

Present status and future directions: Management of curved and calcified root canals

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Abstract

Root canal curvature and calcification introduce factors that increase the risk of procedural accidents during root canal treatment. The inability to achieve patency to the apical third, asymmetrical dentine removal leading to transportation, perforation, and instrument fracture inside the curved trajectories are some of the procedural problems that might jeopardize the management of intraradicular infection and result in poor treatment outcomes. In fact, curved and constricted canals introduce such complexity that total instrumentation concepts and specially designed instruments have been developed to deal with the challenge. This narrative review seeks to provide and consolidate the principles necessary for understanding the dynamics of curved and constricted canal management and to improve the understanding for future developments in this field.

KEYWORDS

engine-driven instruments, instrumentation techniques, manual instruments, root canal anatomy, root canal curvature

INTRODUCTION

Root canal treatment encompasses procedures that are designed to maintain or restore the health of the periradicular tissues (European Society of Endodontology, 2006). To remove bacteria and their by-products, the root canal needs to be debrided following specific mechanical goals. Instrumentation of the root canal system has been recognized as one of the most important tasks that can impact the subsequent stages of treatment. From the biological point of view, this procedure aims to provide an environment that favours healing of periapical tissues and at the same time promote the filling of the root canal system (McSpadden, 2007). This procedure begins at the level of the crown with the access cavity preparation and progresses towards the apical terminus with the adequate

shaping of the root canal system. The main goals are (Hülsmann et al., 2005):

1. The access to the pulp cavity and the radicular space.
2. The removal of infected vital or necrotic tissues from the main and lateral extensions of the root canal system.
3. The creation of adequate space for effective disinfection and medication.
4. The preservation of the original anatomy avoiding iatrogenic alterations.
5. Respect to the periapical tissues.
6. The creation of a shape that allows the obturation with current filling methods.
7. The preservation of tooth structure by removing the less possible amount of dentine structure that is necessary to achieve effective disinfection.

Although these objectives are clearly defined, the procedure can become difficult in severely calcified and curved canals. Constricted canals and curvatures introduce factors that can increase the risk of procedural errors during root canal preparation. These errors include transportation, ledges, perforations, instrument separation, asymmetrical dentine removal, and alterations of the internal anatomy (Roane et al., 1985; Schäfer & Dammaschke, 2006). Although these errors are not the direct cause of treatment failure, they decrease the prognosis, because procedural errors decrease the ability of clinicians to eliminate the intracanal infection (Lin et al., 2005). A range of concepts to manage the root canal curvature have been developed to solve this challenge (Abou-Rass et al., 1980; Dodds et al., 1985; Goerig et al., 1982; Mullaney, 1979; Roane et al., 1985; Weine et al., 1975).

The presence of root canal curvatures and calcifications has been listed by several authors as a risk factor that may affect the outcome of root canal treatment (American Association of Endodontists, 2010; Canadian Academy of Endodontics, 2017; Essam et al., 2021; Falcon et al., 2001; Ree et al., 2003; Shah & Chong, 2018). Guidelines have been introduced to determine the level of treatment complexity, the risk for procedural accidents and the need for specialized management. The various classifications of difficulty assessment tools in relation to root canal curvature are summarized in Table 1.

Although these case assessment tools provide an initial framework to differentiate between high and low difficulty curved canals, they do not include detailed guidelines on how to measure root canal curvature (Faraj & Boutsoukis, 2017). For calcified canals, usually the preoperative radiographic appearance of canals is evaluated, and indistinct canal pathways or invisible canals are considered of high difficulty (American Association of Endodontists, 2010).

Due to the high variability of the root canal anatomy, the preparation of highly curved root canals cannot rely in a single strategy. In many cases, multiple approaches are necessary to accomplish the goals of treatment. The aim of this paper is to review the factors that affect the management of curved and constricted canals, to review the concepts for approaching and solving the problems of curved canal management and to reflect on future perspectives and developments.

THE PROBLEM OF CURVED AND CONSTRICTED CANAL INSTRUMENTATION

According to Schilder (1974), root canal systems should be cleaned to remove organic remnants and shaped to

TABLE 1 Root canal treatment difficulty assessment according to the degree of root canal curvature (American Association of Endodontists, 2010; Canadian Academy of Endodontics, 2017; Essam et al., 2021; Falcon et al., 2001; Ree et al., 2003; Shah & Chong, 2018)

	Minimal difficulty Average risk	Moderate difficulty High risk	High difficulty Very high risk
AAE Endodontic Case Difficulty Assessment form & Guidelines	Slight or no curvature (<10°)	Moderate curvature (10°–30°)	Extreme curvature (>30°) or S-shaped
CAE's Case Classification System Form (2017)	Canal curvature I form Small or no curvature (–10°)	Canal curvature J form Moderate curvature (10°–30°)	Canal curvature into C or S form Extreme curvature (+30°)
DETI Score (Ree et al. 2003)	Score A Small or no curvature (<10°)	Score B Moderate to severe curvature >10°	
Falcon et al. (2001) (RIOTN)	Complexity 1 Curvature <15°	Complexity 2 Curvature 15°–40°	Complexity 3 Curvature >40°
Shah and Chong (2018) (EndoApp)	Mild curvature <15°	Moderate curvature 15°–30°	Severe curvature 30°–60°
Essam et al. (2021) (E-CAT)	Small or no curvature <15°	Moderate curvature 30°–45°	Severe curvature 45°–60°
			Exceptional curvature >60° or S-shaped Extremely severe curvature >60°

Note: Curvatures of more than 30° Schneider angle are considered of high difficulty and risk for procedural accidents in most difficulty level assessment forms.

receive a three-dimensional filling. Five mechanical objectives were suggested:

1. Continuously tapering funnel from the apex to the access cavity.
2. Cross-sectional diameter should be narrower at every point apically.
3. The root canal preparation should flow with the shape of the original canal.
4. The apical foramen should remain in its original position.
5. The apical opening should be kept as small as practical.

And four biologic objectives:

1. Confinement of instrumentation to the roots themselves.
2. No forcing of necrotic debris beyond the foramen.
3. Removal of all necrotic or inflamed tissue from the root canal space.
4. Creation of sufficient space for intra-canal medicaments.

These aims can normally be achieved in straight and large root canals. However, this may not necessarily apply when constricted and curved canals are encountered (Figure 1). Human root canals might be curved in different planes and the diameter of the canal can be affected by the physiological ageing process, secondary dentine formation and calcifications. Furthermore, the instrumentation of calcified and curved canals introduces torsional and bending forces that will cause uneven forces that can result in transportation, ledging, apical perforation or instrument fracture (Schäfer & Dammaschke, 2006).

It has been reported that stainless steel instrumentation of curved canals can induce an hourglass shape, resulting in an elbow- and/or a teardrop-shaped foramen defined as zipping (Weine et al., 1975). This elliptical/teardrop-shaped foramen has been also described as foraminal transportation (Schilder, 1974). Transportation during instrumentation is defined as asymmetrical dentine removal due to the tendency of the files to restore their original linear shape when they are working inside a curved trajectory (Glossary of Endodontic Terms, 2020). Moreover, in constricted canals, the anticipated torque and file engagement has been shown to be higher compared to the torque generated in medium-sized or larger canals, when Quantec Series 2000 files were tested (Sattapan et al., 2000a). The increased torsional and bending stresses applied during the instrumentation of calcified and curved canals might result in instrument fractures; torsional failure being slightly more frequent for Quantec Series 2000 files (Sattapan et al., 2000b). A previous tactic to enlarge constricted and curved canals consisted of reducing the

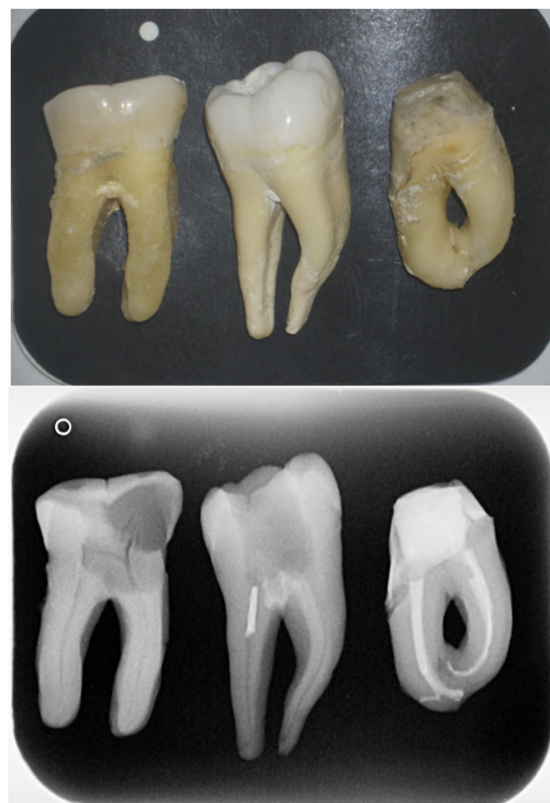


FIGURE 1 Clinical and radiographic image of extracted molars of different curvatures. The root canal system variability is evident.

preparation size (Roane et al., 1985). This tendency for the reduction of preparation size and taper was beneficial for two reasons: (a) smaller preparations relate to less dentine removal of the canal walls and lower risk for undesirable procedural accidents and (b) smaller sized and tapered files have lower metal mass and lower tendency to restore to their original linear shape reducing the likelihood for transportation during enlargement (Roane et al., 1985). Although the problems of curvature and canal constriction appeared to be solved by smaller preparation diameters, the smaller files are always more prone to torsional fracture if they became engaged in constricted canals. Moreover, smaller preparation sizes and tapers might jeopardize the disinfection of the apical third in curved canals when conventional irrigation techniques are used. Several authors found less complete removal of debris when small apical sizes were used whilst others revealed that irrigants are not effective in removing debris from a canal with a small diameter (Amato et al., 2011; Boutsoukis & Gutierrez Nova, 2021; Rodriguez et al., 2011; van der Sluis et al., 2005). According to Roane et al. (1985), variations in the size of preparations should occur in response to the initial root or canal dimensions rather than the degree of root curvature.

The determination of an Anatomically Guided Preparation relates to the determination of the working

length and working width of each root canal (Jou et al., 2004). The working width addresses the horizontal dimensions of a root canal, and was described by the diameter of the canal that corresponded to the tip size of the final hand instrument used up to WL (Jou et al., 2004). Micro-computed tomography research has provided an extensive understanding of the anatomy of the root canal system and morphometric parameters including apical diameter, roundness and geometry of the canals along their length. In the clinical scenario, cone beam computed tomography (CBCT) has also the ability to delineate the canal diameter along the length of the tooth (Patel, Brown, et al., 2019a; Patel, Patel, et al., 2019b).

Wider apical preparations of up to six to eight sizes larger than the first binding file at the apex have been proposed to allow for adequate instrumentation of the apical third (Weiger et al., 2006). However, increased apical instrumentation of curved canals was associated to incomplete apical preparation and unnecessary dentine removal (Elayouti et al., 2011). Moreover, there is no anatomical evidence that the first binding endodontic instrument reflects the diameter of the canal at its terminus (Jou et al., 2004).

A recent systematic review addressed the issue of whether the size of apical instrumentation affects healing in patients undergoing root canal treatment (Aminoshariae & Kulild, 2015). The results of this review confirmed that only one randomized-controlled trial was available. In addition, there were no longitudinal evaluations using three-dimensional imaging. It was concluded that nowadays the best available evidence suggests that for patients with necrotic pulps and apical periodontitis, greater enlargement of the apical third would result in an increased healing in terms of radiographic and clinical outcomes (Aminoshariae & Kulild, 2015). In a more recent prospective randomized clinical trial (Fatima et al., 2021), evaluated the effect of apical preparation size and taper on postoperative pain and healing after primary root canal treatment. Although no difference in postoperative pain was found, apical enlargement to two sizes larger than the initial apical binding file with 4% taper was judged insufficient and resulted in lower success rates compared to larger preparations when two-dimensional images were used to assess healing.

THE EFFECT OF CANAL CURVATURE IN ROOT CANAL TREATMENT OUTCOME

Root canal curvature is the main intraoperative risk factor linked to transportation, asymmetrical dentine removal and instrument separation. Altered root canal morphology has been linked to poor treatment

outcomes. Gorni and Gagliani (2004) reported that the success of retreatment procedures when the apical anatomy was addressed was almost twice compared to teeth in which the root canal anatomy was altered (86 vs. 47%). In a review, the impact of modern nickel-titanium instrumentation on clinical outcomes revealed interesting results (Schäfer & Bürklein, 2012). Evidence from one clinical study suggested that improve maintenance of the anatomical canal curvature and shape resulted in increased success rates (Pettiette et al., 2001). Evidence from another clinical study indicated that ledging of root canals result in poor success rates (Cheung & Liu, 2009). Although these studies revealed that the use of nickel-titanium instruments significantly improved the outcome of nonsurgical root canal treatment compared to the use of hand instruments, three studies failed to reveal any meaningful differences (Fleming et al., 2010; Iqbal et al., 2009; Marending et al., 2005).

Even though instrumentation-induced alterations of the internal anatomy of curved canals, they are not the direct cause of treatment failure. Procedural accidents increase the risk of failure because a necrotic canal space with apical transportation decreases the probability of eliminating intraradicular infection (Lin et al., 2005).

ANATOMY OF THE PULP CHAMBER AND CORONAL ACCESS TO THE CALCIFIED CANAL SYSTEM

The management of calcified and curved canals begins with the pulp chamber access. The pulp chamber is in the centre of the anatomical crown, and its internal anatomy resembles the shape of the occlusal surface. Occasionally, discrete or diffuse calcifications can alter the pulp chamber size. Discrete calcifications may appear as nodules or pulp stones. Pulp stones occur most frequently in the coronal pulp. Based on location, pulp stones can be embedded, adherent, and free (Goga et al., 2008). Adherent and embedded pulp stones can restrict instrumentation if they cause blockage of canal orifices or are located at the curvature level. Diffuse calcifications can generally be observed in root canals of older adults, but they may also be present in the pulp chamber of younger patients affected by caries. Severely calcified teeth are predisposed to tooth perforation during pulp chamber access or the initial location of the canal orifice. Attached stones prevent the easy passage of explorers or other endodontic instruments down the canal. Normally, the calcification process progresses in a coronal-apical direction, so once the initial canal has been captured, an instrument tends to progress easily as it advances towards the canal terminus (McCabe & Dummer, 2012).

To negotiate calcified canals, the anatomy of the pulp chamber must be revealed (Figure 2). Based on the anatomical study of 500 teeth, several laws for aiding the determination of the pulp chamber position as well as the location and number of root canal orifices in each group of teeth have been proposed (Krasner & Rankow, 2004):

- *Law of centrality*: The floor of the pulp chamber is always located in the centre of the tooth at the level of the cemento-enamel junction (CEJ).
- *Law of concentricity*: The walls of the pulp chamber are always concentric to the external surface of the tooth at the level of the CEJ, that is, the external root surface anatomy reflects the internal pulp chamber anatomy.
- *Law of the CEJ*: The distance from the external surface of the clinical crown to the wall of the pulp chamber is the same throughout the circumference of the tooth at the level of the CEJ.
- *Law of symmetry 1*: Except for maxillary molars, the orifices of the canals are equidistant from a line drawn in a mesial-distal direction, through the pulp chamber floor.
- *Law of symmetry 2*: Except for the maxillary molars, the orifices of the canals lie on a line perpendicular to a line

drawn in a mesial-distal direction across the centre of the floor of the pulp chamber.

- *Law of colour change*: The colour of the pulp chamber floor is always darker than the walls.
- *Law of orifice location 1*: The orifices of the root canals are always located at the junction of the walls and the floor.
- *Law of orifice location 2*: The orifices of the root canals are located at the angles in the floor-wall junction.
- *Law of orifice location 3*: The orifices of the root canals are located at the terminus of the root developmental fusion lines.

To take full benefit from these laws, the use of microscopic magnification and coaxial illumination is indispensable. Microscopic exploration through an access cavity can reveal all anatomical variations and limitis of the pulp chamber resulting in the identification of all canal orifices, their topography, and angle of entry. The specific equipment required includes long-shafted miniaturized burs, thin endodontic explorers, highly reflective mirrors, file holders, ultrasonic tips, and diagnostic dyes (Figure 3). Usually, the first penetration to the pulp chamber is done

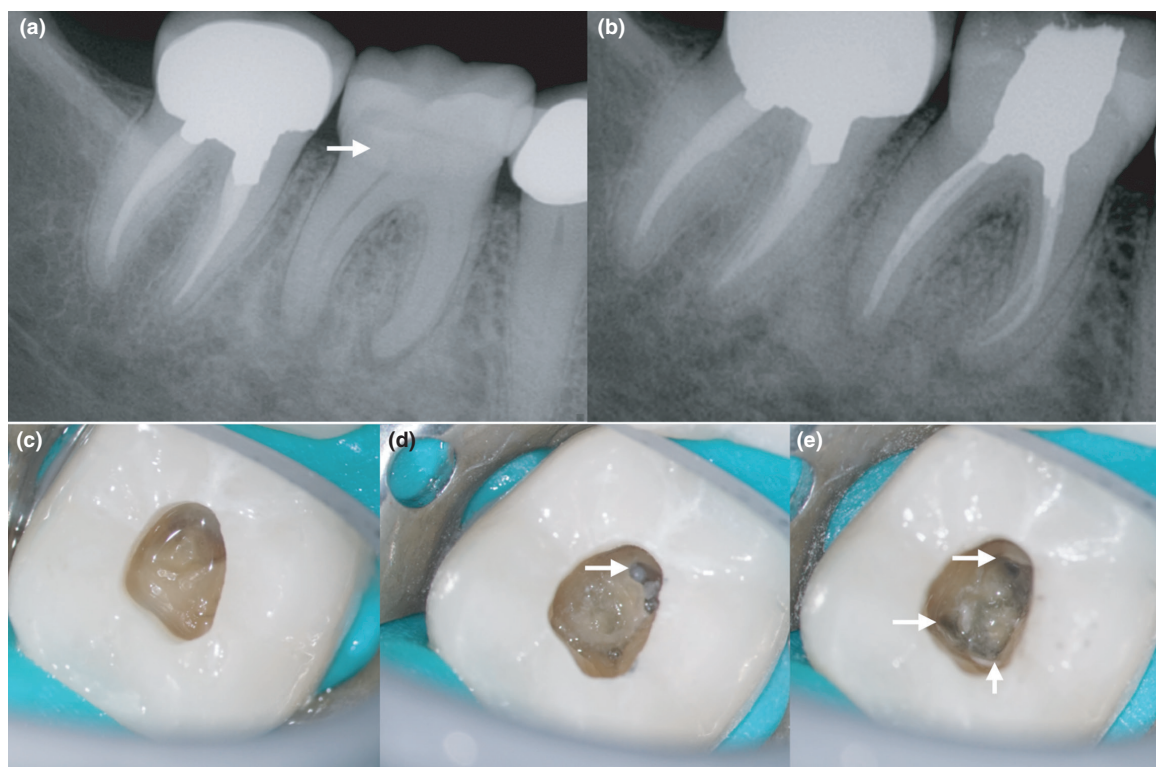


FIGURE 2 Mandibular first molar in an elderly patient. (a) The radiographic image shows the presence of an indirect restoration, a calcified pulp chamber (arrow) and periapical pathosis in the mesial and distal roots. This calcified molar was successfully managed (b) by using Krasner and Rankow principles (c–e). The access is in the centre of the crown (c). The pulp exposure is observed under magnification (d). Canal orifices were found with ultrasonic tips and a sharp endodontic explorer at the junction of the chamber walls and the pulpal floor (e).

with a rounded end tapered diamond bur. Once inside the chamber, non-cutting carbide multiblade burs can be used for the safe enlargement and refinement of the access cavity. For a deeper search of canal orifices through the pulp chamber floor, longer burs of small diameters may be beneficial, such as the conical Endo-Guide (SSWhite, Lakewood, NJ, USA) micro-access fissure burs (Figure 3b) or a round-end low-speed Munce discovery burs (CJM Engineering, Inc. CA, USA; Figure 3c). These burs are useful to clean pulp horns and allow for selective dentine removal. They also provide a visual microscopic corridor that permits directional control under the microscope. Furthermore, thin explorers are useful in the location and determination of the direction of the root canals (DG-16 and JW-17).

The Munce discovery burs are useful when it is necessary to discover canals deep inside the root (Chaniotis & Plotino, 2021). Rhodium surface mirrors allow for great visibility and light transmission, especially through small access cavities or indirect restorations avoiding double image and refraction. Handle files attached to a handle or mounted in a file holder are extremely helpful in negotiating calcified canals under the microscope. The use of ultrasonic diamond tips for access cavity refinement or orifice location allow to remove dentine structure in the proximities of the pulpal floor with great visibility (Figure 3a). Ultrasonic tips are also useful to remove calcifications in the pulp chamber without damaging the access walls or the pulp chamber floor. Furthermore, when ultrasonic tips are used under the microscope to locate root canal orifices, the accessory anatomy can be revealed with minimal dentine removal (Chaniotis & Plotino, 2021).

RADICULAR ACCESS AND CANAL ENLARGEMENT

After coronal access and canal identification, the radicular access and the anatomical root canal preparations

follows. The factors that have been observed to exert an impact on the ability to deliver anatomically guided preparations in curved and calcified root canals can be classified into anatomical factors, instrument-related factors, and disinfection-related factors.

ANATOMY-RELATED FACTORS

Most human root canals are curved to one or multiple planes and multiple degrees; suggesting that a tooth with a straight root canal and a single foramen is the exception rather than the rule (Vertucci 2005). Initial attempts to describe and classify root canal curvatures (Nagy et al., 1995) suggested four categories: straight or I form (28% of the root canals), apically curved or J form (23% of the root canals), entirely curved or C form (33% of the root canals) and multicurved or S form canals (16% of the root canals; Nagy et al., 1995). Additional radiographic assessment of the frequency and degree of canal curvatures revealed that 84% of root canals are curved at least in one direction and that 17.5% of all curved canals exhibited a secondary curvature to a different plane and are classified as s-shaped (Schäfer et al., 2002). In another radiographic study, all canals in mesial roots of mandibular molars were found to be curved in the clinical view, whilst 30% of the curved canals exhibited a secondary curvature in the proximal view (Cunningham & Senia, 1992).

The most widely used method of measuring the root canal curvature magnitude is by using the Schneider angle of curvature (Schneider, 1971). According to this classification, root canals presenting an angle of 5° or less could be classified as straight canals, canals presenting an angle between 10° and 20° as moderate, and root canals presenting a curve greater than 25° as severely curved canals (Schneider, 1971). Severely curved canals are also frequently referred in the literature as dilacerated. The term dilaceration is defined as a deviation or bend in the linear

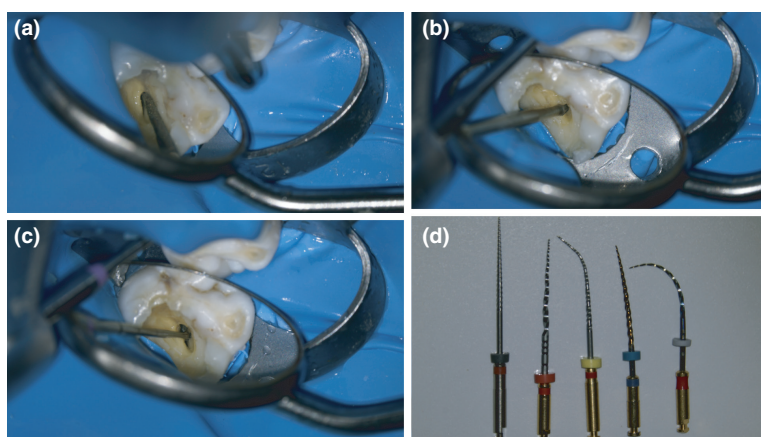


FIGURE 3 (a) Expanding the access cavity with ultrasonics, (b) Endo-Guide bur in use, (c) Munce bur in use, (d) Engine-driven instruments of different heat treatments.

TABLE 2 Prevalence of root dilacerations amongst tooth types % (Bodrumlu et al., 2012; Hamasha et al., 2002; Kuzekanani & Sadeghi, 2019; Ledesma-Montes et al., 2019; Malcic et al., 2006; Miloglu et al., 2010; Nabavizadeh et al., 2013; Udoe & Jafarzadeh, 2009)

	Hamasha et al., 2002 (Jordan)	Ledesma-Montes et al. (2019) (Mexico)	Malcic et al., 2006 (Croatia)	
<i>Tooth type</i>				
	Prevalence (Periapical)	Frequency (Panorax)	Prevalence (Periapical)	Prevalence (Panorax)
Maxillary		54.4		
Central Incisor	0.4	0.8	1.2	0.53
Lateral Incisor	1.2	13.6	7.0	1.43
Canine	0	2.4	3.6	0.74
First Premolar	3.2	12	4.5	3.32
Second Premolar	4.7	13.6	6.7	4.10
First Molar	3.4	6.4	15	7.01
Second Molar	3.4	4.8	11.4	7.84
Third Molar	1.3		8.1	8.46
Mandibular		45.6		
Central Incisor	0.5	0	1.7	0.42
Lateral Incisor	0	2.4	0	0.32
Canine	0.5	7.2	1.2	0.93
First Premolar	3.3	9.6	2.1	1.42
Second Premolar	2.8	6.4	1.5	1.99
First Molar	5.6	7.2	2.2	0.45
Second Molar	3.6	12	1.7	1.99
Third Molar	19.2		24.1	30.92
Total	3.8	1.6		

Note: Higher prevalence is highlighted with red colour, followed by orange and green. Most studies agree that the prevalence of dilacerations is higher in mandibular third molars, followed by maxillary lateral incisors and maxillary premolars.

relationship of a crown of a tooth to its root (Jafarzadeh & Abbott, 2007). The criteria for describing root dilaceration vary amongst different authors. According to Hamasha et al. (2002), and Malcic et al. (2006), a tooth is considered to have a dilaceration if there is at least a 90° angle along the axis of the root, whereas others defined dilaceration as a deviation from the normal axis of the tooth of 20° or more in the apical third of the root (Chohayeb, 1983). The prevalence of dilacerated roots amongst different tooth types as reported in the literature can be seen in Table 2 (Bodrumlu et al., 2012; Hamasha et al., 2002; Kuzekanani & Sadeghi, 2019; Ledesma-Montes et al., 2019; Malcic et al., 2006; Miloglu et al., 2010; Nabavizadeh et al., 2013; Udoe & Jafarzadeh, 2009).

Although all highly curved canals might be described as dilacerated canals, the term dilaceration is frequently referred to root canals that combine an increased angle of curvature with a small radius of curvature. The radius of curvature describes the abruptness of curvature (Pruett

et al., 1997) and is defined as the radius of a circle passing through the curved part of the canal. Thus, two canals can present the same angle of curvature, but different abruptness of curvature (Pruett et al., 1997). The instrumentation difficulties for a curved canal trajectory significantly will increase as the angle of curvature increases and the radius of curvature decreases (Al-Sudani et al., 2012).

The location of the curvature has been reported to have a much greater impact in the ability of mechanical instruments to negotiate around curvatures than the angle of curvature. Studies have revealed that the fatigue resistance of NiTi files significantly decreases if the point of maximum curvature is shifted from an apical to a more coronally located position (Alghamdi et al., 2020; Gao et al., 2011; Lopes et al., 2011, 2013). Moreover, increased length of the arc of curvature usually means a large radius. The shorter the length of curvature the more abrupt the deviation becomes at the same degree of curvature, hence representing a smaller radius of curvature (Gao

Nabavizadeh et al., 2013 (Iran)	Bodrumlu et al., 2012 (Turkey)	Miloglu et al., 2010 (Turkey)	Kuzekanani and Sadeghi (2019) (Iran)	Udoeye and Jafarzadeh (2009) (Nigerian)
Prevalence (Periapical)	Prevalence (Periapical)	Prevalence (Periapical)	Prevalence (Periapical)	Prevalence (Periapical)
		4.3		
0.2	0.7	0	0.5	0
0.2	4.6	3.3	0.75	2.8
0	1.8	1.1	0.50	0
0.2	2.4	3.2	1	1.7
0	2.9	5.1	1	
1.3	5.8	6.7	1	4.7
0.2	4.9	5.4	0.5	3.8
	5	7.4	1	3.7
		4.4		
0.2	0.1	0	0	0
0	0	0	0	0
0	1.3	1.3	0.75	0
0	2.2	4.6	1.25	7.5
0.2	2.7	4.3	0.25	
0.7	4.9	5.3	0.50	0
1.6	5.2	5.5	0.5	1.2
	10.7	12.8	3.5	1.3
	4	4.3	1.65	

et al., 2011). Thus, as the curve (arc) of length decreases, the reduced radius of curvature will lead to an increase in stress and strain for the instruments used for enlargement (Gao et al., 2011).

Previous studies describing the characteristics of root canal curvatures had one common clinical objective; the preoperative risk assessment to avoid procedural accidents such as transportation and unexpected instrument separation during clinical treatment. Moreover, measuring the geometrical anatomical characteristics of curved canals and plotting the anatomical canal pathways might help the planning of predictable protocols to manage the challenge of curved canals. Recently the techniques for measurement of root canal curvature were reviewed with the objective to address the most suitable technique for clinical and research use (Hartmann et al., 2019). Although there was a lack of consensus on the ideal technique, clinical experience and imaging-related factors were likely to influence the choice of technique to measure root canal curvature.

In routine root canal treatment, single or multiple periapical radiographs are used. However, these images provide a two-dimensional representation of the root canal anatomy that only allows the analysis of the mesial and distal curvatures (Cunningham & Senia, 1992; Stropko, 1999). An additional proximal view angled radiograph might be able to disclose some missing anatomical features (Slowey, 1974). Although two off-angled projections of the anatomical features may sometimes disclose sufficient information needed to plan the instrumentation approach, current CBCT imaging can provide detailed information and eliminate most of the limitations of two-dimensional image (Patel, Brown, et al., 2019a; Patel, Patel, et al., 2019b). Defining the angle, radius, length, and location of the curvatures in the mesio-distal and the bucco-lingual plane should allow the clinician to plan the most appropriate instrumentation protocol for most challenging cases of curved and constricted canal anatomy (Schneider 1971, Pruett et al., 1997, Schäfer et al., 2002, Gunday et al., 2005)

(Figure 4). Recently, a CBCT-based 3D endodontic software was introduced for the diagnostic plotting of access cavity designs and canal curvatures in three dimensions. This diagnostic software was suggested to decrease the stress levels when managing calcified and curved canal cases (Patel, Brown, et al., 2019a; Patel, Patel, et al., 2019b).

INSTRUMENT-RELATED FACTORS

In general, instruments used in curved and constricted canals can be divided to two major categories. Instruments that are manipulated by hand (manual instruments) and instruments that are mounted in an engine-driven motor (engine-driven).

Manual instruments and curved canals

Instruments design and metallurgy

Early endodontic hand instruments were made from carbon steel. Carbon steel suffered from considerable corrosion, damage during sterilization, and a decrease in torque and angular deflection (Younis, 1977). These instruments were replaced by stainless steel alloys. The mechanical property of conventional stainless steel is unaffected by sterilization with no decrease in cutting efficiency after several sterilization cycles. Conventional stainless steel hand files provide excellent control and sharp long-lasting surfaces (Schäfer, 1997). However, due to the reduced flexibility and lack of superelasticity, the efficient instrumentation of curved canals is mostly problematic. Root

canal hand instruments can be divided into three different types: Reamers, K-files, and Hedström files (Schäfer, 1997). According to ISO standardization (International Organization for Standardization, 2019), reamers are symbolized by a triangle, K-files by a square, Hedström files by a circle. These symbols do not necessarily represent the true cross section of the instruments. All stainless steel instruments tend to straighten upon bending and are prone to produce transportation and ledging of the root canal trajectories. The following observations have been made on the use and efficacy of hand files (Tepel & Schäfer, 1997):

- Hedström files used in a linear filling working motion result in severe straightening of the curved canals by removing excess material from the outer side of the apical curvature and their use is not recommended.
- Conventional stainless steel reamers and K-files caused severe transportation of the outer curvature and resulted in straightening.
- Reamers and K-files made of Titanium-Aluminium resulted in similar undesirable shaping effects as conventional stainless steel instruments.
- Flexible stainless steel instruments with modified non-cutting tips removed material nearly equally well and performed always better in the curved canals.

The main disadvantage of a 0.02 mm/mm tapered instrument is its tendency to straighten and create narrow canal shapes limiting the access of irrigants and medications to the apical third. Attempts at overcoming these deficiencies resulted in several instrumentation techniques that aimed to decrease iatrogenic defects and produce

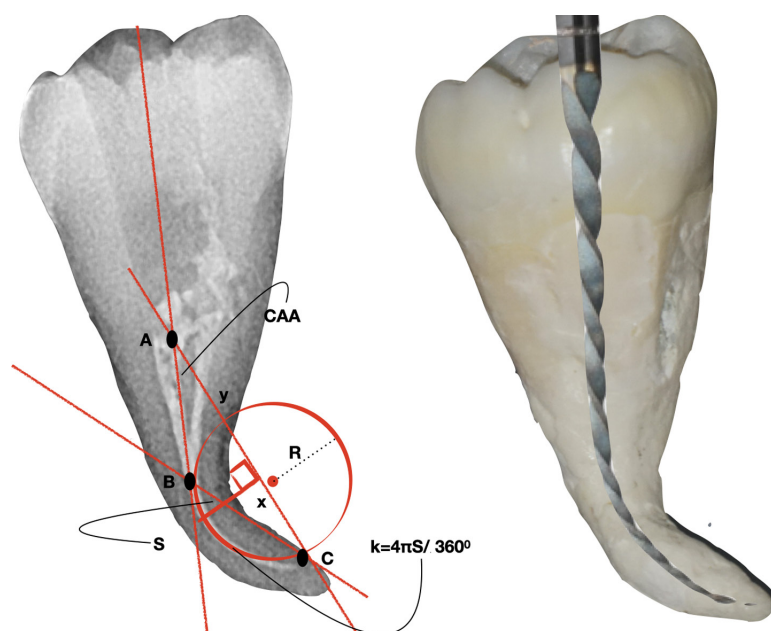


FIGURE 4 Geometrical measurements of curvature parameters. S: Schneider Angle, CAA: Canal Access Angle, y: Curvature Distance, x: Curvature Height, R: Radius of Curvature, k: Length of Curvature. (Schneider 1971, Pruett et al. 1997, Schäfer et al. 2002, Gunday et al. 2005).

preparations with a flared shape. Tapered NiTi files became available to address this problem. The graphic representation of hand instrumentation techniques for curved canals in a chronological order can be seen in Figure 5. Some of these techniques are still valid nowadays and they are used frequently for glide path and permeabilization before the initiation of engine-driven instrumentation.

A reproducible glide path prior to instrumentation is recommended to minimize procedural errors and improves the instrument shaping ability (Berutti et al., 2012). Typically, small files are necessary for initial negotiation; however, these instruments lack the rigidity necessary to negotiate calcified canals and can often distort when vertical watch-winding forces are apically directed (Allen et al., 2007; Kobayashi, 1997). Conical instruments have the rigidity but are too bulky to slide through a constricted space (Allen et al. 2007). To solve these problems, additional manual glide path finders have been introduced (i.e., C+ files). These files attempt to manage the difficulty of calcified canals by modifying tip geometry, by heat tempering stainless steel to increase stiffness, or by using carbon steel to enhance sharpness (Allen et al., 2007; Ashby

& Jones, 1992). According to Allen et al. (2007) variations in design have also been considered to expand the balance between size, and increased rigidity, (Camps & Pertot, 1994; Cormier et al., 1988; Dearing et al., 2005; Krupp et al., 1984; Turpin et al., 2001). The comparison of the dimensions, physical properties, and rigidity of various pathfinder-type hand instruments and the evaluation of the efficiency, wear, and distortion of these files via a laboratory simulation was studied by Allen et al. (2007). The results reached relevant observations (Allen et al., 2007).

- The pitch of a path-finding file influences flexibility, tactile sense (more surface contact points), and cutting efficiency. The more flutes a path finding instrument has, the less flexible it becomes, and the more points of contact it uses in contributing to tactile sensation. Lesser pitched instruments will be inherently more effective in filing but less effective in reaming (Allen et al., 2007; Koch & Brave, 2002).
- The cross-sectional design of the path finding instrument provides information on potential rigidity, strength, and cutting ability. Most of the files in cross

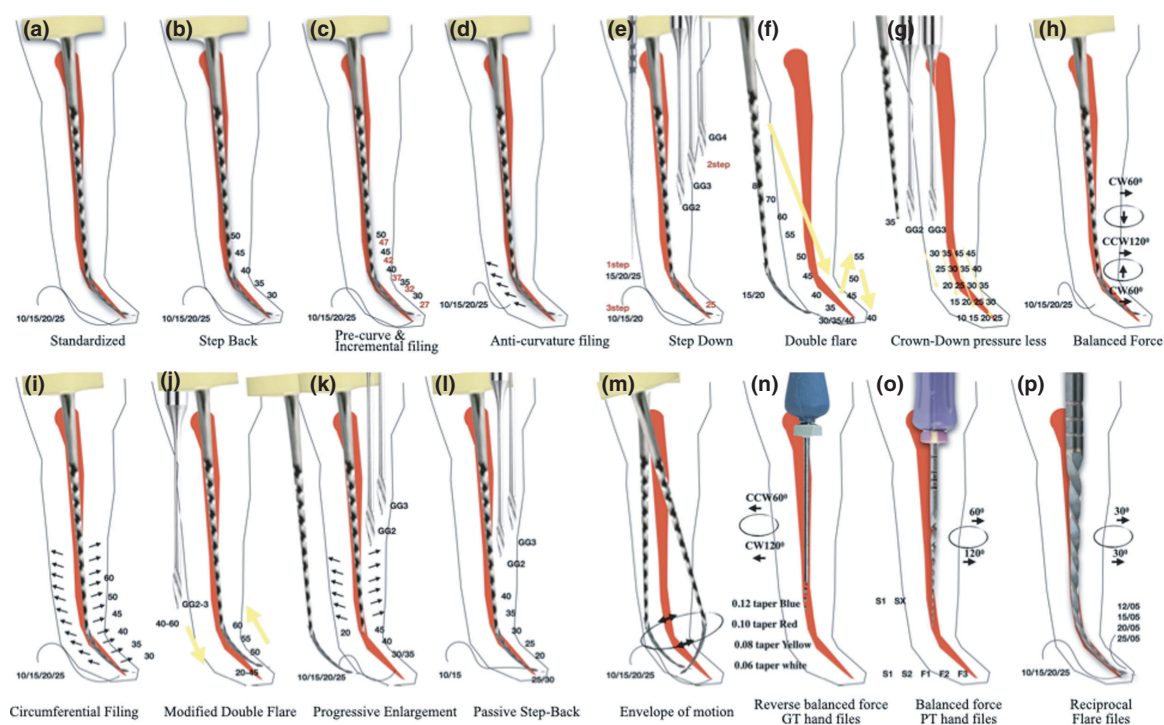


FIGURE 5 Graphic representation of manual techniques for challenging glide path securing. (a) Standardized technique (Ingle, 1961), (b) Step-back technique (Clem, 1969), (c) Pre-curve of stainless steel files and incremental technique (Weine et al., 1970), (d) The anti-curvature filing technique (Abou-Rass et al., 1980), (e) Step down technique (Goerig et al., 1982), (f) Double flare technique (Fava, 1983), (g) Crown-down pressureless technique (Morgan & Montgomery, 1984), (h) The 'balanced force' concept for instrumentation of curved canals (Roane et al., 1985), (i) Circumferential filing (Lim & Stock, 1987), (j) Modified double flare (Saunders & Saunders, 1992), (k) Progressive enlargement technique (Backman et al., 1992), (l) Passive step-back technique (Torabinejad, 1994), (m) Patency and envelope of motion (Schilder, 1974; Yu et al., 2009), (n, o) Hand instrumentation of curved canals with increased tapered Niti files (reverse-balanced force with GT reverse fluting hand files and balanced force with ProTaper hand files; Saunders, 2005), (p) Hand instrumentation of curved canals with increased tapered stainless steel files in 30°–30° reciprocation (flare files).

section exhibited a nearly congruent square shank. One path finding file exhibited pentagonal geometry, suggesting greater shank bulk than square shanked instruments of similar size and taper. Other pathfinding files exhibited D or S cross section geometry showing intermediate shank bulk between square and pentagonal and smaller shank respectively. Smaller shank dimensions relate to less metal mass and less rigidity (Allen et al., 2007; Camps & Pertot, 1994).

- One pathfinding file had greater taper and would be expected to be more rigid, perhaps binding earlier in a constricted canal but resisting deformation because of its robust quadrangular design (Allen et al., 2007; Camps & Pertot, 1994).
- How efficiently an instrument traverses a canal is also influenced by the tip and the proximity of the initial fluting to the tip. Each of the instruments had either a conical or pyramidal tip. The pyramidal tip may better negotiate constricted canals because of increased cutting (Allen et al., 2007; Koch & Brave, 2002).
- Most of the path finding files were twisted from heat-tempered stainless steel blanks; heat tempering is a method of work hardening the alloy, potentially enhancing rigidity. One path finder instrument is composed of carbon steel, which is initially sharper than stainless steel but quicker to corrode in the presence of sodium hypochlorite and sterilization procedures (Allen et al., 2007; Ashby & Jones, 1992).
- Non-heat tempered glide path files and smaller sizes are expected to have greatest degree of flexure. More tapered glide path files are expected to flex less (Allen et al., 2007; Camps & Pertot, 1994).
- Some manual glide path files are available in intermediate sizes. Intermediate sizes relate to a smoother transition between sizes allowing easier passage through the canal constrictions (Allen et al., 2007; Kobayashi, 1997).
- During simulated use, none of the files fractured. However, recordable distortions including buckling, tip flattening, and tip bending were noticed (Allen et al., 2007).
- File distortions were observed by only three out of the 10 clinicians involved in the simulation exercise, suggesting that file distortion may be as much a function of the clinician as of the instrument (Allen et al., 2007).

Selection of instruments, technique, and operator skills are important parameters for the securing and the uneventful creation of the glide path.

Glide path

The starting point of all root canal preparation procedures is the negotiation and securing of a smooth radicular

tunnel from the canal orifice to the physiological terminus (West, 2010). Although in most roots the anatomical glide pathway is always present, the dimensions, content, geometry, and topography in calcified and curved canals render it challenging to follow. Curved and calcified canals requiring root canal treatment might have calcifications (denticles) in sizes from 50 μ m to several mm at any level along the canal walls, pulp chamber or at the level of the curvature (Goga, 2008). The passage of small files to the terminus of the canal beyond the calcifications allow the clinician to establish unobstructed patency of the canal before the initiation of the mechanical preparation (Khatavkar & Hedge, 2010; West, 2010). This reduces the risk of ledging the curved trajectories (Young et al., 2007). In most instrumentation techniques, coronal pre-flaring of the canal and the preparation of a glide path is suggested (Berutti et al., 2009; West, 2010). Coronal pre-flaring has been shown to reduce the incidence of instrument fracture (Roland et al., 2002). A pre-established glide path has been shown to reduce the stress on rotary root canal instruments at the tip, therefore reducing the risk of instrument fracture (Patino et al., 2005).

A glide path can be prepared with stainless steel K-files or engine-driven instruments. The advantages of using K-files include better tactile sensation, reduced risk of fracture, better understanding of the anatomy (when removed from curved canals, they often retain an impression of the canal anatomy alerting the operator to the topography of the most significant curves), and ability to be used in tortuous canals trajectories. This is because they come in smaller sizes than engine-driven glide path files. The disadvantages include the higher operator fatigue, the technique sensitivity especially for the inexperienced operator, the increased time required for glide path creation, the risk of introduction of canal aberrations, change of the original anatomy, and the increased apical debris extrusion (Cassim & van der Vyver, 2013).

The advantages of engine-driven glide path files include reduced instrumentation time, decreased probability for canal aberrations (ledges, zips, foraminal transportation), better root canal anatomy preservation, reduced operator fatigue, and reduced apical debris extrusion. The disadvantages include the increased risk of torsional failure when engaged inside the anatomy, the decreased tactile sensation, the additional cost and the limitation of their use only after the initial glide path is secured (Cassim & van der Vyver, 2013). It has been suggested that during the mechanical preparation of curved and constricted canals, no engine-driven instrument should be used where a hand instrument has not been placed before (Bergmans et al., 2001). All available NiTi engine-driven glide path files have non-cutting tips and because of their extreme

flexibility, they are not designed for the initial negotiation and securing of the glide path (Young et al., 2007).

Techniques for securing the glide path

Although hand files can produce undesirable effects during the instrumentation, they are extremely useful for the initial negotiation of curved and calcified root canals. Establishing and securing the glide path in calcified and curved canals might be the most challenging part of the instrumentation procedure and it is mainly a hand instrument procedure. Any narrow and curved pathway from the canal orifice to the radiographic foramen that blocks the negotiation of sizes 06–10 K-file can be defined as a challenging glide path. Glide paths larger than this can be enlarged predictably with rotary or reciprocating instruments without the absolute need of using stainless steel hand files. Engine-driven glide path files will work best in these situations, even for inexperienced operators (Berutti et al., 2009).

West (2010) described four reasons a size 10 K-file would not follow to the radiographic terminus and suggested solutions:

- The canal pathway might be blocked with collagen, debris, fibrotic tissue, or calcifications. The solution might be to make an abrupt apical curve on a smaller file (typically 0.06 or 0.08), follow gently and touch the blockage, remove the file, irrigate, re-curve, and repeat until the file moves deeper (West 2010).
- The angle of access and the angle of incidence are not the same. In other words, the canal might be curved in a way that does not correspond to the curvature given to the file used to negotiate. The solution might be patience and randomization. (West 2010).
- The diameter of the tip of the file used might be wider than the canal dimensions. The solution might be as simple as to choose a smaller file (West 2010).
- The diameter of the shaft of the file used might be wider than the canal dimensions, blocking further negotiation. The solution might be either to change to a smaller file or remove some coronal restrictive dentine and try again with the same file (West 2010).

To be able to secure the challenging glide path, there are certain steps to be followed.

Negotiation and glide path

Once the canal orifice is found, sizes 06–10 K-files are selected for initial canal exploration. The tip of the file

is inserted in the canal orifice and the file is left alone to bounce to the canal direction of access. The use of a lubricant is beneficial. The file is used with watch-winding movements until resistance is obtained. If the file reaches length, the canal can be enlarged in a standardized approach with hand files or rotary instruments (Figure 5a; Ingle, 1961). As a rule, the largest the manual glidepath that can be achieved the more uneventful the engine-driven instrumentation will be. stainless steel files larger than size 15, 0.02 mm/mm taper become more rigid to work around curvatures with filing movements and should be used with the balanced force technique (Roane et al., 1985), see Figure 5h. The file is inserted by using clockwise rotation and light inward pressure. The cutting is accomplished by using counterclockwise rotation and inward pressure. Continuing counterclockwise rotation past 120°, once the cutting is achieved, enlarges the canal to the file cutting diameter. Furthermore, counterclockwise rotation helps to ensure full diameter enlargement (Roane et al., 1985). Upon completing each cut, the file is again positioned for cutting by using a clockwise placement stroke of one-half or less revolution. Each placement is followed by a counterclockwise cutting rotation. This sequence is repeated until working depth has been reached (Roane et al. 1985). When enlargement has been accomplished, a final clockwise cleaning rotation is used to load canal debris into the flutes and to elevate that debris away from the apical foramen (Figure 5h).

Sometimes stepping back farther from the apical preparation with each progressively largest hand files and balanced force technique might be more beneficial in a curved canal than the standardized preparation (Figure 5b,i; Clem, 1969; Torabinejad, 1994). In challenging situations in which the file is blocked short of the radiographic terminus, the second step of the process of challenging glidepath should be initiated.

Challenging glide path securing

At the level of blockage, a working radiograph might be beneficial to reveal the exact level and possibly the reason for blockage. Further apical advancement of the size 10 K-file might be hindered because of the following reasons:

- The canal curvature begins at this level (Figure 6a,c,d).
- The canal might split to two or more branches (Figure 6a).
- The canal might be constricted to a smaller size (Figure 6b).
- The canal content might be fibrotic, calcified, and resistant to penetration.

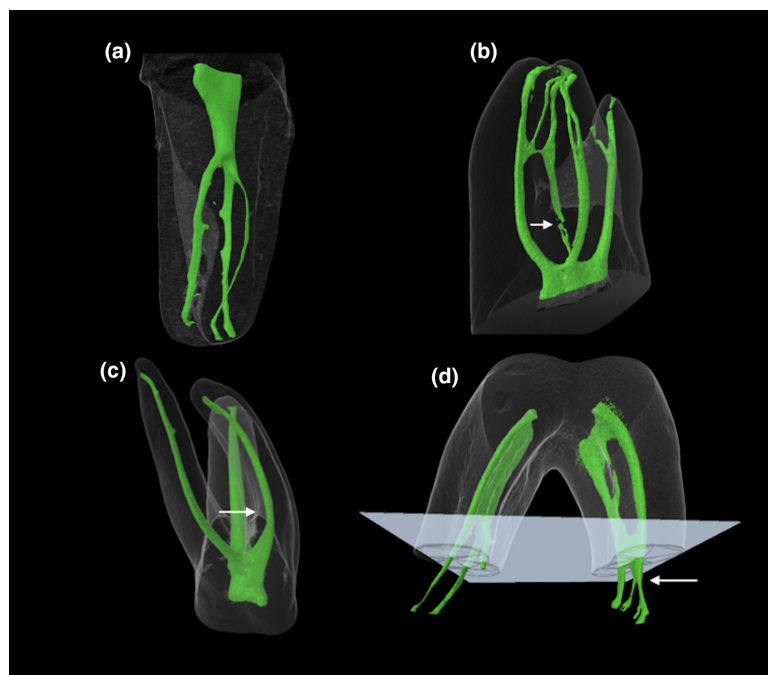


FIGURE 6 A. Mandibular premolar with 3 canals constricted and curved. B. Maxillary second molar showing a MB2 calcified canal at the cervical third (arrow) and complex apical anatomy. C. Maxillary molar with long and narrow MB root. The arrow points the danger zone. D. Mandibular molar showing multiplanar curvatures in the apical third of the mesial root.

- e. The canal might have a pathological alteration of the internal anatomy like internal resorption and the file might be stuck in the resorptive area.
- f. The canal might have an iatrogenic alteration of the anatomy such as a ledge that blocks further negotiation.
- g. The canal might have a coronal constriction that is large enough to allow the tip of the size 10 K-file to negotiate but not the full length of the tapered instrument (Figure 6b).
- h. The canal might be iatrogenically blocked with dental debris from a previous attempt to negotiate.

The clinical techniques to manage a blocked canal are:

- a. If the canal curvature is blocking further negotiation, then the length and radius of curvature must be determined and replicated to the scouting K-file (Figure 7; Weine et al., 1970). The pre-curved file must be smoothly guided to the same spot without pressure and with watch-winding movements (Figure 5c). In cases of small radius curvatures (abrupt), pre-flaring of the canal orifice is usually required so that the pre-curved file can fit inside the canal. Once inside the canal, the file is slowly guided up to the level of the blockage. At this point, the pre-curved file is rotated clockwise or counterclockwise so that the tip of the file faces the inner side of the curve. The objective is for the tip of the file to negotiate below the curvature (Figure 7a,b). A notched silicon stop in the shaft of the hand file is used to control the movement of the tip of the pre-curved file. Once the

pre-curved file negotiates below the curvature, the envelope of motion (Schilder, 1974; Yu et al., 2009) is applied. The file rotates clockwise by keeping a coronal resistance so that the files does not screw deeper inside the canal. By doing this envelope of motion, dentine is removed from the point of the curvature and the radius of the curvature becomes slightly larger. The curvature becomes smoother and easier to negotiate deeper with the same file (Figure 5m). Sometimes this step is enough to reach to the radiographic terminus with watch-winding movements. In the apical preparation, files are used in the following manner. To assure accuracy, all files are measured before pre-curving the working end. A curve is placed in the most apical portion of the file (Figure 7c). The curved file is inserted into the canal and worked apically using a stem-winding motion and light apical pressure. Once the file reached WL, it is withdrawn several mm, then worked to length and withdrawn again (Figure 5k). This sequence is repeated until the file can slide easily to WL without using the stem-winding motion (progressive enlargement technique; Backman et al., 1992). Directional anti-curvature filing (Figure 5d) or circumferential filing (Figure 5i) of less than 0.5 mm amplitudes with the size 10 K-file will smoothen the curvature before starting the automated instrumentation (Abou-Rass et al., 1980; Lim & Stock, 1987). With a size 10 K-file becoming extremely loose, the rotary/reciprocating instrumentation can be safely initiated. In severe curvatures, larger taper nickel-titanium manual files can be also

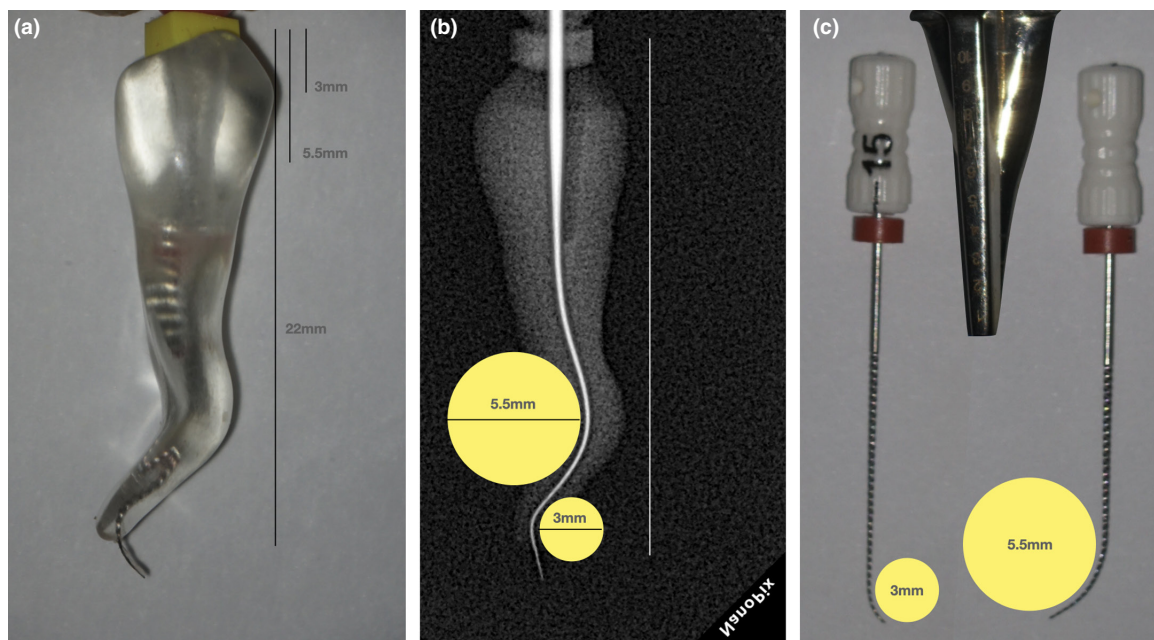


FIGURE 7 a. S-shaped transparent training model with a 15 K file extruding the apical exit and measuring bars for the calculation of the radius (DRSK training models, drsk.com, Sweden), b. Radiographic projection of the double curved training model and calculation of the curvature radius (5mm radius middle third curvature, 3mm radius apical third curvature), c. Endo-Bender instrument (Sybron Endo) is used to replicate curvatures of different radius in stainless steel K files. The pre-curved files are used to negotiate below the corresponding curvatures.

used safely with balance force movements (Figure 5o) or reverse-balanced force (Figure 5n) in files of reverse direction flute design (Saunders, 2005).

- b. Blockage because of splitting canals can be managed the same way as curved canals with the only difference that the canal curves simultaneously to more than one direction. Each direction followed will lead into a different canal. A preoperative CBCT is very helpful to understand the topography and number of the splitting canals. The magnification and illumination provided by an operating microscope are indispensable tools in cases with deep splitting pathways. Visualization of the splitting point under the microscope will facilitate the negotiation and securing of the glide paths. Straight line access and enlarging the canal above the splitting point will facilitate additionally the whole procedure and will provide a visual corridor to the different branches of the split. Once the glide path in all branches is secured, rotary instrumentation can be initiated (Figure 8).
- c. If the canal is smaller than size 10 K-file, the solution might be as simple as choosing a smaller size 0.08 or 0.06 file. If a combination of curvature and smaller canal exists, then the curved pathway management protocol should be followed with smaller files. If a combination of splitting and smaller canal exists, then the pathways below the splitting point should be followed with smaller files.
- d. If the canal below the blockage is calcified or fibrotic, the tissue might resist further penetration. The solution is the use of stiffer files that can withstand more pressure. Abundant irrigation with NaOCl solutions alternative with EDTA 17% might be able to soften the fibrotic or calcified tissues respectively and allow further file penetration (Hülsmann et al., 2003; Zehnder, 2006). If a combination with curved pathways exists, then the curved pathway management protocol should be followed with stiffer pre-curved files and the same motion.
- e. Pathologic alterations of the internal anatomy (internal resorption).
- f. Iatrogenic alterations of the internal anatomy (ledges, perforations). If a pathologic or iatrogenic alteration of the internal anatomy exists, the curved management protocol should be followed. Each alteration of the internal anatomy, pathologic or iatrogenic, can be translated and correspond to a curve. The radius of this curve is replicated in the file and the canal below the alteration or the ledge can be negotiated. Once the alteration is bypassed, short amplitude push and pull movements of the file can smoothen the pathway and render it reproducible and secured. Very useful in these situations are stainless steel hand files with larger tapers. These files can be used in 30°–30° CW-CCW manual motion or even mounted in a special reciprocating handpiece (M4 handpiece, Sybron Endo) reducing hand fatigue

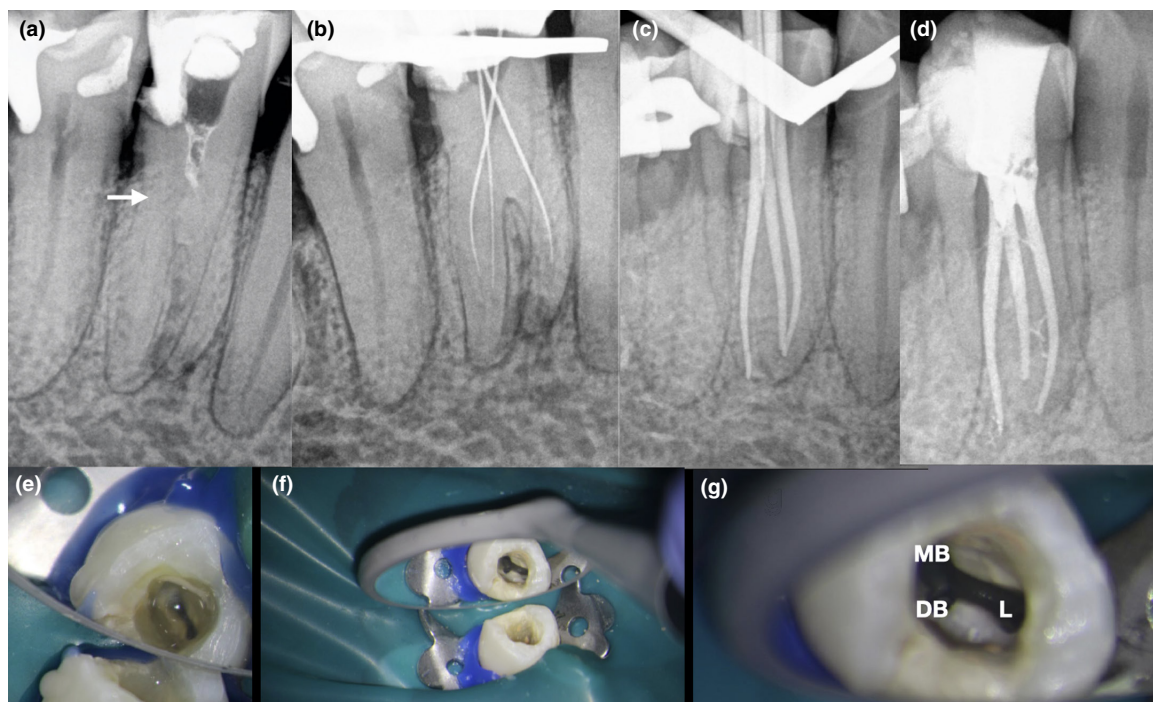


FIGURE 8 Mandibular first premolar with a previously initiated treatment and symptomatic apical periodontitis. Unusual anatomy, intracanal medication at the coronal third, and calcified canals are observed in the preoperative image (a). Number 6 and 8 C+ hand instruments in the MB, DB and lingual canal. Instrumentation was completed by hand files ISO# 06-15, and .04 NiTi instruments. (C-D) cone fit and obturation of the case. Note the access cavity before and after the refinement with ultrasonic tips (e-g).

and accelerating the whole securing procedure (Figure 5p).

- g. The securing of the glide path in canals that have a coronal constriction can be easily managed with removal of the coronal constriction with flaring (Figure 5f,j; Fava, 1983; Saunders & Saunders, 1992) or the crown-down sequence of manual files and gates-Glidden burs (Figure 5e,g; Goerig et al., 1982; Morgan & Montgomery, 1984).
- h. Iatrogenic blockage needs stiff instruments and abundant irrigation to overcome. Fibrotic or calcified pathways resist file advancement. The techniques described above might be difficult to work if the canal is blocked. To unblock the pathways, frequent irrigation is needed with alternative use of a chelator and sodium hypochlorite (Hülsmann et al., 2003; Zehnder, 2006). The chelator will act in the inorganic component of dentinal mud blockage exposing collagenous matrix. The exposed organic collagenous matrix can be dissolved with sodium hypochlorite. The use of stiff pre-curved instruments in combination with the suggested irrigation protocol might provide a small pathway for penetration of the files to WL. Once WL is reached, a change to softer K-files is required for further securing of the glide path with minimal deviations from the initial pathway.

- i. In some cases, combination of two or more of the above solutions might be required to secure the glide path. Changing between the different solutions back and forth might also be required to achieve a successful glide path securing outcome.

The challenging glide path securing should be effectively managed by following the suggested steps prior to any engine-driven instrumentation. The preparation of a glide path prior to shaping with engine-driven instruments has been shown to provide better results in terms of mechanical failure, shaping ability, apical debris extrusion and dentinal defect formation, when compared with the absence of glide path creation (Berutti et al., 2012; Kwak et al., 2018).

Engine-driven instruments and curved canals

If the absence of curvature, conventional stainless steel files would have results as good as the one produced by nickel-titanium instruments. Stainless steel files can maintain sharp edges longer. Unfortunately, most of the canals in the human dentition are curved. Root canal curvatures can cause excessive torsional stresses

and cyclic fatigue on conventional stainless steel files resulting in undesirable canal transportation and instrument separation. Moreover, hand instrumentation can extrude debris or push them laterally into the lateral anatomy. In contrast, mechanical instrumentation can collect and remove debris from the canal system in a coronal direction. The introduction of NiTi alloys allowed the manufacturing of tapered files that can be used with rotation or reciprocation movements (Baumann, 2004; Walia et al., 1988). Innovations adopted by manufacturers has allowed the production of new NiTi alloys. The hybridization of new systems provides greater security and adaptability for curved canals management.

Engine-driven instruments design

Nowadays, more than 200 different engine-driven instruments are available in the market. It is imperative to recognize instrument features that improve efficacy or pose possible risks for curved canal management.

The following considerations are important in formulating techniques to approach difficult cases (McSpadden, 2007):

1. A file with a more efficient cutting design requires less torque, pressure, or time to accomplish root canal enlargement.
2. In a straight canal, the ability of a file to withstand torsion is related to the square of its diameter.
3. In a curved canal, the ability of a file to resist fatigue has an inverse relationship with the square of its diameter.
4. The torque required to rotate a file varies directly with the surface area of the file's engagement in the canal.
5. Fatigue of a file increases with the number of rotations of the file in a curvature.
6. Fatigue of a file increases with the degree of curvature of the canal.
7. To improve efficiency, the smaller the surface area of a file engaged in the canal, the greater the rotation speed should be.
8. The more spirals a flute has per unit length around the shaft of a ground file, the less resistance to torsion deformation there is, but the more flexible the file is.
9. The fewer spirals a flute has per unit length around the shaft of a ground file, the more it resists torsion deformation, but the more rigid it is.
10. The sharper the cutting blade of a file, the fewer spirals per unit length the file should have.

11. The greater the number of flutes with similar helix angles, the greater the tendency of the file to screw into the canal and become bound.
12. Maximum engagement of a file occurs when it progresses into the canal at a rate that is equal to its feed rate, the rate the file progresses into the canal without the application of positive or negative pressure.
13. Less canal transportation occurs with a file having greater flexibility, an asymmetrical cross section design, and/or a land.

Incorporating designs and techniques to reduce any of these forces is very important in curved canal management.

Engine-driven NiTi instruments metallurgy

The mechanical properties of NiTi alloys for curved canal management vary according to their chemical composition and thermal treatment during manufacturing (Figure 3d). Heat treatments consist of controlled heating and cooling under controlled conditions to obtain specific properties that will improve clinical behaviour (Shen et al., 2011). The heat treatments performed to improve the NiTi alloy properties might be beneficial for the management of curved and constricted canals and include in chronological order (Gavini et al., 2018):

- Electropolishing (electrochemical surface treatment; 1999): It is a surface treatment leading to the reduction of manufacturing defects with the goal to increase the cutting efficiency and fatigue resistance of the file (Gavini et al., 2018; Anderson et al., 2007).
- M-wire (2007): It is a unique thermomechanical procedure at various temperatures, applied before the machining of a new NiTi alloy composed of 55.8% Ni. The final alloy contains both martensitic and R phases whilst maintaining the pseudoplasticity. The objective is to produce an instrument of higher cyclic fatigue resistance and enhanced mechanical properties compared to conventional superelastic NiTi files (Gambarini et al., 2008, 2011; Gavini et al., 2018).
- R-phase (2008): It is a thermomechanical procedure that generates an additional R-phase change in the crystal structure of the alloy. This allows twisting of the wire rod to create the flutes by plastic deformation and heat treating it to recrystallization. It improves flexibility and strength. An additional special oxidation bath surface treatment increases the hardness of the file without changing its flexibility. This twisting process ensures greater resistance than grinded instruments (Gambarini et al., 2010; Gavini et al., 2018).

- CM wire (2010): The nitinol SE508 alloy is machined and subjected to a heating and cooling process that will give the alloy control over the shape memory effect, allowing the instruments to be free from restoring forces, more flexible and fatigue resistant (Gavini et al., 2018). These instruments present less nickel (52%) than conventional alloys (54%–57%). The Af temperature of CM files is 47⁰ C suggesting that at room and body temperature, the instrument is composed from martensite, R-phase, and some austenite compared to conventional NiTi which is purely austenitic. Although CM files have lower tensile strength than conventional alloys, they have a higher capacity to withstand deformation before fracture (Gavini et al., 2018), indicating their superior flexibility. The reduction of the restoring forces, the extreme fatigue resistance and the superior flexibility render these instruments ideal to be used in curved canals (Bürklein et al., 2014; Gavini et al., 2018).
- CM Blue Wire & CM Gold Wire (2012 & 2014): It is a heat treatment process for NiTi CM alloys, the instruments are continuously heat-treated and then cooled, which results in a surface colour corresponding to the thickness of the layer of titanium oxide (Gavini et al., 2018). In the NiTi Blue Wire alloy, the thickness is 60–80 nm, whereas in the NiTi Gold alloy, this thickness is 100–140 nm (Gavini et al., 2018). The rigid titanium oxide layer compensates for the loss of hardness enhancing cutting efficiency and wear resistance (Gavini et al., 2018). These systems also have better fatigue resistance and flexibility for curved canal management (Plotino et al., 2014; Gavini et al., 2018).
- Max Wire (2015): This heat treatment results in an instrument that at temperatures greater than 35°C, shifts from the martensitic to the austenitic phase (Gavini et al., 2018). This provides the instrument a semi-circular shape that allows it to project against the walls of the root canal when rotating, performing eccentric rotary motion (Gavini et al., 2018). The main purpose of this instrument was to provide supplementary cleaning of the canal at the end of chemical and mechanical preparation, (Bao et al., 2017; Gavini, 2018). Recently, a shaping Max Wire instrument also became available (Gavini et al., 2018).
- EDM Wire (2016): NiTi CM 495 alloy is manufactured using spark erosion technology. The EDM manufacturing method seems to improve the fracture strength and cutting efficiency of the instruments. XRD analysis of these instruments revealed the presence of monoclinic martensite B19 structure and rhombohedral R-phase (Iacono et al., 2017; Gavini et al., 2018).

The Improved flexibility and high cyclic fatigue of heat-treated NiTi files, combined with the lack of restoring

force, are ideal properties for the management of curved and calcified canals (Figure 3d). Although instrument designs and metallurgy are relevant steps for the management of curved canals, developing a consistent technique to use these instruments is even more important.

Engine-driven instrumentation techniques

General engine-driven technique considerations

McSpadden (2007) suggested nine considerations for the safer engine-driven instrumentation of curved canals with superelastic NiTi files (McSpadden, 2007):

1. Select the tip design that will not burnish or transport the canal (non-cutting guiding tips).
2. Advance a file into the canal with no more than 1 mm increments with insert/withdraw motions (usually three pecking movements and remove to clean flutes and canal).
3. To advance a particular file the first 1 mm into a canal after it becomes engaged, a minimal specific pressure needs to be applied (feed rate of the file). If the pressure to advance the file needs to be increased above the level of its feed rate or if a negative pressure (screwing-in force) is encountered, change to a smaller sized and tapered file or circumferentially file coronal to this position will minimize the applied stresses.
4. File advancement into the canal should be able to occur at a rate of at least ½ mm per second without increasing the pressure for insertions.
5. If a file has more than a 0.02 taper, do not advance more than 2 mm beyond the preparation of the previous file if any part of the file is engaged in a curvature.
6. Except for 0.02 tapered files having a size diameter of 0.20 mm and smaller, do not engage more than 6 mm of the file's working surface if the file is engaged in a curvature.
7. Apply light apical pressure on any file whilst advancing into the canal and try to avoid negative (screw in) forces around curvatures by using smaller tapered files and files of asymmetrical cross section.
8. Beyond the point of curvature in the apical zone, the file diameter should be no greater than 0.60 mm for a 0.02 taper, 0.55 mm for 0.04 taper, 0.50 mm for 0.06 taper, and 0.35 mm for a 0.08 taper. (This consideration is the result of testing for 45° curvatures having 8 mm radii and applies only to these dimensions for rotary conventional NiTi files. File diameters should be smaller for more severe curvatures and can be adjusted larger for less severe ones.)

9. When any of the parameters cannot be met, changing to a file having a different taper in the technique sequence will usually enable re-adherence to the parameters.

Adherence to these principles combined with frequent irrigation, patency maintenance, and cleaning of the flutes can ensure an uneventful shaping for most rotary systems (McSpadden, 2007). However, in challenging highly curved and constricted root canals, these general considerations might not be always adequate to accomplish the goals of treatment. For these cases, several instrumentation techniques have been established and reported in the literature. Although the following engine-driven instrumentation techniques are suggested to provide solutions in complicated clinical scenarios, independent studies evaluating their safety, validity, and reproducibility are still lacking.

Specialized engine-driven technique considerations

The zone technique. This technique was developed by McSpadden (2007). During root canal instrumentation of curved canals, variations in the pressure required for progressing into the canal determine if the curvatures are threatening for the file used (McSpadden, 2007; Figure 9a). One of the greatest challenges in making

that determination is the force required for rotating a file relative to the force necessary to progress through the curvature (McSpadden, 2007). A severe curvature in the apical third of the canal could be less threatening than a moderate curvature in the mid-root or the cervical portion of the canal. The ability of an instrument to resist the cyclic fatigue has an inverse relationship with the square of its diameter. The same inverse relationship applies also for the flexibility (McSpadden, 2007). Therefore, the smaller diameter tip of a file can negotiate an apical curvature easier than the larger diameter portion can negotiate the same amount of curvature in the coronal or mid-root part of the canal (McSpadden, 2007).

According to the testing of instruments for 45° curvatures having 8 mm radii, McSpadden (2007) introduced some file diameter limitations that should not be exceeded during rotary instrumentation with conventional austenitic NiTi files. Beyond the point of the curvature, the rotary NiTi file diameter should be no greater than 0.60 mm for a 0.02 taper, 0.55 mm for a 0.04 taper, 0.50 mm for a 0.06 taper and 0.35 mm for a 0.08 taper (McSpadden, 2007). For more severe curvatures, the file diameter limitations should be smaller and for less severe curvatures could be larger.

Taking into consideration the diameter limitations for 45° curvature with 8 mm radius, McSpadden (2007)

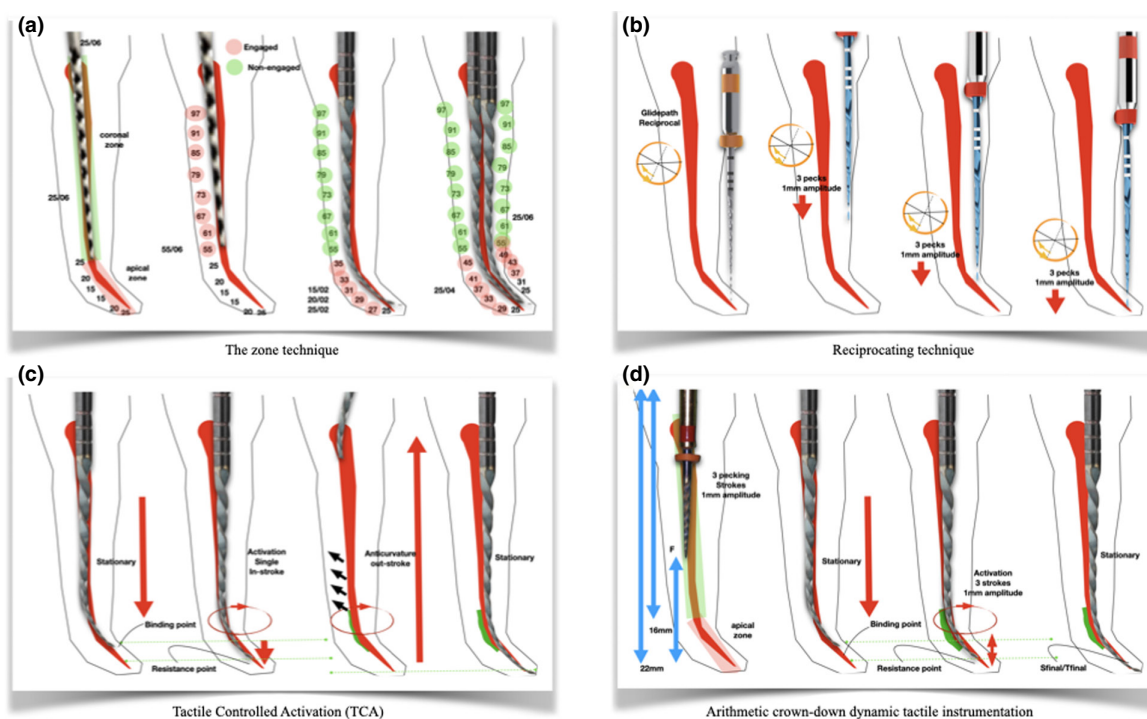


FIGURE 9 A. Graphic representation of the Zone technique (Coronal zone, apical zone and protocol diameters are represented) (McSpadden 2007), B. Graphic representation of the single file reciprocating technique (3 pecks of 1 mm amplitude guide the reciprocating file to length after 3 insertions) (Yared 2008), C. Graphic representation of the stationary, in-stroke and out-stroke steps of the single stroke Tactile Controlled Activation (TCA) technique (Chaniotis & Filippatos 2017), D. Graphic representation of the maximum coronal zone flaring depth calculation for dentine preservation and the 3- stroke apical zone file activation below the curvature according to the arithmetic crown-down dynamic tactile instrumentation technique (Elkholy & Ha 2021).

introduced the zone technique with two objectives in mind to minimize file stress for any type of NiTi rotary file used for the preparation of curved canals. First, the canal diameter coronal to the curvature should be large enough to prevent any engagement in that portion of the canal when any file is being used apical to the curvature, and second, the file diameter is not too large to rotate safely in a curvature.

The technique is divided into two steps.

- a. *Step one.* Determine if there is a curvature of any significance and how far the curvature is from the apex. Dividing the canal into zones according to the location of the curvatures or constrictions in relation to the apex can simplify canal preparation with each zone having a different technique. Initial methods for dividing the canal into zones relied on the tactile feedback during file insertion. With a non-rotating file smaller than the canal passively advanced, the depth at which resistance is met denotes the terminus of the coronal zone and the beginning of the canal deviation. With a rotating file, the coronal zone is denoted whenever the pressure needed for additional advancement to occur, whilst using 1 mm increments, is exceeded. Nowadays, the coronal and apical zones can be determined three dimensionally with the use of CBCT imaging and specific software.
- b. *Step two.* Determine the distance each of the files having different sizes and tapers can safely be advanced around curvatures and which size file will need to be used in the coronal zone to prevent any subsequent file from binding in the apical zone.

By using the diameter limitations for a curvature of 45° and 8 mm radii, the following formula is suggested:

$$\text{Length that the file can be projected around the curvature} = \frac{\text{diameter limitation} - \text{file tip size}}{\text{file taper}}$$

(Diameter limitations: no more than 0.60 mm for 0.02 taper, 0.55 mm for 0.04 taper, 0.50 mm for 0.06 taper and 0.35 mm for 0.08 taper).

For example: The WL of a curved canal with an angle of 45° and 8 mm radius is 16 mm (apical and coronal zone). The intended enlargement of the canal according to the initial canal dimensions is aimed at 30/04. The curvature length from the point that the canal starts to deviate to the apical foramen is 6 mm (apical zone). According to the formula suggested, 0.55 is the diameter limitations for 0.04 tapered files (–)0.30 tip diameter equals (=)0.25, divided by 0.04 equals 6.25. The length of the 30/04 file that can be projected safely beyond the given curvature is

6.25 mm. Since the length of the apical zone is 6 mm, the 30/04 file can be rotated to full length with relative safety. Before reaching the apical zone with rotary files, the coronal zone needs to be enlarged to a size $0.30 + (6 \times 0.04) = 0.30 + 0.24 = 0.54$ mm to prevent any engagement in that point of the canal whilst using the 30/04 file to length. A common mistake is to use tip diameters at the terminus of the coronal zone that are smaller at that point than the diameters for files used in the apical zone. Care must be taken not to ledge and alter the root canal anatomy at the terminus of the coronal zone. This can be achieved by frequent recapitulations with small stainless steel hand files and adherence to the estimated coronal zone length. File sequencing can be flexible if it adheres to the principles. If the target of the desired final apical enlargement is 30/06, then according to the previous formula, the diameter limitation of 0.50 (–) tip size 0.30 = 0.20 (÷) taper 0.06 = 3.33 mm. This means that a 30/06 file can be safely projected around the curvature in the apical zone only for 3.33 mm. The 30/06 file is not safe to use to full length since the length of the apical zone below the curvature is 6 mm. The desired final preparation for the canal needs to be rearranged to fit the diameter limitations. The final enlargement can shift to a shape of smaller taper or smaller tip size to fit the diameter limitations.

Diameter limitations in canals having different curvatures can be extrapolated mathematically. Two factors are to be considered, the WL and the radius of curvature. If the radius is 16 mm (two times the amount stated in the parameters), the diameter limitation of a 06 taper file is larger than 50 based on the square of the file diameter. For cases with an apical zone greater than 6 mm, curvature more than 45° and radius less than 8 mm, the diameter limitations should be smaller.

Although the calculations seem complicated, with some practice this technique can be mastered with the benefit of efficiency and the reduction of the threat of failure. However, if a technique is required for routine cases with an apical zone of 6 mm, 45° curvature and 8 mm radius, the following technique is suggested with conventional austenitic NiTi rotary files:

25/06 to curvature
55/06 to curvature
25/02 to WL
25/04 to WL
26/06 1 mm short of WL (Figure 9a).

For root canals with different angle than 45° and different radius than 8 mm, appropriate adjustment of the above protocol is required.

If more flexible and fatigue-resistant martensitic heat-treated rotary NiTi files are to be used with the zone

technique, the suggested diameter limitations will have to be re-adjusted to larger sizes for the same parameters of curvature. This adjustment will result in the ability to deliver larger apical preparations during the enlargement of curved root canals. The enlargement technique also will have to be re-adjusted to accommodate larger preparations with heat-treated files. Although the diameter limitations of the zone technique were tested by McSpadden (2007), independent scientific evidence supporting these limitations and the suggested adjustments are lacking. Until further evidence becomes available, these limitations should be applied with caution.

Reciprocating technique. Another development in root canal preparation was the introduction of reciprocating techniques (Bürklein et al., 2012; Yared, 2008; Figure 9b). Rotary nickel-titanium (NiTi) instruments have already enhanced the quality of root canal shaping minimizing procedural accidents (Schäfer et al., 2004). With the introduction of single file reciprocating instruments, it was claimed that the management of curved canals can be obtained with a single instrument. In some cases this step can be obtained without prior glide path preparation. This outcome can be explained by the reciprocating movement. The instruments cut dentine in a counterclockwise (CCW) direction and are released in a clockwise (CW) motion. The instrument will progress into the root canal because the CW rotation is smaller than the CCW rotation (Plotino et al., 2015). The releasing motion removes the stress from the instrument and prevents instrument fracture (Plotino et al., 2015). Because of the reciprocating motion, the instruments should follow the naturally existent root canal path down to the apical ending of the canal (Yared, 2008). Previous authors reported that a large proportion of non-calcified root canals can be prepared with the Reciproc instrument without a previous glide path preparation (De-Deus et al., 2013; Zuolo et al., 2015). The ability of the reciprocation technique to achieve the WL in straight canals without glide path is 96.4%, and for moderately curved canals is 90.7% (De-Deus et al., 2013). The movement suggested with the reciprocating files is 3 pecking insertions with less than 1 mm amplitude. The instrument is clean and the movement is repeated until the instrument reaches the working length (Figure 9b). As a practical rule, in reciprocating systems, it is suggested that if a straight stainless steel size 0.8 K-file cannot reach the full WL, then a glide path procedure is needed. If a straight size 0.8 K-file can reach easily WL, then the glide path securing procedure might not be always required. However, even with the reciprocating systems, a glide path will always facilitate the instrumentation procedures. The introduction of glide path files and heat

treatment can allow the instrumentation of challenging curvatures with this technique. (Figure 10).

Tactile Controlled Activation (TCA) technique. Keeping in mind the complexity of root canal systems and the need to minimize file engagement and torsional loading during instrumentation of dilacerated canals, a novel approach was developed and named Tactile Controlled Activation (TCA) instrumentation technique (Chaniotis & Filippatos, 2017a,b; Figure 9c). The TCA technique can be defined as the single stroke activation of a motionless (stationary) engine-driven file only after it becomes fully engaged inside a patent canal and tactile feedback of the underlying anatomy is gained (Chaniotis & Filippatos, 2017a,b). TCA utilizes file activation only after maximum engagement of the file below the fulcrum of the curvature is achieved and tactile feedback of the anatomy and topography of the curve is gained. By inserting non-rotating files with smaller diameters around curvatures and withdrawing with rotation, the severity of the curvature can be easily determined whilst avoiding excessive stress (McSpadden, 2007). TCA technique is taking advantage of this strategy to avoid stress in highly curved canal systems. It can be divided into three phases: stationary, in-stroke, and out-stroke (Figure 9c).

Stationary phase: After accessing the pulp chamber and locating the canal orifices, technical patency to the apical third is achieved and the glide path is secured at least up to size 10, 0.02 taper. After the glide path is secured, the first automated file to be used should be preferably of equal or slightly larger tip size depending on the location, the angle, and the abruptness of the curvature along the root length. The taper of the first engine-driven file should be 4% or less. The file is mounted on the handpiece of an endodontic motor and passively inserted inside the canal until maximum frictional resistance is met. In hard-to-reach areas, the stationary engine-driven file can be inserted by hand until resistance and the motor can be connected intraorally afterwards before starting the next phase.

In-stroke phase: Before activating the file, it needs to be verified that the tip of the file passed the first curvature. This can be verified with a radiograph (TCA-radiograph) or by keeping strict recordings of the depth of the curvature. Once the file position is verified, the file is activated and pushed slightly apically (in-stroke) until the activated file resists further advancement below the curvature.

Out-stroke phase: Once the first resistance is met, the file is withdrawn from the canal without applying further apical pressure to go deeper (single stroke). During withdrawal, the file can be pushed towards the bulkier root structure away from the curvature and the thinner danger zone (anti-curvature out-stroke). The single in-stroke and out-stroke technique eliminates the risk of

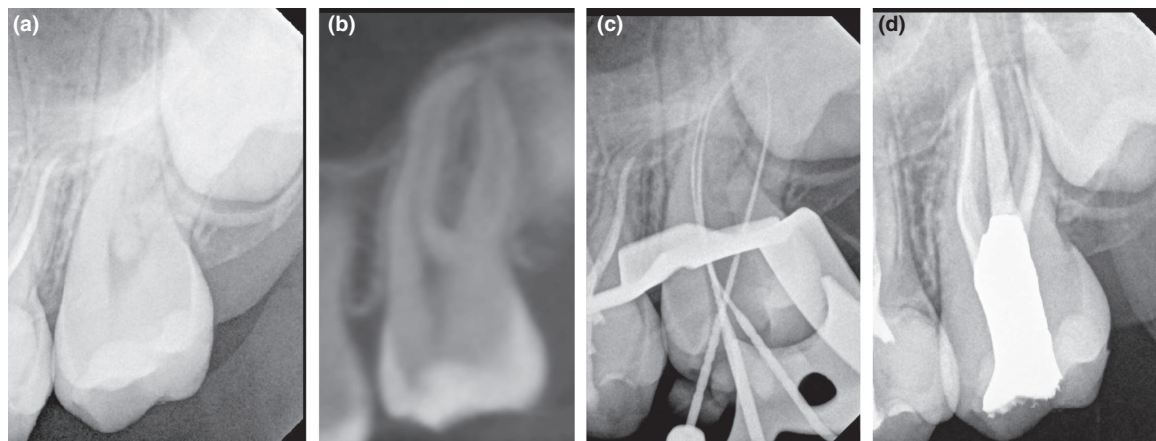


FIGURE 10 Maxillary second molar in a young adult with symptomatic irreversible pulpitis and normal apical tissues. Note the difficulty to assess the root canal anatomy due to the superimposition of the maxillary third molar in the periapical image (a). A limited field of view CBCT revealed the presence of a multiplanar curvature in the mesiobuccal root, proximity of the maxillary sinus and normal apical tissues (b). Glidepath was obtained using hand files (c), the instrumentation was accomplished by using .04 NiTi instruments (d). The result showed adequate preservation of the root structure and a three-dimensional filling in the MB root.

torsional failure of the file that will be activated inside the canal because the file will be moved from the point of maximum engagement without activation to a point of no engagement with activation. This single movement will remove coronal restrictive dentin facilitating the next single strokes without risking torsional failure. Once the file is removed, the flutes are cleaned and checked for any possible deformations followed by irrigation of the canal and patency confirmation. In the next stationary phase, the same file will bind deeper inside the canal passed the curvature. The same cycle is repeated with the same file in a crown-down approach until the file reaches WL. The work to be done by each file is completed when the file can reach WL without having to activate it (stationary). After reaching WL, progressive enlargement is continued in the same way until the desired apical instrumentation width and canal taper is accomplished (Figure 9c). Ideal instruments for TCA technique are the flexible marten-sitic instruments that are free from restoring forces. The TCA technique is not recommended with austenitic NiTi files having restoring forces because of the risk of ledging when activated inside the curvature. The TCA technique aims at the delivery of adequate apical preparations in highly curved canals by minimizing the time of engagement of the activated files around curvatures (Figures 11 and 12). Although the TCA technique described as being safe, even for the most challenging curvatures, independent studies to evaluate the limits of this technique are still lacking, and it should be applied with caution and after practice on extracted teeth.

Arithmetic crown-down dynamic tactile instrumentation technique. This instrumentation technique proposed by Elkholy & Ha (2021) combines the zone technique

(McSpadden, 2007) and the TCA technique (Chaniotis & Filippatos, 2017a,b; Elkholy & Ha, 2021; Figure 9d). The zone technique has the limitation of focusing on the length of file engagement without calculating the maximum insertion depths of higher tapered instruments to prevent over flaring of the canal and preserve pericervical dentine. TCA involves a single activation upon engagement in the curvature and immediately redrawing the file resulting in increased preparation time, whilst coronal flaring is not a prerequisite for this technique and can result in reduced tactile feedback. To overcome these problems and avoid over preparation of the cervical part of the curved canal, a new technique was introduced and named as the arithmetic crown-down dynamic tactile instrumentation technique.

The technique is divided into the following steps (Elkholy & Ha, 2021):

Step 1: Determination of zones

A preoperative radiograph is taken to determine the estimated length and divide the curved canal in two zones: the coronal and apical zone. In a canal with initial estimated length of 22 mm, the boundary between the coronal zone and the apical zone is 16 mm from the incisal edge and 6 mm from the apex.

Step 2: Coronal zone flaring

Coronal flaring is achieved before confirmation of WL and the establishment of the glide path. The depth of insertion of the flaring instrument, whilst preventing overenlargement, is calculated with the following equation:

$$f = 16 - \frac{S_{\text{final}} - S_{\text{current}} + T_{\text{final}} \times 16}{T_{\text{current}}}$$

f: the maximum placement of a coronal flaring instrument that does not flare the canal wider than the final

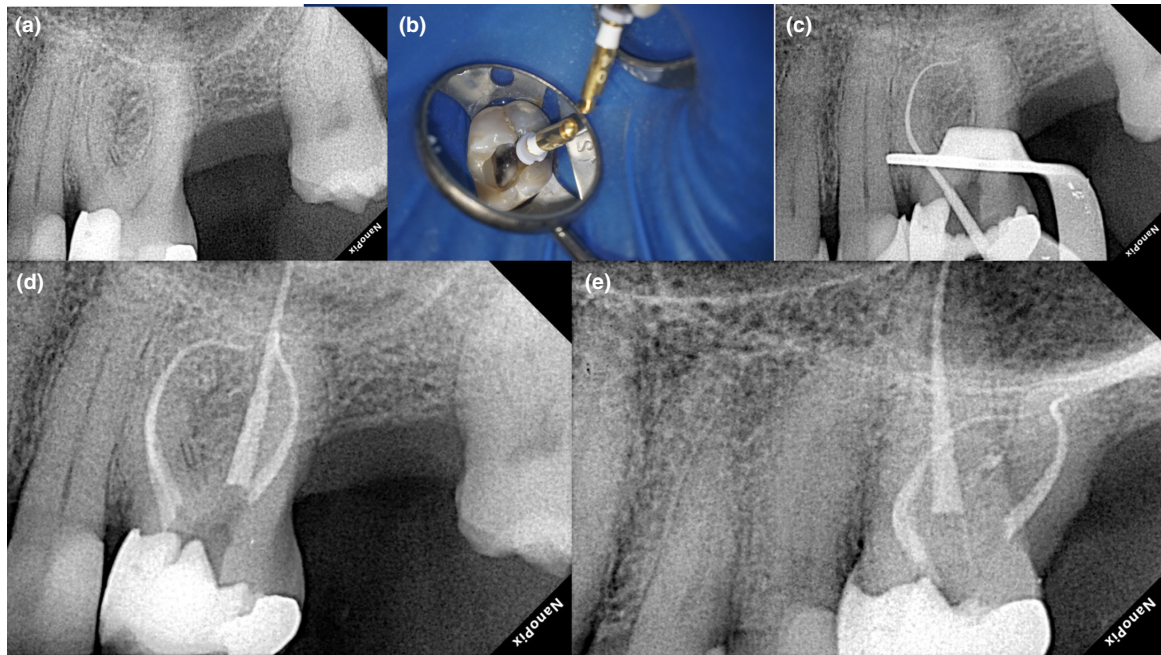


FIGURE 11 Highly curved maxillary molar managed with Tactile Controlled Activation (TCA) instrumentation technique a. Preoperative radiograph, b. 15/04 CM file stationary insert, c. TCA radiograph, d. Straight view postoperative radiograph revealing the curvature parameters in mesio-distal plane (25/.04 mm per mm tapered preparation in the buccal roots), e. Proximal view postoperative radiograph revealing the curvature parameters in the bucco-lingual plane.

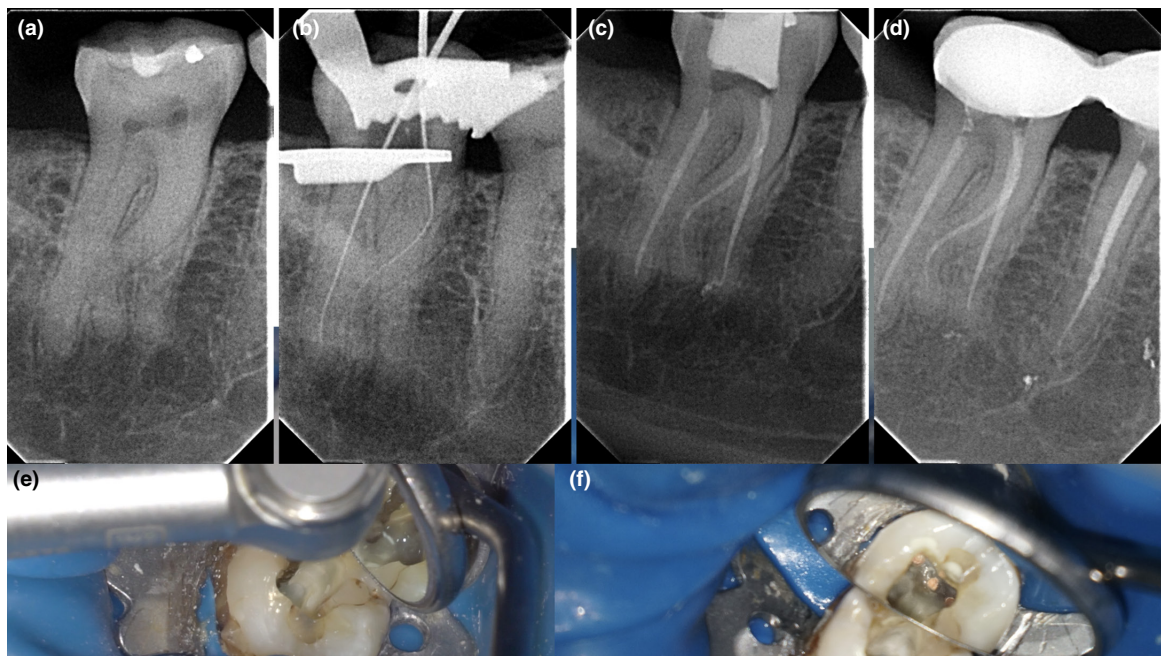


FIGURE 12 A mandibular second molar with asymptomatic irreversible pulpitis and normal apical tissues presenting 2 mesial roots (a). An “S” shaped curvature is present in the MB canal (b), the root can be described as long and thin. The TCA technique was used to achieve a 25/.04 mm per mm tapered preparation (c-f).

intended shaping instrument. This measurement is relative to the apex and will be short of WL

16: the boundary between the coronal and the apical zone as measured from the reference point

S_{final} : the final intended apical size (ISO)

T_{final} : the taper (%) of the final intended apical size

S_{current} : the apical size (ISO) of the crown-down instrument

T_{current} : the taper (%)

The depth of insertion of the coronal flaring instrument can be determined by the following equation:

$$L_{\text{current}} = L_{\text{final}} - f$$

For example: If the first flaring instrument is 17/12 and the final apical enlargement 30/04, by using the first equation:

$$f = 16 - \frac{30 - 17 + 4 \times 16}{12} = 9.6 \text{ mm short of WL.}$$

If the estimated length is 22 mm, then the 17/12 orifice opener could be placed to 12.4 mm from the reference point. Beyond this point, overflaring the coronal third of canal would occur.

The files are suggested in a gentle pecking motion not exceeding 1 mm per stroke and maximum three strokes.

If the next additional flaring instrument to be used just around the curvature is a 25/06 file, according to the equations this file can be inserted

$$f = 16 - \frac{30 - 25 + 4 \times 16}{6} = 4.5 \text{ mm short of WL}$$

or

$$L_{\text{current}} = 22 - 4.5 = 17.5 \text{ mm from the reference point.}$$

Although the second flaring file can be inserted to 17.5 mm, it is suggested not to exceed the boundary of the curvature before the glide path is established (boundary is 16 mm).

Step 3: Canal negotiation, WL, glide path and confirming curvature analysis (securing the glide path)

Canal negotiation and patency can be obtained at this stage using size 08 K-file followed by WL confirmation with an electronic apex locator. The glide path can be enlarged up to a size 10 K-file and the zones can be confirmed. In some curved canals, the glide path creation can be challenging to secure. All the techniques to secure the challenging glide path that were described earlier in this article might be used at this step.

Step 4: Apical advancement

After securing the glide path and confirming the boundaries of the first canal curvature the size 25, 0.06 taper flaring file can be inserted to the 17.5 mm from the reference point boundary as calculated by the equations. Since this depth of insertion is beyond the boundary

of the first curvature, a TCA needs to be applied. The file is inserted passively into the canal until engagement of the walls is tactilely felt and then activated to resistance with activation and redrew from the canal without exceeding the 17.5 mm boundary (Chaniotis & Filippatos, 2017a,b). Although the original technique described suggested a single stroke and remove action, a modification of three strokes of less than 0.5 mm amplitude is suggested to expedite the procedure.

Step 5: Apical zone finishing

After coronal flaring and apical zone flaring, pre-curved martensitic files are inserted into the canal pointing towards the curvature, engaging the walls of the canal and activated until reaching the WL with three gentle apical strokes instead of one at a time as described in the original TCA technique. The sequence suggested is a standardized technique until a size 30, 0.04 taper enlargement can be achieved. The apical curvature file engagement can be minimized by using a sequence of size 20, 0.04 taper, size 25, 0.04 taper and size 30, 0.04 taper to full WL. In more challenging anatomies, smaller size martensitic files might be needed to reach the WL (Figure 9d).

The kinematics of the TCA technique by passively inserting a file until it engages the canal wall followed by activation and withdrawal allows optimum canal engagement for cutting and avoids unnecessary stresses. The modified TCA suggested for the apical curvature enlargement is feasible because of the combination of coronal and apical zone flaring that minimizes the stresses and allows more TCA strokes to take place with minimal engagement. However, multiple strokes should be applied always with caution and only after careful evaluation of anatomical and instrument parameters.

DISINFECTION-RELATED FACTORS

Root canal curvature, as an anatomic factor, can influence the chemo-mechanical preparation. Curved and constricted canals tend to be enlarged to smaller apical preparations reducing the available space for effective disinfection. The ability of an irrigant solution to be distributed in the apical third depends upon the following factors:

- The irrigation delivery technique
- The level of the needle penetration
- The type and gauge of the needle
- The canal anatomy
- The final size and taper of root canal preparation
- The irrigant activation techniques used

(Boutsioukis, Gogos, et al., 2010; Boutsioukis, Lambrianidis, et al., 2010; Boutsioukis, Verhaagen, et al., 2010; Chow, 1983; De Gregorio et al., 2010; Khademi et al., 2006; Sedgley et al., 2005; Solwey, 1979).

In curved and constricted canals, even the smallest needles will stay short from the apical third. Therefore, it is advisable to use enhanced irrigation techniques to improve the disinfection process (Boutsioukis et al., 2010). Strategies that have been developed over the years to improve the chemical process include new systems that either substitute the conventional disinfection strategy or supplement their outcomes. Activation of irrigants with sonic or ultrasonic instruments, negative pressure irrigation techniques, laser-activated irrigation at sub-ablative power levels and the Sonendo multisonic system are some of the strategies to improve the cleaning ability and disinfection efficacy.

The root canal curvature per se limits the irrigant penetration during conventional irrigation. The irrigation efficacy is affected if the canal cannot be adequately shaped or if the needle cannot deliver the irrigant close to the WL (Nguy & Sedgley, 2006). Finer and more flexible irrigation needles (31–32 G) may reach closer the apical third in such cases; however, small needles require three to six times stronger force to be applied to the syringe compared to a 30 G needle, to obtain the same flow rate (Boutsioukis et al., 2007). Other irrigation techniques, such as apical negative pressure irrigation and laser-activated irrigation, are also restricted by the smaller apical preparation of curved and calcified canals (Brunson et al., 2010; Gregorio et al., 2013; Groot et al., 2009). It is also unlikely that sonic or ultrasonic activation can provide clinical advantages in extremely curved canals. Multi-point wall contacts inside constricted canals will probably dampen the oscillation of the activation instrument more than in straight canals (Walmsley & Williams, 1989). Previous authors have confirmed the differences in the performance of ultrasonic activation in straight and curved canals (Amato et al., 2011). On the other hand, another laboratory study could not reveal any influence of curvature on the irrigant penetration apically to an ultrasonic file (Malki et al., 2012). Photon-Initiated Photo-acoustic Streaming (PIPS) also does not seem to provide an advantage against bacteria in root canals prepared to apical sizes smaller than 30 (Pedullà et al., 2012). Based on the available evidence, the main alternatives for irrigant activation in narrow and curved canals are manual dynamic activation using gutta-percha points (Huang et al., 2008) or a multisonic activation system (Molina et al., 2015; Wang et al., 2018). Moreover, increasing the temperature of sodium hypochlorite might decrease its viscosity and improve the flow and effectiveness of the irrigant in curved and narrow canals (Zehnder, 2006).

FUTURE DIRECTIONS

Recently, machine-assisted irrigation, such as PIPS (Fotona LLC) and the multisonic GentleWave (GW) system (Sonendo Inc, Laguna Hills, Ca, USA), have been introduced to improve the cleaning of minimally instrumented canals or even uninstrumented canals (Haapasalo et al., 2014). A non-instrumentation method has the advantage of saving tooth structure, avoiding all the instrumentation risks of curved and constricted root canal management. Recently, the uninstrumented root canal areas of intact premolars cleaned with a non-instrumentation method revealed abundant surface irregularities in different parts of the root canals that were completely clean of tissue remnants and dentine debris (Wang et al., 2018). The results of this study indicate that it is possible to completely clean root canals without instrumentation in intact single-rooted premolars extracted for orthodontic reasons. If the same cleaning result is possible in curved and constricted canals remains to be seen in the future.

Recently, a new method was reported for treatment of calcified teeth called 'Guided Endodontics' (Krstl et al., 2016; Zehnder et al., 2016). A dedicated software (coDiagnostix™, Dental Wings Inc.) is used to align CBCT data to virtually plan a customized access cavity. Subsequently, a template can be created using a 3D printer. This 'static guide' creates a predetermined pathway that allow a minimally invasive access to a calcified root canal. Computer-aided surgical navigation technology has also been incorporated (Chong et al., 2019). The use of CBCT-guided procedures is expected to increase in the future and expand their use to the negotiation and management of curved and aberrant anatomy. At present, a new software program, 3D Endo (Dentsply Sirona), has been developed to be used with the CBCT data sets to evaluate root canals including curvatures. This software allows the clinician to visualize the root canal anatomy, assess the initial canal diameters and determine working length measurements (Patel, Brown, et al., 2019a; Patel, Patel, et al., 2019b).

CONCLUDING REMARKS

This narrative provides the principles necessary for the management of curved and constricted canals. A consistent strategy is based on the following principles: diagnosis of the apical pathosis, preoperative radiographic interpretation of the pulp chamber and canal anatomy, customized design of the access cavity to fit the underlying anatomy, exploration of the pulp chamber under magnification and coaxial illumination, use of ultrasonics and long-shafted burs to locate and penetrate calcifications, securing and maintaining a reproducible glide path, and

safe enlargement of the calcified and curved canals with highly flexible and fatigue-resistant instruments.

CONFLICT OF INTEREST

The authors deny any conflicts of interest.

AUTHORS CONTRIBUTION

Antonis Chaniotis: conceptualization, investigation and writing. **Ronald Ordinola-Zapata:** editing.

ETHICAL APPROVAL

The study does not need ethical approval.

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