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The principles of techniques for cleaning root canals

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Abstract

Chemomechanical preparation of the root canal includes both mechanical instrumentation and antibacterial irrigation, and is principally directed toward the elimination of micro-organisms from the root canal system. A variety of instruments and techniques have been developed and described for this critical stage of root canal treatment. Since their introduction in 1988, nickel-titanium (NiTi) rotary instruments have become a mainstay in clinical endodontics because of their exceptional ability to shape root canals with potentially fewer procedural complications. Safe clinical usage of NiTi instruments requires an understanding of basic metallurgy of the alloy including fracture mechanisms and their correlation to canal anatomy. This paper reviews the biologic principles of preparing root canals with an emphasis on correct use of current rotary NiTi instrumentation techniques and systems. The role and properties of contemporary root canal irrigants is also discussed.

Key words: Nickel-titanium alloy, root canal instrumentation, rotary preparation, irrigation, endodontics.

Abbreviations and acronyms: EDTA = ethylenediamene tetraacetic acid; NaOC1 = sodium hypochlorite; NIET = non-instrumentation endodontic treatment; NiTi = nickel titanium; PAD = photo activated disinfection.

INTRODUCTION

A fundamental aim of endodontic treatment is to prevent or cure apical periodontitis.[1] It is well documented that bacterial infection of the root canal is the primary cause of apical periodontitis.[2-4] In teeth with apical periodontitis, bacteria invade and colonize the entire root canal system, and treatment is directed toward the elimination of micro-organisms from the root canal system and prevention of re-infection.[4] Chemomechanical preparation of the root canal through a combination of mechanical instrumentation and antibacterial irrigation is the critical stage in canal disinfection. This is followed by placement of a root canal filling and coronal restoration in order to seal potential avenues of entry of micro-organisms into the root canal, and to entomb any remaining micro-organisms to prevent their proliferation.

In recent times there have been significant technological advancements to facilitate root canal cleaning and shaping.[5] New instruments have been developed employing superelastic alloys and novel engineering philosophies, and there has been a notable departure from the ISO standard 2 per cent taper (0.02mm per mm) instruments. When seeking evidence for the effectiveness of root canal cleaning procedures, clinicians are largely dependent on findings from *in vitro* studies and clinical trials with microbial load prior to root filling as the outcome being measured. Clinicians must acknowledge that clinical recommendations based on such evidence are deductive and must be interpreted with caution.[6]

With this in mind, the purpose of this paper is to review the biologic principles of chemomechanical root canal preparation emphasizing the correct use of current rotary nickel-titanium (NiTi) techniques and systems. The role of root canal irrigants is also briefly reviewed. Whilst the importance of intracanal medicaments is acknowledged, detailed review is beyond the scope of this paper and is discussed elsewhere in this special issue.

Principles of chemomechanical preparation

Biological objectives

From a biological perspective, the goals of chemomechanical preparation are to eliminate micro-organisms from the root canal system, to remove pulp tissue that may support microbial growth, and to avoid forcing debris beyond the apical foramen which may sustain inflammation.

Mechanical instrumentation is one of the important contributors to bacterial reduction in the infected root canal. Byström and Sundqvist[7] reported a 100–1000 fold reduction in bacterial load after instrumentation with stainless steel hand files and irrigation with physiological saline. However, canals could not be consistently rendered bacteria-free. Also using saline irrigation, Dalton *et al.*[8] compared bacterial reduction after instrumentation with either 0.04 tapered NiTi rotary instrumentation or with a stainless steel K-file step-back technique. There was no significant difference between the two instrumentation techniques with 72 per cent of instrumented teeth still returning a positive culture. The use of irrigating solutions with

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strong antimicrobial activity is therefore an essential adjunct to mechanical preparation in order to further reduce bacterial numbers.[9] In addition, the use of an antibacterial intracanal dressing has been advocated to eliminate bacteria remaining after chemomechanical preparation.

Technical objectives

The technical goals of canal preparation are directed toward shaping the canal so as to achieve the biological objectives and to facilitate placement of a high quality root filling. Schilder[10] recognized that canal shaping should be performed with respect to the unique anatomy of each root and in relation to the technique of root canal filling. He outlined several mechanical objectives for optimal instrumentation:

i. Continuously tapering funnel from the access cavity to apical foramen

A continuously tapering preparation facilitates efficient delivery of antimicrobial irrigant and creates resistance form against which to compact a root filling.

ii. The root canal preparation should maintain the path of the original canal

Canal systems move through multiple geometric planes and curve significantly more than the roots that house them.[10] The use of inflexible instruments to prepare a curved canal results in uneven force distribution in certain contact areas and a tendency of the instrument to straighten itself inside the root canal.[11] As a result, the apical canal is "transported" toward the outer curvature while coronally the canal is "transported" toward the concavity. This transported canal thus adopts an hour-glass shape, and may suffer from inadequate debridement as well as complications such as ledging, root perforation, or excessive thinning of canal walls.

iii. The apical foramen should remain in its original position

Canal transportation may result in damage to the apical foramen, creating a characteristic elliptical shape known as a foraminal rip, zip, or tear. Wu *et al.*[12] demonstrated *in vitro* that apical transportation negatively impacted on apical seal when curved canals were obturated by lateral compaction of gutta percha.

iv. The apical opening should be kept as small as practical

Enlargement of the canal should be in keeping with biological requirements as will be explained below.

Manual instrumentation techniques

Historically, a variety of different techniques have been developed specifically for preparation of canals using ISO standardized 0.02 tapered stainless-steel hand files. The step-back technique described by Mullaney[13] involved preparation of the apical region of the root canal first, followed by coronal flaring to facilitate obturation. When employed in curved canals, this technique often results in iatrogenic damage to the natural shape of the canal due to the inherent inflexibility of all but the smallest stainless steel files.[14-16] In an effort to reduce the incidence of iatrogenic defects, step-down techniques were developed which commence preparation using larger instruments at the canal orifice and then work down the root canal with progressively smaller files.[17-19] Pre-enlarging the coronal region of the canal prior to completing apical preparation provides several advantages, including straighter access to the apical region, enhanced tactile control, as well as improved irrigant penetration and suspension of debris. Studies have shown that step-down techniques produce fewer canal blockages, less apically extruded debris, and a reduced incidence of apical transportation when compared to step-back techniques.[14,20]

In recent times the introduction of NiTi alloy has permitted the manufacture of extremely flexible instruments which are capable of safely preparing curved canals with less straightening compared with stainless steel instruments.[16,21,22] Accordingly, traditional instrumentation techniques such as the step-back method are now phasing out because of the increasing and expanding use of NiTi instruments.[5] It must be realized, however, that because of their extreme flexibility, NiTi instruments are not designed for initial negotiation of the root canal, nor for bypassing ledges. Because of their greater stiffness, small stainless steel instruments should be used for path-finding and to establish canal patency. Creation and subsequent maintenance of a smooth glide-path from the canal orifice to the apical foramen using fine 0.02 tapered hand files is an essential preparatory step before commencing NiTi instrumentation in order to reduce the risk of iatrogenic errors such as ledge formation and instrument fracture.

Rotary NiTi instrumentation

Since the introduction of rotary NiTi instruments in 1988,[23] there has been a growing shift from manual to rotary engine-driven preparation. In a survey of Australian dentists, Parashos *et al.*[5] found that while hand instrumentation was still the most popular method of preparing root canals, the majority of endodontists (64 per cent) and an increasing number of general practitioners were using rotary NiTi instruments. In light of diffusion of innovation research, this relatively new technology has gained enough momentum to eventually become a technique of choice.[5] The numbers of general dentists and specialist endodontists who have adopted this new technology has surpassed the critical level required (10–20 per cent) to ensure that the rate of rotary NiTi adoption becomes self-sustaining.[5,24]

Metallurgy of NiTi alloys

The NiTi alloy used to manufacture endodontic instruments is composed of approximately 56 per cent (wt) nickel and 44 per cent (wt) titanium and is

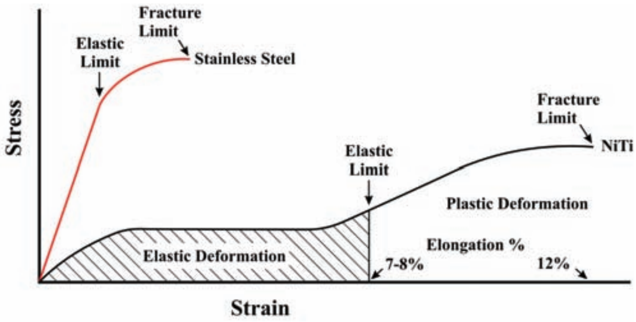


Fig 1. Stress-strain curve: stainless steel (red line) and nickel-titanium (black line). Elastic limit = maximum stress without permanent deformation; fracture limit = stress at which fracture occurs; elongation % refers to the deformation that results from application of a tensile stress, calculated as (change in length/ original length) x 100%.

generically known as 55-Nitinol.[25] The superelasticity of NiTi instruments is related to a stress-induced phase transformation in the crystalline structure of the material. The austensitic phase transforms into the martensitic phase on stressing, and in this form requires only light force for bending.[26] After release of stresses, the metal returns to the austensitic phase and the file regains its original shape. The superelasticity of NiTi allows deformation of as much as 8 per cent strain to be fully recoverable, in comparison to a maximum of less than 1 per cent with alloys such as stainless steel (Fig 1).[25]

The improved flexibility and unique properties of NiTi alloy provides an advantage when preparing curved canals and has made it possible to engineer instruments with greater tapers (4–12 per cent), thereby allowing better control of root canal shape (Fig 2).[26] The result is a predictably machined tapered preparation that facilitates cleaning of the canal and its subsequent obturation.

Shaping ability

NiTi rotary files have become a mainstay in clinical endodontics because of their ability to shape root canals (Fig 3) with fewer procedural complications. Numerous studies using extracted human teeth have concluded that rotary NiTi instruments maintain the original canal curvature better than stainless steel hand

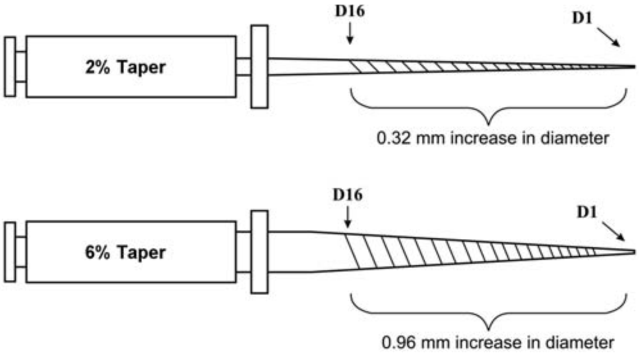


Fig 2. The diameter of the 2% taper instrument increases 0.02mm for every millimetre of length from D1 to D16 on ISO or standard taper. The diameter of the greater tapered instrument increases 0.06mm (6% taper) for every millimetre of length from D1 to D16.

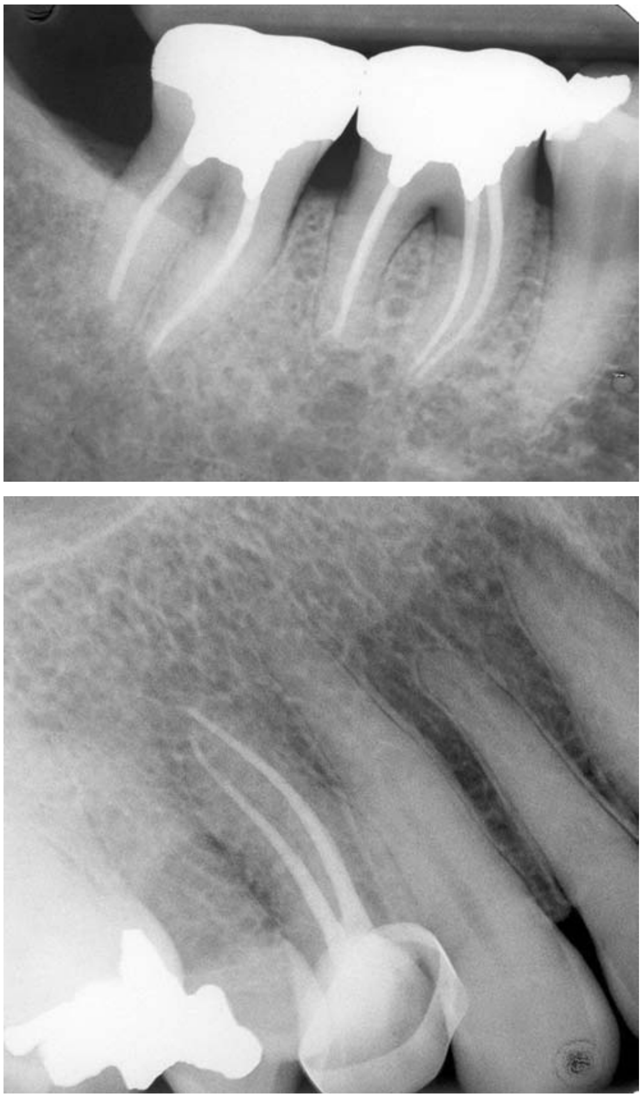


Fig 3. Post-obturation radiographs demonstrating the ability of rotary NiTi instrumentation to maintain canal curvatures.

instruments, particularly in the apical region of the root canal.[16,21,22,27-29] Esposito and Cunningham[21] found that NiTi files became significantly more effective than stainless steel hand files in maintaining the original canal path when the apical preparation was enlarged beyond ISO size 30. Collectively, *in vitro* studies show that NiTi instruments produce significantly less straightening and better centred preparations than stainless steel hand files, thereby reducing the potential for iatrogenic errors.

Despite the considerable shaping advantages offered by rotary NiTi instrumentation, there is very little direct evidence from clinical follow-up studies on the impact of improved canal shapes on healing outcomes. Petiette *et al*.[30] prepared 40 teeth with either NiTi hand files or stainless steel K-files and found that NiTi instrumentation was better at maintaining the original canal shape. When the two groups were recalled one year after completion of endodontic treatment, the authors found a significantly higher healing rate (as assessed by change in densitometric ratio) for teeth prepared with NiTi files. They concluded that instrumentation with NiTi files led to a better prognosis compared with stainless steel files because of better maintenance of original canal shape and access to apical anatomy. However, there is no evidence available for rotary instrumentation with NiTi.

Cleaning ability

Studies investigating the cleaning ability of endodontic instruments have examined their ability to remove debris from root canals, typically assessed by light- or scanning electron microscopy. Tan and Messer[31] found that instrumentation to larger file sizes using rotary NiTi instruments resulted in significantly cleaner canals in the apical 3mm than hand instrumentation. However, neither technique was totally effective in cleaning the apical canal space. After instrumenting curved root canals of extracted human teeth with either rotary NiTi or stainless steel hand files, Schäfer *et al*.[27,29] discovered uninstrumented areas with remaining debris in all areas of the canals irrespective of the preparation technique. Cleanliness was found to decrease from the coronal to the apical part of the root canal. Peters *et al*.[32] used micro-CT data to analyse preparation of root canals of maxillary first molars after instrumentation using K-type hand files and three rotary NiTi file systems. They found that all instrumentation techniques left 35 per cent or more of the canal's dentine surface untouched, with very little difference found between the four instrument types. These findings highlight the limited ability of endodontic instruments to clean the root canal and reinforce the importance of antibacterial irrigation for enhanced disinfection of the canal system.

Working time

While some comparative studies have shown evidence for shorter working times for rotary NiTi preparations when compared with manual instrumentation,[16,22,28] other studies have shown no difference.[27,29] It is likely that working time is more dependent on operator factors and the preparation technique used rather than the instruments themselves. For example, NiTi systems using only a small number of instruments, e.g., ProTaper (Dentsply Maillefer) will prepare canals faster than systems using a large number of instruments, e.g., Lightspeed (Lightspeed Inc., San Antonio, Texas, USA).

Instrument fracture

All endodontic instruments have the potential to break within the canal following improper application. While it is a commonly held perception within the dental profession that rotary NiTi instruments have an increased frequency of breakage compared to stainless steel hand files, current clinical evidence does not support this view.[33] A review of the literature reveals that the mean clinical fracture frequency of rotary NiTi instruments is approximately 1.0 per cent with a range of 0.4–3.7 per cent.[33] In comparison, the mean prevalence of retained fractured endodontic hand instruments (mostly stainless steel files) is approximately 1.6 per cent with a range of 0.7–7.4 per cent.[33]

Safe clinical usage of NiTi instruments requires an understanding of basic fracture mechanisms and their correlation to canal anatomy. Sattapan *et al*.[34] identified two modes of fracture for rotary NiTi instruments; torsional fracture and flexural fracture. Torsional fracture occurs when the tip or any part of the instrument locks into the canal while rotary motion continues. The elastic limit of the metal is exceeded and the instrument shows plastic deformation (unwinding, reverse winding) followed by fracture. Torsional fracture may typically occur if excessive apical force is placed on the instrument and is more likely to occur with smaller size files.[34] Flexural fracture is caused by work hardening and metal fatigue. It occurs at the point of maximum flexure when the instrument is freely rotating in a curved canal, and may initiate from defects in the instrument surface that occur after cyclic fatigue.[34] Flexural fractures showed a sharp break without any accompanying defect, and were found to occur more frequently with larger file sizes, indicating that larger instruments have fewer cycles to failure.[34] In order to avoid flexural fracture, the authors suggested that instruments should be discarded after substantial use. Increased severity of angle and radius of root canal curvature around which the instrument rotates decreases instrument lifespans.[35]

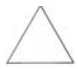
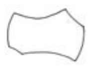
In light of observations that rotary NiTi files may undergo fracture due to fatigue without prior evidence of plastic deformation, single-use of these instruments has been advocated by some,[36] and there is currently no agreement as to a recommended number of uses of these instruments. Parashos *et al*.[37] examined discarded rotary NiTi instruments from 14 endodontists and identified factors that may influence defects after clinical use. This study did not support the routine single use of instruments to prevent fracture based on the conclusion that instrument fracture is a multifactorial problem. The most important influence on defect rate was found to be the operator, which may be related to clinical skill or a decision to use instruments a specified number of times.

In vitro research has indicated that the main factors that may influence fracture of rotary NiTi files include: anatomical conditions such as radius[35,38,39] and angle[35,39,40] of root canal curvature, frequency of use,[41-43] torque setting,[44-46] and operator experience.[47,48] Sattapan *et al*.[34] advise that files should be routinely examined after each use with those showing defects discarded. Incidences of substantial or severe use should influence the single use decision. It is recommended that NiTi instruments be driven by electric motors with torque control and constant speed. The rationale for the use of low-torque or controlled-torque motors with individually adjusted torque limits for each file is to operate instruments below their individual limit of elasticity, thus reducing the risk of fracture.[49]

Impact of instrument design features

In recent years many different rotary NiTi systems have been introduced into endodontic practice. The

Table 1. Design features of current rotary NiTi file systems

Instrument system	Cross-sectional design	Tip design	Taper	Other features
ProFile (Dentsply Maillefer)	 Triple-U shape with radial lands. Neutral rake angle planes dentine walls.	Non-cutting.	Fixed taper. 2%, 4% and 6%.	20-degree helix angle and constant pitch.
GT Files (Dentsply Maillefer)	 Triple-U shape with radial lands.	Non-cutting.	Fixed taper. 4%, 6%, 8%, 10%, and 12%.	Files have a short cutting portion. Variable pitch.
LightSpeed Instruments (Lightspeed, San Antonio TX)	 Triple-U shape with radial lands.	Non-cutting.	Specific instrument sequence produces a tapered shape.	Thin, flexible non-cutting shaft and short cutting head.
ProTaper (Dentsply Maillefer)	 Convex triangular shape, sharp cutting edges, no radial lands. F3, F4, F5 files have U-flutes for increased flexibility.	Non-cutting.	Variable taper along the length of each instrument.	Pitch and helix angle balanced to prevent instruments screwing into the canal.
HERO 642 (MicroMega)	 Triangular shape with positive rake angle for cutting efficiency. No radial lands.	Non-cutting.	Fixed taper. 2%, 4% and 6%.	Variable pitch. Files have a short cutting portion (12-16mm).
K3 (Sybron Endo)	 Positive rake angle for cutting efficiency, three radial lands, and peripheral blade relief for reduced friction.	Non-cutting.	Fixed taper. 2%, 4% and 6%.	Variable pitch and variable core diameter.
FlexMaster (VDW, Munich Germany)	 Convex triangular shape with sharp cutting edges and no radial lands.	Non-cutting.	Fixed taper. 2%, 4% and 6%. 'Intro file' has 11% taper.	Individual helical angles for each instrument size to reduce screw-in effect.
RaCe (FKG, LaChaux De Fonds, Switzerland) EndoWave (J.Morita)	 Triangular shape (except RaCe 15/0.02 and 20/0.02 which have a square shape), two alternating cutting edges, no radial lands.	Non-cutting.	Fixed taper. 2%, 4%, 6%, 8%, and 10%.	Alternating cutting edges along the file length due to alternating twisted and untwisted segments (RaCe), or a continuous wave design (EndoWave). Intended to reduce screw-in effect.
Quantec SC, LX (Sybron Endo)	 S-shape design with double-helical flute, positive rake angle, and two wide radial lands.	Cutting (SC). Non-cutting (LX).	Fixed taper. 2%, 3%, 4%, 5%, 6%, 8%, 10%, and 12%.	Flute space becomes progressively larger distal to the cutting blade.
Mtwo (Sweden and Martina, Padova, Italy)	 S-shape design with two cutting edges, no radial lands. Minimum core width to improve flexibility.	Non-cutting.	Fixed taper. 4%, 5%, 6%, and 7%.	Variable pitch. Steep helical angle designed to reduce screw-in effect.

specific design characteristics vary, such as cross-sectional geometry, tip design, and taper (Table 1), and these factors will influence the flexibility, cutting efficiency and torsional resistance of the instrument. However, the extent to which instrument design characteristics will influence clinical outcomes is difficult to predict.[50]

It is recommended that use of instruments with safety tips is preferable to those with cutting tips such as Quantec SC which have been shown to result in a high incidence of procedural errors including root perforation, zipping and ledging.[51,52] There is some evidence that NiTi instruments with active cutting blades (e.g., ProTaper, FlexMaster, RaCe, Mtwo) show better canal cleanliness than instruments with radial lands (e.g., ProFile). Comparisons of instruments with and without radial lands on the basis of SEM-evaluation of root canal walls for residual debris have shown that radial lands tend to burnish the cut dentine into the root canal wall, whereas instruments with positive cutting angles seem to cut and remove the dentine chips.[53,54] *In vitro* studies have indicated that actively cutting cross-sections do not seem to negatively affect centering of the canal preparation.[54,55] However, instruments with active cutting blades must be used with caution in the apical region as over-instrumentation with these instruments is likely to create an apical zip.[56] Some studies have reported that instrument shaft design does not significantly modify canal shapes of similar apical sizes,[57] while others have shown that a thin and flexible shaft will permit larger apical sizes with less aberrations.[58]

Size of the apical preparation

In a light- and electron-microscopic study of root-filled, asymptomatic human teeth with long-term therapy-resistant periapical lesions, Nair *et al.*[59] found micro-organisms remaining in the apical root canal and concluded that residual bacteria play a significant role in endodontic treatment failures. Sjögren *et al.*[60] stated that the apical canal may harbour a critical amount of micro-organisms that would maintain periradicular inflammation, and Simon[61] considered the apical 3mm of the root canal system to be a "critical zone" in the management of infected canals.

The apical constriction is in theory the narrowest part of the root canal and the location where the pulp ends and the periodontium begins. It is not uniformly round, but is generally either ovoid or irregular,[62] and therefore an instrument size at least equal to the largest diameter of the apical canal is required. Morphology studies indicate that the apical canal is wider than 300 to 350 microns in normal adult teeth,[62-64] and may be larger when resorbing apical periodontitis has developed.[65] The anatomy therefore dictates that a minimum apical preparation of ISO size 30 to 35 or larger is required.[66]

Microbiological studies have shown that larger apical preparation sizes produce a greater reduction in remaining bacteria as compared to smaller apical sizes.[8,67-72] This superior disinfection may be due to several factors. It is known that bacteria penetrate into dentinal tubules at variable distances.[73,74] Larger apical preparations will enhance removal of the more heavily infected inner dentine. It is also known that irrigants exert a greater antimicrobial effect on superficial dentine than deep dentine.[75] Canal enlargement will therefore facilitate access of irrigant to organisms which have penetrated more deeply into the dentine. Shuping *et al.*[67] found that the additional antibacterial effect of sodium hypochlorite (NaOCl) only became evident after instrumentation exceeded ISO size 30-35. The authors suggested that canals must be instrumented to an appropriate size to permit efficient irrigant penetration to the apical region of the canal. In addition to these findings, histologic studies have indicated that increased apical enlargement will lead to cleaner apical preparations as measured by the amount of remaining debris.[31,76]

Another consideration in the choice of final apical preparation size is the impact of final canal shape on root strength. Sathorn *et al.*[77] found that as the size of rotary NiTi preparations increased, the creation of a smoothly rounded canal shape served to eliminate stress concentration sites, thereby reducing fracture susceptibility. Conversely, instrumentation that leads to irregular dentine removal with canal straightening will significantly weaken the root.[78] Lam *et al.*[79] found a lower susceptibility to fracture in roots prepared with rotary NiTi instruments compared to those prepared by hand instrumentation, and believed that this difference was due to the rounder canal shapes produced by rotary files leading to fewer stress concentration sites. Collectively, the evidence indicates that apical enlargement with rotary NiTi instruments does not weaken roots any more than conventional hand instrumentation and may in fact increase fracture resistance.

Few longitudinal studies have examined the impact of apical enlargement on the outcome of endodontic treatment. Most authors have found that there was no difference in healing when it came to apical enlargement.[80-82] Each of these studies, however, shaped canals using exclusively stainless steel hand instruments. Preparing canals to large apical sizes using inflexible steel files is frequently associated with canal transportation that may jeopardise canal disinfection and impair prognosis.[83] Unlike stainless steel instruments, rotary NiTi files are able to predictably "machine" a canal to accurate dimensions, and are able to safely enlarge even curved root canals to sizes not routinely attainable with steel files.[31,84]

In recent times, much emphasis has been placed on the preparation of greater root canal taper. This is largely based on obturation philosophy, whereby root-filling techniques employing thermoplasticised material advocate a canal preparation with greater taper and minimal apical preparation size (ISO size 20, 25, or 30), thereby permitting compaction of the root filling with less chance of extrusion. In focusing on the obturation phase of treatment, these techniques lose sight of the biological goals, and are not designed for optimal chemomechanical debridement of the apical root canal.[66] In infected root canals, the apical preparation is critical, and must be directed toward maximizing microbial control. In this respect, current literature supports the philosophy of larger apical preparation sizes combined with moderate taper.

Termination point of cleaning procedures

The apical extension of root canal instrumentation and obturation has been debated for decades and is a point of controversy. In teeth with a vital although inflamed pulp, bacteria are not present in the apical region of the root canal, and several authors recommend terminating instrumentation 2–3mm short of the radiographic apex in order to leave a clinically normal apical pulp stump.[85,86] This is based on histologic evidence that an aseptically performed partial pulpotomy will stimulate a natural healing process whereby the apical root canal becomes permanently occluded by the formation of cementum-like tissue.[87,88] Following this principle, clinical outcome studies have reported high success rates.[60,80]

In teeth with a necrotic infected pulp, bacteria may penetrate to the most apical part of the root canal and have been observed at the apical foramen.[59] The length of instrumentation is therefore more critical in infected cases and should presumably not be shorter than the apical level of bacteria.[85,86] Ideally, the entire root canal should be instrumented, disinfected and filled, and the clinician must make a case-by-case assessment of where the root canal ends. The traditional concept of apical anatomy is that the root canal narrows toward the apex to form an apical constriction before expanding to form the apical foramen.[64] Yet clinically the determination of apical canal anatomy remains challenging. Dummer *et al.*[89] found that a classic apical constriction was present in less than half of the teeth, while others have suggested that the apical constriction is usually lost in cases of apical periodontitis due to resorptive processes.[61,85,86] The apical foramen is therefore a more useful landmark for the termination point of instrumentation in infected cases, and while Kuttler[64] found that the approximate apex to foramen distance was 0.5mm, there is substantial variability. Wu *et al.*[85] reported that the distance between the apical foramen and the radiographic apex varies from zero to 3mm. Modern multi-frequency electronic apex locators may be used to supplement radiographic determination of canal length, and have been shown to identify the position of the apical foramen to within 0.5mm with 90 per cent accuracy.[90]

Several prognosis studies have assessed the impact of instrumentation and obturation length on the outcome of endodontic treatment. Negishi *et al.*[91] found that teeth in which endodontic instruments were unable to reach the apical foramen had a 5.3 times increased risk of failure than cases with an accessible foramen. In teeth with pre-operative pulp necrosis and apical periodontitis, Chugal *et al.*[92] found that those teeth that healed had working length levels closer to the radiographic apex (0.55±0.12mm) than did teeth with persistent disease (1.73±0.30mm). They reported that every millimetre loss in working length increased the chance of treatment failure by 14 per cent. After conducting a literature search and meta-analysis, Schaeffer *et al.*[93] concluded that teeth obturated 0–1mm from the radiographic apex showed better healing outcomes than teeth obturated greater than 1mm from the apex, while others have found that the best outcome occurs when the root filling extends to within 2mm of the radiographic apex.[94,95] The findings of these studies confirm that the apical canal may harbour a sufficient microbial load to maintain periapical inflammation, and in light of current evidence, it is recommended that canals should be instrumented and filled to within 0.5mm of the radiographic apex, unless it is clinically determined that the canal exits at a greater distance. It is also recognized that the termination point of instrumentation does not always correspond to the final level of obturation. Root fillings carried close to the radiographic apex may be overextended beyond the root canal by a small measure in many cases. Provided the root canal has been cleaned and shaped to permit placement of a well-compacted root filling with establishment of an apical seal, a favourable outcome can still be expected.[93]

Apical patency

During instrumentation, potentially infected dentine debris is produced which may accumulate within the apical canal or be extruded into the periapical tissues. Rotary NiTi instrumentation combined with frequent irrigation has been found to force significantly less debris apically compared to hand instrumentation with K-files.[96,97] Blockages in the apical region of the canal can inhibit disinfection of this critical zone by restricting irrigant access and leading to a loss in the working length. Apical blockage can also predispose to complications such as ledge formation, transportation, or root perforation.[98] Extrusion of debris into the periapical tissues is undesirable and may play a role in flare-ups and in treatment failures.[99] It is therefore preferable to prevent accumulation of dentine debris in the apical portion of the canal.

Use of a patency file has been suggested to prevent occlusion of the apical foramen and to maintain control of working length during instrumentation procedures. This involves passively moving a small flexible hand file (e.g., ISO size eight or 10) up to 1mm through the apical foramen without widening it. It has also been suggested that small patency files can help clean up to the canal terminus during chemomechanical procedures.[100] The issue is controversial however, and in 1997, only 50 per cent of 48 dental schools surveyed in the United States taught patency filing.[101] The benefits of patency filing are as yet untested and there is no research to show either a decrease or an increase in case prognosis. Concerns have been expressed regarding the potential for patency files to extrude debris into the periapical tissues. Izu *et al.*[102] recently analysed the effectiveness of 5.25% NaOCl in preventing inoculation of periapical tissues with infected patency files. They concluded that the NaOCl present in the irrigated root canal was sufficient to kill bacteria on patency files. Other research has shown that there is no apparent influence on the development of post-operative pain after patency files were used,[103,104] suggesting that apical extrusion of debris during patency filing may not be important.

Root canal irrigants

Instrumentation of the root canal system must always be supported by the use of antimicrobial irrigating solutions. Despite technological advances in the ability to shape root canals, at least 35 per cent of root canal surfaces still remain uninstrumented,[32] and cleaning of the canal in terms of soft tissue removal and elimination of bacteria relies heavily on the adjunctive action of chemically active irrigating solutions due to the anatomic complexity of the pulp space. Irrigation is also necessary to suspend and rinse away debris created during instrumentation, to act as a lubricant for instruments, and to remove the smear layer that forms on instrumented dentine surfaces. The smear layer is comprised of inorganic and organic material such as dentine filings and pulp tissue remnants, and may also contain bacteria.[105,106] This layer blocks the entrance to dentinal tubules and may therefore protect bacteria in root dentine from antimicrobial agents.[107] Furthermore, it interferes with a tight adaptation of root canal sealers to dentine walls and may therefore promote bacterial ingress.[108,109] Ideally, root canal irrigants should possess a broad antimicrobial spectrum with potent activity against endodontic pathogen biofilms, and should dissolve pulp tissue remnants, prevent formation of a smear layer during instrumentation or dissolve it once formed, and possess little caustic or allergic potential.[6] The following review will focus on the two solutions most commonly used as root canal irrigants.

Sodium hypochlorite

Sodium hypochlorite (NaOCl) is considered the most ideal irrigant for use throughout instrumentation because it possesses both strong antimicrobial and proteolytic activity. Unlike other irrigants, NaOCl has the unique ability to dissolve necrotic tissue,[110] as well as the organic components of the smear layer.[111]

NaOCl is commonly used for irrigation of root canals in concentrations ranging from 1 to 5.25 per cent. Controversy exists over the most appropriate concentration of NaOCl solutions to be used in endodontics. While the bactericidal activity and tissue dissolution capacity improve with increased concentration of NaOCl,[112,113] so does the tissue toxicity and caustic potential.[114] However, several studies have shown that the reduction of intracanal bacteria is not significantly improved when 5% NaOCl irrigant is used during instrumentation compared to 0.5 per cent.[9,115] This is presumably because unclean areas are the result of the inability of solutions to physically reach these areas rather than the concentration of solution.[116] With regard to tissue-dissolving capacity, Moorer *et al.*[117] found that frequent exchange of hypochlorite solution was more important than the concentration. They suggested that lower concentrations of NaOCl can still achieve good tissue dissolving effects when used in copious amounts and with frequent replenishment. In light of current evidence, use of concentrated solutions of NaOCl greater than 1 per cent does not appear to be justified.

Ethylenediamene tetraacetic acid (EDTA) solution

EDTA (17 per cent) is a chelating agent that removes calcium ions to demineralise the inorganic component of dentine. EDTA irrigation has been advocated to remove the smear layer created by root canal instrumentation. Studies investigating smear layer removal have shown that NaOCl is unable to remove inorganic components of the smear layer.[111,118] EDTA irrigation alone is also unable to completely remove smear layer, leaving behind the organic component.[111] The most effective means of smear layer removal involves a combination of EDTA and NaOCl to remove both inorganic and organic components, with NaOCl as the final flush.[111,118] While EDTA has little if any intrinsic antiseptic activity,[119] it may still contribute to disinfection of the root canal by facilitating removal of the smear layer.

There is evidence that chelating agents such as EDTA are able to chemically interact with NaOCl to reduce the amount of free available chlorine and therefore potentially inhibit the antibacterial activity and tissue dissolution potential of NaOCl preparations.[120] It is therefore recommended that NaOCl irrigation should be employed throughout instrumentation, without alternating it with EDTA. Once canal shaping is complete, canals can be thoroughly rinsed using EDTA to dissolve the smear layer. This should be followed by a final rinse of NaOCl to promote debris removal.[121]

While chelating agents in a paste-type form are available, there is evidence that these pastes are less effective than EDTA solution in smear layer removal.[122] In addition, Peters *et al.*[123] showed that paste-type lubricants were less effective than aqueous solutions at reducing stresses generated during rotary NiTi instrumentation. They observed that pastes tended to adhere to the grooves in endodontic files leading to clogging of the grooves with dentine chips, while fluid irrigants tended to flush dentine debris away from the instrument. Use of paste-type chelators is therefore not recommended.

Use of ultrasonics to enhance root canal cleaning

The use of ultrasonically activated instruments may contribute to cleaning of the root canal system through agitation of the irrigant solution. Ultrasonic energizing of an endodontic instrument results in oscillation (25–40kHz) which initiates fluid movement along the sides of the instrument known as acoustic streaming. This may help to dislodge debris from root canal surfaces and to more efficiently direct irrigant into areas of complex root canal anatomy. Under certain circumstances ultrasonics may instigate the formation and collapse of vacuum bubbles in a liquid; a process known as cavitation, however acoustic streaming appears to be the main mode of action.[124] In addition, ultrasonic energy may produce heat, rendering the sodium hypochlorite solution more effective.[6]

Ultrasonic activation of irrigant should only be used passively after the canal preparation has been completed, employing a narrow non-cutting instrument. A freely oscillating instrument will cause more ultrasound effects in the irrigating solution than a file that binds in the root canal.[125] Furthermore, use of ultrasonic files during canal preparation may lead to gouging of the root canal walls[126] and severe transportation of the canal with zipping and strip perforations.[127]

Several clinical studies have reported greater canal and isthmus cleanliness in the apical region of the root canal when passive ultrasonic activation has been used following canal preparation.[128-130] Collectively, it appears that passive ultrasonics may provide an additional benefit in cleaning root canals, particularly in cases with complex canal anatomy such as the isthmus region,[130] and recesses in oval-shaped canals.[26]

Alternative concepts in the cleaning of root canals

The difficulties in predictably sterilizing the infected root canal system using currently available treatment protocols has stimulated research into novel techniques directed at achieving complete killing of intracanal micro-organisms. *In vitro* studies have shown that both CO_2 and X:YAG lasers possess potent antimicrobial activity, however comparative studies in simulated infected root canals have shown that the effect is either equal to,[131] or weaker than the action of NaOCl irrigation.[132] In addition, complex root canal systems and canal curvatures may reduce the effectiveness of lasers. Photo activated disinfection (PAD) employs a photosensitizer-containing solution which is introduced into the root canal and attaches to the cell wall of bacteria. Irradiation with a low-energy laser at a specific wavelength then leads to the production of free radicals which induce bacterial killing. Seal *et al.*[133] compared the bacterial killing of *Streptococcus intermedius* biofilms in root canals using either PAD or 3% NaOCl irrigation. They found that while PAD was bactericidal, it was unable to achieve a total kill unlike 3% NaOCl irrigation. Other novel techniques aimed at improving root canal disinfection include electro-chemically activated water and ozone gas infiltration. At this point in time, the evidence available suggests that these approaches to root canal disinfection are less effective than NaOCl irrigation.[134,135]

In recent years, a group of Japanese researchers has developed the concept of non-instrumentation endodontic treatment (NIET), employing a mixture of antibacterial drugs for disinfection of the pulp space.[136,137] The antibacterial mixture is called 3Mix-MP, and contains metronidazole, ciprofloxacin, and minocycline (3Mix)[138] in a carrier of macrogol and propylene glycol (MP).[139] The technique involves creation of a "medication cavity" (diameter 1mm and depth 2mm) at the orifice of each root canal as a receptacle for the medication. The 3Mix drugs are then sealed over with glass ionomer cement and a coronal restoration placed. *In vitro* research has demonstrated that the 3Mix-MP drug combination is able to kill bacteria isolated from infected root canals,[138,140] and is able to penetrate through root dentine.[139] While *in vivo* research is scarce, there is some evidence that this technique can be clinically successful in cases where the pulp chamber and root canals are not required for retention of the coronal restoration.[136,137] However, independent clinical trials are required, and concerns have been raised about the possibility of drug side-effects and allergic reactions, and the potential for emergence of antibiotic-resistant bacterial strains.

CONCLUSION

From a biological perspective, root canal treatment is directed toward the elimination of micro-organisms from the root canal system and the prevention of reinfection. Chemomechanical preparation of the root canal involves both mechanical instrumentation and antibacterial irrigation, and is the single most important stage in disinfection of the pulp space. Technological advances in the form of rotary NiTi instruments have led to dramatic improvements in the ability to shape root canals with potentially fewer procedural complications. While measures such as increased apical enlargement or a more effective antimicrobial irrigation regimen may enhance the reduction of the microbial load, predictable eradication of bacteria from the root canal still remains an elusive goal. Further clinical research is needed to strive for complete disinfection of the root canal system in apical periodontitis.

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