy to recover its original shape when heated above the martensite-to-austenite transformation temperature. While the SE is characterized by the ability of the alloy to recover its original shape, even after large strains, it only occurs with the removal of tension without the need for heating (Fig. 4.6). Bending instrument and after applying forces, the instrument regains its original shape [44, 46].

In the last years, manufacturers have been performing additional metallurgical treatments on the NiTi alloys of instruments in order to improve their clinical performance. Among the most used

Fig. 4.2 Representative 3D reconstructions of the external and internal anatomy of curved mesial roots of mandibular molars, before and after root canal preparation. Changes in overall canal shape are visible in the superimposed root canals before (green) and after (red) mechanical preparation



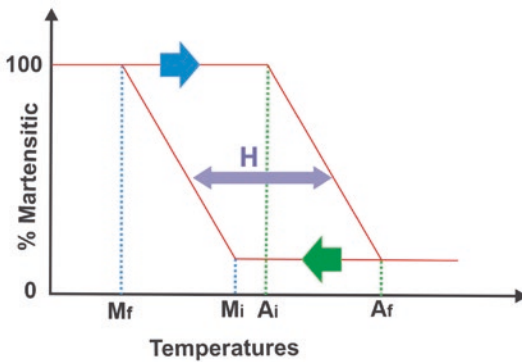


Fig. 4.3 Temperature hysteresis diagram of NiTi alloy. *Mi* martensite start temperature, *Mf* martensite finish temperature, *Ai* austenite start temperature, *Af* austenite finish temperature

treatment procedures are electropolishing and heat treatment. Electropolishing is the process of electrolytically removing components from metal parts in a highly ionic solution using an external source of electrical current. In this process, a very thin layer of material on the surface is removed, resulting in the reduction of microasperities that characterizes metal surfaces. The electropolishing of NiTi mechanized instruments, besides improving the finish of its metallic surface, also makes it more rigid [47–49].

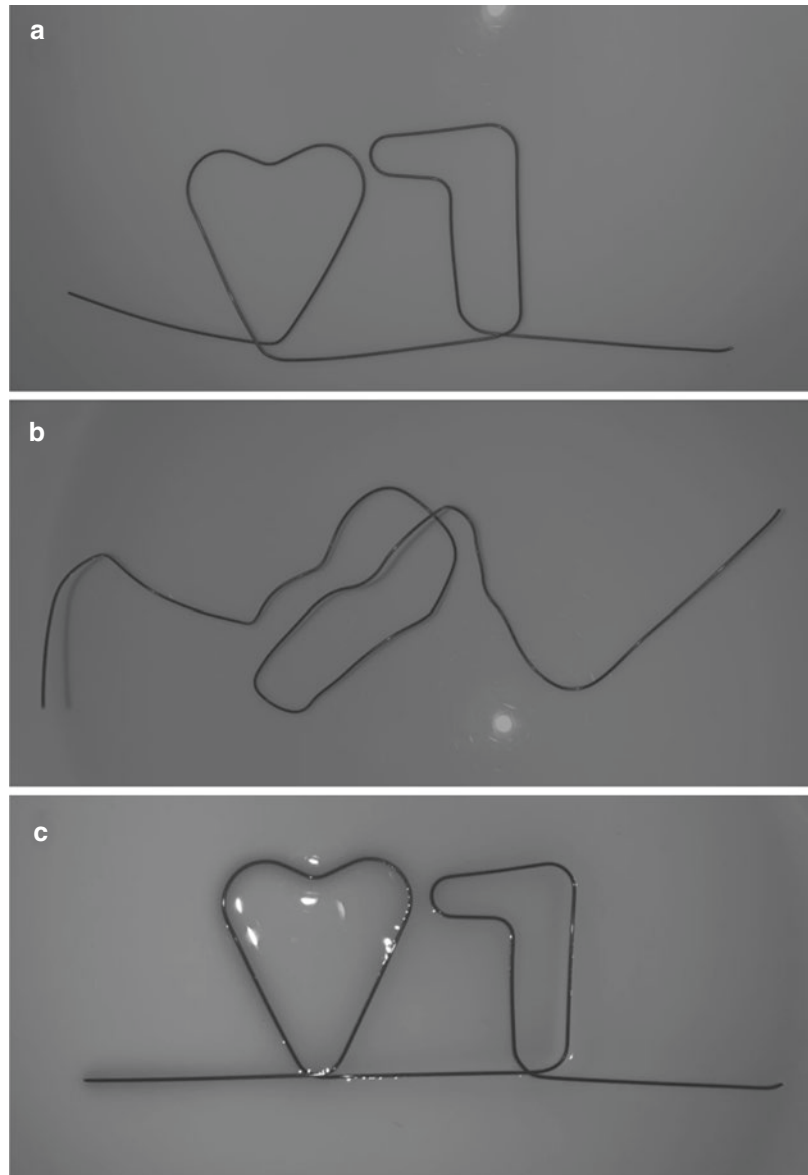
Moreover, technological advances in the thermal management of NiTi alloy have allowed the development of instruments with altered crystalline compositions, which means alloys in intermediate stages between the austenitic and martensitic phases, containing substantial stable martensite phase under clinical conditions [50]. Some examples of thermal treatments are the M-wire (Dentsply Tulsa Dental), R-phase (SybronEndo, Orange, USA), CM-wire (DS Dental, Johnson City, USA), EDM (Coltene/Whaledent AG, Altstätten, Switzerland), Gold and Blue treatments (Dentsply Tulsa Dental), T-wire (MicroMega, Besancon, France), and MaxWire (FKG Dentaire, La Chaux-de-Fonds Switzerland). While M-wire and R-phase instruments maintain an austenitic state, CM-Wire, Gold and Blue heat-treated instruments are composed of substantial amounts of martensite.

MaxWire is in the martensitic state at room temperature and changes to the austenitic state at intracanal temperature.

From a practical point of view, all new thermo-mechanically treated NiTi alloys available on the market demonstrated increased fatigue resistance and flexibility when compared to conventional NiTi alloys [51–57]. It is well known that martensitic alloys also possess higher flexibility than austenitic ones [42, 56]. Due to its improved flexibility, these martensitic instruments are indicated in the presence of extreme curvatures (Fig. 4.7). Another advantage of heat treatment is that these instruments can better maintain the root canal anatomy, so they are supposed to have an equal or better quality of root canal preparation [15, 58–60]. A recent study from Bürklein et al. [61] has demonstrated that both M-wire instruments and their Gold and Blue corresponding files have maintained the original canal curvature well with no significant differences and without fracturing. This means that M-wire files are already flexible enough to maintain root canal curvature, but presumably in most difficult root canals, the more flexible Gold and Blue alloys would better maintain the anatomy. Gold and Blue thermo-mechanically treated files also have better centring ability in both coronal and apical portions with minimal transportation [61], which is a clear advantage from a minimally invasive perspective (Fig. 4.8). The pre-bendability of a martensitic file is helpful to have better access in difficult cases. In a small mouth opening, a martensitic instrument can be pre-bent to have an easier direction, being more conservative in the coronal portion without performing early coronal enlargement and straight-line access. In addition, pre-bending these files for difficult cases permits to overcome ledges or complicated apical anatomy, such as abrupt curvatures.

However, there are also some limitations of heat-treated alloys. The major limitation of a martensitic state instrument is that the martensitic phase has a low transitional temperature, so it requires less energy for deformation. This means that plastic deformation and unwinding of these instruments can be more often experienced

Fig. 4.4 (a) NiTi alloy wire in the original shape; (b) deformed NiTi alloy; (c) NiTi alloy recovering the original shape after being heated above the martensite-to-austenite transformation temperature



(Fig. 4.9). Martensitic thermally treated instruments have a higher angle of rotation to fracture, so they can be rotated more before fracture; the force needed to deform and fracture them is lower [57, 62, 63]. Less stress is needed to deform these files inside the root canals; however, even deformed, they will fracture later. Martensitic files are very flexible and therefore perfect for highly curved root canals; however, extremely flexible instruments may have less

cutting ability. For this reason, these types of instruments may be difficult to advance in very strict root canals, enhancing the risk of distortion. In contrast, austenitic instruments reveal high torque values at fracture; thus, these files might be useful to shape straight or slightly curved constricted root canals. Therefore, it is important to find a balance between mechanical properties and flexibility and the resistance to torsion.

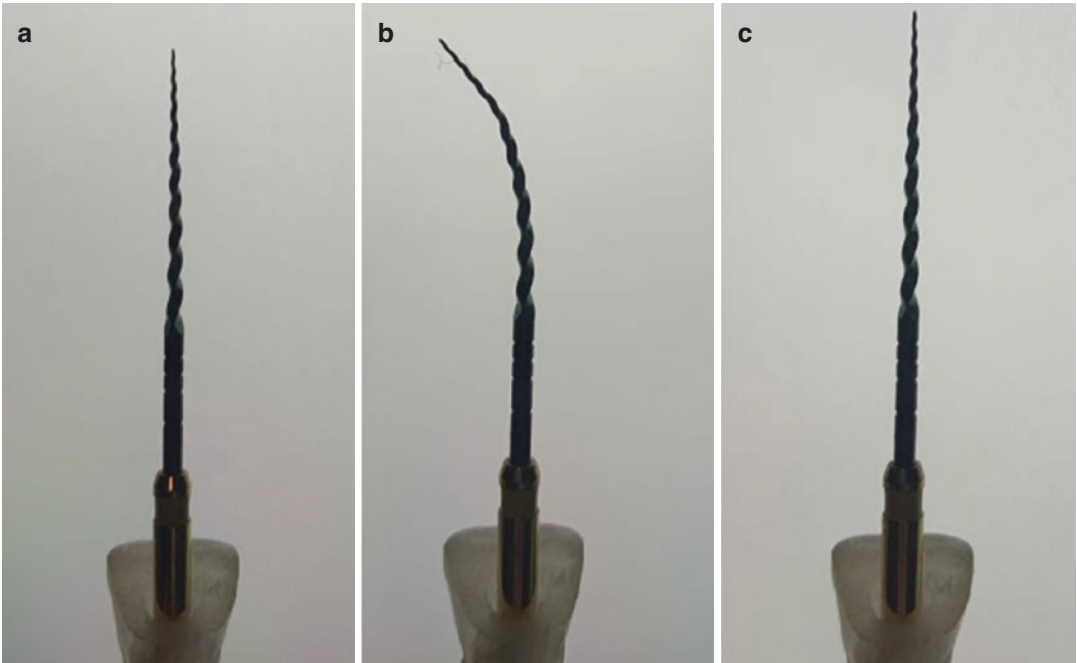


Fig. 4.5 (a) NiTi martensitic instrument in the original shape; (b) deformed NiTi instrument; (c) NiTi instrument recovering the original shape after being heated above the martensite-to-austenite transformation temperature

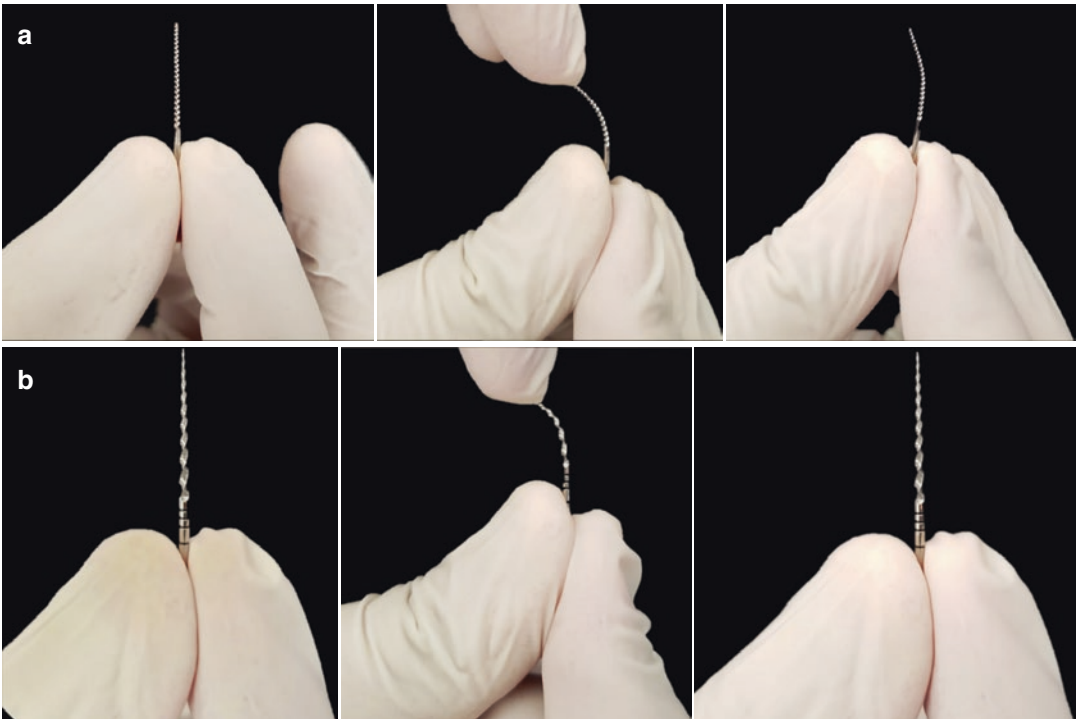


Fig. 4.6 (a) Stainless-steel instrument after the application of tension being plastically deformed; (b) NiTi instrument recovering its original shape after applying forces



Fig. 4.7 An upper premolar with an extreme double curvature



Fig. 4.8 A first upper molar treated with martensitic Blue files demonstrating respect of the original anatomy and a conservative approach



Fig. 4.9 Deformed files from several different brands

4.4.2 Shaping Kinematics

In addition to the advancements related to NiTi alloys, innovative kinematics were developed with the purpose of overperforming the conventional continuous rotation. Nowadays, reciprocating movement stands as a reliable and feasible alternative to the conventional continuous rotation [64]. In fact, reciprocating kinematics have

been extensively described and tested in mechanical endodontic procedures for stainless-steel files since the 1960s [65–74]. This “first mode” of reciprocating movement is based on symmetrical oscillation, in which the forward cutting angle is the same as the backward release angle (i.e. 30° clockwise followed by 30° counterclockwise or 45° clockwise followed by 45° counterclockwise). This kinematic was basically used for

stainless-steel instruments and now it is mainly used for mechanical scouting with stainless-steel instruments. In 2008, Yared proposed an approach to the use of the ProTaper F2 instrument (Dentsply Maillefer, Baillaguetis, Switzerland) in a reciprocating movement [75] as an alternative to the conventional continuous rotation. This “second mode” of reciprocating kinematics is a partial or asymmetrical reciprocation, in which the forward angle is bigger than the backward angle. Doing this movement continuously generates a positive angle, so that a “rotary effect” can be maintained. This means that the reciprocating movement maintains the tendency to naturally advance towards the apex because of the “rotary effect”.

Asymmetrical reciprocation kinematics can be performed using different types of angle combinations (e.g. 60–40°, 108–72° or 150–30°), which overall relieves stress on the instrument by a forward (cutting action, the instrument advances in the canal and engages dentin to cut it) and a backward (release of the instrument, which is immediately disengaged releasing the stress) movement [64]. This new kinematics extended the lifespan of NiTi instruments when compared to continuous rotation [36, 76, 77]. When actioned in reciprocating kinematics, the instruments travel a shorter angular distance than continuous rotation instruments, being subject to lower stress values, which extends its fatigue life [36, 76, 77]. Reciproc (VDW), Reciproc Blue (VDW), WaveOne (Dentsply Maillefer) and WaveOne Gold (Dentsply Maillefer) are the main examples of modern commercially available NiTi systems for root canal preparation using asymmetric reciprocating motion.

There are several advantages of using reciprocating kinematics instead of continuous rotary kinematics. The opening is the possibility of a single variable tapered reciprocating NiTi instrument able to enlarge the root canal into a minimally acceptable taper size, which is indeed appealing by the oversimplification of technical workflow procedure and reducing the overall learning curve. Under a cost-effective perspective, the use of a single disposable NiTi instrument is also advantageous over conventional multi-file rotary systems.

In addition, there is a strong body of evidence showing that reciprocating-based mechanical preparations are safer than conventional continuous rotation [36, 76–79]. Studies reported a lower incidence of fracture for reciprocating instruments (0.13–0.26%) rather than rotary files; thus, reciprocation is considered a safer movement [80–82]. It is of note that this safer shaping in clinical usage is directly related to an improved fatigue resistance shown by reciprocation over conventional continuous rotation. Actually, this was an unexpected but welcome “side-effect” once reciprocation was introduced to reduce torsional failures, but it also increased the resistance to cyclic fatigue failure and consequently the lifespan of instruments [36, 76–78]. Torsional failure occurs when the tip of the instrument is locked in the canal, while the shaft continues to rotate. If the elastic limit of the metal is exceeded, the instrument undergoes plastic deformation, which can be followed by fracture if the load is high enough. When submitted to reciprocation kinematics, an instrument has reduced torsional stress, since during the reciprocating movement the instrument engages dentin during the cutting movement, whereas the opposite movement disengages the instrument immediately afterwards. Moreover, an instrument used in reciprocation lasts longer used in a curvature rather than the same instrument used in rotation [77]. A rearrangement of the NiTi molecular structure of the instrument during the forward and backward movements may happen. Moreover, the backward movement tends to reduce the propagation of initial cracks in metal, thus reducing the possibility of fracture by cyclic fatigue [77]. The more bent the curvature is, the higher the risk of fracture for cyclic fatigue. But reciprocating files are safe to be used in most curved root canals. Since the instrument’s lifespan is increased by the reciprocating movement [36, 76–78], a higher number of root canals can be prepared in a safer way than under continuous rotary movement.

The reciprocating movement has the same or even more cutting efficiency than full rotation. Since the first moment, doubts were raised if the reciprocating movement would reduce cutting efficiency as, until that moment, continuous rota-

tion was considered the optimal movement from a cutting efficiency point of view. However, evidence demonstrated that the same file used both in rotation and in reciprocation has the same cutting ability [83, 84].

Moreover, reciprocating kinematics allows an equal or better quality of preparation. An instrument used in reciprocation has an improved shaping ability as compared to the same instrument used in continuous rotation. A recent study demonstrated that a reciprocating file remains better centred inside the root canals when compared to a rotary file [85]. The superior shaping ability promoted by the reciprocating movement is especially true for instruments with bigger sizes, which yields less canal transportation [86]. Smaller files are not the problem, as they are flexible enough to be used in both rotation and reciprocation without any clue of canal transportation. For single-file techniques, the main reason for these results is that a single-file is usually bigger than the root canal, so it can touch at least two of the opposite sides of the canal walls, the inner and the outer portion, cutting them equally. It resembles the classical “balanced force” technique by Roane et al. [87] for stainless-steel manual files, which was proposed to allow bigger instrument sizes going beyond the canal curvature with controlled canal transportation.

There are two main criticisms of reciprocation preparations: (i) instruments would be more prone to promote the development or propagation of dentinal microcracks and dentinal damage than conventional full-sequence rotary systems and (ii) the accumulation and apical extrusion of debris.

The idea that the reciprocating preparation is more related to root dentinal defects is based on the rationale that using only a single, large-tapered reciprocating instrument, which cuts substantial amounts of dentin in a short period of time, is more aggressive than conventional rotary preparation, which comprises a more progressive and slower cutting of the root dentinal tissue. However, the scenario was created by studies based only on root sectioning methods and direct observation by optical microscopy [88–94] (Fig. 4.10). These methods undoubtedly have a noteworthy drawback related to the destructive

nature of the experiment. Despite the fact that the control groups, which used unprepared teeth, seemed to validate these results because no dentinal defects could be detected, this sort of control does not take into account the potential damage produced by the interplay among three sources of stresses on the root dentin [95]:

1. The mechanical preparation.
2. The chemical attack with sodium hypochlorite-based irrigation.
3. The sectioning procedures per se.

As time went by, it was demonstrated that the correct technology to study microcracks is the 3D micro-CT non-destructive analysis. By using this method, De Deus et al. [95] showed a clear lack of causal relationship between dentinal microcracks development and canal preparation with both rotary and reciprocating systems (Fig. 4.11). This conclusion was later confirmed by other studies from different groups worldwide using the same methodology [96–100]. In addition, more recently, it was demonstrated by the association between the micro-CT analytical platform and a cadaveric experimental model that the so-called root dentinal microcracks, observable in the cross-sectional images, are indeed a phenomenon that belongs to the framework of extracted storage teeth [101] (Fig. 4.12). In other words, root dentinal microcracks are not a true clinical phenomenon, and as such, there is no more room for concerns.

The worldwide rise of reciprocating systems led to another potential drawback: single-file mechanical preparations cutting significant amounts of dentin in short periods of time are prone to force more debris, dentin chips, irrigants, remaining pulp tissue, bacteria, and their by-products through the apex. The basis for this assumption is the clinical impression that reciprocation is an overall forceful movement, which may act as a mechanical piston, pumping debris and irrigants through the apex. However, at least to some measure, this assumption may not have a well-built background, since reciprocation tries to mimic balanced force technique kinematics, which is well known as being a pressureless movement pushing less material periapically [102].

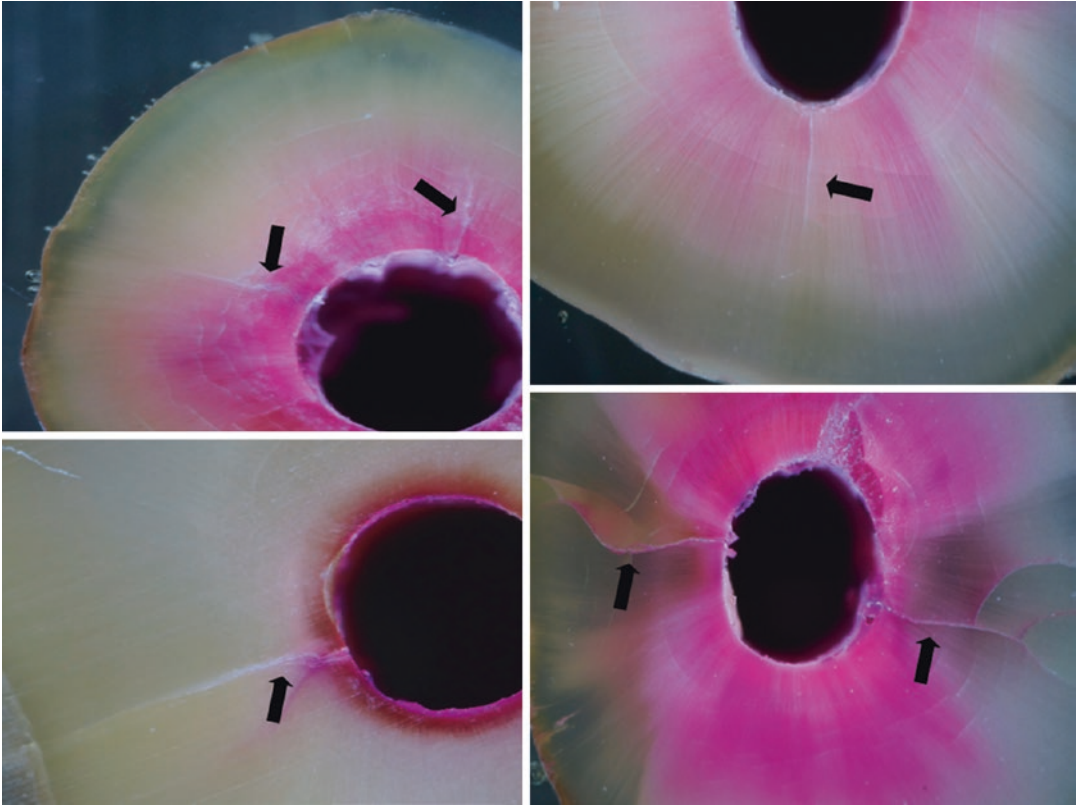


Fig. 4.10 Representative images of root canal slices showing the presence of cracks (arrows) after root canal preparation

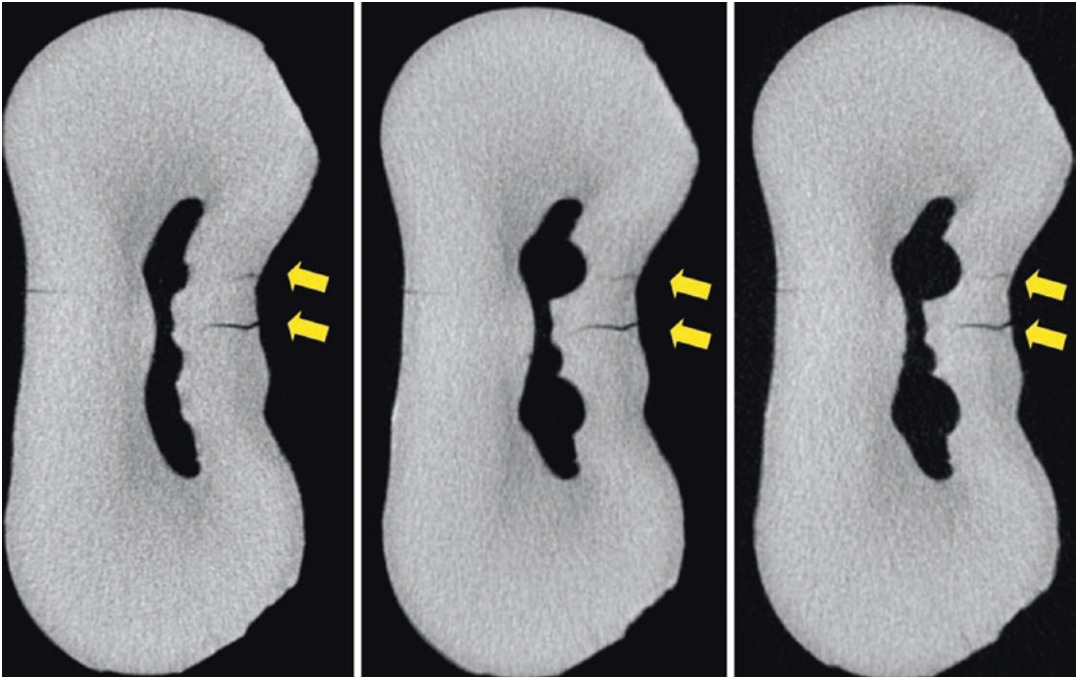


Fig. 4.11 Representative cross-section images of mesial roots of mandibular molars showing the presence of cracks (arrows) before and after preparation of the mesiobuccal and mesiolingual canals

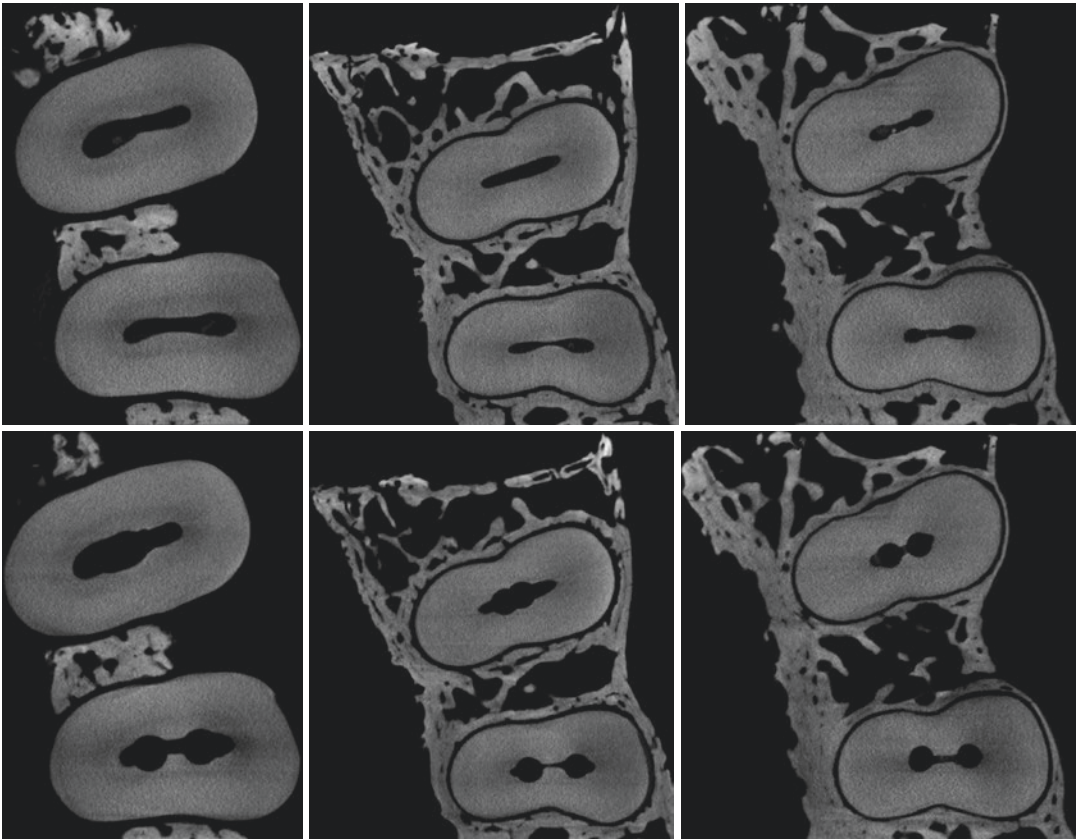


Fig. 4.12 Cross-sectional images of coronal, middle and apical thirds of roots of maxillary premolar teeth before and after root canal preparation

The issue takes place because the flutes of reciprocating instruments are designed to remove debris only in a single direction. In the framework of rotation, the forward movement continually removes dentinal debris coronally, and this is the potential reason why rotary files make a point in this regard. This means that, theoretically, movement kinematics itself may play a role in packing the debris into the irregularities of the root canal space and pushing them beyond the apex as a consequence of the backward movement (relief angle). The counter-argument says that more technical steps tend to extrude more debris and irrigants. This means that, at the end of canal shaping, conventional rotary multi-file systems will extract more undesired material than a single-file preparation.

Several studies have tried to shed some light on this topic [102–111], but the existing research

conclusions remain inconclusive. A recent comprehensive review of the literature [59] concluded that there is no influence of the movement on the accumulation and extrusion of dentinal debris. Therefore, there is no robust evidence that reciprocating files extrude more debris, even if this motion is prone to push debris down. In vivo studies [103, 112] have evaluated the possible effects of debris extrusion by measuring the substances released by the human periodontal ligament and the inflammatory procedures created by different root canal preparation techniques. The first results pointed out that hand-file instrumentation created a significantly higher inflammatory response as compared to both WaveOne and Reciproc reciprocating techniques. Moreover, WaveOne instruments were more related to higher inflammation than Reciproc, possibly due to differences in the design between these files. WaveOne and Reciproc

movements are quite the same, while the triangular design of WaveOne is probably less effective in removing debris, because its larger metal core reduces the depths of the blades and, consequently, the space to carry debris coronally [103]. The second study compared the expression of substance P and calcitonin gene-related peptide in healthy human periodontal ligaments from premolars after root canal preparation with Reciproc Blue, WaveOne Gold, XP-endo Shaper and hand files, and demonstrated lower neuropeptide release for reciprocating files when compared to both XP-endo Shaper and hand files instrumentation [112]. There are also other two *in vivo* studies that demonstrated that reciprocating instruments had similar impacts on the quality of life of patients in primary treatments when compared to rotary files [113], while reporting lower values of post-operative pain when compared to rotary files in retreatments [114].

Therefore, in a general manner, the interplay among several factors of reciprocating systems such as instrument design, improved alloy, fewer instruments, high cutting ability, and reciprocation kinematics can be used to support their clinical usage regarding the apically extruded debris issue [59]. Last but not least, the positive clinical results on post-operative pain restates that the amount of apically extruded debris is well controlled and, for sure, clinically tolerated.

Due to its previously described advantages, mainly due to excellent shaping performance plus a lower instrument fracture rate, associated with an absence of disadvantages when compared to continuous rotary kinematics, it is possible to affirm that reciprocating kinematics *per se* is today the most minimally invasive activation mode for NiTi canal preparation.

4.5 Apical Size and the Limits of Shaping

The presence of microorganisms inside the root canal system space has been widely documented as the major determining factor influencing the outcome of root canal treatment [115–117]. Thus, control of bacteria loads is the seminal goal of

endodontics [118, 119]. Debridement and disinfection protocols search to optimize intracanal bacterial load reduction, as well as vital or necrotic pulp tissue removal, that may serve as substrate for pulp space bacterial recontamination [120, 121]. The complexity of the root canal system space is well reported and known [122, 123], representing the major challenge for root canal treatment protocols. The presence of hard-to-reach areas, such as isthmuses, irregularities, ramifications and accessory canals, root dilacerations and fusions, or even developmental anomalies, such as *dens invaginatus*, may lead to strong limitations in the clinical approach [124].

One of the most relevant areas when considering the necessity of mechanical debridement and disinfection is the apical area. The working length determination is a clinical step that is susceptible to being controlled by the clinician but difficult to be performed with precision. According to Grove [125], the working length should, ideally, have its apical limit at the cemento-dentinal junction, since this is the hard tissues landmark that best approaches the soft tissues zone, which corresponds to the transition of pulp to periodontal tissues. However, this perimeter of this anatomical area can be extensive and variable [126]. Thus, the apical constriction has been presented as the anatomic apical limit, where the root canal instrumentation and obturation should be finished [127]. Important histological studies on apical anatomy, developed in the second half of the past century [128], noticed that the anatomical apex, apical foramen and apical constriction were different morphologic landmarks with different locations among them. Moreover, the area of minor diameter, or apical constriction, usually near the cemento-dentinal junction, displayed an average distance to the centre of the apical foramen of 0.524 mm [128]. The distance between the anatomical apex and the apical constriction may vary from 0.07 mm to 2.69 mm, with an average distance of 0.89 mm [129]. However, recent robust micro-CT-based studies revealed that these differences might even be larger [130] and also different anatomic configurations of the apical constriction have also been described.

Considering the variations, emphasis was given in understanding this not only in the distance between the apical constriction and the anatomical apex but also in the apical typology. The exact location of the apical constriction is extremely difficult to establish in clinical practice. Today, there is no doubt about the superiority of electronic apex locators working length determination over the traditional radiographic method of determining the apical constriction [131, 132]. Actually, the combined method of using the electronic apex locator plus radiographic confirmation is the most reliable approach to determine the apical limit of instrumentation [132]. In the 1960s, Ingle [133] proposed the apical constriction as the apical limit of root canal instrumentation, which became a classic concept in endodontics. Since the narrow diameter position of the apical constriction does not match the radiographic apex, the author recommends that the working length determination should be performed 0.5–1.0 mm short with regard to the radiographic apex. Moreover, the shaping and filling procedures performed at the apical limit through the X-ray could be easily considered as over-instrumentation and overfilling. Ricucci and Langeland [127] have performed a histological evaluation of the periapical tissues in humans at several follow-up periods after root canal treatments. They noticed that, independently of the pulp diagnosis, the results were more favourable when root canal instrumentation and filling had their apical limit at the level or slightly short of apical constriction. Regardless of the symptoms, the inflammatory reaction was always observed when overfilling was present.

Two problems might be associated with the apical limit of the instrumentation: the complex morphology itself and the fact that this complex anatomy may harbour biofilm, which may dictate a poor root canal treatment outcome. Minimizing the impact of infection on treatment outcomes may be performed through careful apical chemo-mechanical instrumentation. Although the choice of the apical constriction might be more easily accepted by both clinical and scientific communities as the reference point for the apical limit of root canal preparation, the

desirable size of the apical preparation still remains controversial. Taking into consideration the documented sizes of apical constriction [128], apical preparations to ISO sizes from 0.25 mm to 0.35 mm have been recommended [133–135]; however, this approach is easy questionable, considering the amount of unprepared intracanal surfaces left behind [136]. Weiger et al. [137] performed an in vitro assessment of the most appropriate apical enlargement for both maxillary and mandibular molars using 212 root canals. The authors concluded that enlarging to more than 0.40 mm above the original apical size in maxillary palatal and mandibular distal canals would lead to a complete circumferential preparation of the original apical morphology in 78% of cases, while the enlargement to more than 0.30 mm in maxillary buccal and mandibular mesial canals was able to completely instrument the apical morphology in 72% of cases. Moreover, the apical preparation to more than 0.60 mm above the original apical size would lead to 98% of cases with a complete circumferential preparation of the original apical anatomy. Globally, this represents 6–8 sizes above the first apical binding file. Although the authors have stated that root canals should be instrumented to larger sizes than normally recommended, it is also important to notice that this may be associated with a higher risk of iatrogenic errors, such as zips, ledges or perforations. These risks are much less common when using NiTi instruments [138]; however, they can still occur, especially in over-preparations, independently of the kinematic used [139].

Although the capacity to mechanically shape the apical portion of the root canal is of major clinical importance, infection control appears to be the seminal condition to trigger the healing process and determine the treatment outcome. Taking this into consideration, some authors addressed bacterial load reduction depending on the apical enlargement. Mickel et al. [140] performed the inoculation of 100 single-rooted teeth with *Enterococcus faecalis*, followed by instrumentation to 1, 2 and 3 sizes above the first crown-down file to reach the apical limit. The authors concluded that there was a signifi-

cant increase in the number of samples with negative cultures in the larger apical sizes. Rodrigues et al. [141] performed the apical preparation up to the first and third instrument of a rotary system, using saline or sodium hypochlorite irrigation, and concluded that the apical instrumentation up to the third instrument provided superior bacterial control, independently of the irrigation used, although superior results were noticed with sodium hypochlorite. Taking these results into consideration, larger apical preparations seem to be able to optimize bacterial control.

When deciding which apical preparation to choose for a particular clinical case, other factors such as smear layer removal, debris extrusion or post-operative pain are also to be considered. A scanning electron microscopic analysis of debris and smear layer present in the apical portion of the root canal after instrumentation with file sizes of 0.20 mm and 0.25 mm with both 4% and 6% tapers, respectively, has shown that, independently of the taper, debridement with the larger file size was superior with regard to smear layer elimination [142]. As for the apical extrusion of debris and bacteria, an *in vitro* study noticed that the debris extrusion was lower when performing instrumentation with crown-down techniques with smaller tapers as opposed to larger taper and full-length linear instrumentation [143]. Regarding the post-operative pain evaluated in randomized clinical trials, the maintenance of apical patency during apical preparation, apparently, does not influence post-operative pain [144], while contradictory information exists on the influence of apical foramen enlargement [145, 146]. The decision of performing or not performing apical patency during root canal instrumentation is not consensual. Some histological studies have noticed acute apical inflammatory responses [126, 127], while others suggest [17] that infected debris might be extruded during root canal treatment procedures when patency is included in the protocol. However, other evidence supports this technical aspect arguing the reduction in accumulation of soft tissue remnants in the apical region [147], which attests to

superior irrigation in the apical third [148] and, ultimately, superior bacterial elimination around the apical foramen [149]. Moreover, the apical patency step also minimizes the risk of iatrogenic errors, such as canal transportation, ledges, apical perforations or loss of working length [147, 150].

Although the decision on which apical size to choose should be based on several factors, it is also important to understand that some *in vitro* assessments are difficult to extrapolate to clinical practice. Understanding how all these variables are clinically combined in the resolution, or not, of clinical cases is also important. A long-term outcome study [151], with observation periods up to 5 years, concluded that apical preparation sizes between 0.20 mm and 0.40 mm and between 0.45 mm and 1.00 mm had exactly the same prognosis. Another retrospective study concluded that there was no difference in the clinical success rate with different apical preparation sizes, although a decrease of the success rate along with an increase of the apical size was also noticed [152]. A randomized controlled trial [153], which followed 167 patients over 12 months after root canal treatment of pulp necrosis cases, used five different groups in which the apical size was enlarged to 2, 3, 4, 5 and 6 sizes above the first apical binding file. The authors concluded that enlarging to 3 sizes larger than the first binding apical file was adequate, and further enlargement did not provide any benefit. This may be seen as a much more conservative approach.

Although preparation size seems to matter with regard to the root canal treatment prognosis, it is also important to balance the advantages of large apical sizes with the conservative approach of the smaller sizes. For these reasons, the authors have developed a clinical concept called “visual gauging” that aims to customize the apical preparation size on the specific canal that should be treated [154]. In this technique, the most important aspect to be evaluated from a clinical point of view to decide the final apical size of enlargement is the type of dentin debris cut that remains on the tip of the instrument. As a consequence, some different clinical conditions may happen

depending on the characteristics of the dentin debris cut by mechanical files:

1. Presence of pulp remnants debris or “pink/red” dentin debris on the tip of the instrument used (in vital cases): pending that the correct working length has been chosen, the diameter of apical preparation is still insufficient and residual pulp is probably still present.
2. Very little dentin debris present inside the flutes of the apical 3–4 mm of the instrument used: the diameter of apical preparation is still insufficient to cut dentinal walls in the apical third.
3. Presence of “yellow/brown” dentin debris on the tip of the instrument used (in necrotic cases): even if probably the instrument is circumferentially cutting dentinal walls in the apical third, this is still contaminated dentin that requires further apical enlargement.
4. Presence of white clean dentin inside the flutes of the apical 1–2 mm of the instrument used: the instrument is cutting sound dentin in the apical third but probably not circumferentially.
5. Presence of white clean dentin inside the flutes of the apical 3–4 mm of the instrument used: presumably the instrument is cutting sound dentin circumferentially in the apical third and this may be the correct size of apical preparation. Results from a microbiological analysis of the different types of dentin that remained on the tip of the instrument described above seem to confirm that less bacteria were present in this last type of dentin cut with respect to the “brown-yellow” type described above (Plotino and Grande unpublished results).

Moreover, a micro-CT study has assessed possible microcrack formation after root canal instrumentation with two different reciprocating and a conventional full-sequence rotary system, with size 25 and after enlarging to size 40. No new cracks were noticed after the initial instrumentation or after the apical enlargement [95]. Thus, remaining minimally invasive in apical size diameters might not suggest superior outcomes from both a microbiological and biomechanical point of view.

4.6 Taper of Root Canal Instrumentation

The main objectives of mechanical instrumentation in endodontics are not only restricted to the removal of vital and necrotic tissues from the root canal system space but also in the creation of enough intracanal space to promote efficient intracanal irrigation and medication in order to control the root canal infection [155, 156]. It also aims to facilitate the root canal obturation procedures and preserve the location and integrity of the root canal apical morphology while avoiding iatrogenic damage of root and root canal anatomy. It should also avoid the aggression of periapical tissues, whether bone or periodontal ligament, while being able to preserve sound dentin in order to allow a good structural prognosis [150]. To achieve these mechanical instrumentation goals, Schilder [157] has idealized five root canal shape design objectives plus four biological objectives. As for the shaping design, it was advocated that the final root canal shape should be a continuous tapering funnel from the apex to the coronal canal opening, the canal cross-sectional diameter should be narrower at every point apically, the shaped canal should preserve the original morphology, the apical foramen should remain in the same position and the apical opening should remain as small as possible. As for the biological objectives of the mechanical preparation, it should be kept confined to the root canal system only, it should not force dentin debris with necrotic tissue beyond the foramen, it should be able to remove all tissues from the intracanal space and it should create enough space for intracanal disinfection [157]. Although intracanal infection is mainly controlled by irrigation, the mechanical instrumentation itself may also significantly reduce the bacterial count. A classic study from Byström and Sundqvist [158] was able to document a significant reduction of the bacterial count between 100- and 1000-fold on teeth with necrotic pulp and apical periodontitis by performing only mechanical instrumentation with saline irrigation. Although a strong reduction was noticed, no case became bacteria-free after the first appoint-

ment, and seven teeth out of a total of 15 became bacteria-free only after the fifth visit. Another study from Orstavik et al. [159] performed the mechanical shape of the root canals in 23 teeth using irrigation only with physiological saline, and concluded that only 13 cases became bacteria-free. Both studies concluded that although a significant bacterial load reduction was noticed after mechanical preparation, the results were clearly insufficient in reducing the bacterial load to a desired level. Another study from Siqueira et al. [160] performed an in vitro assessment on the efficacy of several instrumentation techniques with different regimens in reducing the intracanal bacterial load. After having the root canals inoculated with *Enterococcus faecalis*, they were shaped by using one of two mechanized methodologies and one of four root canal irrigation protocols. The four experimental groups were able to provide a bacterial load decrease between 78.4% (2.5% sodium hypochlorite with citric acid) and 60.3% (2.5% sodium hypochlorite alone) of the original microbial count. As for the control group with instrumentation assisted with saline solution irrigation, the mean bacterial reduction was 38.3%. The authors concluded that all groups reached significantly higher reductions of the microbial load when compared to the saline solution group. Therefore, the combination of mechanical instrumentation with root canal irrigation appears to be the most reliable method to guarantee effective root canal disinfection.

Theoretically, root canal instrumentation with large-tapered instruments would be able to clean more effectively a less tapered root canal. However, due to the complexity of the root canal system morphology, which presents fins, inner surface irregularities, isthmuses, transversal anastomoses or oval canal shapes, the concept of larger tapers has been proved as not having the expected practical relevance with several studies showing similar results in root canal cleanliness when comparing smaller with larger tapers [142, 161–163].

The percentage of untouched inner root canal area after mechanical instrumentation may be as high as 40–55%, according to micro-CT analysis

[11, 164]. A minimally invasive treatment should aim to reduce the amount of untouched inner area not by increasing the instrumentation taper but by using complementary cleaning methods, avoiding unnecessary dentin removal from the middle and coronal portions of the root canal, which ultimately may lead to a lower resistance to root fracture [10]. A recent study has also demonstrated that using modern activation devices may guarantee optimal canal cleanliness in the middle and coronal thirds, even in root canals with a minimal preparation size of 0.20/taper 0.04 [142], but it must be underlined that an increase in the apical diameter of preparation is still needed to obtain cleaner canals in the apical third [59].

Thus, a root canal instrumentation procedure reaching an adequate diameter of apical enlargement while maintaining a reduced taper or a limited maximum coronal file diameter seems to best follow the tendency of modern endodontics, which aims to find a balance between a minimally invasive intervention to minimize unnecessary dental structure removal and the need to reach biological and microbiological objectives in cleaning the root canal space.

4.7 Concluding Remarks

In summary, the era of minimally invasive endodontics is yet in its first childhood depending on more consistent scientific support and improved technology to become a standard affordable class of treatment.

The rationale of this chapter follows from the fact that the current concerns around the so-called minimally invasive endodontics is indeed a pursuit for optimal balance between what should be taken and what should be preserved. In order words, a matter of size. The rationale is that, while an overall smaller size root canal treatment (from the crown to the apex) may better preserve the important PCD tissue and thus improve the long-term retention of the tooth, it may compromise proper disinfection, cleanliness and filling of the root canal space and thus compromise the healing process in infected cases. On the other hand, over-accessed and over-prepared root

canals may not only render disinfection, cleanliness (especially in the coronal and mid-root areas where the majority of bacteria biofilm is present) and filling easier and more effective procedures but also increase teeth predisposition to VRF by a significant reduction of root structure.

Sooner or later, minimally invasive techniques and instruments will be better supported by the rigour of the scientific method. Nevertheless, in the meantime, caution with this topic is very necessary, as common-sense logic would lead to biased ways of thinking that superficial technical approaches such as “ninja accesses” or “non-shaped canals” can improve the long-term retention of teeth.

In its current status, minimally invasive endodontics is a bunch of very technically sensitive approaches strictly and fundamentally based on the operator’s skills and experience. In this scenario, the operative microscope is restated as the backbone of contemporary endodontic practice, which is a strong positive aspect of this discussion. However, there is an important educational cost involved with minimally invasive endodontics that needs to be taken into consideration; therefore, it is key to scientifically test and define how operative procedures can indeed be meaningful in the improvement of the long-term retention of teeth.

References

- Rivera EM, Walton RE. Longitudinal tooth cracks and fractures: an update and review. *Endod Topics*. 2015;33:14–42.
- Arnold LH. Discussion. *J Am Dent Assoc*. 1931;18:483.
- Touré B, Faye B, Kane AW, Lo CM, Niang B, Boucher Y. Analysis of reasons for extraction of endodontically treated teeth: a prospective study. *J Endod*. 2011;37:1512–5.
- Currey JD. The design of mineralized hard tissues for their mechanical functions. *J Exp Biol*. 1999;202:3285–94.
- Kinney JH, Habelitz S, Marshall SJ, Marshall GW. The importance of intrafibrillar mineralization of collagen on the mechanical properties of dentin. *J Dent Res*. 2003;82:957–61.
- Missau T, De Carlo BM, Michelon C, et al. Influence of endodontic treatment and retreatment on the fatigue failure load, numbers of cycles for failure, and survival rates of human canine teeth. *J Endod*. 2017;43:2081–7.
- Rundquist BD, Versluis A. How does canal taper affect root stresses? *Int Endod J*. 2006;39:226–37.
- Eliasson S, Bergstrom J, Sanda A. Periodontal bone loss of teeth with metal posts: a radiographic study. *J Clin Periodontol*. 1995;22:850–3.
- Tian SY, Bai W, Jiang WR, Liang YH. Fracture resistance of roots in mandibular premolars following root canal instrumentation of different sizes. *Chin J Dent Res*. 2019;22:197–202.
- Krikeli E, Mikrogeorgis G, Lyroudia K. In vitro comparative study of the influence of instrument taper on the fracture resistance of endodontically treated teeth: an integrative approach-based analysis. *J Endod*. 2018;44:1407–11.
- Paqué F, Balmer M, Attin T, Peters OA. Preparation of oval-shaped root canals in mandibular molars using nickel-titanium rotary instruments: a micro-computed tomography study. *J Endod*. 2010;36:703–7.
- Paqué F, Peters OA. Micro-computed tomography evaluation of the preparation of long oval root canals in mandibular molars with the self-adjusting file. *J Endod*. 2011;37:517–21.
- Versiani MA, Leoni GB, Steier L, et al. Micro-computed tomography study of oval-shaped canals prepared with the self-adjusting file, Reciproc, WaveOne and Pro-Taper Universal systems. *J Endod*. 2013;39:1060–6.
- De-Deus G, Belladonna FG, Silva EJ, et al. Micro-CT evaluation of non-instrumented canal areas with different enlargements performed by NiTi systems. *Braz Dent J*. 2015;26:624–9.
- Belladonna FG, Carvalho MS, Cavalcante DM, et al. Micro-computed tomography shaping ability assessment of the new blue thermal treated Reciproc instrument. *J Endod*. 2018;44:1146–50.
- Silva AA, Belladonna FG, Rover G, et al. Does ultra-conservative access affect the efficacy of root canal treatment and the fracture resistance of two-rooted maxillary premolars? *Int Endod J*. 2020;53:265–75.
- Siqueira JF Jr. Microbial causes of endodontic flare-ups. *Int Endod J*. 2003;36:453–63.
- Waltimo T, Trope M, Haapasalo M, Ørstavik D. Clinical efficacy of treatment procedures in endodontic infection control and one year follow-up of periapical healing. *J Endod*. 2005;31:863–6.
- Siqueira JF Jr, Roças IN. Clinical implications and microbiology of bacterial persistence after treatment procedures. *J Endod*. 2008;34:1291–301.
- De-Deus G, Belladonna FG, Simões-Carvalho M, et al. Shaping efficiency as a function of time of a new heat-treated instrument. *Int Endod J*. 2019;52:337–42.
- Rover G, Belladonna FG, Bortoluzzi EA, De-Deus G, Silva EJ, Teixeira CS. Influence of access cavity design on root canal detection, instrumentation effi-

- cacy, and fracture resistance assessed in maxillary molars. *J Endod.* 2017;43:1657–62.
22. Zuolo ML, Zaia AA, Belladonna FG, et al. Micro-CT assessment of the shaping ability of four root canal instrumentation systems in oval-shaped canals. *Int Endod J.* 2018;51:564–71.
 23. Kishen A. Mechanisms and risk factors for fracture predilection in endodontically treated teeth. *Endod Topics.* 2006;13:57–83.
 24. Kessler JR, Peters DD, Lorton L. Comparison of the relative risk of molar root perforations using various endodontic instrumentation techniques. *J Endod.* 1983;9:439–47.
 25. Isom TL, Marshall JG, Baumgartner JC. Evaluation of root thickness in curved canals after flaring. *J Endod.* 1995;21:368–71.
 26. Wu MK, van der Sluis LW, Wesselink PR. The risk of furcal perforation in mandibular molars using gates-Glidden drills with anticurvature pressure. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod.* 2005;99:378–82.
 27. Ehrhardt IC, Zuolo ML, Cunha RS, et al. Assessment of the separation incidence of mtwo files used with preflaring: prospective clinical study. *J Endod.* 2012;38:1078–81.
 28. Tan BT, Messer HH. The effect of instrument type and preflaring on apical file size determination. *Int Endod J.* 2002;35:752–8.
 29. Reeh ES, Messer HH, Douglas WH. Reduction in tooth stiffness as a result of endodontic and restorative procedures. *J Endod.* 1989;15:512–6.
 30. Clark D, Khademi J. Modern molar endodontic access and directed dentin conservation. *Dent Clin N Am.* 2010;54:249–73.
 31. Estrela C, Decurcio DA, Rossi-Fedele G, Silva JA, Guedes OA, Borges ÁH. Root perforations: a review of diagnosis, prognosis and materials. *Braz Dent J.* 2018;18:e73.
 32. Abou-Rass M, Frank AL, Glick D. The anticurvature filing method to prepare the curved root canal. *J Am Dent Assoc.* 1980;101:792–4.
 33. Haapasalo M, Shen Y. Evolution of nickel-titanium instruments: from past to future. *Endod Topics.* 2013;29:3–17.
 34. Pasqualini D, Alovisei M, Cemenasco A, et al. Micro-computed tomography evaluation of ProTaper Next and BioRace shaping outcomes in maxillary first molar curved canals. *J Endod.* 2015;41:1706–10.
 35. You SY, Bae KS, Baek SH, Kum KY, Shon WJ, Lee W. Lifespan of one nickel-titanium rotary file with reciprocating motion in curved root canals. *J Endod.* 2010;36:1991–4.
 36. 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;43:1063–8.
 37. Buehler W, Gilfrich J, Wiley RC. Effects of low-temperature phase changes on the mechanical properties of alloys near composition TiNi. *Int J Appl Phys.* 1963;34:1475–7.
 38. Andreasen GF, Morrow RE. Laboratory and clinical analyses of nitinol wire. *Am J Orthod Dentofac Orthop.* 1978;73:142–51.
 39. Civjan S, Huget EF, DeSimon LB. Potential applications of certain nickel-titanium (nitinol) alloys. *J Dent Res.* 1975;54:89–96.
 40. Walia HM, Brantley WA, Gerstein H. An initial investigation of the bending and torsional properties of Nitinol root canal files. *J Endod.* 1988;14:346–51.
 41. Lopes HP, Gambarra-Soares T, Elias CN, et al. Comparison of the mechanical properties of rotary instruments made of conventional nickel-titanium, M-wire, or nickel-titanium alloy in R-phase. *J Endod.* 2013;39:516–20.
 42. Zupanc J, Vahdat-Pajouh N, Schäfer E. New thermomechanically treated NiTi alloys—a review. *Int Endod J.* 2018;51:1088–103.
 43. Zhou H, Peng B, Zheng YF. An overview of the mechanical properties of nickel-titanium endodontic instruments. *Endod Topics.* 2013;29:42–54.
 44. Otsuka K, Wayman CM. Shape memory alloys. 1st ed. Cambridge: Cambridge University Press; 1998.
 45. Alapati SB, Brantley WA, Iijima M, et al. Metallurgical characterization of a new nickel-titanium wire for rotary endodontic instruments. *J Endod.* 2009;35:1589–93.
 46. Otsuka K, Ren X. Physical metallurgy of Ti-Ni based shape memory alloys. *Prog Mater Sci.* 2005;50:511–678.
 47. Lee DH, Park B, Saxena A, Serene TP. Enhanced surface hardness by boron implantation in Nitinol alloy. *J Endod.* 1996;22:543–6.
 48. Rapisarda E, Bonaccorso A, Tripi TR, Fragalk I, Condorelli GG. The effect of surface treatments of nickel-titanium files on wear and cutting efficiency. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod.* 2000;89:363–8.
 49. Rapisarda E, Bonaccorso A, Tripi TR, Condorelli GG, Torrisi L. Wear of nickel-titanium endodontic instruments evaluated by scanning electron microscopy: effect of ion implantation. *J Endod.* 2001;27:588–92.
 50. Thompson SA. An overview of nickel-titanium alloys used in dentistry. *Int Endod J.* 2000;33:297–310.
 51. Al-Hadlaq SM, Aljarbou FA, AlThumairy RI. Evaluation of cyclic flexural fatigue of M-wire nickel-titanium rotary instruments. *J Endod.* 2010;36:305–7.
 52. 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;38:398–401.
 53. Braga LC, Faria Silva AC, Bueno VT, de Azevedo Bahia MG. Impact of heat treatments on the fatigue resistance of different rotary nickel–titanium instruments. *J Endod.* 2014;40:1494–7.
 54. Plotino G, Testarelli L, Al-Sudani D, Pongione G, Grande NM, Gambarini G. Fatigue resistance of rotary instruments manufactured using differ-

- ent nickel-titanium alloys: a comparative study. *Odontology*. 2014;102:31–5.
55. De-Deus G, Silva EJ, Vieira VT, et al. Blue thermomechanical treatment optimizes fatigue resistance and flexibility of the Reciproc files. *J Endod*. 2017;43:462–6.
 56. Silva EJ, Vieira VT, Hecksher F, Dos Santos Oliveira MR, Dos Santos AH, Moreira EJL. Cyclic fatigue using severely curved canals and torsional resistance of thermally treated reciprocating instruments. *Clin Oral Investig*. 2018;22:2633–8.
 57. Silva EJ, Giraldez JFN, de Lima CO, Vieira VTL, Elias CN, Antunes HS. Influence of heat treatment on torsional resistance and surface roughness of nickel-titanium instruments. *Int Endod J*. 2019;52:1645–51.
 58. Bürklein S, Hinschitz K, Dammaschke T, Schäfer E. Shaping ability and cleaning effectiveness of two single-file systems in severely curved root canals of extracted teeth: Reciproc and WaveOne versus Mtwo and ProTaper. *Int Endod J*. 2012;45:449–61.
 59. Plotino G, Ahmed HM, Grande NM, Cohen S, Bukiet F. Current assessment of reciprocation in endodontic preparation: a comprehensive review—part II: properties and effectiveness. *J Endod*. 2015;41:1939–50.
 60. Zanesco C, Só MV, Schmidt S, Fontanella VR, Graziotin-Soares R, Barletta FB. Apical transportation, centering ratio, and volume increase after manual, rotary, and reciprocating instrumentation in curved root canals: analysis by micro-computed tomographic and digital subtraction radiography. *J Endod*. 2017;43:486–90.
 61. Bürklein S, Flüch S, Schäfer E. Shaping ability of reciprocating single-file systems in severely curved canals: WaveOne and Reciproc versus WaveOne Gold and Reciproc blue. *Odontology*. 2019;107:96–102.
 62. Pedullà E, Lo Savio F, Boninelli S, et al. Torsional and cyclic fatigue resistance of a new nickel-titanium instrument manufactured by electrical discharge machining. *J Endod*. 2016;42:56–9.
 63. Silva EJ, Hecksher F, Antunes HDS, De-Deus G, Elias CN, Vieira VTL. Torsional fatigue resistance of blue-treated reciprocating instruments. *J Endod*. 2018;44:1038–41.
 64. Grande NM, Ahmed HM, Cohen S, Bukiet F, Plotino G. Current assessment of reciprocation in endodontic preparation: a comprehensive review-part I: historic perspectives and current applications. *J Endod*. 2015;41:1778–83.
 65. Frank AL. An evaluation of the Giromatic endodontic handpiece. *Oral Surg Oral Med Oral Pathol*. 1967;24:419–21.
 66. Klayman S, Brilliant J. A comparison of the efficacy of serial preparation versus Giromatic preparation. *J Endod*. 1974;1:334–7.
 67. Turek T, Langeland K. A light microscopic study of the efficacy of the telescopic and the Giromatic preparation of root canals. *J Endod*. 1982;8:437–43.
 68. Lehman JW, Gerstein H. An evaluation of a new mechanized endodontic device: the Endolift. *Oral Surg Oral Med Oral Pathol*. 1982;53:417–24.
 69. Spyropoulos S, Eldeeb ME, Messer HH. The effect of Giromatic files on the preparation shape of severely curved canals. *Int Endod J*. 1987;20:133–42.
 70. Ianno NR, Weine FS. Canal preparation using two mechanical handpieces: distortions, ledging, and potential solutions. *Compendium*. 1989;10:100–2, 104–5.
 71. Besse H, Normand B, Labarre P, Woda A. An evaluation of four methods of root canal preparation using 14C urea. *J Endod*. 1991;17:54–8.
 72. Hennequin M, Andre JF, Botta G. Dentin removal efficiency of six endodontic systems: a quantitative comparison. *J Endod*. 1992;18:601–4.
 73. Hülsmann M, Stryga F. Comparison of root canal preparation using different automated devices and hand instrumentation. *J Endod*. 1993;19:141–5.
 74. Dautel-Morazin A, Vulcain JM, Guigand M, Bonnaure-Mallet M. An ultrastructural study of debris retention by endodontic reamers. *J Endod*. 1995;21:358–61.
 75. Yared G. Canal preparation using only one Ni-Ti rotary instrument: preliminary observations. *Int Endod J*. 2008;41:339–44.
 76. Gambarini G, Gergi R, Naaman A, et al. Cyclic fatigue analysis of twisted file rotary NiTi instruments used in reciprocating motion. *Int Endod J*. 2012;45:802–6.
 77. Pedullà E, Grande NM, Plotino G, et al. Influence of continuous or reciprocating motion on cyclic fatigue resistance of 4 different nickel-titanium rotary instruments. *J Endod*. 2013;39:258–61.
 78. Pérez-Higueras JJ, Arias A, de la Macorra JC. Cyclic fatigue resistance of K3, K3XF, and twisted file nickel-titanium files under continuous rotation or reciprocating motion. *J Endod*. 2013;39:1585–8.
 79. 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;27:22–7.
 80. Cunha RS, Junaid A, Ensinas P, Nudera W, Bueno CE. Assessment of the separation incidence of reciprocating WaveOne files: a prospective clinical study. *J Endod*. 2014;40:922–4.
 81. Plotino G, Grande NM, Porciani PF. Deformation and fracture incidence of Reciproc instruments: a clinical evaluation. *Int Endod J*. 2015;48:199–205.
 82. Bueno CSP, Oliveira DP, Pelegrine RA, Fontana CE, Rocha DGP, Bueno CEDS. Fracture incidence of WaveOne and Reciproc files during root canal preparation of up to 3 posterior teeth: a prospective clinical study. *J Endod*. 2017;43:705–8.
 83. Giansiracusa Rubini A, Plotino G, Al-Sudani D, et al. A new device to test cutting efficiency of mechanical endodontic instruments. *Med Sci Monit*. 2014;20:374–8.

84. Gambarini G, Giansiracusa Rubini A, Sannino G, et al. Cutting efficiency of nickel-titanium rotary and reciprocating instruments after prolonged use. *Odontology*. 2016;104:77–81.
85. Pedullà E, Plotino G, Grande NM, et al. Shaping ability of two nickel-titanium instruments activated by continuous rotation or adaptive motion: a micro-computed tomography study. *Clin Oral Investig*. 2016;20:2227–33.
86. Franco V, Fabiani C, Taschieri S, Malentacca A, Bortolin M, Del Fabbro M. Investigation on the shaping ability of nickel-titanium files when used with a reciprocating motion. *J Endod*. 2011;37:1398–401.
87. Roane JB, Sabala CL, Duncanson MG Jr. The 'balanced force' concept for instrumentation of curved canals. *J Endod*. 1985;11:203–11.
88. Hin ES, Wu MK, Wesselink PR, Shemesh H. Effects of self-adjusting file, Mtwo, and ProTaper on the root canal wall. *J Endod*. 2013;39:262–4.
89. Liu R, Hou BX, Wesselink PR, Wu MK, Shemesh H. The incidence of root microcracks caused by 3 different single-file systems versus the ProTaper system. *J Endod*. 2013;39:1054–6.
90. Arias A, Lee YH, Peters CI, Gluskin AH, Peters OA. Comparison of 2 canal preparation techniques in the induction of microcracks: a pilot study with cadaver mandibles. *J Endod*. 2014;40:982–5.
91. Karatas E, Gunduz HA, Kırıcı DO, Arslan H. Incidence of dentinal cracks after root canal preparation with ProTaper Gold, Profile Vortex, F360, Reciproc and ProTaper Universal instruments. *Int Endod J*. 2016;49:905–10.
92. Saber SE, Schafer E. Incidence of dentinal defects after preparation of severely curved root canals using the Reciproc single-file system with and without prior creation of a glide path. *Int Endod J*. 2016;49:1057–64.
93. Bahrami P, Scott R, Galicia JC, Arias A, Peters OA. Detecting dentinal microcracks using different preparation techniques: an in situ study with cadaver mandibles. *J Endod*. 2017;43:2070–3.
94. Kfir A, Elkes D, Pawar A, Weissman A, Tsesis I. Incidence of microcracks in maxillary first premolars after instrumentation with three different mechanize file systems: a comparative ex vivo study. *Clin Oral Investig*. 2017;21:405–11.
95. De-Deus G, Silva EJ, Marins J, et al. Lack of causal relationship between dentinal microcracks and root canal preparation with reciprocation systems. *J Endod*. 2014;40:1447–50.
96. De-Deus G, Belladonna FG, Souza EM, et al. Microcomputed tomographic assessment on the effect of ProTaper Next and Twisted File Adaptive systems on dentinal cracks. *J Endod*. 2015;41:1116–9.
97. De-Deus G, Belladonna FG, Marins JR, et al. On the causality between dentinal defects and root canal preparation: a micro-CT assessment. *Braz Dent J*. 2016;27:664–9.
98. De-Deus G, Carvalhal JCA, Belladonna FG, et al. Dentinal microcrack development after canal preparation: a longitudinal in situ micro-computed tomography study using a cadaver model. *J Endod*. 2017;43:1553–8.
99. Bayram HM, Bayram E, Ocak M, Uzuner MB, Geneci F, Celik HH. Micro-computed tomographic evaluation of dentinal microcrack formation after using new heat-treated nickel-titanium systems. *J Endod*. 2017;43:1736–9.
100. Zuolo ML, De-Deus G, Belladonna FG, et al. Microcomputed tomography assessment of dentinal microcracks after root canal preparation with TRUShape and self-adjusting file systems. *J Endod*. 2017;43:619–22.
101. De-Deus G, Cavalcante DM, Belladonna FG, et al. Root dentinal microcracks: a post-extraction experimental phenomenon? *Int Endod J*. 2019;52:857–65.
102. Al-Omari MA, Dummer PM. Canal blockage and debris extrusion with eight preparation techniques. *J Endod*. 1995;21:154–8.
103. Caviedes-Bucheli J, Moreno JO, Carreno CP, et al. The effect of single-file reciprocating systems on Substance P and Calcitonin gene-related peptide expression in human periodontal ligament. *Int Endod J*. 2013;46:419–26.
104. Koçak S, Kocak MM, Sağlam BC, et al. Apical extrusion of debris using selfadjusting file, reciprocating single-file, and 2 rotary instrumentation systems. *J Endod*. 2013;39:1278–80.
105. Ozsü D, Karatas E, Arslan H, Topcu MC. Quantitative evaluation of apically extruded debris during root canal instrumentation with ProTaper Universal, ProTaper Next, WaveOne, and self-adjusting file systems. *Eur J Dent*. 2014;8:504–8.
106. Silva EJ, Sa L, Belladonna FG, et al. Reciprocating versus rotary systems for root filling removal: assessment of the apically extruded material. *J Endod*. 2014;40:2077–80.
107. Surakanti JR, Venkata RC, Vemisetty HK, et al. Comparative evaluation of apically extruded debris during root canal preparation using ProTaper, Hyflex and Waveone rotary systems. *J Conserv Dent*. 2014;17:129–32.
108. Teixeira JM, Cunha FM, Jesus RO, et al. Influence of working length and apical preparation size on apical bacterial extrusion during reciprocating instrumentation. *Int Endod J*. 2014;48:648–53.
109. Tinoco JM, De-Deus G, Tinoco EM, et al. Apical extrusion of bacteria when using reciprocating single-file and rotary multifele instrumentation systems. *Int Endod J*. 2014;47:560–6.
110. Xavier F, Nevares G, Romeiro MK, et al. Apical extrusion of debris from root canals using reciprocating files associated with two irrigation systems. *Int Endod J*. 2014;48:661–5.
111. De-Deus G, Neves A, Silva EJ, et al. Apically extruded dentin debris by reciprocating single-

- file and multi-file rotary system. *Clin Oral Invest.* 2015;19:357–61.
112. Caviedes-Bucheli J, Rios-Osorio N, Rey-Rojas M, et al. Substance P and Calcitonin gene-related peptide expression in human periodontal ligament after root canal preparation with Reciproc Blue, WaveOne Gold, XP EndoShaper and hand files. *Int Endod J.* 2018;51:1358–66.
113. Oliveira PS, da Costa KNB, Carvalho CN, Ferreira MC. Impact of root canal preparation performed by ProTaper Next or Reciproc on the quality of life of patients: a randomized clinical trial. *Int Endod J.* 2019;52:139–48.
114. Garcia-Font M, Durán-Sindreu F, Morelló S, et al. Postoperative pain after removal of gutta-percha from root canals in endodontic retreatment using rotary or reciprocating instruments: a prospective clinical study. *Clin Oral Investig.* 2018;22:2623–31.
115. Kakehashi S, Stanley HR, Fitzgerald RJ. The effects of surgical exposures of dental pulps in germ-free and conventional laboratory rats. *Oral Surg Oral Med Oral Pathol.* 1965;20:340–9.
116. Lin LM, Skribner JE, Gaengler P. Factors associated with endodontic treatment failures. *J Endod.* 1992;18:625–7.
117. Siqueira JF Jr. Aetiology of root canal treatment failure: why well-treated teeth can fail. *Int Endod J.* 2001;34:1–10.
118. Sjogren U, Figdor D, Persson S, Sundqvist G. Influence of infection at the time of root filling on the outcome of endodontic treatment of teeth with apical periodontitis. *Int Endod J.* 1997;30:297–306.
119. Molander A, Warfvinge J, Reit C, Kvist T. Clinical and radiographic evaluation of one- and two-visit endodontic treatment of asymptomatic necrotic teeth with apical periodontitis: a randomized clinical trial. *J Endod.* 2007;33:1145–8.
120. Haapasalo M, Zandi H, Coil J. Eradication of endodontic infection by instrumentation and irrigation solutions. *Endod Topics.* 2005;10:77–102.
121. Spangberg LS, Haapasalo M. Rationale and efficacy of root canal medicaments and root filling materials with emphasis on treatment outcome. *Endod Topics.* 2005;2:35–58.
122. Ordinola-Zapata R, Martins JNR, Bramante CM, Villas-Boas MH, Duarte MH, Versiani MA. Morphological evaluation of maxillary second molars with fused roots: a micro-CT study. *Int Endod J.* 2017;50:1192–200.
123. Ordinola-Zapata R, Martins JNR, Niemczyk S, Bramante CM. Apical root canal anatomy in the mesiobuccal root of maxillary first molars: influence of root apical shape and prevalence of apical foramina—a micro-CT study. *Int Endod J.* 2019;52:1218–27.
124. Chaniotis A, Guerreiro D, Kottoor J, et al. Managing complex root canal anatomies. In: Versiani M, Basrani B, Sousa-Neto MD, editors. *The root canal anatomy in permanent dentition.* Cham: Springer International Publishing; 2018. p. 343–74.
125. Grove C. Why canals should be filled to the dentinocemental junction. *J Am Dent Assoc.* 1930;17:293–6.
126. Ricucci D. Apical limit of root canal instrumentation and obturation, part 1. Literature review. *Int Endod J.* 1999;31:384–93.
127. Ricucci D, Langeland K. Apical limit of root canal instrumentation and obturation, part 2. A histological study. *Int Endod J.* 1998;31:394–409.
128. Kuttler Y. Microscopic investigation of root apices. *J Am Dent Assoc.* 1955;50:544–52.
129. Dummer PM, McGinn JH, Rees DG. The position and topography of the apical canal constriction and apical foramen. *Int Endod J.* 1984;17:192–8.
130. Versiani MA, Ahmed HM, Sousa-Neto MD, De-Deus G, Dummer PM. Unusual deviation of the main foramen from the root apex. *Braz Dent J.* 2016;27:589–91.
131. Vieyra JP, Acosta J. Comparison of working length determination with radiographs and four electronic apex locators. *Int Endod J.* 2011;44:510–8.
132. Martins JN, Marques D, Mata A, Carames J. Clinical efficacy of electronic apex locators: systematic review. *J Endod.* 2014;40:759–77.
133. Ingle JI. Endodontic cavity preparations. In: Ingle JI, Bakland L, editors. *Endodontics.* 5th ed. Hamilton: BC Decker Inc.; 2002. p. 405–570.
134. Grossman L, Oliet S, Del Rio C. *Endodontic practice.* 11th ed. Philadelphia: Lea&Febiger; 1988.
135. Torabinejad M. Passive step-back technique. *Oral Surg Oral Med Oral Pathol.* 1994;77:398–401.
136. Bolanos OR, Jensen JR. Scanning electron microscope comparisons of the efficacy of various methods of root canal preparation. *J Endod.* 1980;6:815–22.
137. Weiger R, Bartha T, Kalwitzki M, Lost C. A clinical method to determine the optimal apical preparation size. Part I. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod.* 2006;102:686–91.
138. Sant’Anna Junior A, Cavenago BC, Ordinola-Zapata R, De-Deus G, Bramante CM, Duarte MA. The effect of larger apical preparations in the danger zone of lower molars prepared using the Mtwo and Reciproc systems. *J Endod.* 2014;40:1855–9.
139. Silva Santos AM, Portela F, Coelho MS, Fontana CE, De Martin AS. Foraminal deformation after foraminal enlargement with rotary and reciprocating kinematics: a scanning electronic microscopy study. *J Endod.* 2018;44:145–8.
140. Mickel AK, Chogle S, Liddle J, Huffaker K, Jones JJ. The role of apical size determination and enlargement in the reduction of intracanal bacteria. *J Endod.* 2007;33:21–3.
141. Rodrigues RCV, Zandi H, Kristoffersen AK, et al. Influence of the apical preparation size and the irrigant type on bacterial reduction in root canal-treated teeth with apical periodontitis. *J Endod.* 2017;43:1058–63.
142. Plotino G, Ozyurek T, Grande NM, Gundogar M. Influence of size and taper of basic root canal preparation on root canal cleanliness: a scanning electron microscopy study. *Int Endod J.* 2019;52:343–51.

143. Aksel H, Kucukkaya Eren S, Cakar A, Serper A, Ozkuyumcu C, Azim AA. Effect of instrumentation techniques and preparation taper on apical extrusion of bacteria. *J Endod.* 2017;43:1008–10.
144. Arora M, Sangwan P, Tewari S, Duhan J. Effect of maintaining apical patency on endodontic pain in posterior teeth with pulp necrosis and apical periodontitis: a randomized controlled trial. *Int Endod J.* 2016;49:317–24.
145. Silva EJ, Menaged K, Ajuz N, Monteiro MR, Coutinho-Filho TS. Postoperative pain after foraminal enlargement in anterior teeth with necrosis and apical periodontitis: a prospective and randomized clinical trial. *J Endod.* 2013;39:173–6.
146. Saini HR, Sangwan P, Sangwan A. Pain following foraminal enlargement in mandibular molars with necrosis and apical periodontitis: a randomized controlled trial. *Int Endod J.* 2016;49:1116–23.
147. Abdulrab S, Rodrigues JC, Al-Maweri SA, Halboub E, Alqutaibi AY, Alhadainy H. Effect of apical patency on postoperative pain: a meta-analysis. *J Endod.* 2018;44:1467–73.
148. Vera J, Hernandez EM, Romero M, Arias A, van der Sluis LW. Effect of maintaining apical patency on irrigant penetration into the apical two millimeters of large root canals: an in vivo study. *J Endod.* 2012;38:1340–3.
149. Siqueira JF Jr. Reaction of periapical tissues to root canal treatment: benefits and drawbacks. *Endod Topics.* 2005;10:123–47.
150. Hülsmann M, Peters OA, Dummer PM. Mechanical preparation of root canals: shaping goals, techniques and means. *Endod Topics.* 2005;10:30–76.
151. Kerekes K, Tronstad L. Long-term results of endodontic treatment performed with a standardized technique. *J Endod.* 1979;5:83–90.
152. Hoskinson SE, Ng YL, Hoskinson AE, Moles DR, Gulabivala K. A retrospective comparison of outcome of root canal treatment using two different protocols. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod.* 2002;93:705–15.
153. Saini HR, Tewari S, Sangwan P, Duhan J, Gupta A. Effect of different apical preparation sizes on outcome of primary endodontic treatment: a randomized controlled trial. *J Endod.* 2012;38:1309–15.
154. Plotino G, Grande NM. Root canal shaping and debridement. ED. Piccin; 2020.
155. Sjögren U, Hagglund B, Sundqvist G, Wing K. Factors affecting the long-term results of endodontic treatment. *J Endod.* 1990;16:498–504.
156. Endal U, Shen Y, Knut A, Gao Y, Haapasalo M. A high-resolution computed tomographic study of changes in root canal isthmus area by instrumentation and root filling. *J Endod.* 2011;37:223–7.
157. Schilder H. Cleaning and shaping the root canal. *Dent Clin N Am.* 1974;18:269–96.
158. Byström A, Sundqvist G. Bacteriologic evaluation of the efficacy of mechanical root canal instrumentation in endodontic therapy. *Scand J Dent Res.* 1981;89:321–8.
159. Orstavik D, Kerekes K, Molven O. Effects of extensive apical reaming and calcium hydroxide dressing on bacterial infection during treatment of apical periodontitis: a pilot study. *Int Endod J.* 1991;24:1–7.
160. Siqueira JF Jr, Rocas IN, Santos SR, Lima KC, Magalhaes FA, de Uzeda M. Efficacy of instrumentation techniques and irrigation regimens in reducing the bacterial population within root canals. *J Endod.* 2002;28:181–4.
161. van der Sluis LW, Wu MK, Wesselink PR. The efficacy of ultrasonic irrigation to remove artificially placed dentine debris from human root canals prepared using instruments of varying taper. *Int Endod J.* 2005;38:764–8.
162. Arvaniti IS, Khabbaz MG. Influence of root canal taper on its cleanliness: a scanning electron microscopic study. *J Endod.* 2011;37:871–4.
163. Zarei M, Javidi M, Afkhami F, Tanbakuchi B, Zadeh MM, Mohammadi MM. Influence of root canal tapering on smear layer removal. *N Y State Dent J.* 2016;82:35–8.
164. Guimaraes LS, Gomes CC, Marceliano-Alves MF, Cunha RS, Provenzano JC, Siqueira JF Jr. Preparation of oval-shaped canals with TRUShape and Reciproc systems: a micro-computed tomography study using contralateral premolars. *J Endod.* 2017;43:1018–22.