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PRINCIPLES OF CLEANING AND SHAPING
ENDODONTIC INSTRUMENTS
STEPS OF CLEANING AND SHAPING

CONTENT

Cleaning and Shaping the Root Canal System

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CHAPTER OUTLINE

Clinical endodontics encompasses a number of treatments, but they have in common the goal of preventing and treating microbial contamination of pulps and root canal systems. Treatment of traumatic dental injuries and prophylactic treatment of vital pulps are fundamentally different from pulpectomies and root canal instrumentation of teeth with infected pulps (see Chapter 1 for more details on diagnosis).

Endodontic therapy is directed toward one specific set of aims: to cure or prevent periradicular periodontitis.[353,526] The ultimate aim is for patients to retain their natural teeth in function and aesthetics.

To date, many treatment modalities, including the use of nickel-titanium rotary instruments, have not consistently provided a statistically relevant impact on treatment outcomes.[375] This poses a problem in the age of evidence-based therapy, because new therapeutic techniques should deliver improved clinical results over standard procedures. However, the few pertinent clinical trials[99,375,387] and numerous in vitro studies do suggest that certain practices in canal preparation and disinfection are more appropriate than others. This chapter will summarize relevant information.

Orthograde root canal treatment is a predictable and usually highly successful procedure, both in relatively straightforward (Fig. 6-1) and more complex cases (Fig. 6-2). Studies and reviews report favorable outcome rates of up to 95% for the treatment of teeth diagnosed with irreversible pulpitis[39,103,157] and positive outcome rates of up to 85% for infected, necrotic teeth.[102,158,345,375,408]

Microorganisms can breach dental hard-tissue barriers through several avenues, the most common being dental caries (Fig. 6-3). Shaping and cleaning procedures (Box 6-1) as part of root canal treatment are directed against microbial challenges to the root canal system. However, disinfection per se does not guarantee long-term retention of root canal-treated teeth; there is good evidence that this outcome is closely related to placement of an adequate coronal restoration.[21,346,400,425] Moreover, the impact of preservation of radicular structural strength should not be underestimated.[172]

PRINCIPLES OF CLEANING AND SHAPING

Endodontists agree that a major biologic aim of root canal therapy is to address apical periodontitis by disinfection and subsequent sealing of root canal systems. However, considerable disagreement exists over how this goal should be achieved. Although the terms *cleaning* and *shaping* are often used to describe root canal treatment procedures,[417] reversing the order to *shaping* and *cleaning* more correctly reflects the fact that enlarged canals direct and facilitate the cleaning action of irrigants and the removal of infected dentin.

Planktonic microorganisms in the pulp cavity and coronal root canal may be readily killed by irrigants early in a

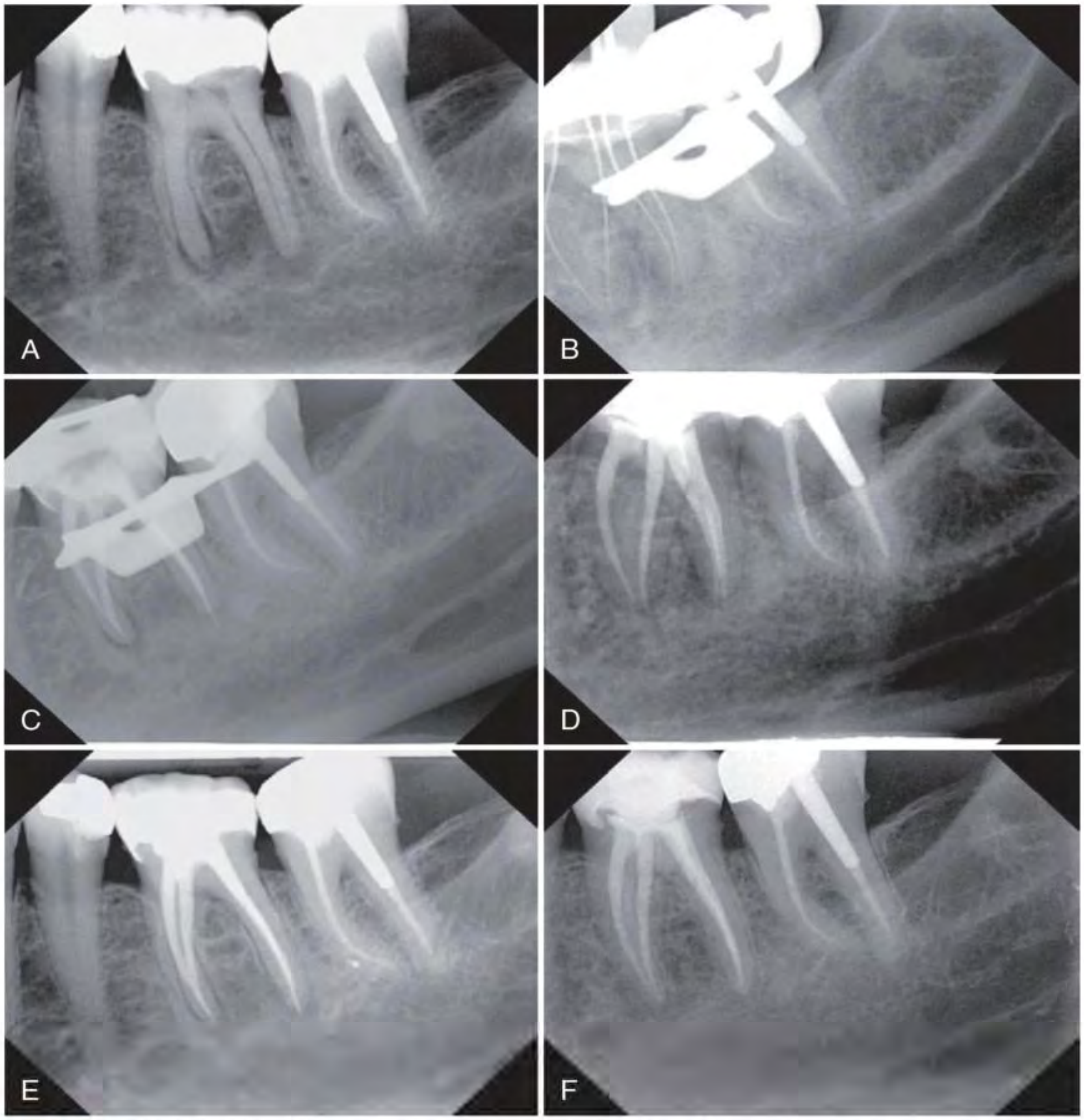


FIG. 6-1 Effect of routine root canal treatment of a mandibular molar. **A,** Pretreatment radiograph of tooth #19 shows radiolucent lesions adjacent to both mesial and distal root apices. **B,** Working length radiograph shows two separate root canals in the mesial root and two merging canals in the distal root. **C,** Posttreatment radiograph after shaping of root canal systems with nickel-titanium rotary files and obturation with thermoplasticized gutta-percha. **D,** Six-month recall radiograph after restoration of tooth #19 with an adhesively inserted full ceramic crown; some periradicular bone fill can be seen. **E,** One-year recall radiograph displays evidence of additional periradicular healing. **F,** Five-year recall radiograph; tooth not only is periapically sound but also clinically asymptomatic and fully functional.

BOX 6-1

Basic Objectives in Cleaning and Shaping

The primary objectives in cleaning and shaping the root canal system are to do the following:

- Remove infected soft and hard tissue
- Give disinfecting irrigants access to the apical canal space
- Create space for the delivery of medicaments and subsequent obturation
- Retain the integrity of radicular structures

procedure, but bacteria in less accessible canal areas or in biofilms still can elicit or maintain apical periodontitis. In everyday practice, these bacteria can be targeted only after mechanical root canal preparation.

Mechanical Objective

An ideal mechanical objective of root canal instrumentation is complete and centered incorporation of the original canals into the prepared shape, meaning that all root canal surfaces are mechanically prepared (*green areas* in Fig. 6-4, *A* and *B*). This goal is unlikely to be met with current techniques.[359,386]

Preparation errors such as deviations, zipping, and perforations should be absent. Although these negative effects of canal

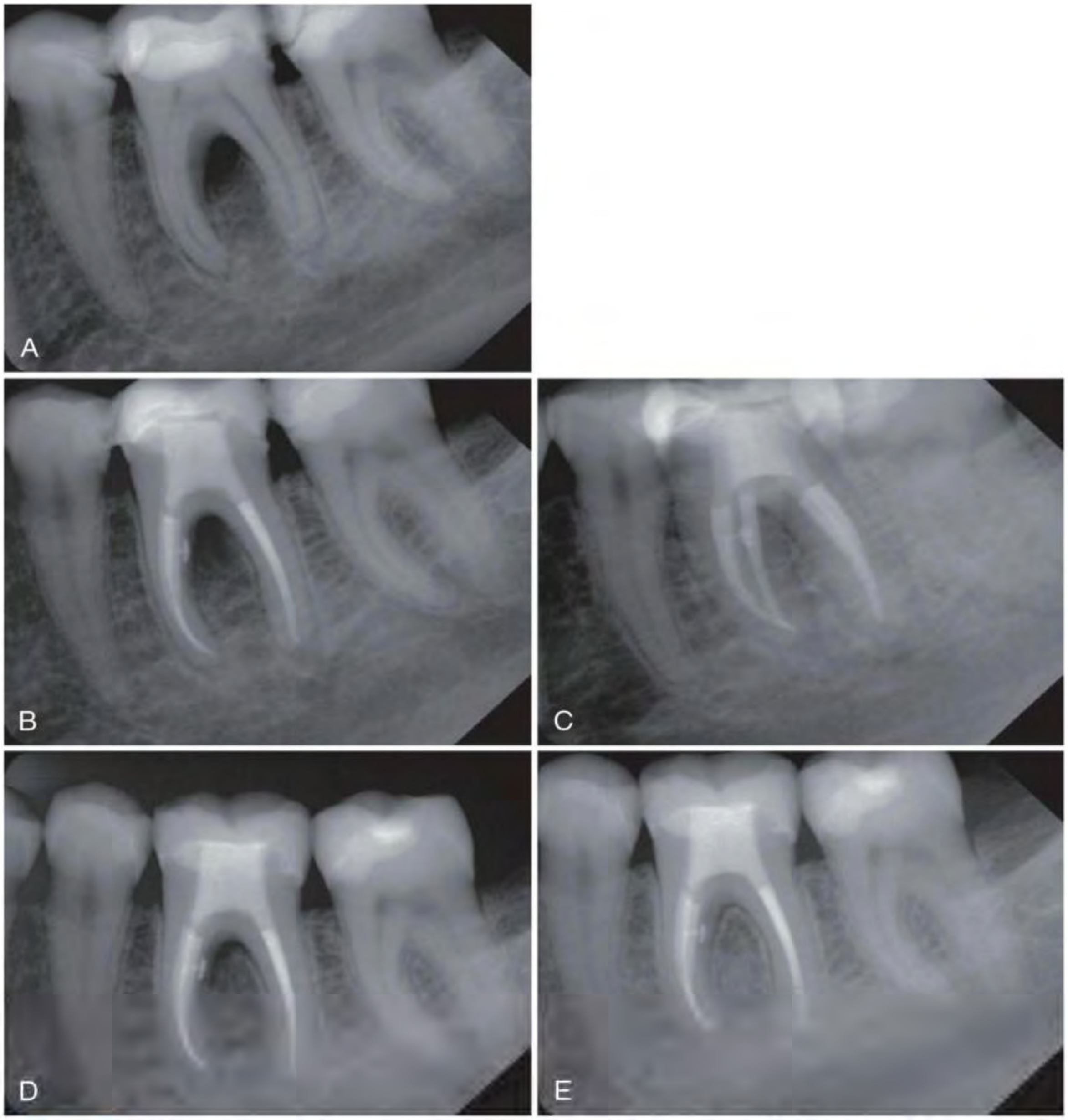


FIG. 6-2 Root canal treatment in a case of apical and interradicular pathosis. **A,** Pretreatment radiograph of tooth #19 shows an interradicular lesion. **B-C,** Posttreatment radiographs after root canal preparation and obturation. Note the lateral canal in the coronal third of the root canal. **D-E,** Two-month recall radiograph suggests rapid healing. (Courtesy Dr. H. Walsch.)

shaping and other procedural mishaps (discussed later) per se may not affect the probability of a favorable outcome,[290] they leave parts of the root canal system inaccessible for disinfection and are undesirable for that reason alone.

Another important mechanical objective is to retain as much cervical and radicular dentin as possible so as not to weaken the root structure, thereby preventing root fractures. Before root canal shaping, dentin wall thickness dimensions of 1 mm and below have been demonstrated in anatomic studies.[127,164] Straightening of canal paths can lead to thinning of curved root walls (Fig. 6-5). Although no definitive minimal radicular wall thickness has been established, 0.3 mm is considered critical by some authors.[287] To avoid overpreparation and outright perforations, adequate access cavity preparation and optimal enlargement of the coronal third of the root canal has to be ascertained (discussed later).

Biologic Objective

Schilder suggested that canals should be prepared to a uniform and continuous taper[445]; however, this guideline was aimed at facilitating obturation rather than targeting antimicrobial efficacy. For optimal disinfection, the preparation shape and antimicrobial efficacy are intimately related through the removal of infected pulp and dentin (Fig. 6-6) and creation of space for delivery of irrigants.

Traditionally, fluids have been dispensed passively into root canals by syringe and needle (Fig. 6-7). When delivered with passive needle irrigation, solutions have been shown to progress only 1 mm farther than the tip of the needle.[189,396,426] Enlarged apical canals and finer needles are likely to allow increasingly deeper needle placement, and this improves debridement and disinfection of canals.[5,12,147,532] However,

FIG. 6-3 Root canal therapy as part of a comprehensive treatment plan. The patient, who was recovering from intravenous drug addiction, requested restorative dental treatment. Because of extensive decay, several teeth had to be extracted, and nine teeth were treated endodontically. Root canal treatment was aided by nickel-titanium rotary instruments, and obturation was done with lateral compaction of gutta-percha and AH26 as the sealer. Microsurgical retrograde therapy was performed on tooth #8, and the distobuccal root of #14 had to be resected. Metal-free adhesively luted restorations were placed, and missing mandibular teeth were replaced by implants. **A,** Pretreatment intraoral status, showing oral neglect. **B,** Posttreatment intraoral status at 4-year follow-up, showing fully functional, metal-free, tooth-colored reconstructions. **C,** Panoramic radiograph at 4-year recall shows sound periradicular tissues in relation to endodontically treated teeth. (Restorations done by Dr. Till N. Göhring.)

thorough cleaning of the most apical part of any preparation remains difficult,[561] especially in narrow and curved canals.[16,211,404]

Technical Objective

Although a continuous taper that encompasses the original shape and curvature of a given root canal is an accepted goal, final apical preparation size remains a much-disputed entity in root canal therapy, as does final taper of the preparation.[47] Arguments were made for better disinfection with larger sizes (i.e., #50 or greater)[89,415] in combination with smaller tapers of .02 to .05. Others found no difference whether the selected final size was small or large.[105,570] A self-adjusting file was introduced,[327] which does not prepare canals to a specific normed size; its debridement effect is thought to result from a greater radicular wall contact, notably in buccolingually wide canals.[361]

Clinical Issues

A wide spectrum of possible strategies exists for attaining the goal of removing the canal contents and eliminating infection. Lussi and colleagues introduced an approach to removing canal contents and accomplishing disinfection that did not involve the use of a file: the noninstrumentation technique.[303,304] This system consisted of a pump, a hose, and a special valve that was cemented into the access cavity (Fig. 6-8, *A*) to provide oscillation of irrigation solutions (1% to 3% sodium hypochlorite) at a reduced pressure. Although several in vitro studies suggested that canals can be cleaned and subsequently filled using this noninvasive system (see Fig. 6-8, *B* and *C*),[304,305] preliminary clinical results have not been as convincing (see Fig. 6-8, *D*).[25]

At the opposite end of the spectrum is a treatment technique that essentially removes all intraradicular infection through extraction of the tooth in question (see Fig. 6-8, *E* and *F*). Almost invariably, periradicular lesions heal after extraction of the involved tooth.

Clinical endodontic therapy takes place somewhere along this spectrum of treatment strategies. This is reflected in some of the controversies that surround the cleaning and shaping process, such as how large the apical preparation should be and what are the correct diameter, length, and taper.[250] Once the decision has been made to initiate endodontic treatment, the clinician must integrate his or her knowledge of dental anatomy, immunology, and bioengineering science with clinical information.

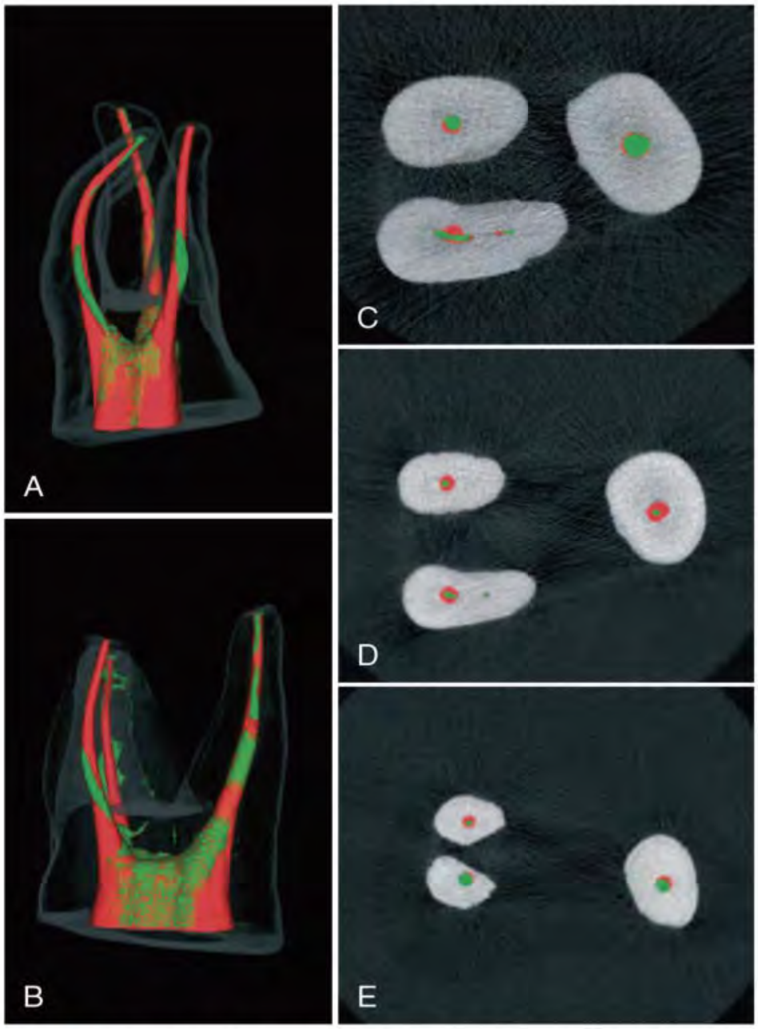


FIG. 6-4 Example of a desired shape, with the original root canal fully incorporated into the prepared outline. **A-B,** Microcomputed tomography reconstructions in clinical and mesiodistal views of a maxillary molar prepared with a NiTi rotary system. The *green area* indicates the pretreatment shape, and the *red area* indicates the posttreatment shape. Areas of *mixed red and green* indicate no change (i.e., no removal of radicular dentin). **C-E,** Cross sections of the coronal, middle, and apical thirds; the pretreatment cross sections *(green)* are encircled by the posttreatment outlines *(red)* in most areas. (*A-B,* From Hübscher W, Barbakow F, Peters OA: Root-canal preparation with FlexMaster: canal shapes analysed by micro-computed tomography, *Int Endod J* 36:740, 2003.)

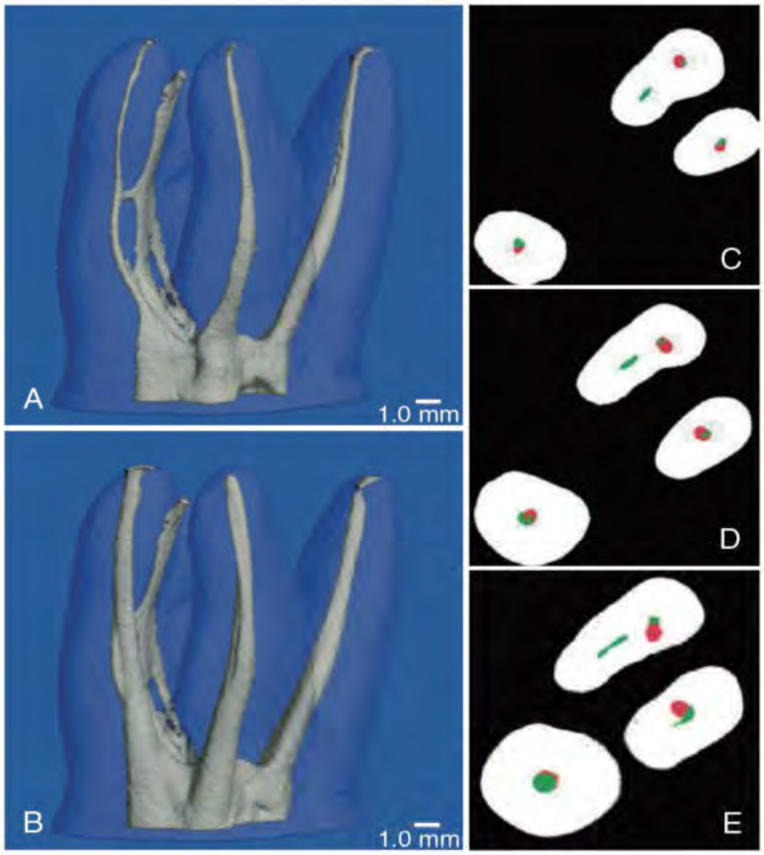


FIG. 6-5 Example of excessive thinning of dental structure during root canal treatment. **A-B,** Microcomputed tomography reconstructions show pretreatment and posttreatment root canal geometry of a maxillary molar. **C-E,** Cross sections of the coronal, middle, and apical thirds with pretreatment canal cross sections. Note the transportation and thinning, in particular, in the main mesiobuccal canal.

Endodontic therapy has been compared to a chain of events, wherein the chain is only as strong as each individual link. For the purposes of this chapter, shaping and cleaning of the root canal system is considered a decisive link, because shaping determines the efficacy of subsequent procedures. It includes mechanical debridement, the creation of space for the delivery of medicaments, and optimized canal geometries for adequate obturation.[373] These tasks are attempted within a complex anatomic framework, as recognized in the early 20th century by Walter Hess[218] (Fig. 6-9; see also Chapter 5 for a complete description of root canal anatomy).

A clinician must choose appropriate strategies, instruments, and devices to overcome challenges and accomplish precise preparation in shape, length, and width. This allows endodontic therapy to address various forms of the disease processes described previously (Fig. 6-10). Recall radiographs taken at appropriate intervals predictably demonstrate longevity and favorable outcomes (see Figs. 6-1, 6-2, and 6-11) if a systematic approach to root canal shaping is adhered to (see Box 6-1).

Endodontic files traditionally have been manufactured according to empiric designs, and most instruments still are conceived based on individual clinicians' philosophies rather than developed through an evidence-based approach. Similar to the development of composite resins in restorative dentistry, the development of new files is a fast and market-driven process. With new instruments becoming available, the clinician may find it difficult to pick the file and technique most suitable for an individual case. Clinicians must always bear in mind that all file systems have benefits and weaknesses. Ultimately, clinical experience, handling properties, usage safety, and case outcomes, rather than marketing or the inventor's name, should decide the fate of a particular design. The following section describes typical instruments used in root canal shaping.

ENDODONTIC INSTRUMENTS

General Characteristics

Design Elements

Root canal preparation instruments such as K-files and nickel-titanium rotary instruments follow certain design principles

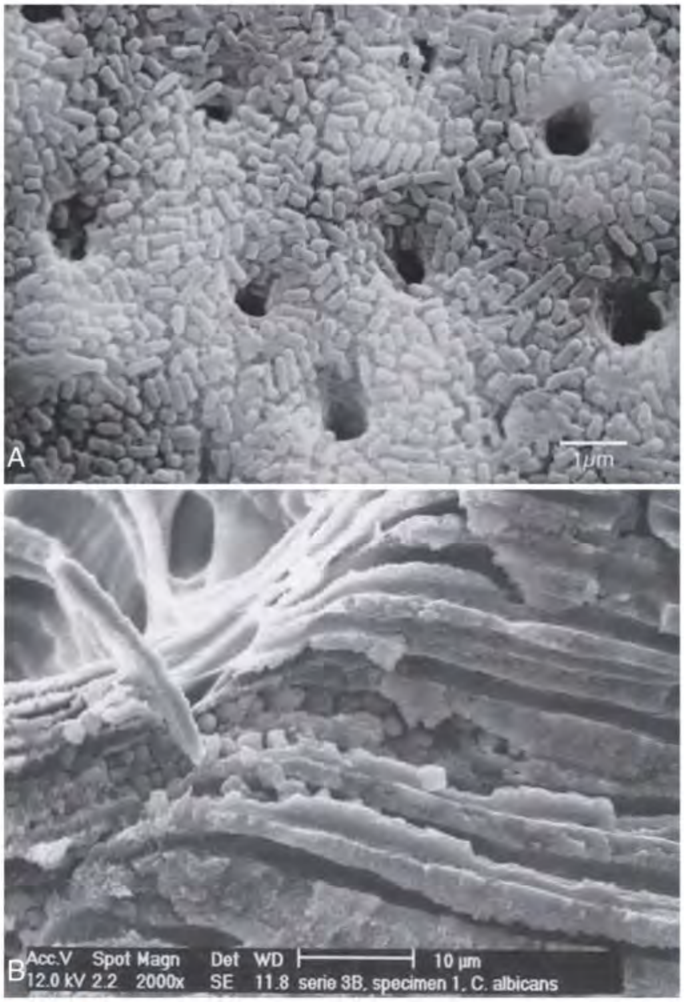


FIG. 6-6 Presence of microorganisms inside the main root canal and dentinal tubules. **A**, Scanning electron micrograph of a root canal surface shows a confluent layer of rod-shaped microbes (×3000). **B**, Scanning electron micrograph of a fractured root with a thick smear layer and fungi in the main root canal and dentinal tubules. (*A*, Courtesy Professor C. Koçkapan. *B*, Courtesy Professor T. Waltimo.)

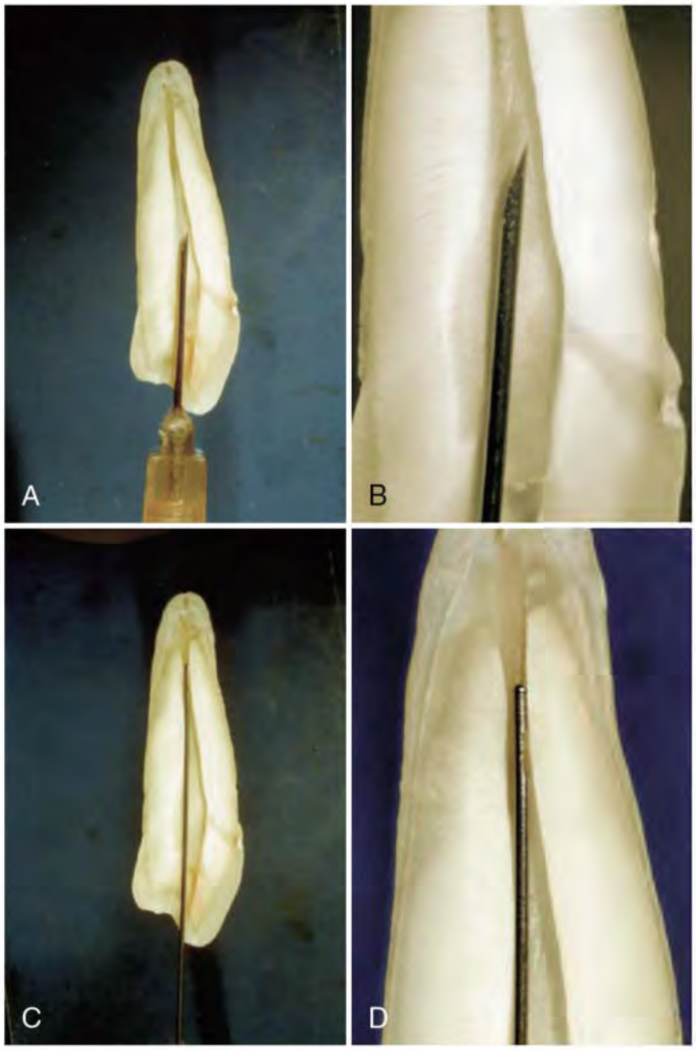


FIG. 6-7 Irrigation needles inserted into prepared root canals. **A-B**, A 27-gauge needle barely reaches the middle third. **C-D**, A 30-gauge, side-venting needle reaches the apical third in adequately enlarged canals.

that relate to drills and reamers used for work in wood and metal, respectively, whereas other instruments such as broaches and Hedström files do not find a direct technologic correlate. Design elements such as the tip, flutes, and cross sections are considered relevant for files and reamers used in rotary motion. These pertinent aspects are briefly described next; for a more detailed review, the reader is referred to the literature.[181,420,427,483]

Tip Design

In root canal preparation, an instrument tip has two main functions: to guide the file through the canal and to aid the file in penetrating deeper into the canal. A clinician unfamiliar with the tip design, in particular of a rotary instrument, may do either of the following: (1) transport the canal (if the tip is capable of enlarging and is used too long in one position in a curved canal) or (2) encounter excessive torsion and break the file (if a noncutting tip is forced into a canal with a smaller diameter than the tip).

The angle and radius of its leading edge and the proximity of the flute to its actual tip end determines the cutting ability of a file tip. Cutting ability and file rigidity determine the propensity to transport the canal. The clinician must keep in mind that as long as a flexible file with a noncutting tip is engaged, 360-degree canal transportation is unlikely to occur.[410]

Studies have indeed shown that tip design affects file control, efficiency, and outcome in the shaping of root canal systems.[330,331] The tip of the original K-file resembled a pyramid; instrument tips have been described as *cutting, noncutting*, and *partially cutting*, although no clear distinction exists among the three types (Fig. 6-12).

Noncutting tips, also called *Batt tips*, are created by grinding and smoothing the apical end of the instrument (see Fig. 6-12, *A*). A tip modification was introduced with the Flex-R file, which was manufactured fully by grinding so that the transitional angles were smoothed laterally between the tip and the instrument's working parts.[411] Similar techniques are required to manufacture NiTi K-files.[512]

For NiTi rotary files, typically rounded noncuttings tips are used (see Fig. 6-12, *B*), which effectively prevent preparation errors that were found with earlier so-called safe cutting tips.[236] One exception to this rule is the type of rotary

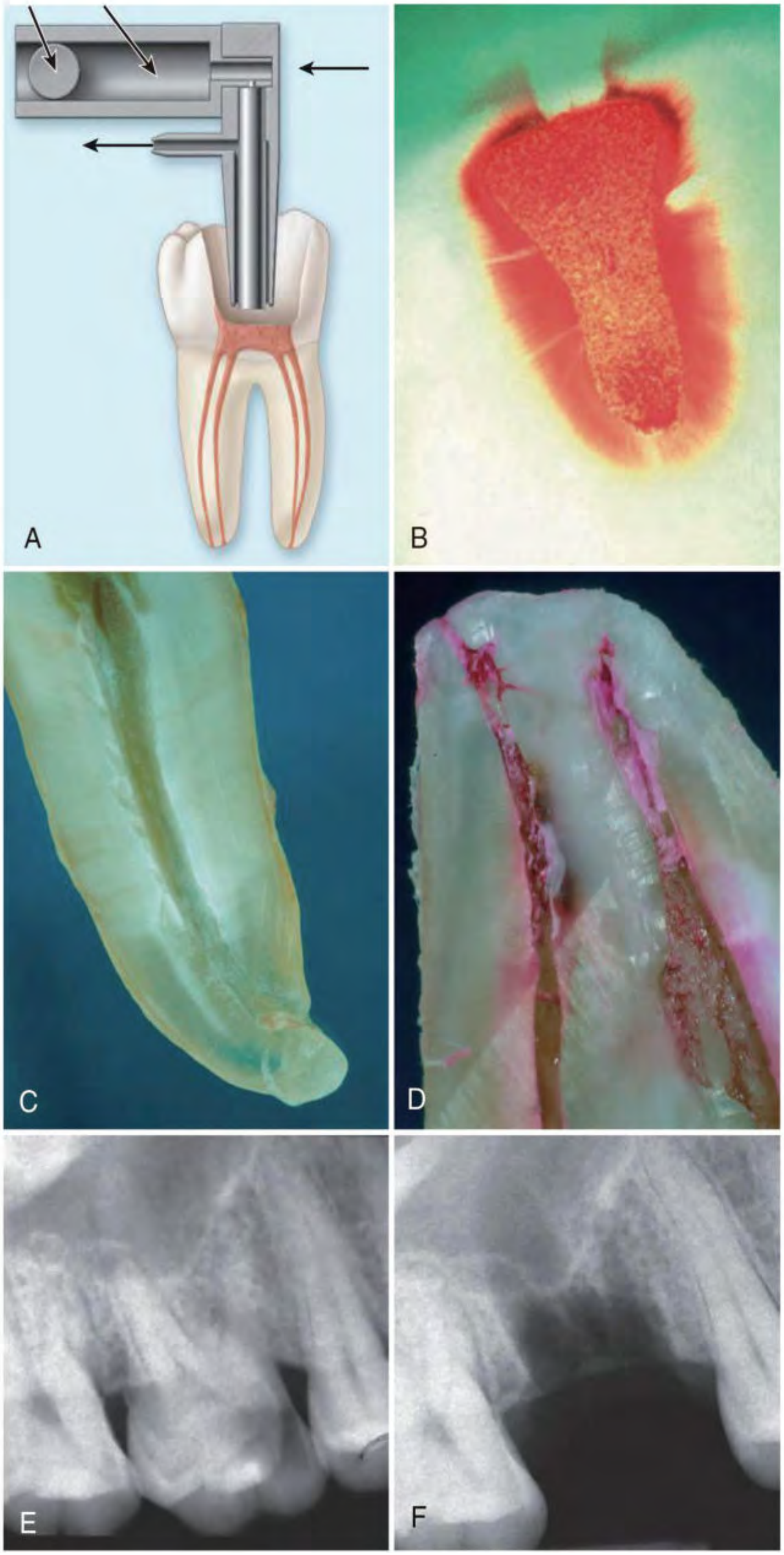


FIG. 6-8 Spectrum of strategies for accomplishing the primary aim of root canal treatment: elimination of infection. **A,** Schematic diagram of minimally invasive therapy using the noninstrumentation technique (NIT). **B,** Example of teeth cleaned in vitro using NIT. Note the clean intracanal surface, which is free of adhering tissue remnants. **C-D,** Examples of teeth cleaned in vivo and later extracted to investigate the clinical effects of NIT. Note the relatively clean, tissue-free canal space in **C** and the significant tissue revealed by rhodamine B staining in **D. E-F,** Course of maximally invasive therapy; apically involved tooth #30 was extracted, effectively removing the source of periradicular inflammation. (*A-B,* Courtesy Professor A. Lussi. *C-D,* Courtesy Professor T. Attin. *E-F,* Courtesy Dr. T. Kaya.)

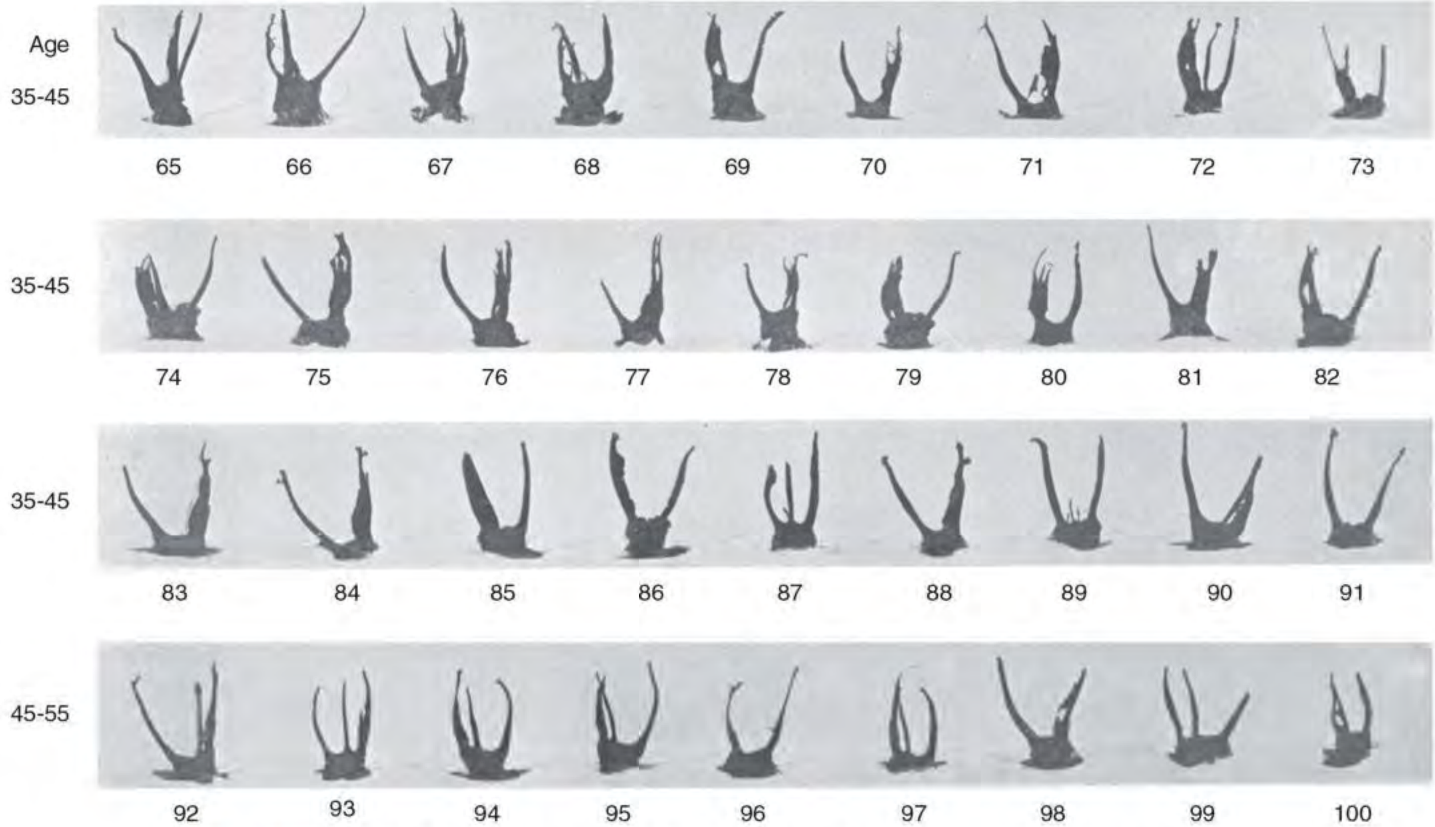


FIG. 6-9 Panel of 36 anatomic preparations of maxillary molars from the classic work by Professor Walter Hess of Zurich. Note the overall variability of root canal systems and the decrease of canal dimensions with age. (From Hess W: *The anatomy of the root canals of teeth of the permanent dentition,* London, 1925, John Bale, Sons & Danielsson.)

specifically designed as a retreatment instrument; cutting tips in that case facilitate removal of the existing root canal filling material and are sufficiently safe.

Longitudinal and Cross-Sectional Design

The *flute* of the file is the groove in the working surface used to collect soft tissue and dentin chips from the wall of the canal. The effectiveness of a flute depends on its depth, width, configuration, and surface finish. The surface with the greatest diameter that follows the groove (where the flute and land intersect) as it rotates forms the *leading (cutting) edge,* or the *blade* of the file. The cutting edge forms and deflects chips along the wall of the canal and severs or snags soft tissue. Its effectiveness depends on its angle of incidence and sharpness.

Some instruments have a feature between trailing and cutting edge that forms a larger contact area with the radicular wall; this surface is called a radial land (Fig. 6-13). Such a land is thought to reduce the tendency of the file to thread into the canal. It also supports the cutting edge and limits the depth of cut; its position relative to the opposing cutting edge and its width determine its effectiveness. On the other hand, landed files are typically less cutting efficient compared to triangular cross sections.[380]

To reduce frictional resistance, some of the surface area of the land that rotates against the canal wall may be reduced to form the *relief*. The angle the cutting edge forms with the long axis of the file is called the *helical angle* (see Fig. 6-13).

If a file is sectioned perpendicular to its long axis, the *rake angle* is the angle formed by the leading edge and the radius of the file through the point of contact with the radicular wall. If the angle formed by the leading edge and the surface to be cut is 90 degrees, the rake angle is said to be neutral. The rake angle may be *negative* or *scraping* (Fig. 6-14, *A*) or *positive* or *cutting* (Fig. 6-14, *C*).

The *cutting angle* is considered a better indication of a file's cutting ability and is determined by measuring the angle formed by the leading edge of the file and a tangent to the radicular wall in the point of contact. The clearance angle corresponds to the cutting angle at the trailing edge of the file and, in case of reciprocating action, becomes the cutting angle. The sum of cutting angle and rake angle is 90 degrees.

The *pitch* of the file is the distance between a point on the leading edge and the corresponding point on the adjacent leading edge (the distance from one "spiral twist" to the next) (see Fig. 6-13). The smaller the pitch or the shorter the distance between corresponding points, the more spirals the file has and the greater the helix angle. Although K-files have a constant pitch typically in the range of 1 mm, many NiTi rotaries have a variable pitch, one that changes along the working surface. When variable pitch is used, usually tighter spirals are located close to the tip of the file and more space between the flutes is located toward the coronal part of the file. A longitudinal section through an instrument reveals the *core* (see Fig. 6-13). The outer diameter of a tapered instrument increases from the file tip toward the handle; depending

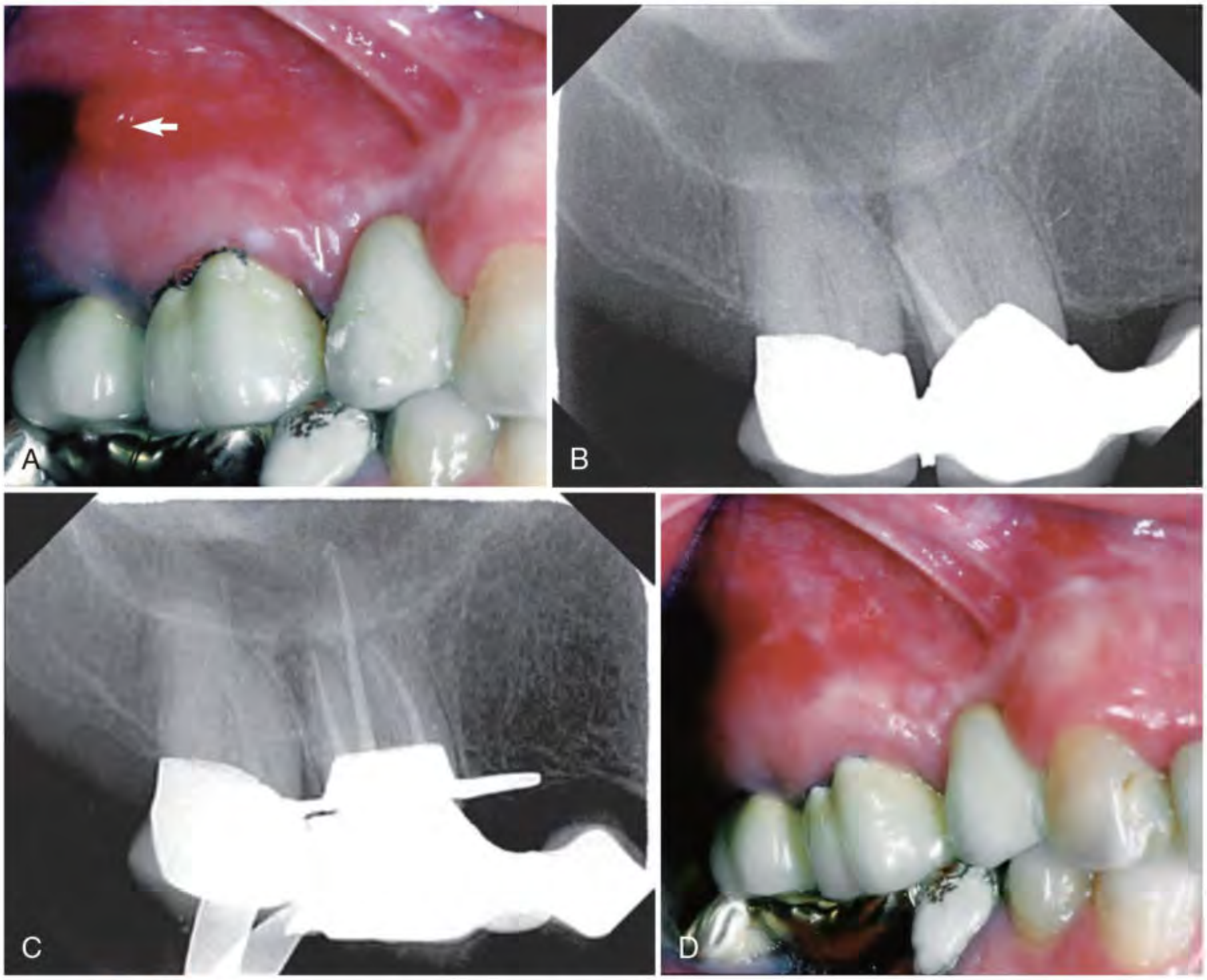


FIG. 6-10 Sinus tract as a sign of a chronic apical abscess and effect of routine root canal treatment. **A,** Intraoral photograph of left maxillary region with draining sinus tract *(arrow)* periapical to tooth #14. **B,** Pretreatment radiograph with gutta-percha point positioned in the sinus tract, pointing toward the distobuccal root of #14. **C,** Finished root canal fillings after 2 weeks of calcium hydroxide dressing. **D,** Intraoral photograph of the same region as in **A,** showing that the sinus tract had closed by the time obturation was performed.

on core dimensions, the flute may become proportionately deeper, resulting in a *core taper* that may be different from the *external taper*.

The cutting angles, helix angles, and external and core tapers may vary along the working surface of the file, and the ratios of these quantities can vary among instruments of the same series. A change in any of these features may influence the file's effectiveness or its propensity for breakage as it progresses into the canal space.

Taper

The taper usually is expressed as the amount the file diameter increases each millimeter along its working surface from the tip toward the file handle. For example, a size #25 file with a .02 taper would have a 0.27-mm diameter 1 mm from the tip, a 0.29-mm diameter 2 mm from the tip, a 0.31 mm diameter 3 mm from the tip, and so forth. Instruments can have constant or variable taper: Some manufacturers express the taper in terms of percentage (e.g., a .02 instrument has been said to have a 2% taper; Fig. 6-15). Current instrument developments include variations in helical angle, pitch, and taper along the cutting portion, which along with variations in alloy and rotational speed (rpm) all affect cutting behavior.[380] The ability to determine cross-sectional diameter at a given point on a file can help the clinician determine the file size in the point of curvature and the relative stress being placed on the instrument. Instruments with greater tapers are designed so that the tip of the instrument functions as a guide and the middle and coronal part of the instrument's working part is the one engaging the canals walls.

ISO Norms

Standardized specifications have been established to improve endodontic instrument quality.[238] For example, the International Standards Organization (ISO) has worked with the Fédération Dentaire Internationale (FDI) to define specifications. These standards are designated with an ISO number. The American Dental Association (ADA) also has been involved in this effort, as has the American National Standards Institute (ANSI); these standards are designated with an ANSI number. However, new instrument designs have resulted in a need for reconsideration of the standards.

Two ISO standards pertain to endodontic instruments. ISO No. 3630-1 deals with K-type files as does ANSI No. 28), Hedström files (ANSI No. 58), and barbed broaches and rasps (ANSI No. 63). ISO No. 3630-3 deals with condensers,

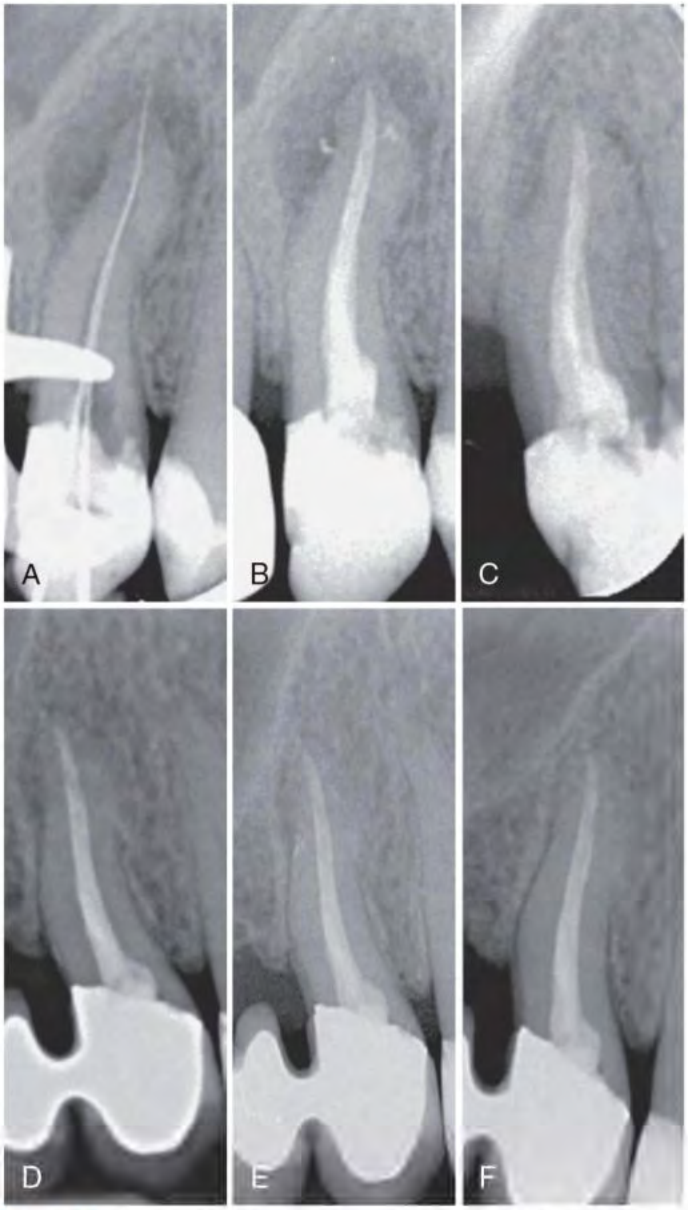


FIG. 6-11 Relationship of radicular anatomy and endodontic disease as shown by filled accessory canals. **A,** Working length radiograph of tooth #13 shows lesions mesially and distally but not apically. **B,** Posttreatment radiograph shows the accessory anatomy. **C,** Six-month recall radiograph before placement of the restoration. **D,** Two-year recall radiograph after resection of the mesiobuccal root of tooth #14 and placement of a fixed partial denture. Excess sealer appears to have been resorbed, forming a distal residual lesion. **E,** Four-year recall radiograph shows almost complete bone fill. **F,** Seven-year recall radiograph; tooth #14 is radiologically sound and clinically within normal limits.

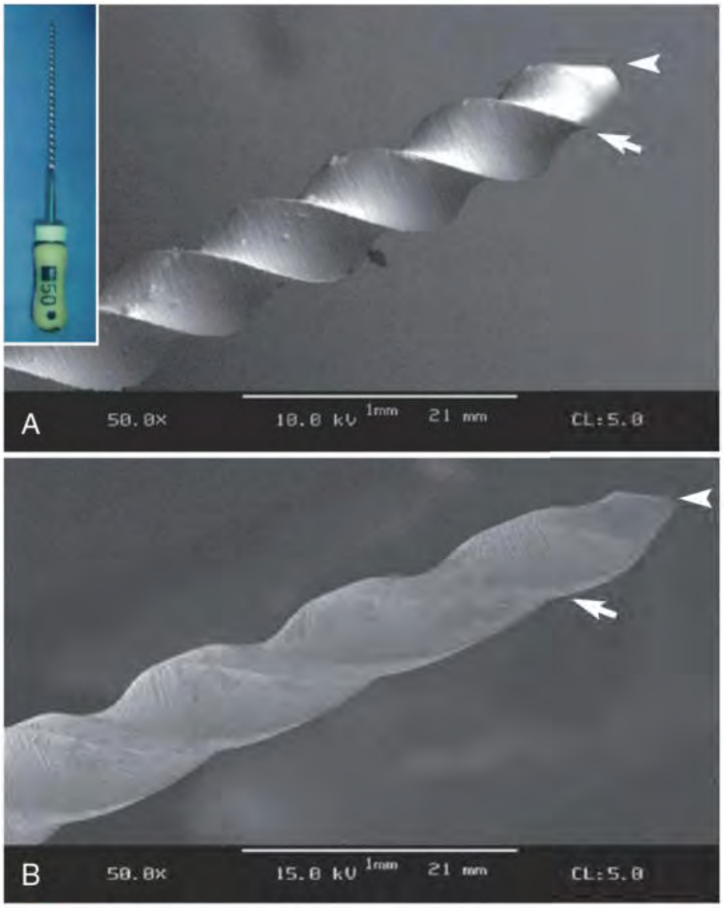


FIG. 6-12 Comparison of the flute geometry and tip configuration of a hand file *(inset)* and a NiTi rotary instrument. **A,** K-file with sharp cutting edges *(arrow)* and Batt tip *(arrowhead)*. ***B***, GT rotary file with rounded, noncutting tip *(arrowhead)*, smooth transition, and guiding radial lands *(arrow)*.

pluggers, and spreaders (ANSI No. 71); however, the term *ISO-normed instruments* is often used as a synonym for K-files (see Fig. 6-15).

One important feature of ISO-normed hand instruments is a defined increase in tip diameter of 0.05 or 0.1 mm, depending on the instrument size (Fig. 6-16). ISO-normed K- and Hedström files (Fig. 6-17) are available in different lengths (21, 25, and 31 mm), but all have a 16-mm-long section of cutting flutes (see Figs. 6-12 and 6-15). The cross-sectional diameter at the first rake angle of any file is labeled D0. The point 1 mm coronal to D0 is D1, the point 2 mm coronal to D0 is D2, and so on up to D16. The D16 point is the largest diameter of an ISO-normed instrument. Each file derives its numeric name from the diameter at D0 and is assigned a specific color code (see Fig. 6-15).

Another aspect of ISO files is the standard taper of 0.32 mm over 16 mm of cutting blades, or 0.02 mm increase in diameter per millimeter of flute length (.02 taper). Thus, a size #10 instrument has a diameter of 0.1 mm at D0 and a corresponding diameter of 0.42 mm at D16 [0.1 mm + (16 * 0.02 mm)]. For a size #50 instrument, the diameters are 0.5 mm at D0 and 0.82 mm at D16.

The ISO-normed design is a simplification that has specific disadvantages, and it may explain the clinical observation that enlarging a root canal from size #10 to #15 is more difficult than the step from size #55 to #60. The introduction of K-type files with tip sizes between the ISO-stipulated diameters seemed to solve the problem. However, the use of such files is not universally recommended, perhaps because the approved machining tolerance of ±0.02 mm could negate any intended advantages. Moreover, although ±0.02 mm tolerance is stipulated by the ISO norm, most manufacturers do not adhere to it.[253,449,499,581]

Another suggested modification relates to tips with a constant 29% percentage of diameter increments. This sizing pattern creates smaller instruments that carry less of a workload. However, the intended advantage is offset by larger diameters, because the 29% increase between successive files is

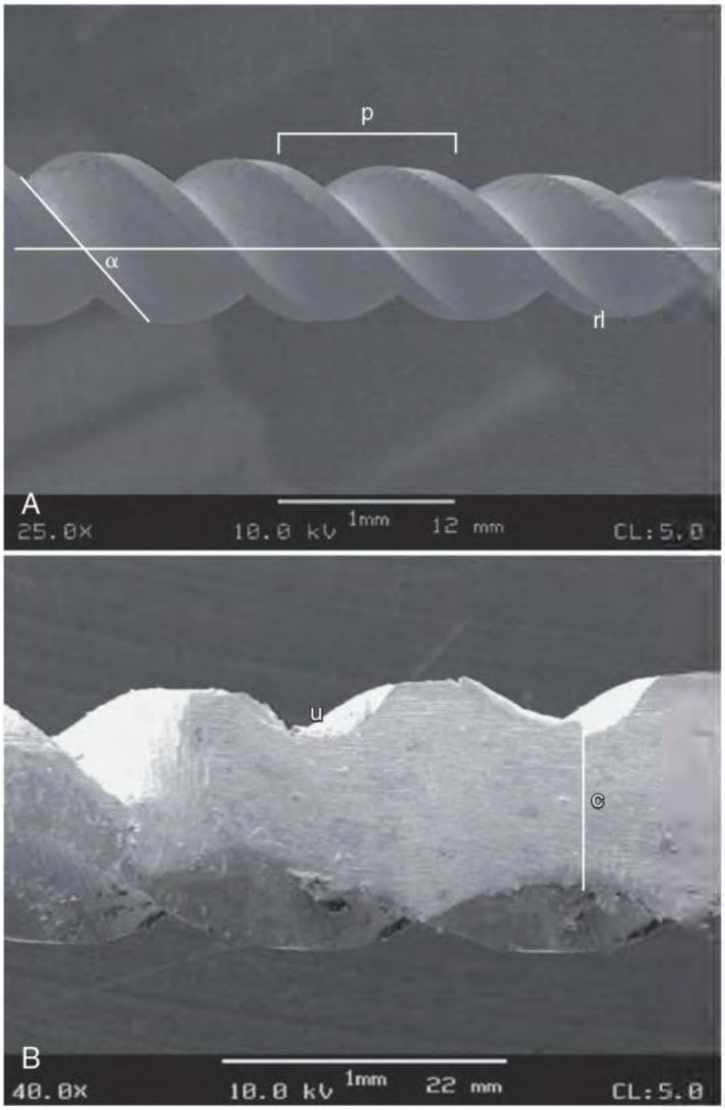


FIG. 6-13 Design characteristics of nickel-titanium rotary instruments. **A**, Lateral view showing the details of the helical angle, pitch *(p)*, and the presence of guiding areas, or radial lands *(rl)* (scanning electron micrograph [SEM], ×25). **B**, Ground working part of the instrument in **A**, showing U-shaped excavations and the dimension of the instrument core *(c)*.

actually greater than the percentage change found in the ISO file series.

Further changes to the numbering system for files with different sizes have been implemented by several manufacturers. One system has introduced "half" sizes in the range of #15 through #60, resulting in instruments in sizes #15, #17.5, #20, #22.5, and so on.

Alloys

There are currently two principally different types of alloys used for endodontic instruments, stainless steel and nickel-titanium. Most manually operated endodontic instruments are fabricated from stainless steel and have considerable resistance to fracture. A clinician who is careful in applying force and adheres to a strict program of discarding instruments after use should have few instrument fractures. Stainless steel files are comparably inexpensive so that adequate cleaning and sterilization for reuse of files in sizes up to #60 may not be cost effective. If this is the case, files in the range up to #60 may be considered disposable instruments.[490]

Several burs and instruments designed for slow-speed handpiece operation such as Gates Glidden drills, Peeso burs, and pilot drills for intraradicular posts are also manufactured from stainless steel. Instruments designed for rotary root canal instrumentation, however, are typically made of nickel-titanium.[454] This alloy offers unique properties, specifically flexibility and corrosion resistance.

Physical and Chemical Properties of Steel and Nickel Titanium Alloys

Basic engineering terms relate to metals and their behavior when used to manufacture endodontic instruments. Stress-strain diagrams describe the response of metal wires under loading depending on their crystal configuration (Fig. 6-18).

During the development of the equiatomic *nitinol* [this acronym is derived from *ni*ckel-*ti*tanium investigated at the *N*aval *O*rdinance *L*aboratory] alloy (55% [by weight] nickel and 45% [by weight] titanium), several effects were noted that relate to its specific crystal arrangement with two stable main phases, *austenite* and *martensite* (Fig. 6-19): a shape memory effect as temperature- and strain-dependent pseudoelasticity, all attributable to specific thermodynamic properties of the new alloy.[77,133,356,517]

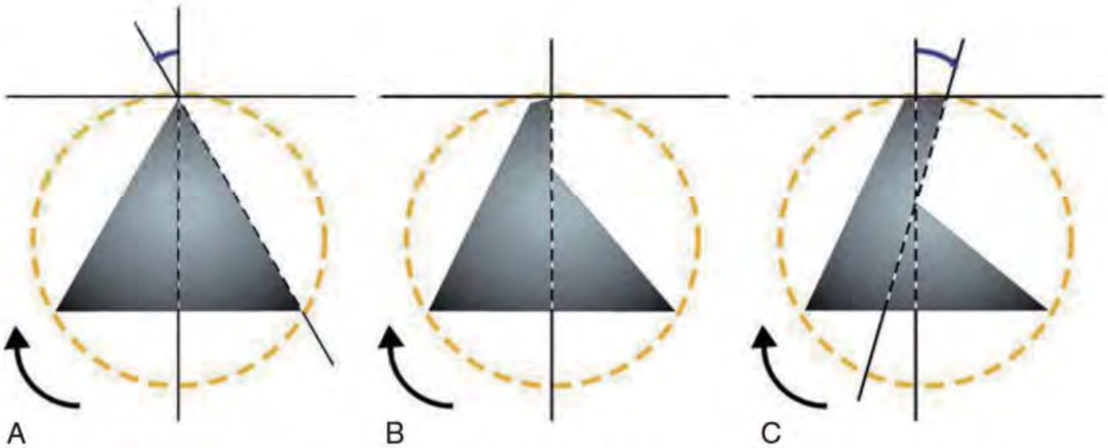


FIG. 6-14 The rake angle of an endodontic file can be negative (**A**), neutral (**B**) or positive (**C**).

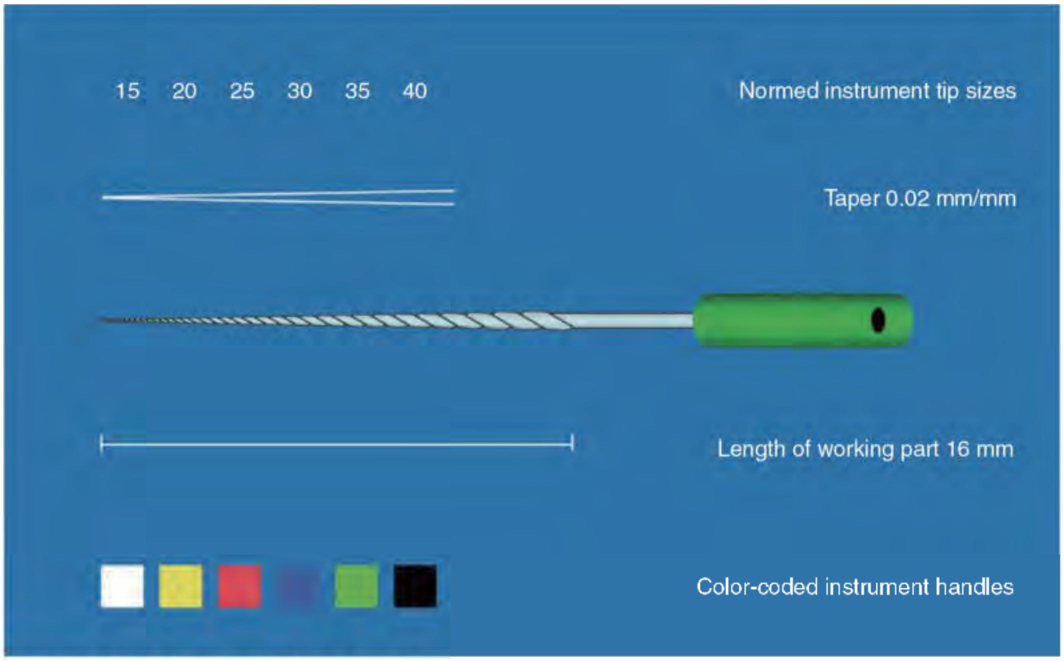


FIG. 6-15 Schematic drawing of an ISO-normed hand instrument size #35. Instrument tip sizing, taper, and handle colors are regulated by the ISO/ANSI/ADA norm.

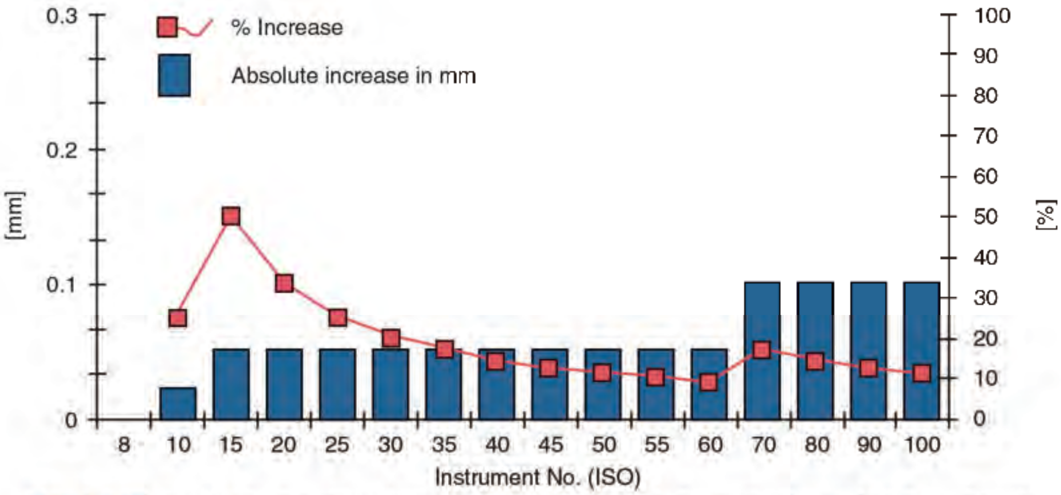


FIG. 6-16 Increase in tip diameter in absolute figures and in relation to the smaller file size. Note the particularly large increase from size #10 to size #15.

Walia and colleagues thought that the pseudoelastic properties of 55-nitinol might prove advantageous in endodontics and initially tested hand instruments.[542] They found that size #15 NiTi instruments were two to three times more flexible than stainless steel instruments; moreover, the instruments showed superior resistance to angular deflection.[542]

Furthermore, hardly any plastic deformation of cutting flutes was recorded when an instrument was bent up to 90 degrees, and forces required to bend endodontic files to 45 degrees were reduced by 50% with NiTi.[454,542] Serene and colleagues speculated that heat, probably during sterilization cycles, could even restore the molecular structure of used NiTi files, resulting in an increased resistance to fracture.[454] Such a behavior is claimed to occur for current martensitic instruments.[377]

These unusual properties are the result of a molecular crystalline phase transformation in specific crystal structures of the austenitic and martensitic phases of the alloy.[517] External stresses transform the austenitic crystalline form of NiTi into a martensitic crystalline structure that can accommodate greater stress without increasing the strain. As a result, a NiTi file has transformational elasticity, also known as *pseudoelasticity*, or the ability to return to its original shape after being deformed (see Fig. 6-19, *B*). This property dictates that typically NiTi instruments are manufactured by milling rather than twisted; twisting incorporates plastic deformation and is used, for example, to produce stainless steel K-files.

Similar to the application of deforming forces, heat can also result in phase transformation (see Fig. 6-19, *A*) from austenite to martensite and vice versa.[209,329] Moreover, thermal conditions during the production of the raw wire can be used to modify its properties, most important of which is its flexibility.[192,461] For austenitic endodontic instruments, a recoverable

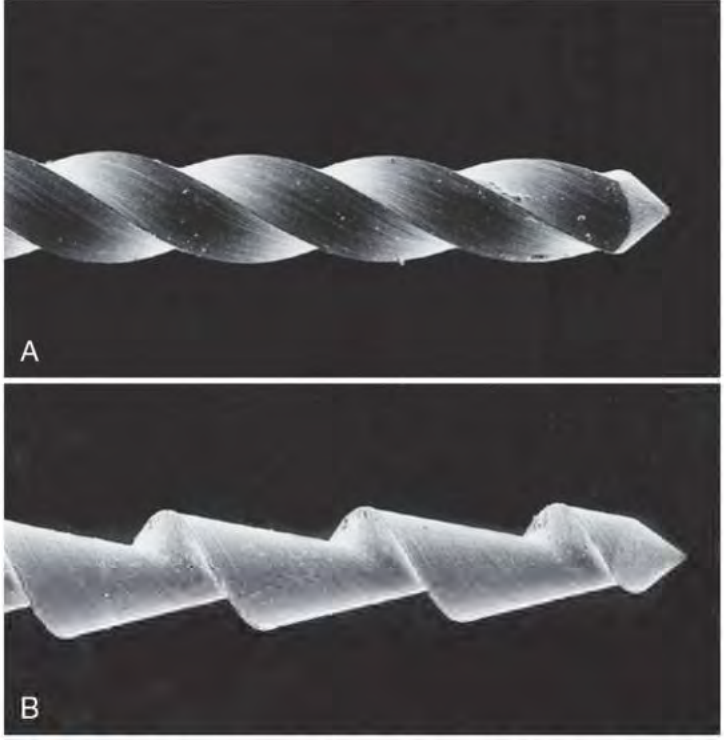


FIG. 6-17 Scanning electron micrographs of endodontic hand files fabricated by twisting (K-file size #40, **A**) and grinding (Hedström file #50, **B**). (Both images courtesy Dentsply Maillefer, Ballaigues, Switzerland).

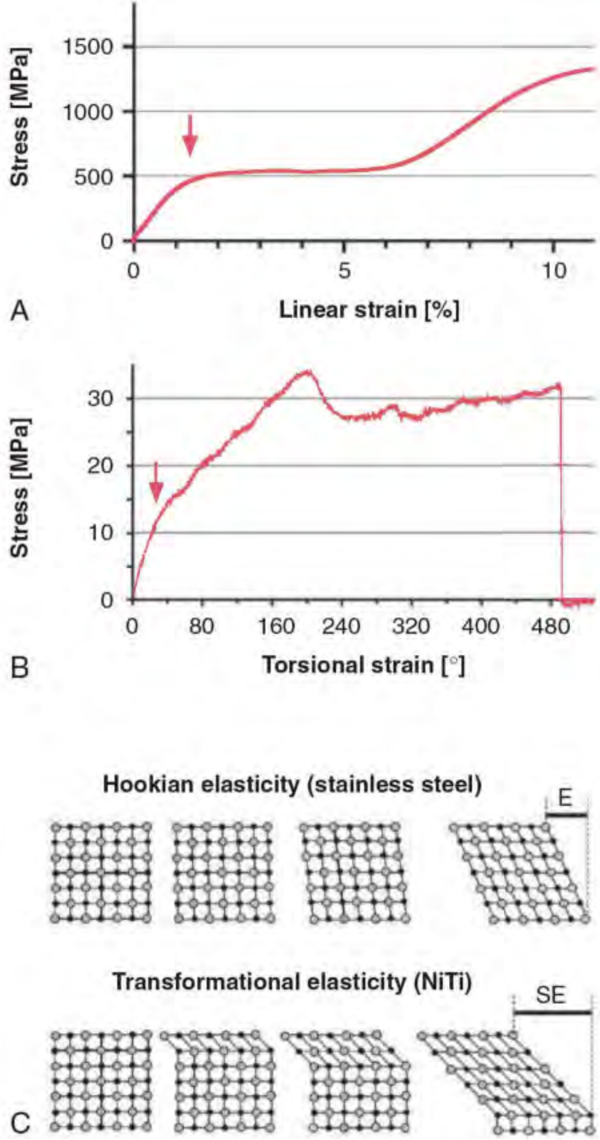


FIG. 6-18 Stress-strain behavior of nickel-titanium alloy. **A**, Schematic diagram of linear extension of a NiTi wire. **B**, Torque to failure test of a size #60, #.04 taper ProFile NiTi instrument. Note the biphasic deformation, indicated by arrows in **A-B**. **C**, Comparison of stainless steel and nickel-titanium crystal lattices under load. Hookian elasticity accounts for the elastic behavior *(E)* of steel, whereas transformation from martensite to austenite and back occurs during the pseudoelastic *(PE)* behavior of NiTi alloy. (*C*, Modified from Thompson SA: An overview of nickel-titanium alloys used in dentistry, *Int Endod J* 33:297, 2000.)

elastic response of up to 7% is expected (Fig. 6-20). However, more martensitic instruments will have less of an elastic range and are more likely to plastically deform during use.[377,461]

Experiments designed to test fracture resistance demonstrate physical properties of endodontic instruments; following the pertinent ISO norm, 3630-1 graphs such as those shown in Fig. 6-20 are generated and compared among different designs.

Attempts to improve the NiTi alloy continue, and reports indicate that new NiTi alloys may be five times more flexible than currently used alloys.[225,461] NiTi instruments may have imperfections such as milling marks, metal flash, or rollover.[135,454,524,542] Some researchers have speculated that fractures in NiTi instruments originate at such surface imperfections.[11]

Surface irregularities may provide reservoirs of corrosive substances, most notably sodium hypochlorite (NaOCl). Chloride corrosion may lead to micropitting[428] and possibly subsequent fracture in NiTi instruments.[202] Immersion in various disinfecting solutions for extended periods (e.g., overnight soaking) produced corrosion of NiTi instruments and subsequent decreased torsional resistance.[350,486] For ProTaper,[52] RaCe, and ProFile385 instruments, 2-hour immersion damaged the integrity of the alloy. Other authors did not find a corrosion-related effect on K3-files[36] or ProFile instruments.[120]

Regular reprocessing procedures do not seem to significantly affect NiTi rotary instruments.[293,330,503] In one study, only limited material loss occurred when NiTi LightSpeed instruments were immersed in 1% and 5% NaOCl for 30 to 60 minutes.[84] Corrosion of NiTi instruments used in the clinical setting, therefore, might not significantly contribute to fracture except when the instruments are immersed in warmed NaOCl for longer than 60 minutes. In the majority of studies, sterilization procedures do not appear to negatively impact torsional strength[221,464] or fatigue resistance[79,220] of most NiTi instruments: austenitic[538] and martensitic[92] alloy behaved grossly similarly in this aspect.

There is an ongoing discussion over the impact of other aspects of clinical usage on the mechanical properties of NiTi rotaries. Most likely, clinical usage leads to some changes in the alloy, potentially through work hardening.[10,254]

Another strategy to improve surface characteristics is electropolishing; also surface coatings and ion implantation have been tried. Electropolishing is a process that removes surface irregularities such as flash and bur marks. It is thought to improve material properties, specifically fatigue and corrosion resistance; however, the evidence for both these claims is

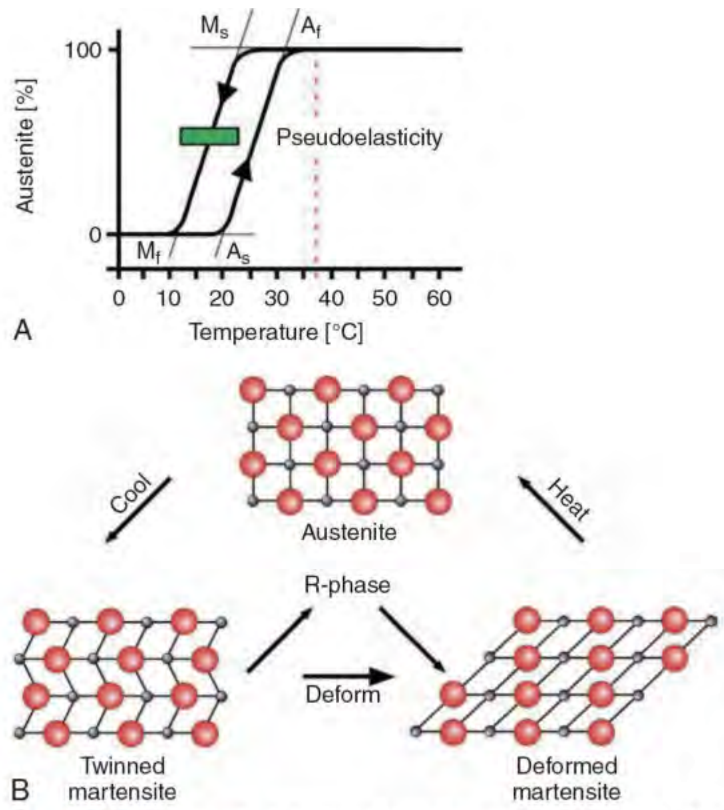


FIG. 6-19 Pseudoelastic behavior of Nickel titanium is based on the two main crystal configurations, martensite and austenite, which depend on temperature (**A**) and applied strain (**B**). Formation of the respective configuration initiates at the start temperatures, M_s and A_s.

mixed. One study found an extension of fatigue life for electropolished instruments,[20] whereas others found no improvement of fatigue resistance of electropolished instruments.[78,100,217] Boessler and colleagues suggested a change in cutting behavior with an increase of torsional load after electropolishing.[59]

Corrosion resistance of electropolished NiTi rotaries is also controversial. One study found superior corrosion resistance for electropolished RaCe instruments,[63] whereas another study demonstrated similar corrosion susceptibility for RaCe and nonelectropolished ProFile instruments.[385] Attempts have been made to improve surface quality by coating it with titanium nitride.[398,438] The latter process also seems to have a beneficial effect on cutting efficiency.[438]

Perhaps more relevant than surface treatment are modification of the base alloy that significantly alter material properties within the atomic ratio.[369] The first commercialized alloy was M-Wire (SportsWire, Langley, OK), which was shown to have higher fatigue resistance with similar torsional strength.[249] More recently, instrument are produced through production process that include annealing and cooling steps to create instruments that, after cold working during the production process, are more martensitic during dental treatment, as defined by their M_s temperature (see Fig. 6-19, A). Under clinical conditions these alloys are more flexible[510] and present higher fatigue resistance.[377] Examples are the newly introduced gold and blue alloys types (Dentsply Tulsa Dental Specialties, Tulsa, OK) or so-called controlled memory alloy used in Hyflex instruments (Coltene Endo, Cuyahoga Falls, OH).

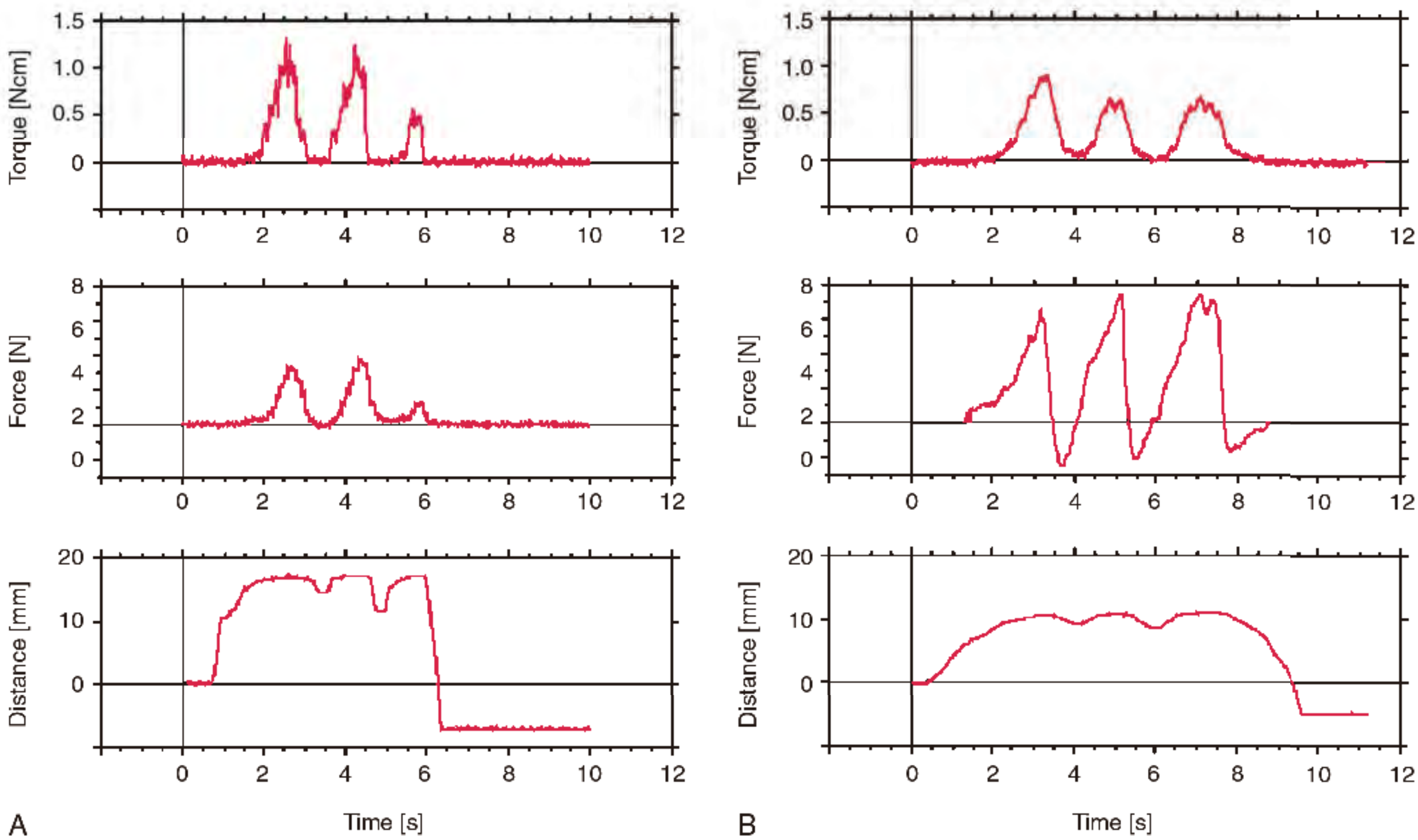


FIG. 6-20 Physical factors (torque, axial force, and insertion depth) that affect root canal instrumentation documented with a torque-testing platform. **A**, ProFile size #45, #.04 taper used in a mildly curved canal of a single-rooted tooth, step-back after apical preparation to size #40. **B**, FlexMaster size #35, #.06 taper used in a curved distobuccal canal of a maxillary first molar, crown-down during the initial phase of canal preparation.

Manually Operated Instruments

Endodontic trays contain many items familiar from general dentistry but certain hand instruments are designed specifically for endodontic procedures. This includes instruments employed for procedures inside the pulp space, for example hand and engine-driven instruments for root canal preparation, and energized instruments for root canal shaping. Special instruments and devices for root canal obturation are selected for filling prepared canal spaces.

K-Type Instruments

Manually operated instruments are generically called *files*. Defined by function, files are instruments that enlarge canals with apico-coronal insertion and withdrawal motions.

Historically, root canal instruments were manufactured from carbon steel. Subsequently, the use of stainless steel greatly improved the quality of instruments. More recently, K-type files manufactured from NiTi were introduced (NiTi-Flex, Dentsply Maillefer, Ballaigues, Switzerland).

Files were first mass produced by the Kerr Manufacturing Co. of Romulus, Michigan, in the early 1900s, hence the name "K-type" file (or K-file) and K-type reamer (K-reamer). K-files and K-reamers were manufactured by the same process—that is, by twisting square or triangular metal blanks along their long axis, producing partly horizontal cutting blades (see Fig. 6-17, *A*). Three or four equilateral, flat surfaces were ground at increasing depths on the sides of a piece of wire, producing a tapered pyramidal shape. The wire then was stabilized on one end, and the distal end was rotated to form the spiral instrument. The number of sides and the number of spirals determine whether the instrument is best suited for filing or reaming. Generally, a three-sided configuration with fewer spirals (e.g., 16 per 16-mm working portion) is used for reaming (i.e., cutting and enlarging canals with rotational motions). A file has more flutes per length unit (e.g., 20) than a reamer, whereas a three- sided or triangular configuration is generally more flexible than a four-sided one.[437]

K-type instruments are useful for penetrating and enlarging root canals. Generally, a reaming motion (i.e., constant file rotation) causes less transportation than a filing motion (translational or "in and out" motion).[171,482] (*Transportation* is defined here as the excessive loss of dentin from the outer wall of a curved canal in the apical segment, as described in more detail later.)

Stainless steel K-files may be precurved by overbending. This procedure subjects the file to substantial strain and should therefore be done carefully. Permanent deformation occurs when the flutes become wound more tightly or opened more widely (Fig. 6-21). When such deformation occurs, the instrument should no longer be used; file fracture is likely to occur during clockwise motion after plastic deformation.[456]

Interestingly, although the force required for failure is the same in both directions of rotation,[271,278] failure occurs in the counterclockwise direction at half the number of rotations required for failure in the clockwise direction. Therefore, K-type instruments should be operated more carefully when pressure is applied in a counterclockwise direction.

Cross-sectional analysis of a K-file reveals why this design allows careful application of clockwise and counterclockwise rotational and translational working strokes: the cross section is symmetrical with negative rake angles, allowing dentin to be adequately cut in both clockwise and counter-clockwise direction.

Reamers are instruments that are similar to K-files in overall design, but they have fewer cutting flutes per mm of the working surface. They are more appropriate for twisting motion and are less frequently used today.[437]

H-Type Instruments

H-type instruments, also known as Hedström files (see Fig. 6-17, *B*), are milled from round, stainless steel blanks. These files are very efficient for translational strokes,[437] because of a positive rake angle and a blade with a cutting rather than a scraping angle. Rotational working movements are strongly discouraged because of the possibility of fracture. Hedström

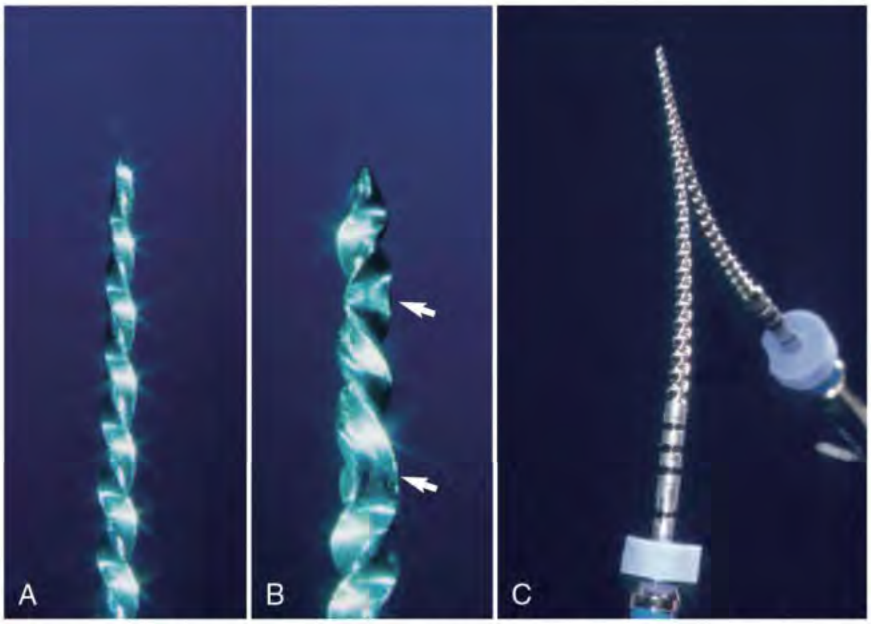


FIG. 6-21 Deformation of endodontic instruments manufactured from nickel-titanium alloy. **A** and **B**, Intact and plastically deformed ProFile instruments (*arrow* indicates areas of permanent deformation). **C**, ProFile instrument placed on a mirror to illustrate elastic behavior.

files up to size #25 can be efficiently used to relocate canal orifices and, with adequate filing strokes, to remove overhangs. Similarly, wide oval canals can be instrumented with Hedström files as well as with rotary instruments. On the other hand, overzealous filing can lead to considerable thinning of the radicular wall and strip perforations (Fig. 6-22). As with stainless steel K-files, Hedström files have been described as disposable instruments.[490]

Bending Hedström files results in points of greater stress concentration than in K-type instruments. These prestressed areas may lead to the propagation of cracks and ultimately fatigue failure.[200] Note that clinically, fatigue fractures may occur without visible signs of deformation.

Hedström files are produced by grinding a single continuous flute into a tapered blank. Computer-assisted machining technology has allowed the development of H-type instruments with complex forms. This process, called *multiaxis grinding*, allows adjustment of the rake angle, helix angle, multiple flutes, and tapers and is also used to fabricate the majority of NiTi instruments. Because the H-file generally has sharper edges than the K-file, it has a tendency to thread into the canal during rotation, particularly if the instrument's blades are nearly parallel. Awareness of threading-in forces is important to avoid instrument failure.

Effectiveness and Wear of Instruments

The ability of an endodontic hand instrument to cut and machine dentin is essential; however, no standards exist for either the cutting or the machining effectiveness of endodontic files, nor have clear requirements been established for resistance to wear. In any study of the effectiveness of an instrument, two factors must be investigated: (1) effectiveness in cutting or breaking loose dentin and (2) effectiveness in machining dentin.

Attempts have been made to evaluate the effectiveness of an instrument when used with a linear movement.[437,442] Collectively, these studies showed that instruments might differ significantly, not only when comparing brands and types but also within one brand and type. For K-files, effectiveness varies 2 to 12 times between files of the same brand. This variation for Hedström files is greater, ranging from 2.5 to more than 50 times.[498] The greater variation among Hedström files is easy to understand because the H-file is the result of more individual grinding during manufacture than the conventional K-file, which is difficult to alter much during the manufacturing process. For example, during the grinding of a Hedström file, the rake angle can be modified to neutral or even slightly positive; this is impossible to achieve with a K-file.

During canal preparation, a file's rake edge shaves off dentin that accumulates in the grooves between the rake edges. The deeper and larger this space, the longer the stroke can be before the instrument is riding on its own debris, making it ineffective.

These design variations and the rake angle of the edges determine the effectiveness of a Hedström file. Of the hybrid files, the K-Flex (SybronEndo, Orange, CA) file has properties similar to those of K-files. The Flex-R file (Integra Miltex, York, PA), which is a ground instrument with a triangular cross section similar to a K-file, more closely resembles a Hedström file in its variations in cutting behavior. It also is more effective at substrate removal than the K-files but cannot measure up to the H-files' ability to machine radicular dentin.[498]

FIG. 6-22 Result of an overenthusiastic attempt at root canal treatment of a maxillary second molar with large stainless steel files. Multiple strip perforations occurred; consequently, the tooth had to be extracted.

Barbed Broaches

Barbed broaches (Fig. 6-23) are produced in a variety of sizes and color codes. They are manufactured by cutting sharp, coronally angulated barbs into metal wire blanks. Broaches are intended to remove vital pulp from root canals, and in cases of mild inflammation, they work well for severing pulp at the constriction level *in toto*. The use of broaches has declined since the advent of NiTi rotary instruments, but broaching occasionally may be useful for expediting emergency procedures (see Chapter 18) and removing materials (e.g., cotton pellets or absorbent points) from root canals.

Low-Speed Engine-Driven Instruments

Burs

Specialized burs are available for endodontic access cavities. These burs are used in both high-speed and slow-speed handpieces and are manufactured from stainless steel. Access cavity preparation and used materials are described in detail in Chapter 5).

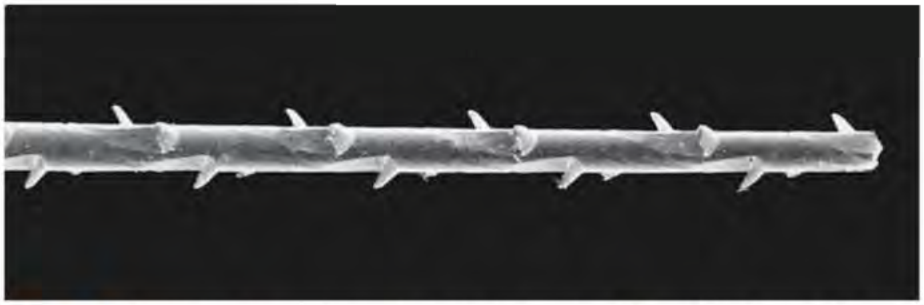


FIG. 6-23 Scanning electron micrograph of a barbed broach. (Moyco Union Broach, York, PA.)

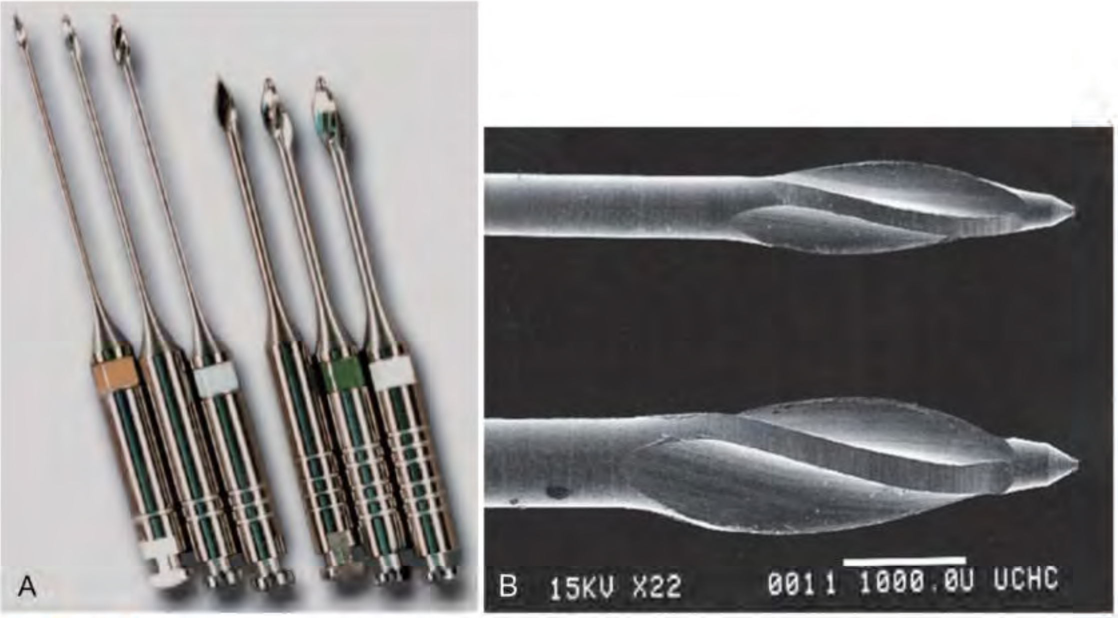


FIG. 6-24 **A,** Various Gates-Glidden (GG) burs made of stainless steel and scanning electron micrograph (**B**, working tip). (*A*, From Johnson WT: *Color atlas of endodontics,* St Louis, 2002, Saunders.)

Gates-Glidden Drills

Gates-Glidden (GG) drills (Fig. 6-24) have been used for more than 100 years without noteworthy design changes. Gates Glidden drills are typically used to enlarge coronal canal areas.[119] When misused, GG drills can dramatically reduce radicular wall thickness.[173,242]

GG drills are sized from 1 to 6 (with corresponding diameters of 0.5 to 1.5 mm); the number of rings or color-coding on the shank identifies the specific drill size. GG instruments are available in various lengths and by several manufacturers. Each instrument has a long, thin shaft with parallel walls and a short, oval cutting head with safety tips (Fig. 6-24, *B*); these drills are produced in stainless steel and NiTi varieties. Because of their design and physical properties,[68] GG drills are side-cutting instruments; they can be used to cut dentin as they are withdrawn from the canal (i.e., on the outstroke).[417] Used this way, their cutting action can deliberately be directed away from external root concavities in single-rooted and furcated teeth. GG drills should be used only in the straight portions of a canal.[522]

Two procedural sequences have been proposed: with the step-down technique, the clinician starts with a large drill and progresses to smaller ones; conversely, with the step-back technique, the clinician starts with a small drill and progresses to larger ones. With the step-down approach, the clinician must select a GG instrument with a diameter that allows introduction into the respective orifice and progression for about 1 mm. The subsequent smaller instruments progress deeper into the canal until the coronal third has been preenlarged. This technique efficiently opens root canal orifices and works best when canals exit the access cavity without severe angulations. Opened orifices simplify subsequent cleaning and shaping procedures and help establish a smooth glide path from the access cavity into the root canal system.

With the step-back approach, a small GG instrument is introduced into the canal, and dentin is removed on the outstroke. This process is repeated with the next larger GG instrument, which is again worked shorter than the preceding smaller one. In this way, the coronal third of the root canal is enlarged and dentin overhangs are removed.

When used adequately, GG instruments are inexpensive, safe, and clinically beneficial tools. Gates-Glidden drills may be used safely and to their fullest potential at 750 to 1500 rpm. High revolutions per minute (rpm), excessive pressure, an incorrect angle of insertion, and the use of GG instruments to aggressively drill into canals have resulted in mishaps such as strip perforation. The preferred mode of action for GG drills is against the outer canal wall, away from the canal curvature. Also, cyclic fatigue may cause GG instruments to fracture when used in curved canal areas, and the short cutting heads may fracture with high torsional loads. As with nickel-titanium rotary instruments, GG drills work best when used in electric gear reduction handpieces rather than with air motors.

Peeso Drills (Reamers)

Peeso drills are typically used in root canal preparation either for coronal flaring or during post preparation. These drill are at this point manufactured mostly from stainless steel by milling similar to the Gates Gliddens. Peeso drills are also used in the electric slow-speed handpiece; the rotational speed is the range of 800 to 1200 rpm; the cutting flutes are more parallel and longer compared to GG drills but shorter than the 16 mm prescribed for ISO-normed hand files. Peeso drills are classified as type P and type B-I, as defined by ISO norm 3630-2.[299] The sizing for these drills is also numbers 1 to 6, similar to GGs. Peeso drills are available with cutting and noncutting tips and should be used with caution to avoid excessive preparation and thinning of radicular dentin walls.[4]

Engine-Driven Instruments for Canal Preparation

Instrument Types

Engine-driven instruments for root canal preparation made of stainless steel have been in use for more than half a century—for the first decades, mainly in handpieces that permitted reciprocation (alternating clockwise-counterclockwise motion). The major two problems with this type of instrument were canal transportation (discussed later) and file fracture. This

TABLE 6-1

Grouping of Instruments According to Their Mode of Cutting and Details

Group	Enlargement Potential	Preparation Errors	Fracture Resistance	Clinical Performance
I ProFile[1], ProSystem GT, GTX[1], Quantec[2], Pow-R[3], Guidance[4], K3[2] LightSpeed var.[2]	+, Depending in sizes, often time consuming	++ Low incidence, usually <150 μm canal transportation	+/– Fatigue + Torsional load, depending on system	++ Good, depending on treatment conditions; no difference between instruments shown so far, except for inexperienced clinicians, who perform better with landed instruments
II ProTaper var.[1], RaCe[5], Hero 642[6], FlexMaster[7], Mtwo[7], Sequence[8], Alpha[9]… ProFile Vortex[1] Twisted File[1]	+/–, Good with use of hybrid techniques	+/–, Overall more demanding in clinicians' ability	+ Fatigue +/– Torsional load, depending on taper, handling	
III, EndoEZE AET[12], Liberator[11]… WaveOne[1], Reciproc[7] OneShape[6] SAF	Limited	Varies, Liberator— EndoEZE AET— WaveOne, Reciproc+	Varies + with WaveOne, Reciproc	Varies

Manufacturers:
Grouping of instruments according to their mode of cutting and details about manufacturers. Group I consists of radial-landed instruments with reaming action. Group II instruments have a triangular cross section and cutting action. Group III is made up of instruments with unusual geometry, movement, or sequence.

changed with the advent of NiTi rotaries from about the early 1990s; the much more flexible alloy allowed continuous rotation and reduced both canal preparation errors and instrument fracture compared to earlier engine driven techniques.

Currently, more than 50 types of rotary instrument systems have been described and more continue to be developed. The instruments vary greatly in terms of design, alloy used, and recommended cutting movement (Table 6-1). Various built-in features may help prevent procedural errors, increase efficiency, and improve the quality of canal shaping.

For example, a longer pilot tip may guide the instrument and help to stay centered in the canal long axis. Alternatively, a file can be given an asymmetric cross section to help maintain the central axis of the canal.

Another direction of instrument development is the prevention of instrument fractures (Fig. 6-25). There are several ways to modify an instrument to make it less likely to fracture; for example, increasing the core diameter will increase torsional resistance. Another approach is to use a torque-limiting motor (discussed later). Alternatively, a zero taper or nearly parallel and fluted working portion of the file can be provided for curved canals so that the apical portion of the canal can be enlarged without undue file stress and compression of debris. More recently a reciprocation motion was reapplied to NiTi rotary instruments to prevent threading-in and instrument fractures in general.

Yet another, more recent, direction of instrument development is to improve shaping as it relates to circumferential root canal wall contact. One example for this strategy is a file manufactured from an expandable and flexible hollow NiTi tube, the so-called Self-adjusting File (ReDent-Nova, Ra'anana, Israel, Israel) (Fig. 6-26). More recently, a substantial S-shape was superimposed onto a flexible NiTi rotary that provides a larger envelope of motion while maintaining a limited maximum flute diameter (TRUShape, Dentsply Tulsa Dental Specialties).

Marketed files vary greatly in terms of their specific design characteristics, such as tip sizing, taper, cross section, helix angle, and pitch (see Fig. 6-13). Some of the early systems have been removed from the market or relegated to minor roles; others, such as ProFile (Dentsply Tulsa Dental Specialties), are still successfully used. More recently added instruments vary in cross-sectional and longitudinal design (Fig. 6-27). However, the extent to which clinical outcome changes (if any) will depend on design characteristics is difficult to forecast.[375,381]

Most instruments described in the following section are manufactured by a grinding process, although some are produced by laser etching and yet others by plastic deformation under specific heating and cooling processes. Surface quality has been considered an important detail because cracks that arise from superficial defects may play a role in instrument fracture.[11] Moreover, surface defects such as metal flash and rollover are common in unused NiTi instruments.[135,314]

Many variables and physical properties influence the clinical performance of NiTi rotaries.[272,374,454,512] Clinical practice has generated much of what is known about NiTi instruments, including reasons for instrument fracture[33] and instrument sequences. These instruments have substantially reduced the incidence of relevant canal shaping errors,[387] but they are also thought to fracture somewhat more easily than hand instruments.

Table 6-1 and the following sections describe the instrument groups most widely used for root canal preparation at this point in time. Most basic strategies apply to all NiTi rotary instruments, regardless of the specific design or brand. However, three design groups need to be analyzed separately: group I, instruments designed for passive preparation; group II, rotary instruments designed for active cutting; and group III, unique designs that do not fit in either group I or group II.

Group I: Passive Preparation; Presence of Radial Lands

The first commercially successful rotary instruments were ProFile (Dentsply Tulsa Dental Specialties), LightSpeed (marketed in its current form by SybronEndo), and GT rotaries (Dentsply Tulsa Dental Specialties) and have in common a cross section with so-called radial lands. These are created by three round excavations, also known as the U-shape. The

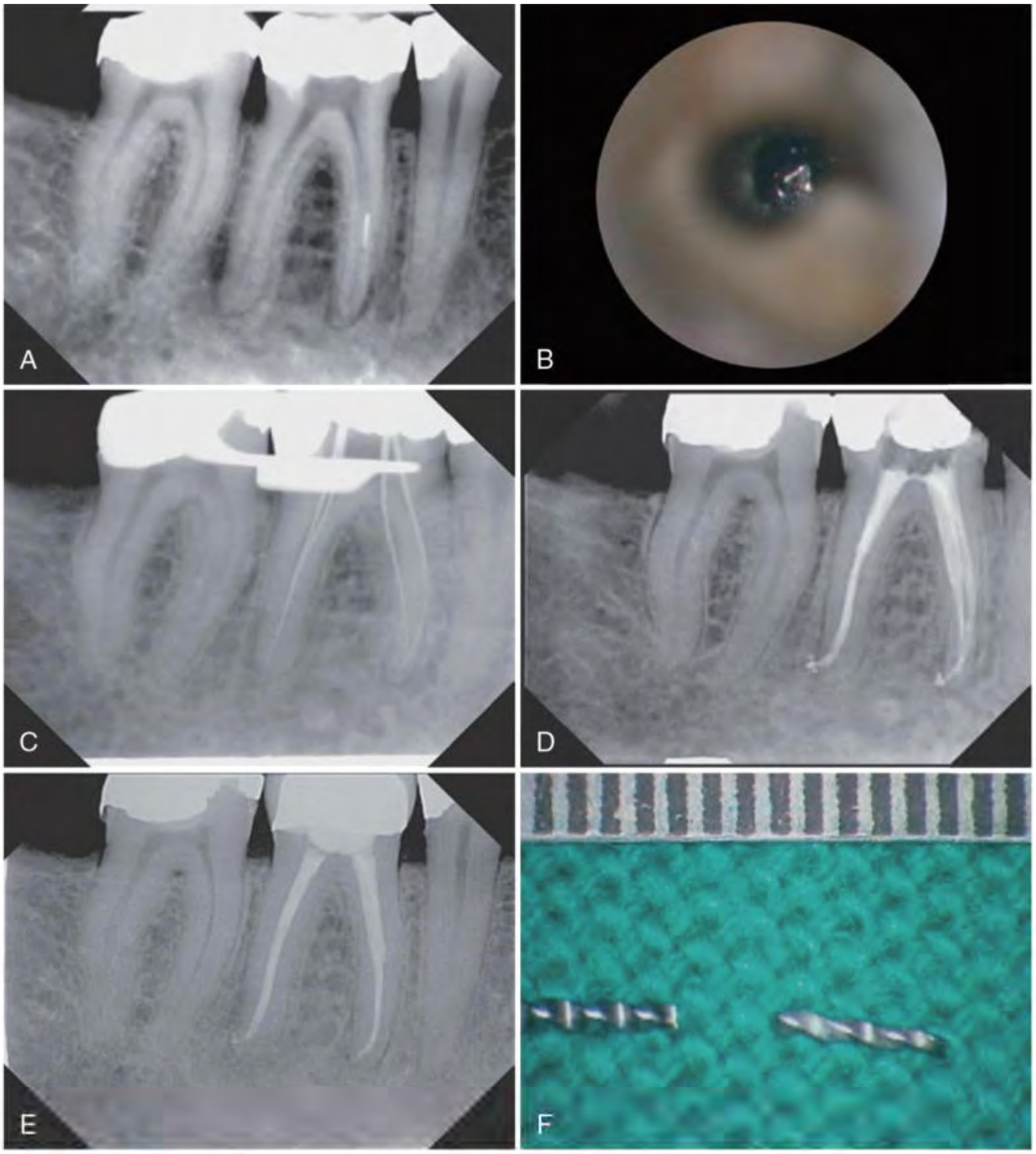


FIG. 6-25 Removal of a fractured NiTi instrument from a mesiolingual canal of a mandibular molar. **A**, Fragment located in the middle third of the root. **B**, Clinical aspect of the fragment after enlargement of the coronal third of the root canal with modified Gates-Glidden drills, visualized with an operating microscope (×25). **C**, Radiograph taken after removal of the fragment; four hand files have been inserted into the canals. **D**, Final radiograph shows slight widening of the coronal third of the mesiolingual canal and fully sealed canal systems. A full crown was placed immediately after obturation. **E**, Recall radiograph 5 years after obturation shows sound periradicular tissues. **F**, Removed fragment and separated file (gradation of ruler is 0.5 mm).

design of the instrument tip and also the lateral file surface (radial land) guide the file as it progresses apically. This makes rotaries listed in group I fairly safe regarding preparation errors. On the other hand, it results in a reaming action rather than cutting of dentin and this makes them inefficient. Moreover, the smear layer produced with radial-landed rotaries is different in consistency and amount compared to the debris and smear created by cutting files.[366,373]

LightSpeed

The LightSpeed file, developed by Drs. Steve Senia and William Wildey in the early 1990s and now also known as LS1, was introduced as an instrument different from all others because of its long, thin, noncutting shaft and short anterior cutting head. The same design principles apply to the currently available LSX instrument (SybronEndo) that is manufactured not by milling but by a stamping process. A full set consists of 25 LightSpeed LS1 instruments in sizes #20 to #100, including half sizes (e.g., 22.5, 27.5); LSX does not have half sizes, and a set includes sizes #20 to #80.

The original LightSpeed is a widely researched NiTi rotary instrument,[50,392,394,459,513,514] and most reports have found that the system has a low incidence of overall and specific preparation errors. One report found similar shaping abilities for LSX and LightSpeed LS1 assessed with a double-exposure technique.[240]

FIG. 6-26 The SAF instrument. The instrument is made as a hollow, thin NiTi lattice cylinder that is compressed when inserted into the root canal and adapts to the canal's cross section. It is attached to a vibrating handpiece. Continuous irrigation is applied through a special hub on the side of its shank. Inset shows the abrasive surface of the instrument. (Courtesy ReDent-Nova, Ra'anana, Israel.)

ProFile

The ProFile system (Dentsply Tulsa Dental Specialties) was introduced by Dr. Ben Johnson in 1994. ProFile instruments have increased tapers compared with conventional hand instruments. The ProFile system was first sold as the "Series 29" hand instruments in .02 taper, but it soon became available in .04 and .06 tapers. The tips of the ProFile Series 29 rotary instruments had a constant proportion of diameter increments (29%). Later, a ProFile series with ISO-sized tips (Dentsply Maillefer) was developed and marketed in Europe.

Cross sections of a ProFile instrument show a U-shape design with radial lands (Fig. 6-28) and a parallel central core. Lateral views show a 20-degree helix angle, a constant pitch, and bullet-shaped noncutting tips (see Fig. 6-12). Together with a slightly negative rake angle, this configuration facilitates a reaming action on dentin rather than cutting. Also, debris is transported coronally and is effectively removed from the root canals.

ProFile instruments shaped canals without major preparation errors in a number of in vitro investigations.[74,75,515,516] A slight improvement in canal shape was noted when .04 and .06 tapered instruments were used in an alternating fashion.[73] Loss

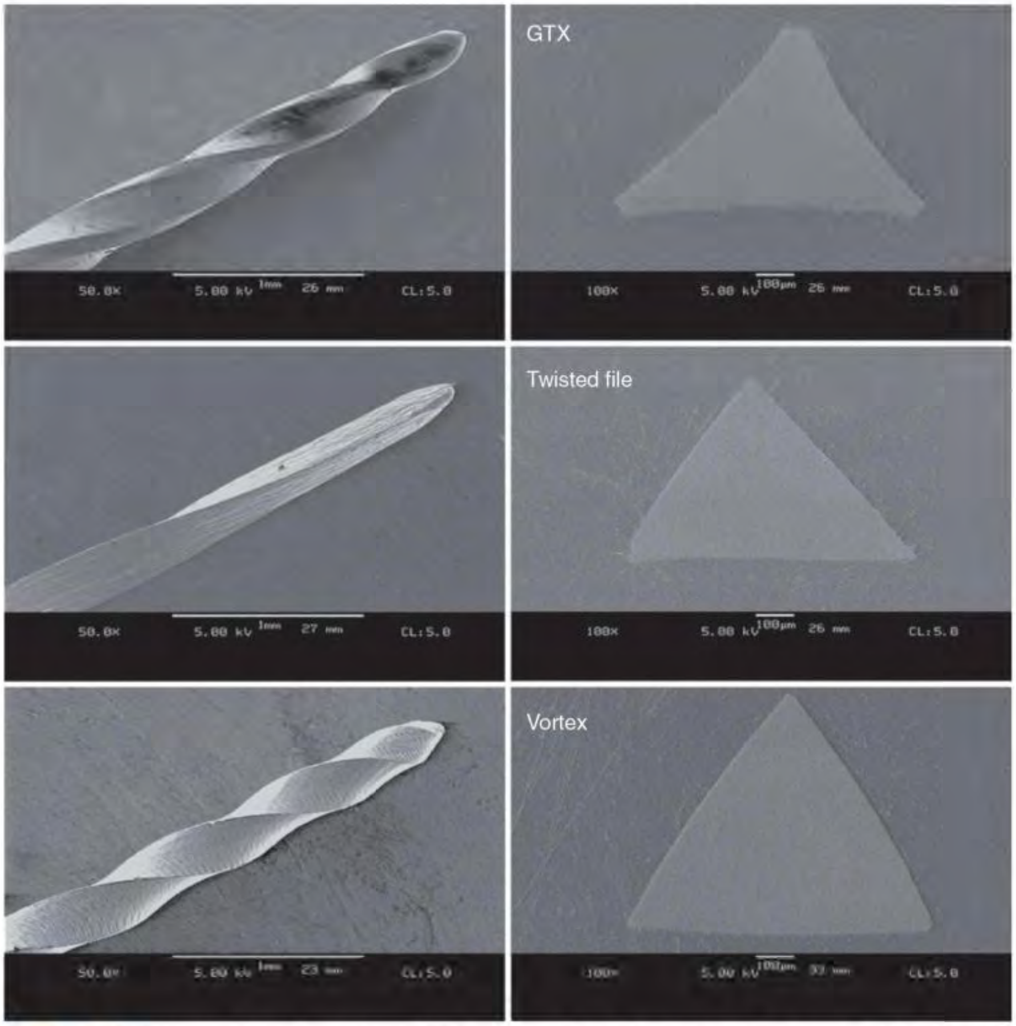
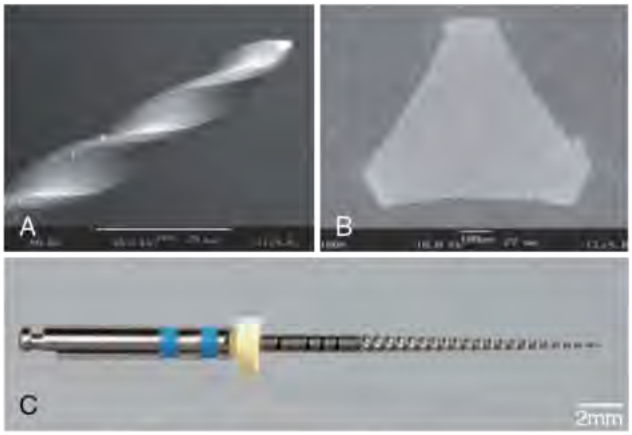


FIG. 6-27 Scanning electron micrographs (SEM) of current nickel titanium rotary instruments, seen laterally (left panel, ×50) and in cross sections (right panel, ×100). Note the radial landed cross section of the GTX instrument



D

No. of instruments/set	Tip sizes	Size increments	r.p.m. (recommended)	Lengths
Orifice Shapers: 6	20-80	10; from 60: 20	150 to 350, low apical force, torque to fracture and working torque dependent on instrument size	19 mm
ProFile .06: 6	15-40	5		21 mm, 25 mm, some 31 mm
ProFile .04: 9	15-90	5; from #45: 15; from #60: 30		
ProFile .02: 6	15-45	5		
Profile Series 29	13-100	Varies, 29%		21 mm, 25 mm

FIG. 6-28 Design features of a ProFile instrument. **A**, Lateral view (scanning electron micrograph [SEM], ×50). **B**, Cross section (SEM, ×200). **C**, Lateral view. **D**, Design specifications.

of working length did not exceed 0.5 mm[73-75,515,516] and was not affected by the use of .06 tapered instruments.[73] Comparative assessments in vitro suggested that ProFile prepared mesial canals in mandibular molars with less transportation than K3 and RaCe.[9]

A more recent addition to the ProFile family of instruments was Vortex (Dentsply Tulsa Dental Specialties). The major change lies in the nonlanded cross section, whereas tip sizes and tapers are similar to existing ProFiles, hence these files are placed in group 2 (discussed later).

GT and GTX Files

The Greater Taper, or GT file, was introduced by Dr. Steve Buchanan in 1994. This instrument incorporates a radial landed cross-sectional design and was marketed as ProFile GT (Dentsply Tulsa Dental Specialties). The system was first produced as a set of four hand-operated files and later as engine-driven files. The instruments came in four tapers (.06, .08, .10, and .12), and the maximum diameter of the working part was 1 mm. The design limited the maximum shank diameter and decreased the length of the cutting flutes with increasing taper. The instruments had a variable pitch and a growing number of flutes in progression to the tip; the apical instrument diameter was 0.2 mm. Instrument tips were noncutting and rounded; these design principles are mostly still present in the current incarnation, the GTX instrument. The main differences are the M-Wire alloy type used and minor design and handling changes.

Studies on GT files found that the prepared shape stayed centered and was achieved with few procedural errors.[173,208] A shaping assessment using micro-computed tomography [μCT; see Fig. 6-4 as an example)] showed that GT files machined statistically similar canal wall areas compared with ProFile and LightSpeed preparations.[386] These walls were homogeneously planed and smooth.[366,573] The more recently introduced GTX variant is manufactured from M-Wire and does not appear to have significantly improved physical properties[254] or shaping capacity.[241] GT instruments were available for small (tip size #20), medium (tip size #30), and large canal diameters (tip size #40).

K3

In a sequence of design developments by their inventor, Dr. McSpadden, the Quantec 2000 files were followed by the Quantec SC, the Quantec LX, and the current K3 system (all by SybronEndo). The overall design of the K3 is similar to that of the ProFile in that it includes instruments with .02, .04, and .06 tapers. The most obvious difference between the Quantec and K3 models is the K3's unique cross-sectional design: a slightly positive rake angle for greater cutting efficiency, wide radial lands, and a peripheral blade relief for reduced friction. Unlike the Quantec, a two-flute file, the K3 features a third radial land to help prevent threading-in.

In the lateral aspect, the K3 has a variable pitch and variable core diameter, which provide apical strength. This intricate design is relatively difficult to manufacture, resulting in some metal flash.

Like most other current instruments, the K3 features a round safety tip, but the file is about 4 mm shorter than other files (although it has the same length of cutting flutes) because of the so-called Axxess handle. The instruments are coded by ring color and number.

Tested in vitro, K3's shaping ability seems to be similar to that of the ProTaper[51] and superior to that achieved with hand instruments.[440] More recently, when curved canals in lower molars were shaped to a size #30 .06,[14] K3 files had less canal transportation in a modified Bramante model than RaCe but more than ProFile.

Summary

Radial landed rotary instruments are considered very safe, even when accidentally taken beyond the confines of the root canal. Fracture resistance to torsional loading and cyclic varies depending on specific instrument design. The limited cutting efficacy of these files was perceived as a downside and is a reason that the market share has diminished.[55] However, their excellent track record in clinical applications and research continues to support the use of rotaries listed in group I.

Group II: Active Cutting; Triangular Cross Section

Rotaries in group II all have a more active cutting flute design in common. Radial lands are absent (see Fig. 6-13), and this fact results in a higher cutting efficacy. This translates to a higher potential for preparation errors, in particular when the instrument is taken through the apical foramen, thus eliminating the guide derived from the noncutting tip.

ProTaper Universal

The ProTaper system originally comprised six instruments: three shaping files and three finishing files. This set is now complemented by two larger finishing files and a separate set of three rotaries tailored to retreatment procedures. The instruments were designed by Drs. Cliff Ruddle, John West, and Pierre Machtou. In cross sections, ProTaper shows a convex triangle with sharp cutting edges and no radial lands. The cross section of finishing files F3, F4, and F5 is slightly relieved for increased flexibility. The three shaping files have tapers that increase coronally, and the reverse pattern is seen in the five finishing files.

Shaping files nos. 1 and 2 have tip diameters of 0.185 mm and 0.2 mm, respectively, 14-mm-long cutting blades, and partially active tips. The finishing files (F1-F5) have tip diameters of 0.2, 0.25, 0.3, 0.4, and 0.5 mm, respectively, between D0 and D3, and the apical tapers are .07, .08, .09, .05, and .04, respectively. The finishing files have rounded noncutting tips.

Two aspects of handling have been emphasized for ProTaper. The first is the preparation of a glide path, either manually[368] or with special rotary instruments.[53] An enlargement to a size approaching the subsequent rotaries' tips, at least larger than the file's core diameter, prevents breakage and allows assessment of the canal size.[368] This means that the glide path should correspond to a size #15 or #20. The second specific recommendation is the use of a more laterally directed "brushing" working stroke. Such a stroke allows the clinician to coronally direct larger files away from danger zones and counteract any "threading-in" effect.[58] Both usage elements should be considered good practice for other instruments, particularly for more actively cutting ones.[391]

In a study using plastic blocks, ProTaper created acceptable shapes more quickly than GT rotary, ProFile, and Quantec instruments,[573] but it also created somewhat more aberrations. This was recently corroborated comparing preparations of mesial root canals in mandibular molars ex vivo with ProTaper Universal to Alpha (Gebr. Brasseler GmbH & Co. KG-Komet, Lemgo, Germany).[536] In a comparison of ProTaper and K3 instruments (SybronEndo), Bergmans and colleagues found few differences, with the exception of some transportation by the ProTaper into the furcation region.[51] A study using µCT showed that the ProTaper created consistent shapes in constricted canals, without obvious preparation errors, although wide canals may be insufficiently prepared with this system.[384] It has been recommended that ProTaper be combined with less tapered, more flexible rotaries to reduce apical transportation.[244]

A newer version of this system, called ProTaper Next was introduced in 2013. Current research suggests that mechanical properties of these instruments, manufactured from M-Wire, are better than ProTaper Universal.[23,138,370]

No data are currently available on shaping outcomes or clinical results.

HERO 642, HERO Shaper

Several systems in group II (see Table 6-1) were designed with positive rake angles, which provide greater cutting efficiency. HERO instruments (MicroMega, Besançon, France) are an example. The original version was known as *HERO 642* (the acronym *HERO* stands for *h*igh *e*lasticity in *ro*tation), and the name has now changed into HERO Shaper, with little apparent differences in the instrument design.

Cross sections of HERO instruments show geometries similar to those of an H-file without radial lands. Tapers of .02, .04, and .06 are available in sizes ranging from #20 to #45. The instruments are relatively flexible but maintain an even distribution of force into the cutting areas.[528,529] HERO instruments have a progressive flute pitch and a noncutting passive tip, similar to other NiTi rotary systems. The instruments are coded by handle color.

Research with HERO files indicates a shaping potential similar to that of the FlexMaster[230] (VDW, Munich, Germany) and ProFile,[164] although in one study HERO files induced more changes in cross-sectional anatomy.[179] HERO instruments also caused some aberrations when used in simulated canals with acute curves,[517] but they were safer than Quantec SC instruments (SybronEndo).[236] More recently, HERO Shapers had a better centering ability compared to RaCe instruments in resin blocks.[28] Using a modified Bramante technique in vitro, earlier HERO 642 and current HERO Shaper rotaries showed no differences in canal cross sections before and after shaping.[28]

FlexMaster

The FlexMaster file system is currently unavailable in the United States but popular in Europe. It features .02, .04, and .06 tapers. The cross sections have a triangular shape, with sharp cutting edges and no radial lands. This makes for a relatively solid instrument core and active cutting ability. The overall manufacturing quality seems high, with minimal metal flash and rollover.

FlexMaster files have rounded, passive tips; the tip diameters range from 0.15 to 0.7 mm for .02 instruments and 0.15

to 0.4 mm for.04 and .06-tapered files. In addition to the standard set, the Intro file is available, which has a .11 taper and a 9-mm cutting part. The instruments are marked with milled rings on the instrument shaft, and the manufacturer provides a system box that indicates sequences for narrow, medium-size, and wide canals.

Several studies indicate that the FlexMaster allows centered preparations in both constricted and wider canals[227] and that it performed on par with other systems.[230,550] Clinical studies confirmed that the FlexMaster showed superior shaping characteristics compared with K-files.[441] Also, novice dental students were able to shape plastic blocks successfully with the FlexMaster after a short training period.[484,485] Tested in a well-described model of simulated canals, FlexMaster instruments led to few aberrations but took longer than preparations with RaCe files.[325] Moreover, FlexMaster appeared to be less effective than RaCe in removing dye from the walls of simulated canals prepared to size #30 but were more effective than ProFile.[446]

RaCe, BioRaCe, BT Race

The RaCe file has been manufactured since 1999 by FKG and was later distributed in the United States by Brasseler (Savannah, GA). The name, which stands for *r*eamer with *a*lternating *c*utting *e*dges, describes just one design feature of this instrument. Light microscopic imaging of the file shows flutes and reverse flutes alternating with straight areas; this design is aimed at reducing the tendency of files to thread into a root canal. Cross sections are triangular or square for .02 instruments with size #15 and #20 tips. The lengths of cutting parts vary from 9 to 16 mm.

The surface quality of RaCe instruments has been modified by electropolishing, and the two largest files (size #35, .08 taper and size #40, .10 taper) are also available in stainless steel. The tips are round and noncutting, and the instruments handles are color-coded and marked by and milled rings. RaCe instruments have been marketed in various packages to address small and large canals; recently they are sold as BioRaCe, purportedly to allow larger preparation sizes, with an emphasis on the use of .02 tapered instruments.

Few results of in vitro experiments comparing RaCe to other contemporary rotary systems are available,[443,444] Canals in plastic blocks and in extracted teeth were prepared by the RaCe system with less transportation than with ProTaper files.[443] In another study, ProTaper and RaCe performed similarly when canals were prepared to an apical size #30.[360] When preparing to a size #40, RaCe files prepared canals rapidly and with few aberrations or instrument deformities.[397] The newer BioRaCe instrument sequence utilizes .02 tapered instruments to promote larger apical sizes. As with any rotary system, this is also possible in a hybrid hand-rotary technique. BioRace instruments prepared S-shaped canals in plastic blocks (to size #40) similarly to ProTaper and MTwo but were superior when combined with S-Apex.[62] In a clinical study, Rocas and colleagues found no significant differences between NiTi hand file preparation and BioRace regarding the reduction of bacterial load.[413] A new variant, BT RaCe, has been introduced and incorporates different tip designs, as well as different sequences.

EndoSequence

The EndoSequence rotary instrument is produced by FKG in Switzerland and marketed in the United States by Brasseler. This instrument adheres to the conventional length of the cutting flutes, 16 mm, and to larger tapers, .04 and .06, to be used in a crown-down approach. The overall design, including the available tapers and cross sections, is thus similar to many other files; however, the manufacturer claims that a unique longitudinal design (called alternating wall contact points [ACP]) reduces torque requirements and keeps the file centered in the canal. It also has varying, comparatively small helical angles. Another feature of the EndoSequence design is an electrochemical treatment after manufacturing, similar to that of RaCe files, resulting in a smooth, polished surface. This is thought to promote better fatigue resistance, hence a rotational speed of 600 rpm is recommended for EndoSequence.[264] Most in vitro results, however, suggest that EndoSequence is not superior to other files in cyclic fatigue resistance.[217,277,401]

Twisted File

In 2008, SybronEndo presented the first fluted NiTi file manufactured by plastic deformation, a process similar to the twisting process that is used to produce stainless steel K-files: the Twisted File (TF). According to the manufacturer, a thermal process allows twisting during a phase transformation into the so-called R-phase of nickel-titanium. The instrument is currently available with a size tip from #25 to #50 and in tapers from .04 to .12.

The unique production process is thought to result in superior physical properties; indeed, early studies suggested significantly better fatigue resistance when size #25 .06 taper Twisted Files were compared to K3 instruments of the same size GTX instrument.[163] Moreover, as determined by bending tests according to the ISO norm for hand instruments, 3630-1, Twisted Files size #25 .06 taper were more flexible than ProFiles of the same size.[162] Others found similar levels for fatigue resistance for TF and Profile of similar size.[277]

A more recent development for TF is the use of an electric motor that allows different file movement, both continuous rotation and reciprocation, depending on the clinical situation (TF Adaptive, SybronEndo).

ProFile Vortex

Profile Vortex files are manufactured from NiTi. Two versions are on the market, one made from M-Wire and another from so-called blue wire (Vortex Blue, which showed greater resistance to cyclic fatigue and increased torque resistance), and they have varying helical angles to counteract the tendency of nonlanded files to thread into the root canal. Vortex instruments are recommended to be used at 500 rpm; higher rotational speed results in less torque generated.[37] Canal preparation with ProFile Vortex in vitro was similar to other rotary instruments.[83,563] Vortex instruments are available in sizes #15 to #50 and in .04 and .06 tapers.

MTwo

This instrument, originally sold in Italy by Sweden e Martina, was put onto the European market in 2004. The instrument has a two-fluted S-shaped cross section. The original strategy allowed for three distinct shaping approaches after the use of a basic sequence with tip sizes from #10 to #25 and tapers ranging from .04 to .06. Subsequent enlargement was meant to create apical sizes up to #40 .04 or, alternatively, to #25 .07 or to larger apical sizes with so-called apical files. MTwo is a well-researched and cutting-efficient instrument; clinically it is an example for the so-called single length technique. Canal shapes with MTwo were similar to other contemporary root canal instruments, either in rotation or reciprocation.[80]

Summary

The market share for rotary files without radial lands continues to expand because of perceived higher efficacy. The overall incidence of clinically relevant preparation errors (details are discussed later) appears to be low, in spite of more aggressive cutting by files without radial lands. Instrument fractures remain a concern, as does the tendency of continuously rotating instruments to thread or pull into the canal, specifically as working length is approached.

Group III, Special Cases

WaveOne, Reciproc

A way to mitigate problems with continuous rotation (e.g., taper lock, fatigue fracture, threading-in) is to return to reciprocation, which had been used decades ago (e.g., in the Giromatic handpiece).[233] A case report[566] described this approach using ProTaper F2 in reciprocation. Based on experiments evaluating the maximal rotational angle before plastic deformation for the selected instrument, a forward angle of 144 degrees followed by a reverse rotation of 72 degrees was recommended.[566] This cycle continues at 400 rpm until working length is reached.

Subsequently two instruments specifically designed for reciprocation were brought to the market: WaveOne (Tulsa Dentsply Dental Specialties) and Reciproc (VDW, currently not available in the United States). WaveOne instruments are available in three tip sizes, #21, #25, and #40, with tapers of .06 and .08, respectively. Corresponding sizes for Reciproc are tips of #25, #40, and #50 with tapers of .08, .06, and .05, respectively. Both instruments feature variable tapers that are largest toward the tips. The main WaveOne cross section is triangular, similar to ProTaper, whereas Reciproc is a two-fluted file with a design similar to MTwo.

Special motors are used for both systems to provide reciprocation action with alternating counterclockwise and clockwise rotations of about 150 to 170 and 30 to 50 degrees, respectively.[151]

Both files are machined with left-leaning flutes; therefore, the cutting direction for both is clockwise. One problem that may occur with this design is the transportation of dentin debris into the apical area, rather than moving debris coronally. There is mixed evidence for this phenomenon[81,124] in vitro. Clinically, frequent careful cleaning of the cutting blades with a moist gauze is recommended.

The shaping ability of these systems, according to current in vitro data, seems similar to that of established systems with continuous rotation.[80,324,537]

Self-Adjusting File

The self-adjusting file (SAF; ReDent-Nova) represents a different approach, both in file design and mode of operation.[327] The file is really a cylindrical, hollow device, designed as a thin-walled NiTi lattice with a lightly abrasive surface (see Fig. 6-26). An initial glide path is established up to a #20 K-file to allow the insertion of the SAF file. The file is proposed to be compressed from its 1.5 mm diameter into dimensions equivalent to those of a #25 K-file. It is operated with a handpiece that generates in-and-out vibrations (4000 per minute) and 0.4 mm amplitudes. As noted, the file is hollow, which allows for continuous irrigation through the file while operated in the root canal.

In vitro data for this system suggest that indeed more wall contact is made compared to rotary files,[361,382] resulting in better debridement and antimicrobial efficacy.[289,472] Shaping quality is also on par with rotary instruments.[382,537]

Endo-Eze

The Giromatic handpiece (MicroMega), a rotary instrument system in use since 1969, delivers 3000 quarter-turn reciprocating movements per minute. Special rasps and barbed broaches made from stainless steel were most often used in Giromatic handpieces, but K-type and H-type instruments may also be used. The preparation quality with this system was insufficient in curved canals, and the technique fell into disregard.[233]

The Endo-Eze file system (Ultradent, South Jordan, UT) is a more recently introduced addition using a similar motion, provided by special equipment or an original Giromatic handpiece. The set has four engine-driven instruments that are designed to clean the middle third of the canal. The sizes and tapers are #10 and #13, with tapers ranging from 0.02 to 0.04. In this system, the use of stainless steel hand instruments is suggested for the apical third of the canal.

Preparation quality in curved canals appeared to be inferior to NiTi rotaries.[349,358] In straight canals, Endo-EZE performed similar to FlexMaster.[419]

Sonic and Ultrasonic Instruments

An alternative way of instrumenting root canals was introduced when clinicians became able to activate files by electromagnetic ultrasonic energy. Piezoelectric ultrasonic units are also available for this purpose. These units activate an oscillating sinusoidal wave in the file with a frequency of about 30 kHz.

Two types of units, ultrasonic and sonic, are marketed. Ultrasonic devices, which operate at 25 to 30 kHz, include the magnetostrictive Cavi-Endo (Dentsply Caulk, Milford, DE), the piezoelectric ENAC (Osada, Tokyo), the EMS Piezon Master 400 (Electro Medical Systems, Vallée de Joux, Switzerland), and the P5 Neutron (Acteon Satelec, Merignac Cedex, France) (Fig. 6-29). Sonic devices, which operate at 2 to 3 kHz, include the Sonic Air MM 1500 (MicroMega), the Megasonic 1400 (Megasonic Corp, House Springs, MO), and the Endostar (Syntex Dental Products, Valley Forge, PA).

FIG. 6-29 Example of an ultrasonic unit. (Neutron P5 piezoelectric, courtesy Acteon Satelec, Merignac Cedex, France).

Ultrasonic device holders can fit regular types of instrument blanks (e.g., K-files), whereas sonic devices use special inserts known as Rispi-Sonic, Shaper-Sonic, Trio-Sonic, or Heli-Sonic files.

Although similar in function, piezoelectric units have some advantages over the magnetostrictive systems. For example, piezoelectric devices generate little heat, so no cooling is needed for the handpiece. Magnetostrictive systems, however, generate considerable heat, and a special cooling system is needed in addition to the cooling effect provided by root canal irrigation. Working without water-cooling becomes essential when using an operating microscope, because the water spray may obstruct visualization.

The piezoelectric transducer transfers more energy to the file than does the magnetostrictive system, making it more cutting efficient. The file in an ultrasonic device vibrates in a sinus wave–like fashion. A standing wave has areas with maximal displacement (i.e., antinodes) and areas with no displacement (i.e., nodes). The tip of the instrument exhibits an antinode. If powered too high, especially with no contact with the canal wall, the instrument may break because of the intense vibration. Therefore, files must be used only for a short time, must remain passive within the canal, and the power must be controlled carefully. The frequency of breakage in files used for longer than 10 minutes may be as high as 10%, and the breakage normally occurs at the nodes of vibrations.[7] Ultrasonic devices have been linked to a higher incidence of preparation errors and to reduced radicular wall thickness.[298,321,582]

Summary

An abundance of NiTi systems is currently on the market. Table 6-1 lists these instruments systematically and illustrates some of the most relevant properties. Most systems included in Table 6-1 have files with tapers greater than the .02 stipulated by the ISO norm. Differences exist in tip designs, cross sections, and manufacturing processes. In vitro tests have continued to identify the effect of specific designs on shaping capabilities and fracture resistance. A desirable goal is the instrumentation of more canal surface, in an effort to make biofilm more susceptible to subsequent chemical disinfection. At the same time, instrumentation paradigms that conserve more dentin appear desirable to promote long-term function.[172] Meaningful differences in clinical outcomes in regard to various specific design variations have yet to be ascertained.[187,375,443]

Motors

Motors for rotary instruments have become more sophisticated since the simple electric motors of the first generation in the early 1990s (Fig. 6-30, *A*). Electric motors with gear reduction are most suitable for rotary NiTi systems, because they ensure a constant rpm level and constant torque. They can also be programmed to provide alternative rotation patterns, for example, reciprocation with freely selectable angles of rotation.[151] Electric motors often have presets for rpm and torque and are capable of delivering torques much higher than those required to break tips. Some authors think that torque-controlled motors (see Fig. 6-30, *B* to *D*) increase operational safety.[160] Others have suggested that such motors may mainly benefit inexperienced clinicians.[569] These motors probably do not reduce the risk of fracture caused by cyclic fatigue, and even if the torque is below the fracture load at D3, a fracture at a smaller diameter (D2) is still possible.

To complicate matters further, a differential exists between torque at failure at D3 and the working torque needed to operate an instrument effectively (Fig. 6-31 and Box 6-2).[57,374,383,432] In many cases the working torque is greater than the torque required to fracture the instrument's tip.

This differential between working torque and tip fracture load is especially large, with files having a taper equal to or greater than .06; therefore, these files are rather ineffective in

FIG. 6-30 Examples of motors used with rotary nickel-titanium endodontic instruments. **A**, First-generation motor without torque control. **B**, Fully electronically controlled second-generation motor with sensitive torque limiter. **C**, Frequently used simple torque-controlled motor. **D**, Newer-generation motor with built-in apex locator and torque control.

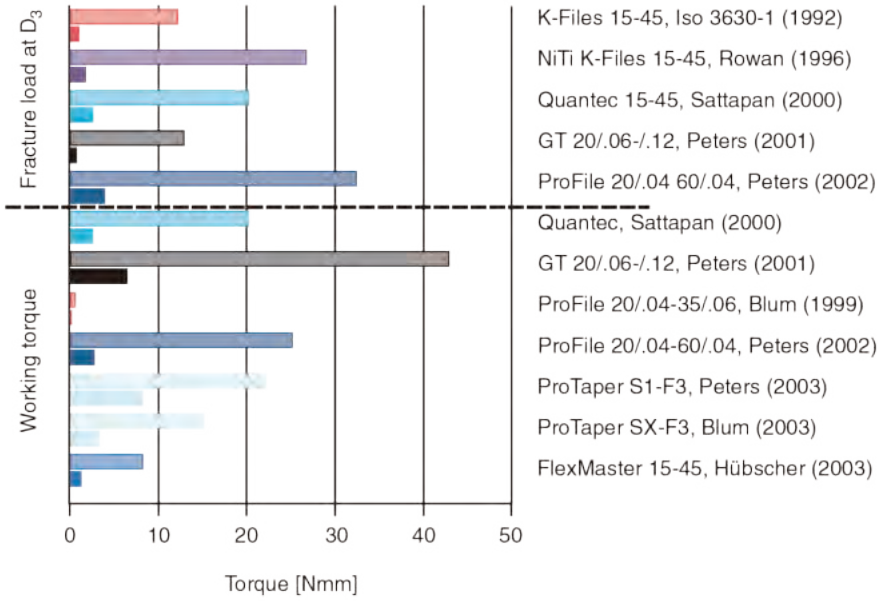


FIG. 6-31 Diagram comparing fracture loads at D_3 *(upper section of graph)* to torques occurring during preparation of root canals *(lower section of graph)*. Filled columns represent the largest file in each set, and open columns show the scores of the most fragile file (see text and Box 6-3 for details).

BOX 6-2

Instrument Breakage with Torsional Load (MacSpadden Factor)

For rotary instrument tips, susceptibility to breakage is governed by the quotient of torque needed to fracture divided by working torque. Simply put, the larger the value, the safer the file.

most torque-controlled motors. Future motors will likely offer more microprocessor controlled features—for example, information about the specific instrument being used, such as the presets and the usage history.

Certain motors have built-in apex locators (see Fig. 6-30, D). This type of motor may be programmed to stop a rotary instrument when working length is reached or go into reverse gear. Similar changes in movement can occur in an adaptive fashion, depending on the torsional load that the instrument experiences in the root canal. The TF Adaptive motor (SybronEndo) is an example for this technology.

Some of the factors, besides the motor itself, that may influence the incidence of fracture in engine-driven NiTi rotary instruments are lubrication, specific instrument motion, and speed of rotation. It cannot be overemphasized that NiTi rotary instruments should be used only in canals that have been flooded with irrigant. Although lubricants such as RC-Prep (Premier Dental Products Co., Plymouth Meeting, PA) and Glyde (Dentsply Maillefer) have been recommended in the past, their benefit may be restricted to plastic blocks[19] and less relevant when rotary instruments engage dentin surfaces. Moreover, experimental data for dentin suggest that the use of lubricants fails to reduce torque values during simulated canal preparation.[61,376] Finally, because of chemical interactions between NaOCl and ethylenediamine tetra-acetic acid (EDTA),[183] alternating irrigants and using lubricants that contain EDTA may even be counterproductive. Details in irrigation solution interactions are described later in this chapter.

For instrument motion, some manufacturers recommend a pecking, up-and-down motion. This not only prevents threading in of the file, it is also thought to distribute stresses away from the instrument's point of maximum flexure, where fatigue failure would likely occur.[285,394] However, such in-and-out movements did not significantly enhance the life span of ProFile .04 taper or GT rotary instruments rotated around a 5-mm radius cylinder with a 90-degree curve.[374,379] Furthermore, large variations were noted in the lengths of the fractured segments.[226,530] This suggests that ductile fractures may originate at points of surface imperfections. Files made of more martensitic alloy tend to work better with longer sweeping or brushing strokes. The notion of "brushing" is not directly related to a paintbrush motion, as this would predispose a file to bending and subsequent fatigue.[391] It rather refers to stroking against the wall away from the danger zone, the inner curvature of a curved root.

Rotational speed may influence instrument deformation and fracture. Some studies indicated that ProFile instruments with ISO-norm tip diameters failed more often at higher rotational speed,[131,159] whereas other studies did not find speed to be a factor.[116,252] For Vortex, 300 rpm reduced the generated torque and force; this higher rpm preset did not result in an increase of instrument fractures in vitro.[37]

Clinicians must fully understand the factors that control the forces exerted on continuously rotating NiTi instruments (Box 6-3). To minimize the risk of fracture and prevent taper lock, motor-driven rotary instruments should not be forced in an apical direction. Similarly, acute apical curves limit the use of instruments with higher tapers because of the risk of cyclic fatigue. The incidence of instrument fracture can be reduced to an absolute minimum if clinicians use data from well-designed torque and stress studies. Adequate procedural strategies, such as an adequate glide path, a detailed knowledge of anatomic structures, with avoidance of extreme canal

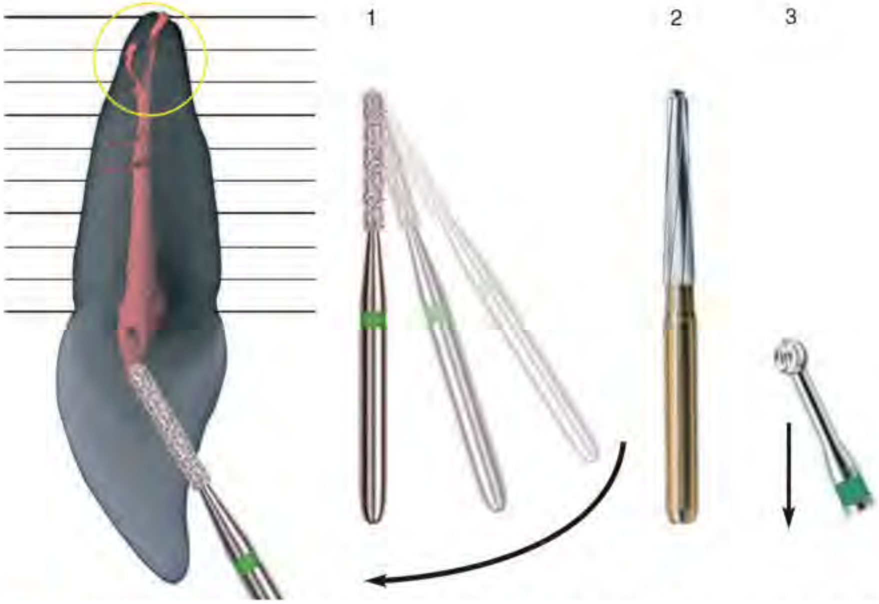


FIG. 6-32 Sequence of instruments used for optimal preparation of an access cavity (e.g., in an incisor). A parallel-sided diamond or steel bur is used to remove overlying enamel in a 90-degree angle toward the enamel surface *(1)*. The bur is then tilted vertically to allow straight-line access to the root canal *(arrow)*. A bur with a noncutting tip (e.g., Endo-Z bur or ball-tipped diamond bur) is then used to refine access *(2)*. Overhangs or pulp horns filled with soft tissue are finally cleared with a round bur used in a brushing or pulling motion *(3)*.

BOX 6-3

Factors Governing the Potential for Nickel-Titanium Rotary Instrument Fractures

- Clinician's handling (most important)
- Combination of torsional load, bending, and axial fatigue
- Root canal anatomy
- Manufacturing process and quality

configurations, and specific instrumentation sequences may also improve shaping results.

Certain procedures have evolved for removing fractured instruments from root canals (see Fig. 6-25); these are discussed in detail elsewhere in this book (see Chapters 8 and 19). Most of those methods require the use of additional equipment, such as a dental operating microscope and ultrasonic units. However, the best way to deal with instrument fracture is prevention. An understanding of the anatomy of the root canal system, together with a clear plan for selecting, sequencing, and using shaping instruments, can certainly help prevent procedural mishaps.

STEPS OF CLEANING AND SHAPING

Access: Principles

Access cavity preparation is essential for root canal treatment and is described in detail elsewhere in this book (Chapter 5). It should be emphasized at this point that mishaps during access (e.g., perforation) significantly affect the long-term outcome of a root canal treated tooth. Overenlargement or gouging during access significantly reduces structural strength[402] and may lead to root fracture and nonrestorable conditions.

Rationally, the use of a cylindrical diamond bur, followed by a tapered fluted bur with noncutting tip and perhaps a small round bur, is recommended (Fig. 6-32). One experiment suggested that more conservative access cavities, in particular in premolars, may increase fracture resistance and permit similar shaping outcomes.[270] The use of ultrasonically powered tips under magnification is aimed at achieving ideal access cavities (Fig. 6-33), including discovery and perhaps relocation of the canal orifices.

Coronal Preflaring

The extension of an access cavity into the coronal-most portion of the root canal is called *coronal flaring*. If a canal is constricted, mineralized, or difficult to access, flaring the coronal portion prior to any deep entry into the root canal is beneficial. This canal modification should be preceded by a scouting step, in which a small (e.g., size #10) K-file is passively placed several millimeters into the root canal. Tools for preflaring include Gates Gliddens (Fig. 6-34) and dedicated NiTi instruments (Fig. 6-35). Both step-back and step-down sequences have been recommended for Gates Gliddens, whereas NiTi rotaries are typically used in a crown-down sequence. More recently, specific orifice shaping rotaries have been developed that are used as a single instrument, rather than a sequence.

The use of laterally cutting NiTi rotaries allows the clinician to modify the root canal orifice to form a receptacle for subsequent instrumentation. This is related to removal of coronal mineralization and to relocation of the canal pathway by removal of dentin overhangs. For example, a second mesiobuccal canal typically exits the pulp chamber toward the mesial under a dentin shelf and then curves toward the distal. It is this curve in a small canal that often leads to formation of a ledge, which in turn prevents shaping to length.

Preenlargement of the coronal half to two thirds of a root canal allows files unimpeded access to the apical one third and

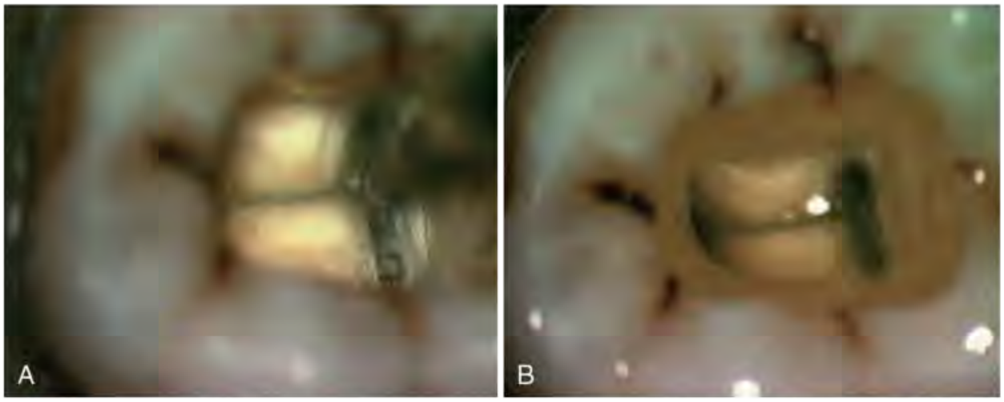


FIG. 6-33 Clinical views of an access cavity in a mandibular molar. A, As seen through an operating microscope (×20). B, Modification with an ultrasonically activated tip.

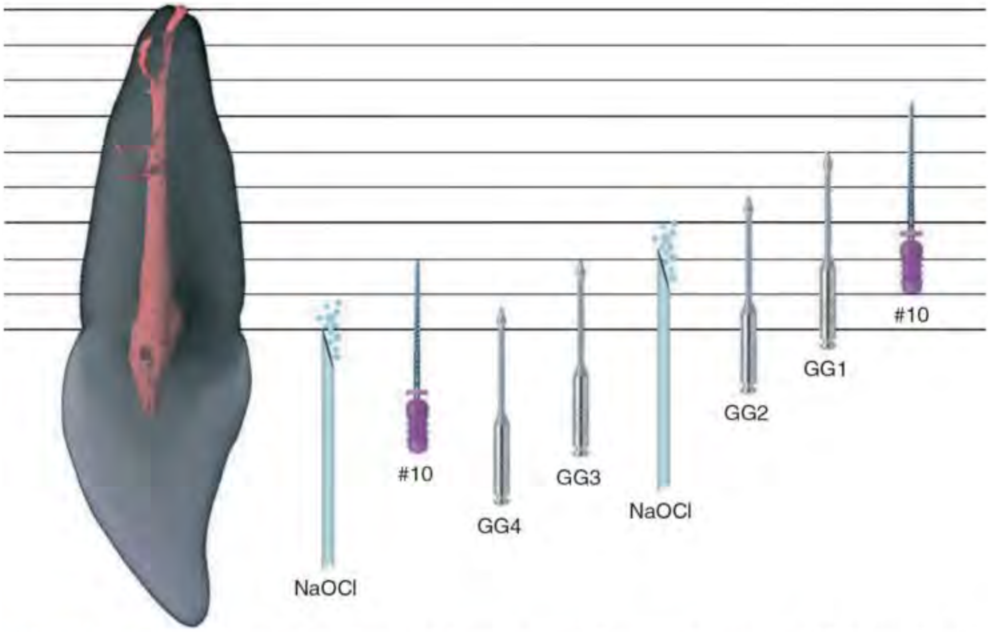


FIG. 6-34 Diagram of coronal enlargement in a maxillary anterior tooth. After preparation of the access cavity (see Fig. 6-32) and copious irrigation, Gates-Glidden burs are used in a step-down manner to enlarge the orifice and provide straight-line access into the middle third of the canal. Precurved size #10 K-files are used to explore the canal path and dimension.

gives the clinician better tactile control in directing small, adequately precurved negotiating files (Fig. 6-36).

One of the purported benefits of early coronal flaring is access of disinfecting irrigation solutions, but this has not been confirmed in experiments. On the other hand, a documented benefit of coronal flaring is mitigation of working length changes during canal preparation.[496]

Comparatively little is known about the efficacy of individual flaring instruments. One study compared the cutting efficacy of radial-landed and triangular cross sections.[338,380] The latter were shown to be more cutting efficient compared to radial-landed design; somewhat surprisingly, flexible martensitic alloy was cutting more rapidly compared to conventional NiTi alloys.

Patency File

A *patency file* is a small K-file (usually a size #10 or #15) that is passively extended slightly beyond the apical foramen. The use of a patency file has been suggested for most rotary techniques. This step is thought to remove accumulated debris, to help maintain working length, and to translate into greater clinical success.[345] One concern with the patency file was that instead of having a cleaning effect, the file would push contaminated debris through the foramen. However, an in vitro study suggested that the risk of inoculation was minimal when canals were filled with NaOCl.[243] Maintaining patency throughout an endodontic procedure does not lead to an increase in posttreatment symptoms.[22] Only initial clinical evidence exists favoring the use of a patency file; however, experience suggests

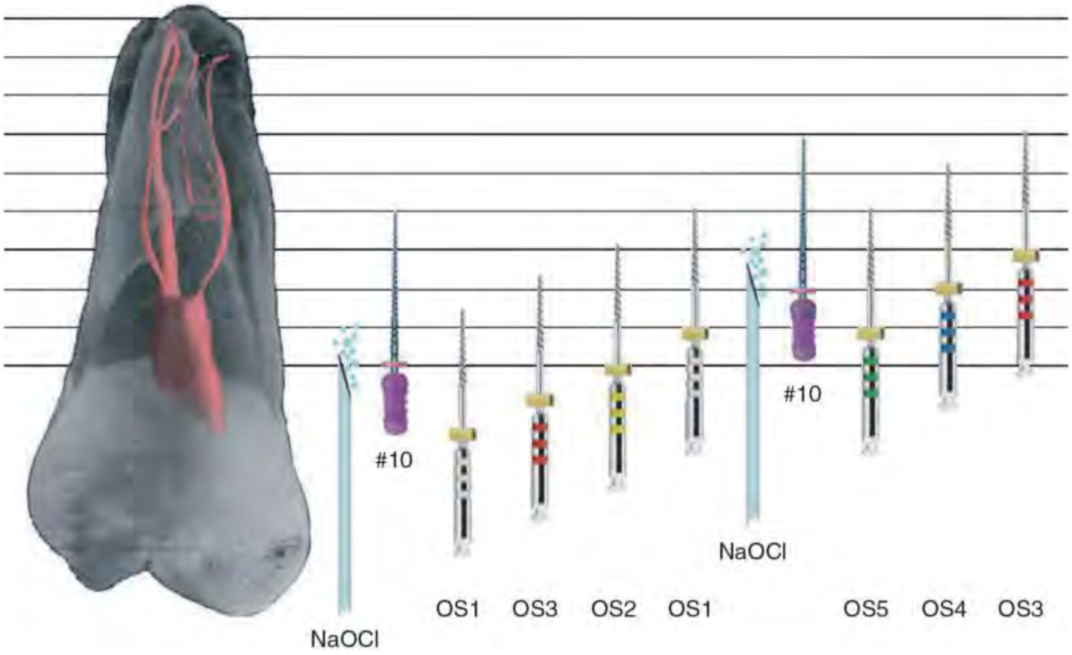


FIG. 6-35 Diagram of coronal enlargement in a more complicated maxillary posterior tooth. This maxillary molar presents several difficulties, including a narrow mesiobuccal canal that exits the pulp cavity at an angle. A possible approach in a case involving difficult entry into the root canal system is to use a small orifice shaper (OS1) after ensuring a coronal glide path with a K-file. Use of a sequence of orifice shapers (OS3 to OS1) then allows penetration into the middle third of the root canal. Wider canals can accept a second sequence of orifice shapers. Copious irrigation and securing a glide path with a size #10 K-file are prerequisites for use of NiTi rotary instruments.


FIG. 6-36 Various precurved, stainless steel hand files for pathfinding and gauging. Compare the curves in the instruments to the ones in a plastic training block (gradation of ruler is 0.5 mm).

that this technique involves relatively little risk and provides some benefit as long as small files are used carefully.

Working Length Determination

Devices

Radiographs, tactile sensation, the presence of moisture on paper points, and knowledge of root morphology have been used to determine the length of root canal systems. Following earlier experiments by Custer,[110] Sunada developed the first commercialized electronic apex locator,[501] suggesting that the apical foramen could be localized using a direct electric current. Currently, the electronic apex locator is considered an accurate tool for determining working length.[153] One study reported that the use of electronic apex locators in a dental student clinic resulted in a higher quality of obturation length control and an overall reduction in the number of radiographs taken.[152] However, these devices must not be considered flawless, because several variables are known to affect their accuracy. For example, immature roots can present problems.[234] Once roots mature (i.e., form a narrow apical foramen) and instruments are able to contact the canal walls, an electronic apex locator's accuracy greatly improves. Some investigators have found no statistical difference between roots with vital and necrotic tissue.[175,319] Because apical root resorption is prevalent in necrotic cases with longstanding apical lesions,[541] it may be concluded that apical resorption does not have a significant effect on the accuracy of electronic apex locators.

Some clinicians have advocated the use of the electronically determined working length in lieu of working length estimations using the placement of a file in the canal and a radiograph. However, combined use of both of these techniques has been shown to result in greater accuracy.[136] Furthermore, radiographs may add essential anatomic information that could be missed if electronic apex locators are used exclusively.

The first two generations of electronic apex locators were sensitive to the contents of the canal and irrigants used during treatment. The development of an algorithm called the *ratio measurement method* distinguished the third generation of apex locators.[263] To arrive at this method, the impedance of the canal was measured with two current sources of different frequencies, and a quotient was determined using the electrical potentials proportional to each impedance.[263] This study found that

FIG. 6-37 **A**, Root ZX apex locator with lip clip and file holder. **B**, NRG miniature electronic apex locator. (*A*, Courtesy J Morita, Irvine, CA. *B*, Courtesy MedicNRG, Kibutz Afikim, Israel.)

electrolytes did not have a significant effect on the accuracy of the unit. This means that clinically canal contents need not be dried, but fluids in contact with crowns or coronal metallic restoration materials could conduct currents and lead to false results.

Some third-generation apex locators are the Endex Plus, or Apit (Osada, Los Angeles, CA), the Root ZX (J. Morita, Kyoto, Japan),[153,276] and the Neosono Ultima EZ (Acteon Satelec). The Endex Plus device uses 1 and 5 kHz and provides apex location based on subtraction. The Root ZX emits currents at frequencies of 8 and 0.4 kHz and provides apex location based on the resulting quotient. In addition to latest model apex locators, manufacturers have developed smaller models (Fig. 6-37, *B*).

Apex locators are generally safe to use; however, manufacturers' instructions state that they should not be used on patients with pacemakers without consulting the patient's cardiologist. However, when connected directly to cardiac pacemakers in vitro, electronic apex locators did not interfere with the function of the pacemaker,[165] and they did not interfere with the functioning of any of the cardiac devices tested in a clinical study under electrocardiogram monitoring.[556]

Strategies

Anatomic studies and clinical experience suggest that typically teeth are 19 to 25 mm long. Most clinical crowns are approximately 10 mm long, and most roots range from 9 to 15 mm in length. Roots, therefore, can be divided into thirds that are 3 to 5 mm long. An important issue in root canal treatment is the apical end point of the prepared shape in relation to the apical anatomy. Traditional treatment has held that canal preparation and subsequent obturation should terminate at the *apical constriction*, the narrowest diameter of the canal (Fig. 6-38). This point is thought to coincide with the cementodentinal junction (CDJ) (see Chapter 12) and is based on histologic sections and ground specimens. However, the position and anatomy of the CDJ vary considerably from tooth to tooth, from root to root, and from wall to wall in each canal. Moreover, the CDJ cannot be located precisely on radiographs. For this reason, some have advocated terminating the preparation in necrotic cases at 0.5 to 1 mm short of the radiographic apex and 1 to 2 mm short[206,407,562] in cases involving irreversible pulpitis. Although there is no definitive validation for this strategy at present,[435] well-controlled follow-up studies seem to support it.[476,478]

Working to shorter lengths may lead to the accumulation and retention of debris, which in turn may result in apical blockage (Fig. 6-39). If the path to the apex is blocked, working to short lengths may contribute to procedural errors such as apical perforations and fractured instruments. Such obstacles (which consist of collagen fibers, dentin mud, and, most important, residual microbes) in apical canal areas are a major cause of persistent or recurrent apical periodontitis,[196,342,466] or *post-treatment disease*[156,559] (also see Chapters 14 and 15).

Using an electronic apex locator has helped clinicians identify the position of apical foramina more accurately and allow safe canal shaping as close as 0.5 mm to the canal terminus.

Canal Enlargement/Preparation

Rationale

Like the position of the apical constriction, apical diameters are difficult to assess clinically.[274] Some have recommended gauging canal diameters by passing a series of fine files apically until one fits snugly. However, such an approach is likely to result in underestimation of the diameter.[555] This is a crucial point because the initial canal size is a major determinant for the desired final apical diameter.

An ongoing debate exists between those who prefer smaller apical preparations combined with tapered shapes and those who favor larger apical preparations for better removal of infected dentin and to allow irrigation fluids access to the apical areas (Table 6-2). Both sides stress the importance of maintaining the original path of the canal during preparation; otherwise, bacteria in the apical one-third of the root canal may not be reached by sufficient amounts of an antimicrobial agent.[335] Investigators demonstrated a higher percentage of

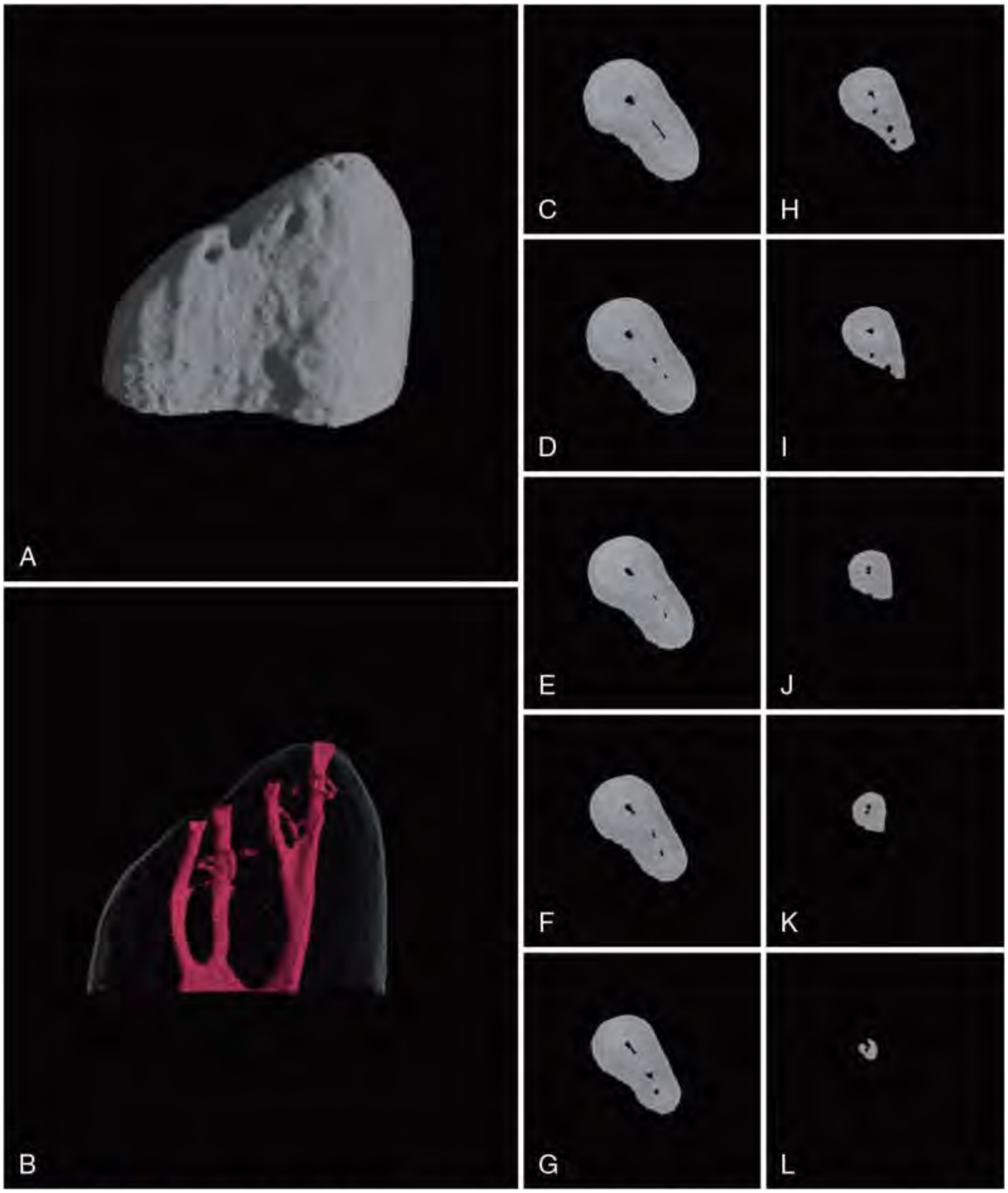


FIG. 6-38 Microcomputed tomographic scan of anatomy of the apical 5 mm of a mesiobuccal root (8 μm resolution). A-B, Three-dimensional reconstruction of outer contour and root canal systems. C-L, Cross sections of root at 0.5 mm apart.

TABLE 6-2

Characteristics of Wide and Narrow Apical Preparations

Root Canal Preparation	Benefits	Drawbacks
Narrow apical size	Minimal risk of canal transportation and extrusion of irrigants or filling material Can be combined with tapered preparation to counteract some drawbacks Less compaction of hard tissue debris in canal spaces	Little removal of infected dentin Questionable rinsing effect in apical areas during irrigation Possibly compromised disinfection during interappointment medication Not ideal for lateral compaction
Wide apical size	Removal of infected dentin Access of irrigants and medications to apical third of root canal	Risk of preparation errors and extrusion of irrigants and filling material Not ideal for thermoplastic obturation

FIG. 6-39 Presence of dentin dust as a possible source of microbial irritation. Tooth #18 underwent root canal therapy. The clinician noted an apical blockage but was unable to bypass it. Unfortunately, intense pain persisted and at the patient's request, the tooth was extracted a week later. **A**, Mesial root of tooth #18; mesial dentin has been removed. **B**, Magnified view (×125) of rectangle in **A** shows an apical block (gradation of ruler is 0.5 mm).

bacterial elimination in single-root canal systems by using a combination of significant enlargement of the apical third and NaOCl irrigation.[89] Preparation errors (e.g., zips, canal transportation) may occur in larger preparations, with both stainless steel and NiTi instruments (Fig. 6-40).

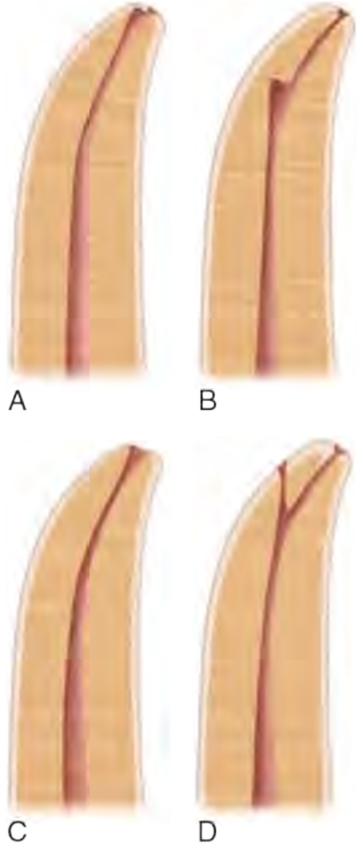


FIG. 6-40 Schematic diagrams showing the most common preparation errors. **A**, Apical zip. **B**, Ledge. **C**, Apical zip with perforation. **D**, Ledge with perforation.

Thorough disinfection of the apical part of a root canal is essential, because this area is most likely to harbor residual intraradicular bacteria.[343] Wider apical preparations remove potentially infected dentin, allowing the delivering needle and subsequently the antimicrobial irrigant to penetrate the root canal more deeply.[101,147]

A study investigating rotary NiTi files of three tapers (.06, .08, and .10) with file tips in sizes #20, #30, and #40 showed that size #20 instruments left significantly more debris in the apical third compared with size #40 instruments.[532] On the other hand, a study in which half the samples were prepared to a size #25 file and the other half to a size #40 file found no statistically significant difference in bacterial growth after instrumentation, with no growth observed after 1 week of treatment with a $Ca(OH)_2$ dressing.[570] Step-down sequences with additional apical enlargement to ISO size #35 and a serial step-back technique with no apical enlargement were compared, using NaOCl and EDTA as irrigants. Here, no significant difference was detected in colony-forming units with or without apical enlargement.[105] These researchers concluded that dentin removal in the apical third might be unnecessary if a suitable coronal taper is achieved.

Despite the disagreement over the appropriate width of a preparation (see Table 6-2), these studies suggest that root canal preparations should be confined to the canal space, should be sufficiently wide, and should incorporate the original root canal cross sections (see Fig. 6-4).

Traditional cleaning and shaping strategies (e.g., the step-back technique) focused immediate preparation of the apical third of the root canal system, followed by various flaring techniques to facilitate obturation.[180,436,518] In an attempt to reach the canal terminus, the clinician first selected a small file, placed an appropriate curve on the instrument, and then tried to work the file to full length. If the terminus could not be reached, the file was removed and, after irrigation, either the same file or a smaller one was inserted. However, not infrequently, full length was not obtained, either because of blockage or because of coronal binding.

Coronal binding is caused by overhangs at the orifice level and when the canal is less tapered than an instrument, making it bind coronally. Moreover, a straight root often contains a curved canal, such as buccal and lingual curvatures that cannot be seen on radiographs.[109,389] In addition, passing a precurved negotiating file through a coronally tight canal will straighten the instrument.[487]

Various instrumentation sequences have been developed for hand and rotary instruments; these are discussed later in this chapter. However, the shape of the access cavity is *the* prerequisite that must be optimized before any canal preparation can take place (see Chapter 5).

As stated previously, preparation of an adequate access cavity (see Fig. 6-32) may involve the use of a cylindrical diamond or fissure bur, a safety-ended drill for additional enlargement, and round burs to remove overhangs on outward strokes. The access cavity shape must allow instruments unimpeded access to the middle third of the root canal system. Ultrasonically powered instruments used under an operating microscope greatly facilitate removal of mesial dentin shelves in mandibular molars (see Fig. 6-33, *A and B*) and other teeth. Preexisting restorations allow for ideal access cavities that serve as reservoirs of irrigants (see Fig. 6-33, *C*).

Basic cleaning and shaping strategies for root canal preparation can be categorized as crown-down, step-back, apical widening, and hybrid techniques. In a crown-down approach, the clinician passively inserts a large instrument into the canal up to a depth that allows easy progress. The next smaller instrument is then used to progress deeper into the canal; the third instrument follows deeper again, and this process continues until the terminus is reached. Both hand and rotary instruments may be used in a crown-down manner. However, instrument sets with various tip diameters and tapers allow the use of either decreasing tapers or decreasing diameters for apical progress. Debate continues as to which of those strategies is superior for avoiding taper lock; currently, no compelling evidence favors either of them.

In the step-back approach, working lengths decrease in a stepwise manner with increasing instrument size. This prevents less flexible instruments from creating ledges in apical curves while producing a taper for ease of obturation.

As discussed previously, the aim of apical widening is to fully prepare apical canal areas for optimal irrigation efficacy and overall antimicrobial activity. Apical enlargement has been broken down into three phases: preenlargement, apical enlargement, and apical finishing.[545]

Most rotary techniques require a crown-down approach to minimize torsional loads,[57] and they reduce the risk of instrument fracture. Used sequentially, the crown-down technique can help enlarge canals further. All basic techniques described so far may be combined into a hybrid technique to eliminate or reduce the shortcomings of individual instruments.

Root canal preparation can be broken down into a series of steps that parallel the insertion depths of individual instruments. Anatomic studies and clinical experience suggest that most teeth are 19 to 25 mm long. Most clinical crowns are approximately 10 mm long, and most roots range from 9 to 15 mm in length. Roots, therefore, can be divided into thirds that are 3 to 5 mm long.

Provided adequate tools are used and the access cavity design is appropriate, excessive thinning of radicular structures can be avoided (see Fig. 6-5). Vertical root fractures and perforations are possible outcomes of excessive removal of radicular dentin in zones that have been termed *danger zones*.[15] Overenthusiastic filing, for example, may lead to more procedural errors (see Figs. 6-22 and 6-40). On the other hand, ideal preparation forms without any preparation errors and with circular incorporation of the original canal cross sections may be achieved with suitable techniques (see Fig. 6-4).

Dedicated NiTi instruments have been introduced or suggested for coronal preenlargement, such as the ProFile orifice shapers, GT accessory files, the ProTaper SX, the FlexMaster Intro file, and the size #40, .10 taper or size #35, .08 taper RaCe files. These instruments are better suited than GGs and safer for more difficult cases (see Figs. 6-34 and 6-35).

Techniques

Standardized Technique

The standardized technique adopts the same working length definition for all instruments introduced into a root canal. It therefore relies on the inherent shape of the instruments to impart the final shape to the canal. Negotiation of fine canals is initiated with lubricated fine files in a so-called watch-winding movement. These files are advanced to working length and worked either in the same hand movement or with "quarter-turn-and-pull" until a next larger instrument may be used. Conceptually, the final shape should be predicted by the last instrument used (Fig. 6-41). A single matching gutta-percha point may then be used for root canal filling. In reality, this concept is often violated: curved canals shaped with the standardized technique will be wider than the last used instrument,[14] exacerbated by the pulling portion of the hand movement. Moreover, adequate compaction of gutta-percha in such small a taper (~.02) is difficult or impossible[13] (see Chapter 7).

The standardized technique was hampered by the very standardization of the instruments used to perform the technique. Specifically, the similar size increment by 0.05 mm up to size 55 was clinically more difficult to achieve moving from size #10 to size #15, compared to the step from size #40 to #45. In very small files (sizes #6 to #10), the problem is partly resolved by several key points: (1) apical dimensions are such that a size #6 file does not significantly remove dentin other than in severely calcified cases; (2) a size #8 file taken 0.5 to 1 mm long to establish patency (discussed later in the chapter) contacts the desired end point of the preparation with a diameter approaching the tip size of a #10 file; (3) similarly, placing a size #10 file just minutely through the foramen eases the way for passive insertion of the subsequent #15 file to full length.[417]

Step-Back Technique

Realizing the importance of a shape larger than that produced with the standardized approach, one investigator suggested the step-back technique,[552] incorporating a stepwise reduction of the working length for larger files, typically in 1-mm or 0.5-mm steps, resulting in flared shapes with 0.05 and 0.10 taper, respectively (Fig. 6-42). Incrementally reducing the working length when using larger and stiffer instruments also reduced the incidence of preparation errors, in particular in curved canals. This concept appeared to be clinically very effective.[339]

Although the step-back technique was primarily designed to avoid preparation errors in curved canals, it applies to the preparation of apparently[109,439] straight canals as well. Several modifications of the step-back technique have been described over the years. Another investigator advocated the insertion of progressively larger hand instruments as deep as they would passively go in order to explore and provide some enlargement prior to reaching the working length.[518]

Step-Down Technique

Other investigators described a different approach.[174] They advocated shaping the coronal aspect of a root canal first, before apical instrumentation commenced. This technique is intended to minimize or eliminate the amount of necrotic debris that could be extruded through the apical foramen during instrumentation.[146] Moreover, by first flaring the coronal two thirds of the canal, apical instruments are unimpeded through most of their length. This in turn may facilitate greater control and less chance of zipping near the apical constriction.[280]

Crown-Down Technique

Numerous modifications of the original step-down technique have been introduced, including the description of the crown-down technique.[150,317,433] The more typical step-down technique includes the use of a stainless steel K-file exploring the apical constriction and establishing working length. In

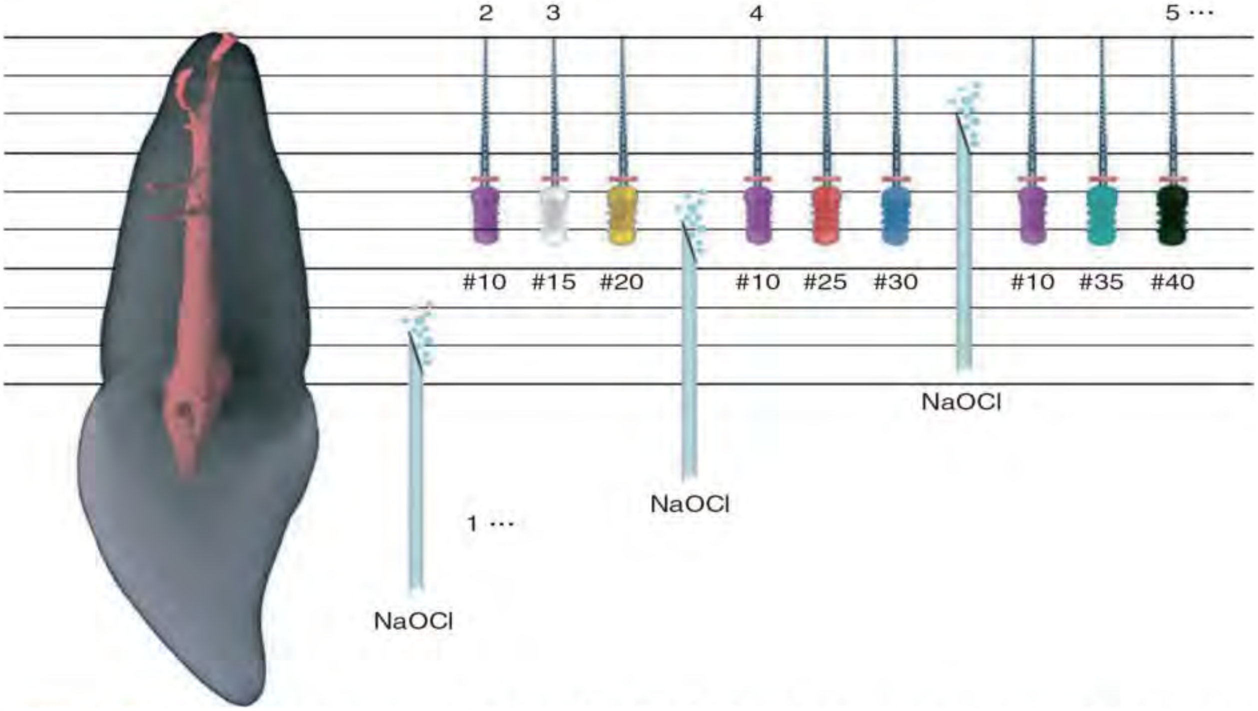


FIG. 6-41 Root canal instrumentation with hand files: Part I. After the orifice has been accessed and copious irrigation performed *(1),* the working length (WL) is determined. A size #10 or #15 K-file is advanced to the desired apical preparation end point, aided by an electronic apex locator *(2)*. The apical canal areas are then enlarged with K-files *(3)* used in the balanced force technique (see Fig. 9-43). Frequent, copious irrigation with sodium hypochlorite is mandatory to support antimicrobial therapy. Frequent recapitulation with fine K-files is recommended to prevent blockage *(4).* Apical enlargement is complete to the desired master apical file (MAF) size *(5),* which depends on pretreatment canal sizes and individual strategy. Typically, size #40 or larger may be reached in anterior teeth, as in this example. File sizes larger than #20 may be used with NiTi instruments (e.g., NiTiFlex).

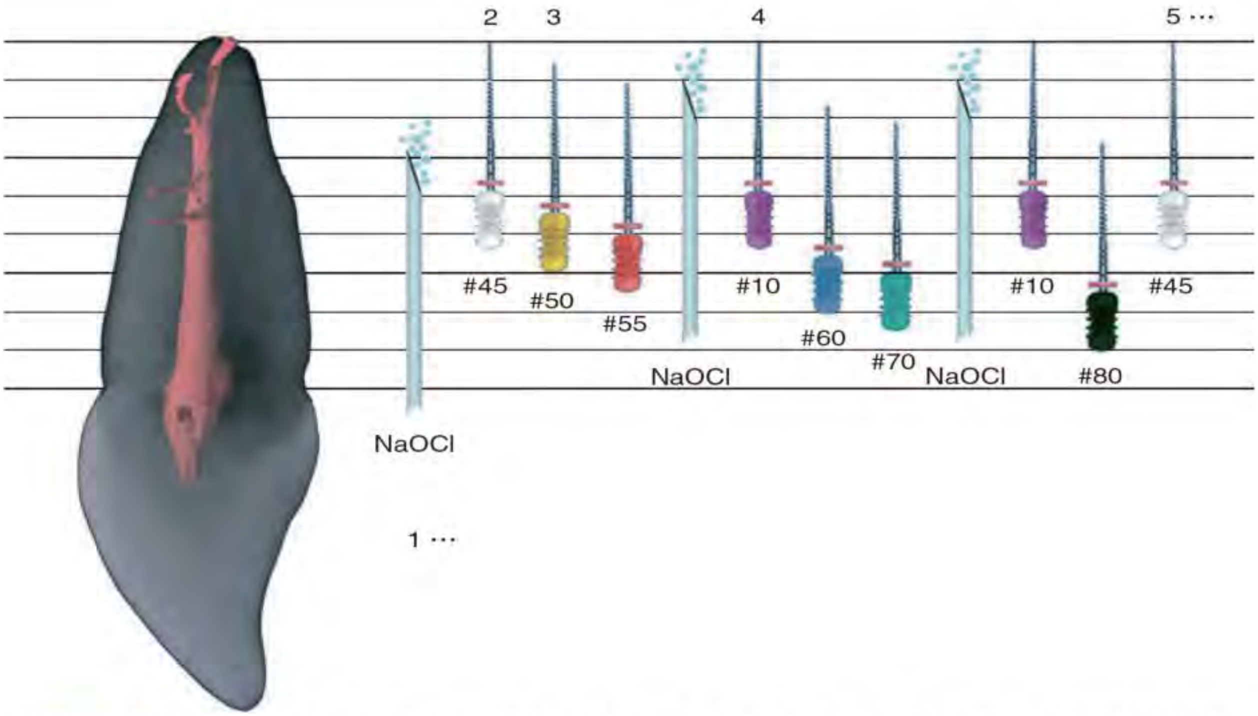


FIG. 6-42 Root canal instrumentation with hand files: Part II. Frequent irrigation with sodium hypochlorite *(1)* is more efficient after the working length (WL) is reached, because irrigation needles may penetrate deeper into the canal. Canal taper is increased to further improve antimicrobial efficiency and to simplify subsequent obturation. Hand instruments are set to decreasing working length in 0.5 mm increments (step-back) from the master apical file (MAF) (*2 and 3*). A fine K-file is used to recapitulate to WL during the procedure *(4),* and the MAF is used as a final recapitulation *(5)* to ensure that remaining dentin chips have been removed.

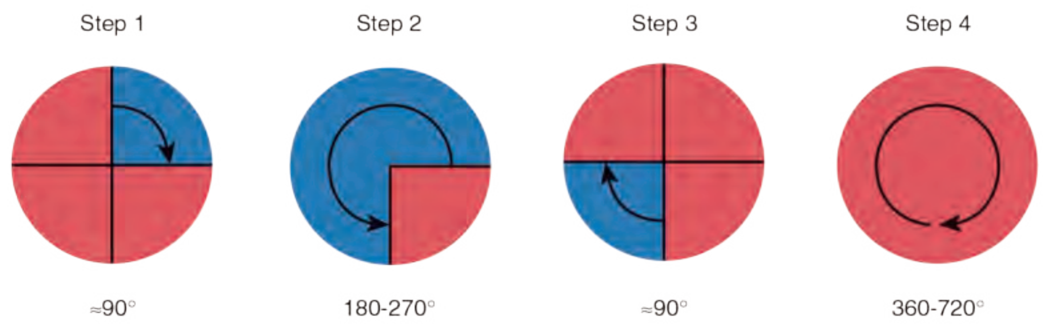


FIG. 6-43 Diagram of handle movements during balanced force hand preparation. **Step 1:** After pressureless insertion of a Flex-R or NiTiFlex K-file, the instrument is rotated clockwise 90 degrees, using only light apical pressure. **Step 2:** The instrument is rotated counterclockwise 180 to 270 degrees; sufficient apical pressure is used to keep the file at the same insertion depth during this step. Dentin shavings are removed with a characteristic clicking sound. **Step 3:** This step is similar to step 1 and advances the instrument more apically. **Step 4:** After two or three cycles, the file is loaded with dentin shavings and is removed from the canal with a prolonged clockwise rotation.

contrast, a crown-down technique relies more on coronal flaring and then determination of the working length later in the procedure.

To ensure penetration during step-down, one may have to enlarge the coronal third of the canal with progressively smaller GG drills or with other rotary instruments. Irrigation should follow the use of each instrument and recapitulation after every other instrument. To properly enlarge the apical third and to round out ovoid shape and lateral canal orifices, a reverse order of instruments may be used starting with a size #20 (for example) and enlarging this region to a size #40 or #50 (for example). The tapered shape can be improved by stepping back up the canal with larger instruments, bearing in mind all the time the importance of irrigation and recapitulation.

The more typical crown-down, or double-flare, technique[150] consisted of an exploratory action with a small file, a crown-down portion with K-files of descending sizes, and an apical enlargement to size #40 or similar. The original technique included stepping back in 1-mm increments with ascending file sizes and frequent recapitulations with a small K-file and copious irrigation. It is further emphasized that significant wall contact should be avoided in the crown-down phase to reduce hydrostatic pressure and the possibility of blockage. Several studies demonstrated more centered preparations in teeth with curved root canals shaped with a modified double-flare technique and Flex-R files compared to shapes prepared with K-files and step-back technique.[434,433] A double-flare technique was also suggested for ProFile rotary instruments.[447]

Balanced Force Technique

Regarding hand movements, a general agreement exists that the so-called balanced force technique creates the least canal aberrations with K-files. This technique has been described as a series of rotational movements for Flex-R files,[412] but it can also be used for K-files and other hand instruments such as GT hand files. Many explanations have been offered for the obvious and undisputed efficacy of the balanced force approach,[94,275,439] but general agreement exists that it provides excellent canal-centering ability, superior to other techniques with hand instruments.[30,71,283]

The balanced force technique involves three principle steps.[412] The first step (after passive insertion of an instrument into the canal) is a clockwise rotation of about 90 degrees to engage dentin (Fig. 6-43). In the second step, the instrument is held in the canal with adequate axial force and rotated counterclockwise to break loose the engaged dentin chips from the canal wall; this produces a characteristic clicking sound. Classically, in the third step, the file is removed with a clockwise rotation to be cleaned; however, because files used with the balanced force technique are not precurved, every linear outward stroke essentially is a filing stroke and may lead to some straightening of the canal path. Therefore, in many cases, the clinician may advance farther apically rather than withdrawing the file, depending on the grade of difficulty.

Rotary Instrumentation

NiTi rotary instruments are an invaluable adjunct in the preparation of root canals, although hand instruments may be able to enlarge some canals just as efficiently when used in appropriate sequences. Hand instruments should be used only after coronal preenlargement (e.g., with GG drills). After preenlargement, the access cavity and canals are flooded with irrigant, and a precurved scouting file is advanced into the canal. A lubricant when using hand instruments can help prevent apical blockage in this early stage. Once the working length has been established (aided by an electronic apex locator and radiographically verified), apical preparation to begins to facilitate a glide path for subsequent rotary instrumentation (Fig. 6-44).

The term *glide path* has been used in endodontics since the early 2000s[384] and relates to securing an open pathway to the canal terminus that subsequent engine-driven instruments can follow. The typical minimum glide path is a size #15 to #20 K-file and should be confirmed with a straight, not precurved file. Various small engine-driven instruments were introduced to simplify this process, such as Pathfiles (Dentsply Maillefer),[53] Scout RaCe (FKG Dentaire SA, La Chaux-de-Fonds Switzerland),[344] and G-file (MicroMega).[112] Copious irrigation and frequent recapitulations with a smaller file to working length may be required, and in some instances, clinicians must devise creative strategies using small crown-down or step-back sequences.

Fig. 6-45 illustrates the development of two different shapes in the mesial root canals of a mandibular molar, clearly showing that substantial areas of the root canal surface in either case are not instrumented, even when apical size #50 or 0.09 taper are reached (see the red areas in Fig. 6-45, *G* and *I*).

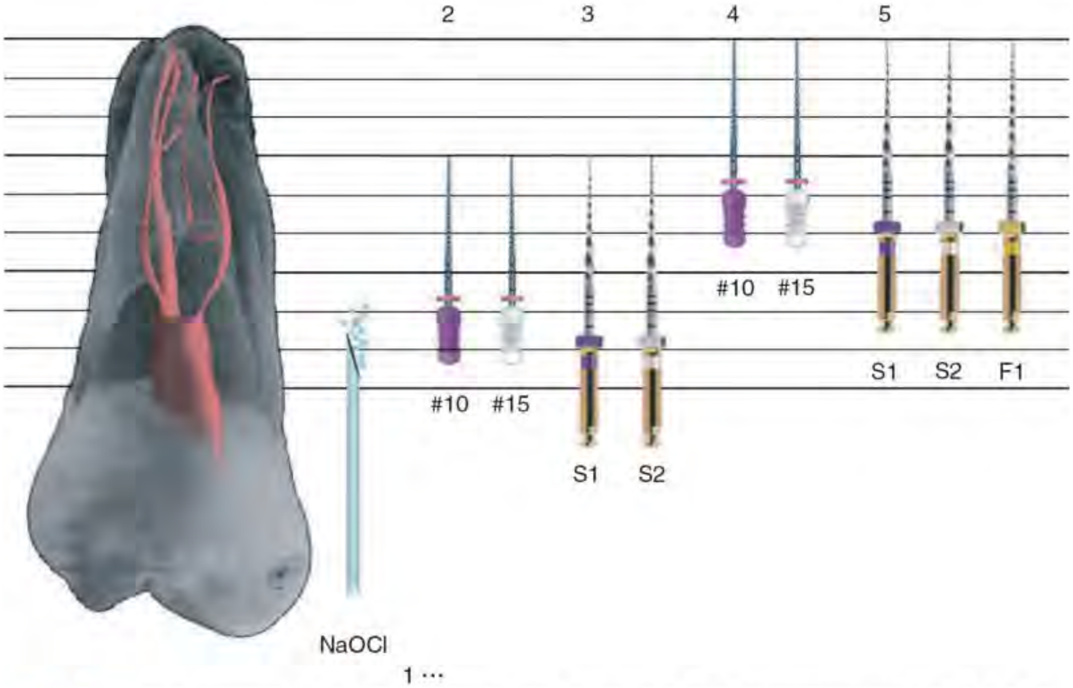


FIG. 6-44 Instrumentation of root canals with ProTaper instruments. After irrigation and scouting (*1* and *2*), the coronal thirds are enlarged with shaping files S1 and S2. Hand files then are used to determine the WL and to secure a glide path. Apical preparation is completed with S1 and S2. Finishing files are used to the desired apical width.

Specific NiTi Instrumentation Techniques

Crown Down

This was the dominant approach for many years and is still being used, for example, for ProFile and several others (ProFile Vortex, HERO 642, K3, and FlexMaster). It must be noted that the manufacturers' instructions for these systems vary somewhat, and the instructions for GT rotary, RaCe, and the Twisted File vary even more. Clinicians should always read the manufacturers' instructions for details on working with those instruments.

Working length is determined after any coronal preenlargement , and an open glide path is secured with K-files up to size #15 or #20, depending on the canal anatomy. If canal size permits, canal preparation begins with .06 taper instruments in descending tip diameters.[57] In more difficult small canals, .06 tapers are followed by .04-tapered instruments, also with descending tip diameters. Apical preparation is performed either with multiple shaping waves, as suggested for GT rotary files,[76] or in a step-back manner.[445] Recapitulation with a small hand file is recommended throughout the preparation.

Single Length

The approach for ProTaper Universal and ProTaper Next instruments differs from that for many other NiTi rotary files (except MTwo, WaveOne and Reciproc) in that no traditional crown-down procedure is performed (see Fig. 6-44).

Size #10 and #15 hand files are passively inserted into the coronal two thirds of a root canal as path-finding files, which confirm the presence of a smooth, reproducible glide path. This step is essential for ProTaper shaping instruments, because they are mostly side cutters and have fine, fragile tips.

Shaping files S1 and S2 are then passively inserted into the scouted canal spaces, which have been filled with irrigant (preferably NaOCl). If necessary, the SX file can be used at this stage to relocate orifices or remove obstructing dentin. After each shaping file is used, the canals are reirrigated, and a size #10 file is used to recapitulate to break up debris and move it into solution. This process is repeated until the depth of the path-finding #10 or #15 file is reached.

After irrigation, the apical third is fully negotiated and enlarged to at least a size #15 K-file, and the working length is confirmed (see Fig. 6-44). Depending on the canal anatomy, the rest of the apical preparation can be done with engine-driven ProTaper shaping and finishing hand files. As an alternative, handles can be placed on these instruments so that they can be used for the balanced force technique.

ProTapers S1 and S2 are then carried to the full working length, still in a floating, brushing motion. The working length should be confirmed after irrigation and recapitulation with a K-file, aided by an electronic apex locator or radiographs. Because of the progressive taper and more actively cutting flutes higher up in the ProTaper design, interferences in the middle and coronal thirds are removed at this stage.

The preparation is finished with one or more of the ProTaper finishing files, used in a nonbrushing manner; because of their decreasing taper, these files will reach the working length passively. Recapitulation and irrigation conclude the procedures (see Fig. 6-44).

LightSpeed Technique

Since the introduction of LightSpeed instruments, the manufacturer's guidelines have changed. This section presents a version used for the original LightSpeed rather than the LS variant (Fig. 6-46).

After access and coronal preenlargement with the instrument of choice, working lengths are obtained, and apical enlargement is done with at least a loose-fitting size #15 K-file. LSX instruments are then slowly advanced to working length

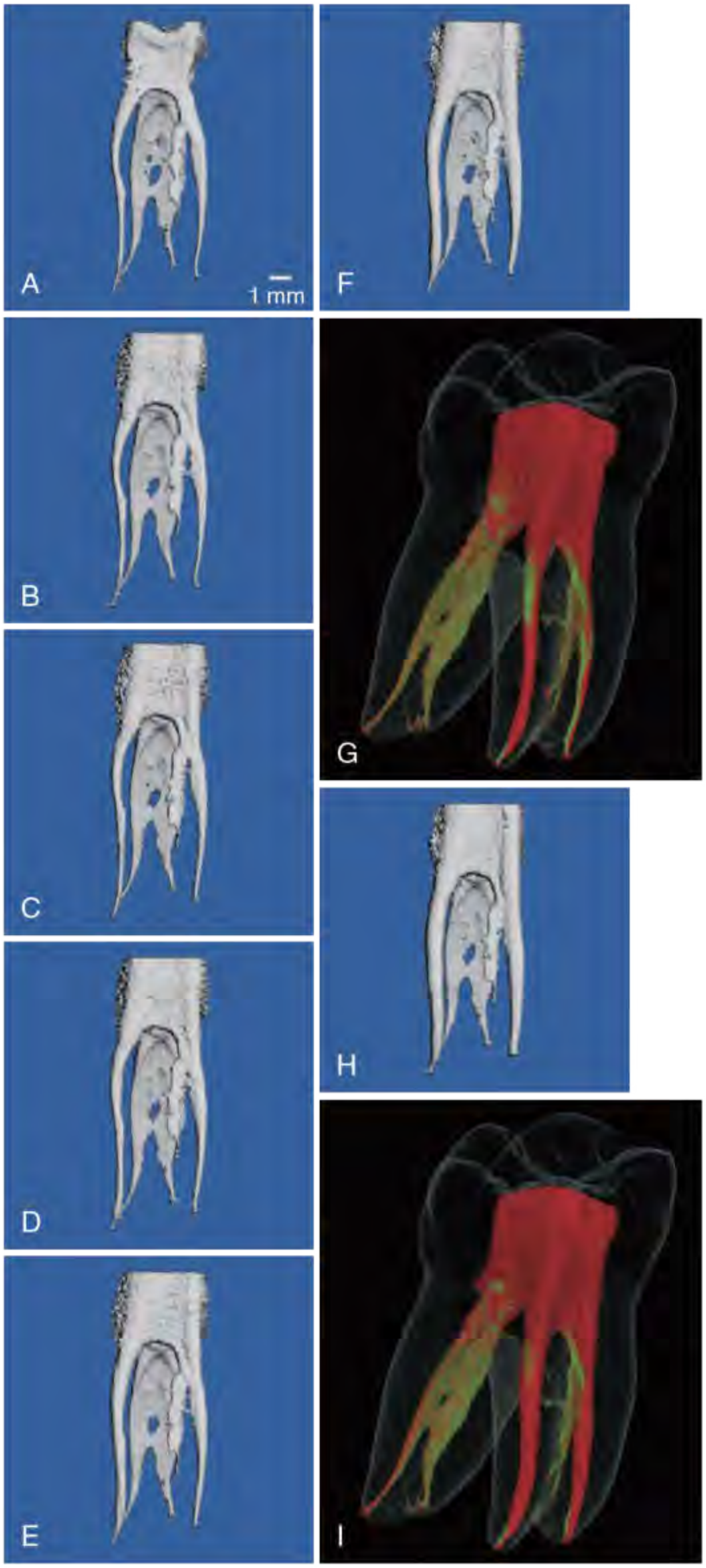


FIG. 6-45 Stepwise enlargement of mesial root canal systems in an extracted mandibular molar demonstrated with microcomputed tomography (μCT) reconstructions. The buccal canal *(left)* was prepared with a LightSpeed (LS) instrument, and the lingual canal *(right)* was shaped with a ProTaper (PT) instrument. **A**, Pretreatment view from the mesial aspect. Note the additional middle canal branching from the lingual canal into the coronal third. **B**, Initial preparation and opening of the orifices, aided by ultrasonically powered instruments. **C**, First step of root canal preparation, up to LightSpeed size #20 and ProTaper shaping file S1. **D**, Further enlargement to LS size #30 and PT shaping file S2. **E**, Apical preparation to LS size #40 and PT finishing file F1. **F**, Additional enlargement to LS size #50 and PT finishing file F2. **G**, Superimposed μCT reconstructions comparing the initial canal geometry *(in green)* with the shape reached after use of the instruments shown in **F**. **H**, Final shape after step-back with LS instruments and PT finishing file F3. **I**, Superimposed μCT reconstructions comparing initial geometry and final shape. Note the slight ledge in the buccal canal after LS preparation and some straightening in the lingual canal after PT preparation.

while registering tactile feedback. The first instrument that experiences resistance 4 mm short of working length is the final apical size; it is then advanced to working length like the smaller instruments before. The next larger instrument is placed to 4 mm short of working length. This prepares the apical 5 mm for a matching SimpliFill obturator (SybronEndo). Midroot shaping is then accomplished with sequentially larger LSX instruments. Finally, the so-called master apical rotary, or MAR, is used to recapitulate to the working length.

All LightSpeed instruments are used in the following way: a slow, continuous apical movement is used until the blade binds; after a momentary pause, the blade is advanced further with intermittent ("pecking") motions.

Technique with the Self-Adjusting File

For this unusual file, a coronal flaring step—for example, with a G—precedes exploration with small K-files, including verification of patency and determining of working length. A glide path to a size #20 is considered appropriate; then the selected self-adjusting file is introduced into the canal with continuous irrigation through the center of the hollow file at a rate of approximately 5 ml/min. This maintains a continuous flow of active irrigant that carries with its outflow tissue debris and the dentin mud generated by the file. One file is used throughout the procedure. It is initially compressed into the root canal and gradually enlarges while cleaning and shaping the canal.

The file can rotate passively around its long axis and is guided by the operator to working length. The file is initially compressed into the root canal and gradually enlarges while cleaning and shaping the canal. The suggested time frame of instrumentation per canal dictates the final size and is approximately 3 to 4 minutes.[60] Obturation may commence with various techniques that allow plastifying gutta-percha (see Chapter 7).

Hybrid Techniques

For some time, combining various NiTi preparation systems have been suggested[89,545] to address certain shortcomings of current instruments (Box 6-4). Although many combinations are possible, the most popular and useful ones involve coronal preenlargement followed by different additional apical preparation sequences. However, clinicians must keep in mind that anatomic variations in each canal must be addressed individually with specific instrument sequences. Most important, oval canals extend deep into the apical area,[505,551,560] and apical foramina may in fact be oval in most cases.[70] Naturally, a rotating file can produce a round canal at best (Fig. 6-47); therefore, a strategy must be devised for adequately shaping oval canals without overly weakening radicular structure (compare Figs. 6-4 and 6-5). One hybrid approach completely prepared 95%

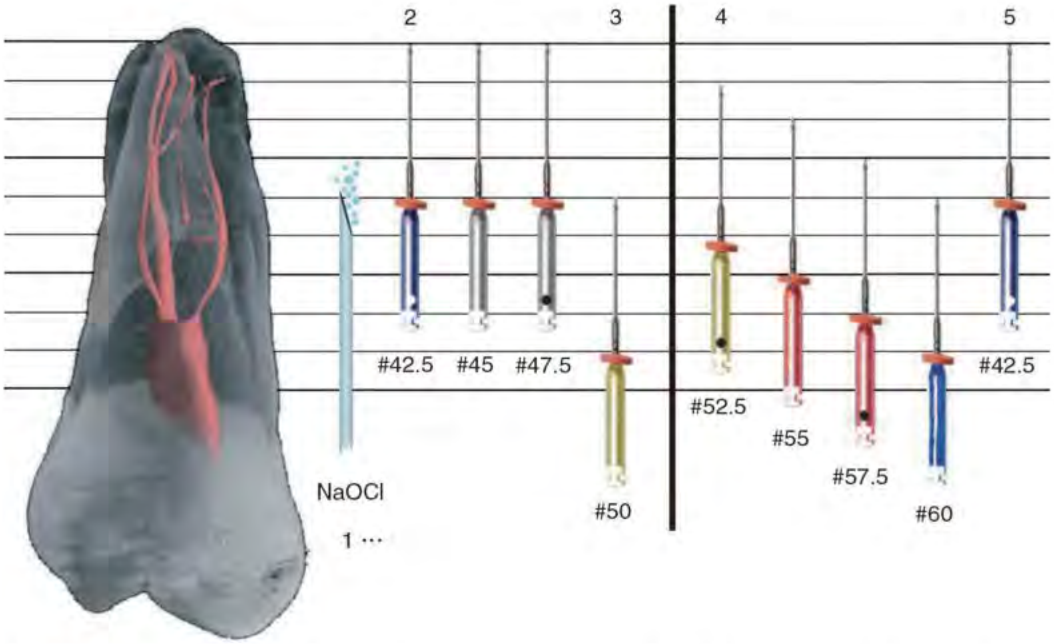


FIG. 6-46 Finishing of LightSpeed preparations to allow obturation. With the canal system flooded *(1)*, apical preparation *(2)* is continued until an LS instrument requires 12 pecks to reach the working length (WL). The next LS instrument *(3)* then is used to a point 4 mm short of the WL to prepare for LightSpeed's SimpliFill obturation system. Alternatively, canals may be flared for other root canal filling techniques by preparing with each subsequent instrument 1 mm shorter *(5)*.

BOX 6-4

Benefits of Using a Combination of Instruments for Endodontic Therapy

- Instruments can be used in a manner that promotes their individual strengths and avoids their weaknesses (most important).
- Hand instruments secure a patent glide path.
- Tapered rotary instruments efficiently enlarge coronal canal areas.
- Less tapered instruments allow additional apical enlargement.

or more of all such canals and resulted in extremely wide apical sizes that may be difficult to achieve with most instrument systems.[255,257,256]

Histologic slides (see Fig. 6-47) and µCT reconstructions show critical areas that were not mechanically prepared despite the use of various individual rotary techniques. The aim of hybridizing NiTi rotary techniques, therefore, is to increase apical size using a fast and safe clinical procedure.

Various clinicians have used this type of hybrid procedure in their practices (see Figs. 6-2 and 6-10). The principle involves the use of a variety of instruments: for example, GG drills and K-files for establishing straight-line access; ProTaper instruments for body shaping and apical preenlargement; NiTi K-files or LightSpeed instruments for apical widening; and various instruments for final smoothing.[545]

After a stainless steel file has confirmed a smooth glide path into the coronal two thirds, irrigation and mechanical preparation with a sequence of ProTaper shaping files opens and preenlarges the apical third (Fig. 6-48). Once the working length has been established, the apical third is flooded with

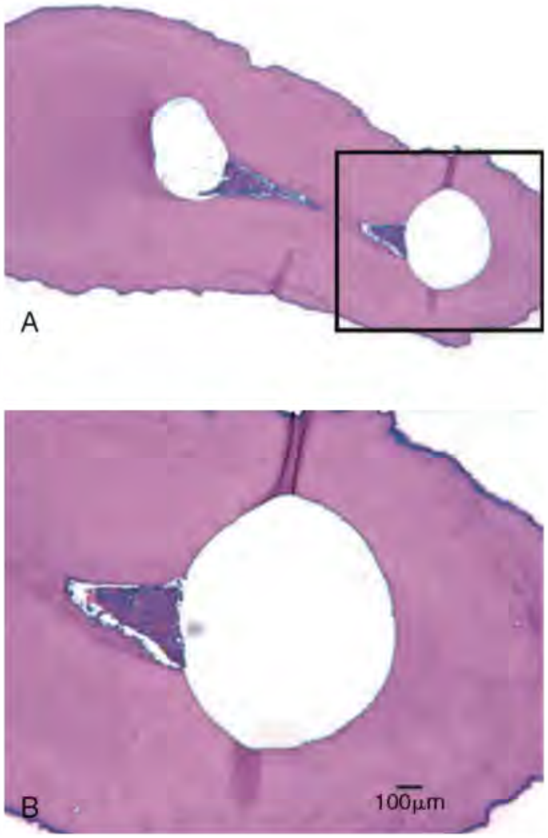


FIG. 6-47 Remaining potentially infected tissue in fins and isthmus configuration after preparation with rotary instruments. **A**, Cross section through a mesial root of a mandibular molar, middle to coronal third of the root. Both canals have been shaped; the left one is transported mesially (×10). **B**, Magnified view of rectangle in **A**. Note the presence of soft tissue in the isthmus area (×63). (Courtesy Professor H. Messer.)

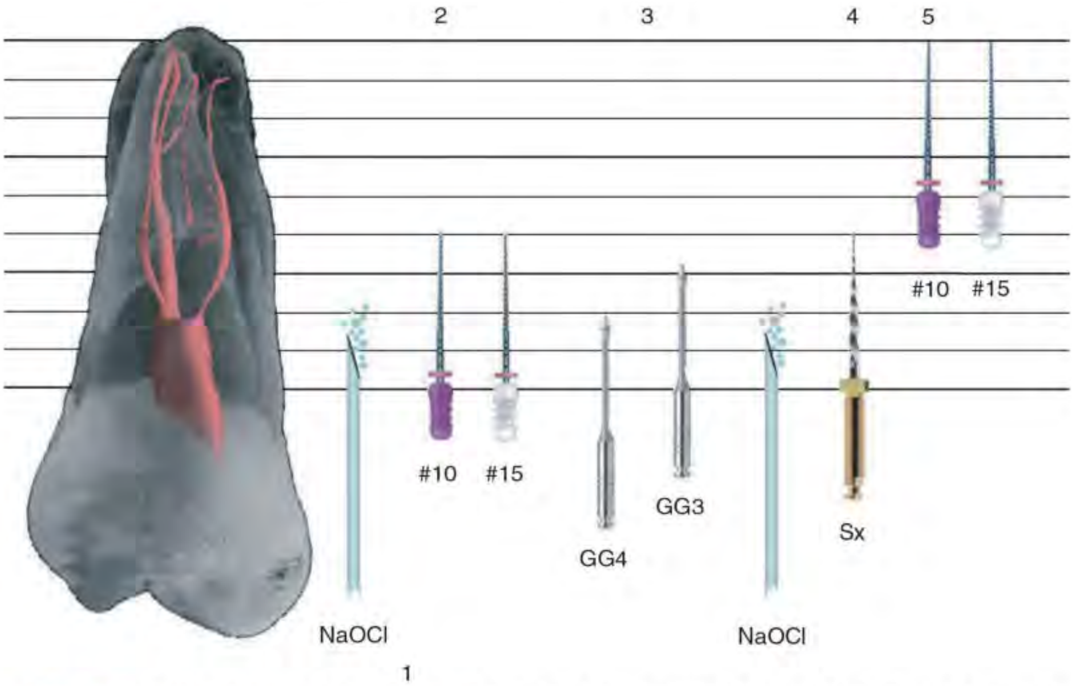


FIG. 6-48 Hybrid technique: Part I. After irrigation *(1)* and scouting *(2)*, GG drills *(3)* or ProTaper SX files *(4)* are used for coronal preenlargement and to secure straight-line access to the middle third. Precurved K-files are then used to explore and determine the working length *(5)*.

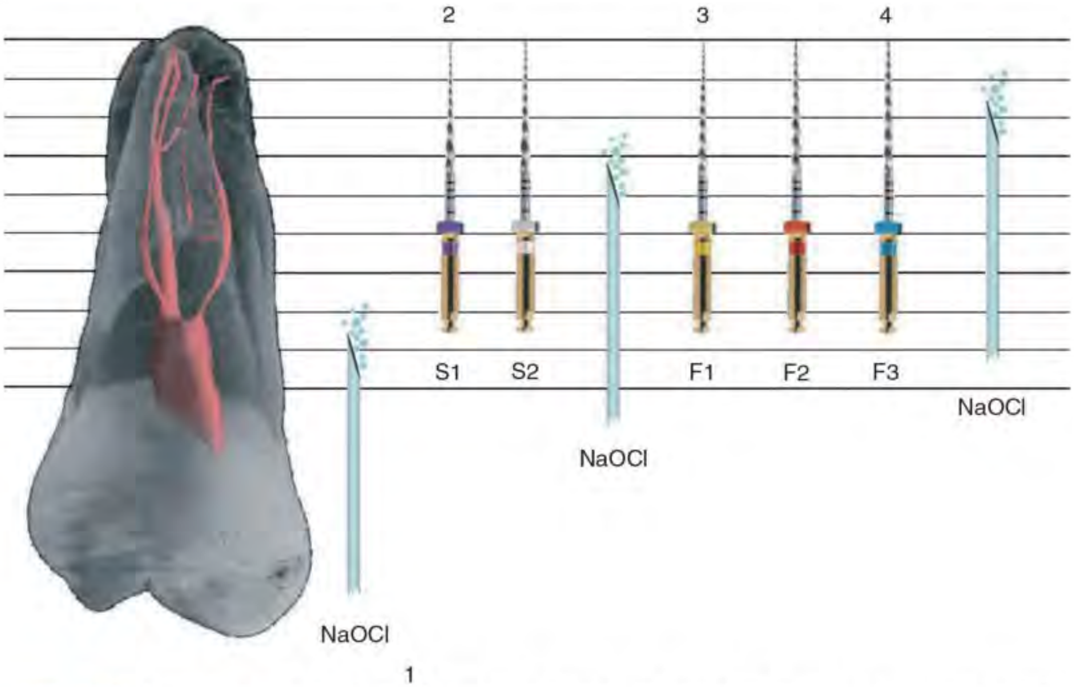


FIG. 6-49 Hybrid technique: Part II. In canal systems flooded with irrigant *(1)*, ProTaper shaping instruments S1 and S2 *(2)* and then finishing instruments F1 and F2 *(3)* are used to preenlarge the apical third, allowing irrigants access to the canals. Finishing instrument F3 may be used if feasible *(4)*.

NaOCl and further enlarged with ProTaper finishing files F1 and F2. The F3 ProTaper finishing file is relatively inflexible, and because of its side-cutting action, it should be used with caution in curved canals (Fig. 6-49). Further enlargement is possible with the F4 and F5 instruments, but these files may not be used in more acutely curved canals. The effectiveness of techniques combining different rotary instruments in enlarging canals recently was documented using superimposed root canal cross sections (Fig. 6-50). This method can help identify insufficiently prepared areas and weakening of the radicular structure.

A different approach, using, for example, NiTi K-files, .02 tapered rotaries (e.g., RaCe), or LightSpeed LSX (Fig. 6-51), may be also advantageous if larger sizes are desired. Finally, the overall shape may be smoothed with either engine-driven or handheld instruments. Handheld ProTaper or GT instruments may aid removal of acute apical curvatures or ledges and provide access to apical canal areas for irrigants.

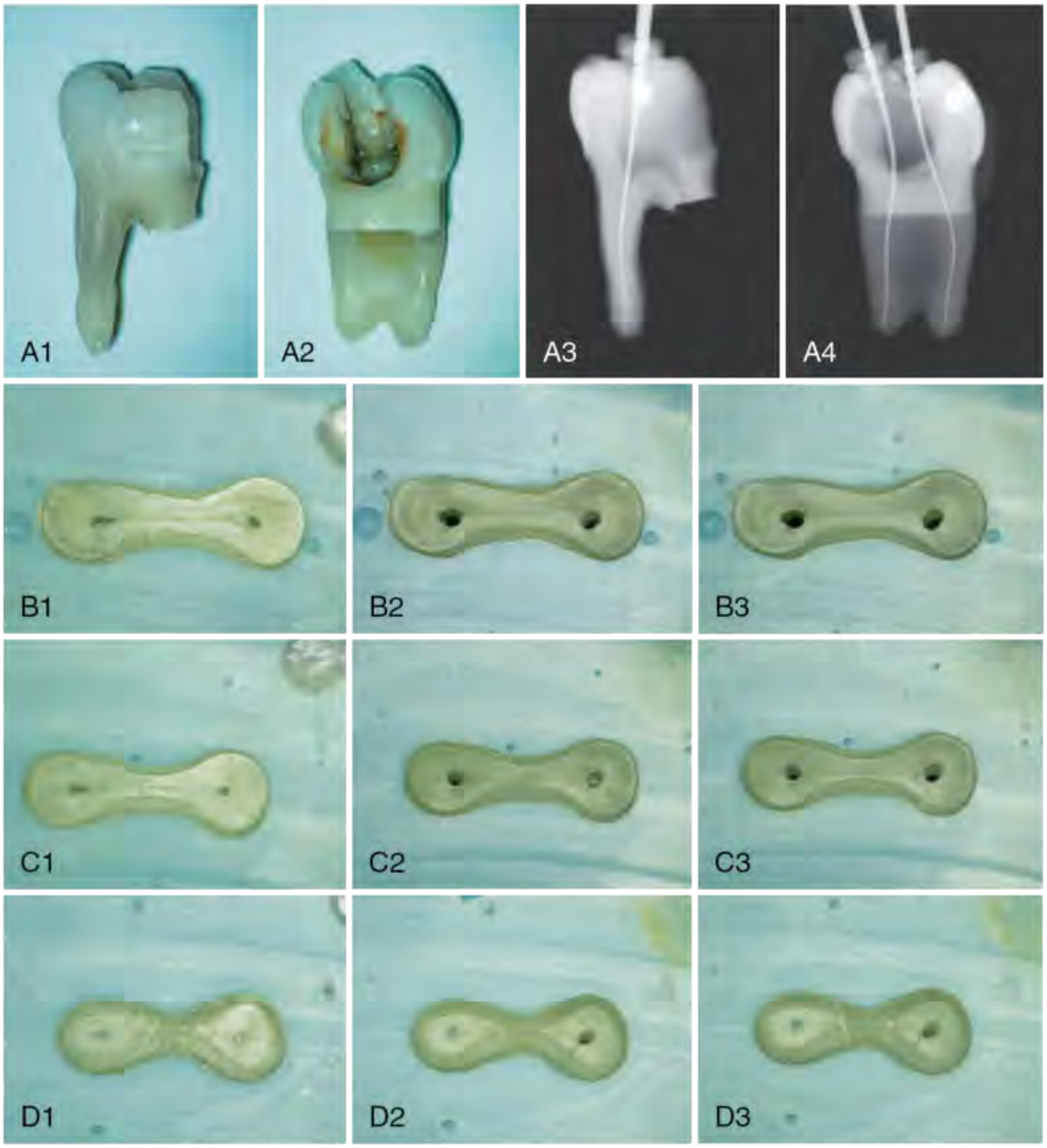


FIG. 6-50 Effect of a hybrid technique on root canal anatomy studied in a Bramante model. **A1-A4**, Both mesial canals of an extracted mandibular molar have been instrumented. Canal cross sections are shown before instrumentation (**B1-D1**). **B2-D2**, Cross sections after preenlargement with a ProTaper F3 file (*left canal*) and a size #45, #.02 taper instrument *(right canal)*. The final apical sizes were LightSpeed (LS) #50 and size #50, #.02 taper in the left and the right canal, respectively. (Courtesy Drs. S. Kuttler, M. Gerala, and R. Perez.)

Some hybrid systems seem to work better than others, but the deciding factors are likely the root canal anatomy and an adequate preparation goal.

Most cases requiring root canal therapy lend themselves to canal preparation with many different systems. Depending on the individual anatomy and the clinician's strategy, various sequences may be used. Mesiobuccal roots of the maxillary molar can show substantial curvature; rotary instrumentation or hybrid techniques allow preservation of the curvature and optimal enlargement. Occasionally hand instruments other than ISO-normed files are used in these cases to ensure a smooth, tapered shape or to eliminate ledges.

Final Apical Enlargement

Conceptually, file sizes during canal preparation were termed *initial apical file, master apical file,* and *final file* (or IAF, MAF, and FF, respectively). The first file to bind, the IAF, is supposed to give clinicians a guide in determining the final size of their canal preparation. On the other hand, many current instrumentation techniques have, due to their design, predefined final sizes—for example, WaveOne shaping aims at final sizes #25 .08 taper and #40, .08 taper.

Whichever apical size was conceptually aimed for, after shaping the overall canal to a tapered form, the apical size at that point should be assessed during apical gauging. K-files or K-Flexofiles are often recommended for this step; the files should be gently moved toward the working length (WL), and the binding point should be noted. The presence of an apical narrowing would translate into the fact that the WL may be reached without shaping effort with the desired size during gauging; however, the next larger size will stay back by a small distance. Finally, it should be verified that patency is maintained.

If apical gauging suggests that the canal is undershaped, additional enlargement is done with any technique appropriate to the specific anatomy of the root canal, often necessitating a hybrid technique.

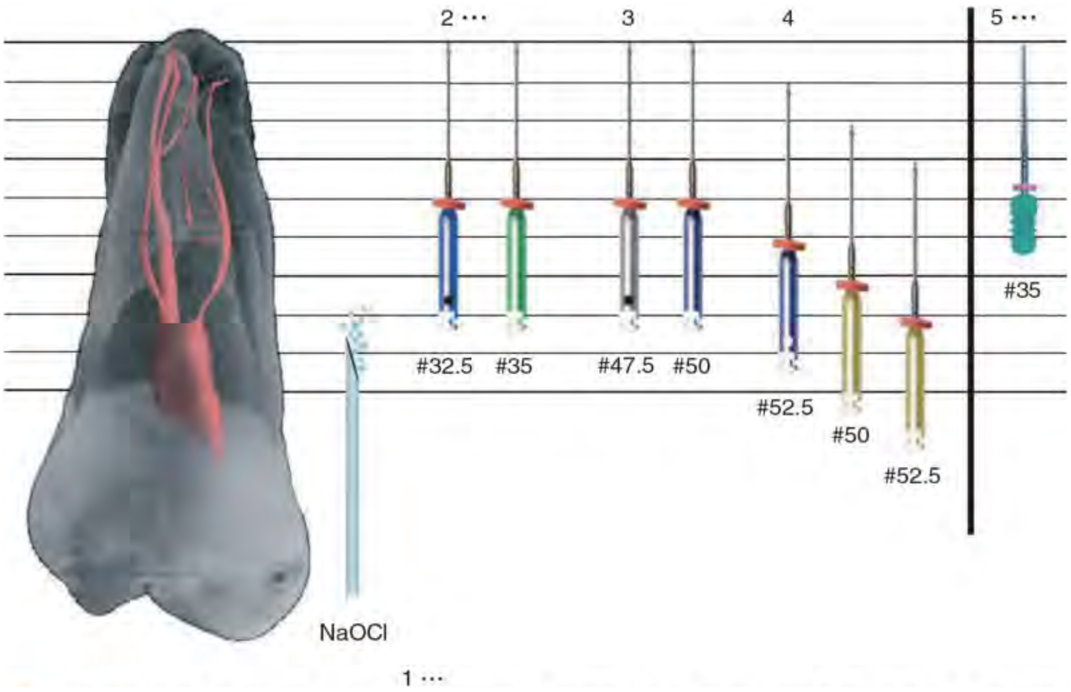


FIG. 6-51 Hybrid technique: Part III. Under irrigation *(1)*, LightSpeed instruments may be used to enlarge substantially (*2* and *3*) and to flare the apical section *(4)*. NiTi hand instruments *(5)* may be used similarly (see text for a more detailed explanation).

DISINFECTION OF THE ROOT CANAL SYSTEM

Hydrodynamics of Irrigation

Irrigation dynamics refers to how irrigants flow, penetrate, and readily exchange within the root canal system as well as the forces they produce. A better understanding of the fluid dynamics of different modes of irrigation will contribute to achieving predictable disinfection of the root canal system. Hence, in endodontic disinfection, the process of delivery is as important as the antibacterial characteristics of the irrigants.[65]

Irrigation is defined as "to wash out a body cavity or wound with water or a medicated fluid" and aspiration as "the process of removing fluids or gases from the body with a suction device." Disinfectant, meanwhile, is defined as "an agent that destroys or inhibits the activity of microorganisms that cause disease."[106]

The objectives of irrigation in endodontics are mechanical, chemical, and biologic. The mechanical and chemical objectives are as follows: (1) flush out debris, (2) lubricate the canal, (3) dissolve organic and inorganic tissue, and (4) prevent the formation of a smear layer during instrumentation or dissolve it once it has formed.[42] The mechanical effectiveness will depend on the ability of irrigation to generate optimum streaming forces within the entire root-canal system. The chemical effectiveness will depend on the concentration of the antimicrobial irrigant, the area of contact, and the duration of interaction between irrigant and infected material.[65] The final efficiency of endodontic disinfection will depend on its chemical and mechanical effectiveness.[190]

The biologic function of irrigants is related to their antimicrobial effects. In principle, irrigants should (1) have a high efficacy against anaerobic and facultative microorganisms in their planktonic state and in biofilms, (2) inactivate endotoxin, and (3) be nontoxic when they come in contact with vital tissues, and (4)b not cause an anaphylactic reaction.[42]

Efficiency of root canal irrigation in terms of debris removal and eradication of bacteria depends on several factors: penetration depth of the needle, diameter of the root canal, inner and outer diameter of the needle, irrigation pressure, viscosity of the irrigant, velocity of the irrigant at the needle tip, and type and orientation of the needle bevel (Fig. 6-52).

Penetration Depth of the Needle

The size and length of the irrigation needle—in relation to root canal dimensions—is of utmost importance for the effectiveness of irrigation.

Diameter of the Root Canal

The apical diameter of the canal has an impact on needle penetration depth (see earlier in this chapter for details regarding apical preparation size (see Fig. 6-7, Table 6-2).[72,578]

Inner and Outer Diameter of the Needle (Fig. 6-53, *A* and *B*)

The external needle diameter is of relevance for the depth of introduction into the root canal and for rigidity of the tip, an important consideration for irrigation of curved canals. Common 27 gauge injection needles have an external diameter of 0.42 mm, but smaller irrigation tips with external diameters of 0.32 mm (30 gauge) are available.[235] The Stropko Flexi-Tip (30 gauge) needle is fabricated from nickel-titanium to improve penetration into curved root canals.[205]

Irrigation Pressure

The internal diameter determines the pressure necessary for moving the syringe plunger. The speed of the plunger

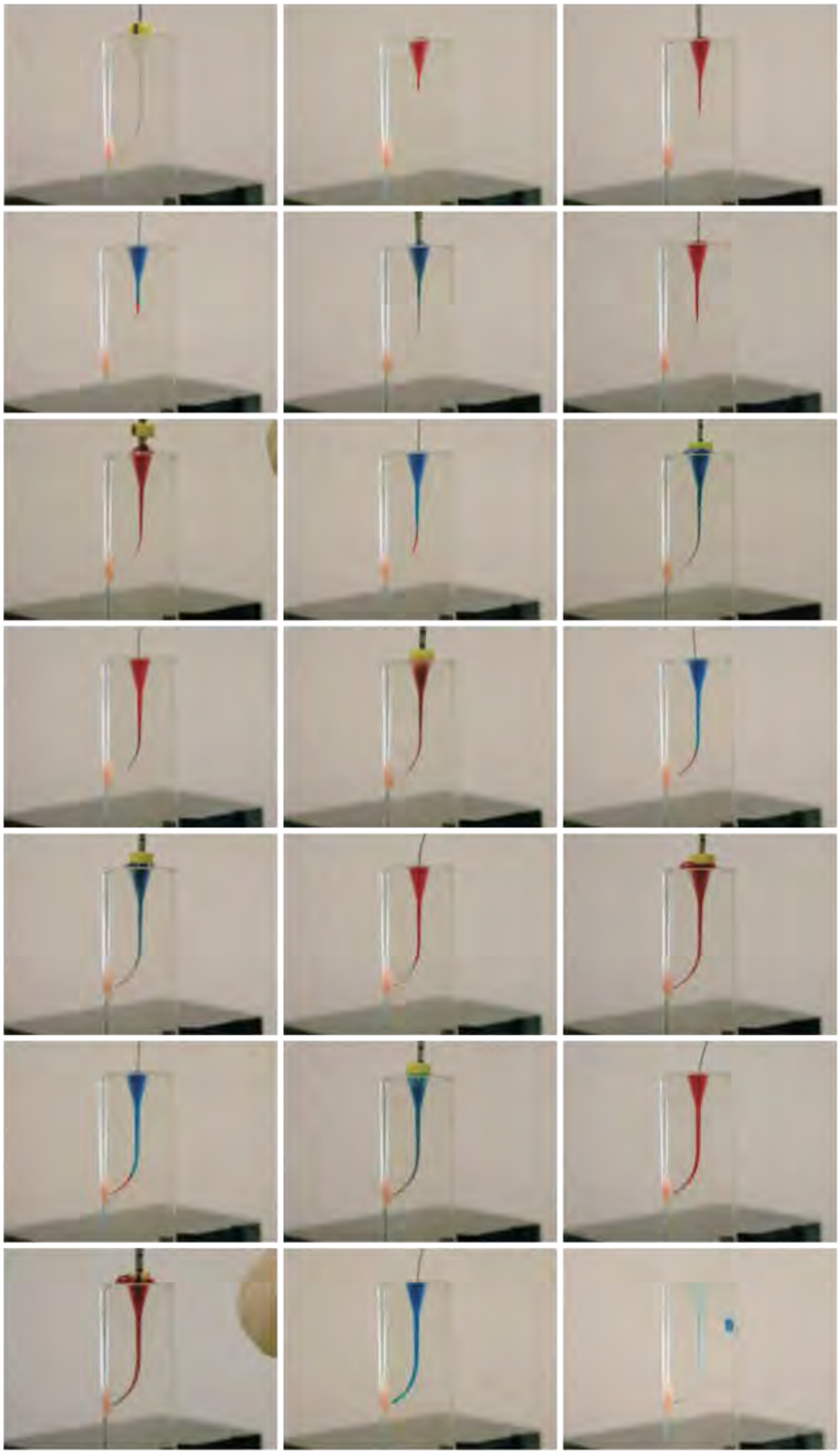


FIG. 6-52 Irrigation and movement of irrigants depends on canal shape. Sequential enlargement of a canal in clear plastic block was performed with a sequence of ProFile instruments in accordance with the manufacturer's recommendations. Alternating irrigation with blue and red fluid was done after each preparation step. Note the apical presence of irrigant after sufficient shape has been provided. Note the distribution of fluid immediately after irrigation with a 30-gauge needle.

determines the velocity with which the irrigant is extruded. Narrow needles require more pressure onto the plunger and extrude the irrigant with higher velocity than large needle sizes, which extrude greater amounts of irrigants but cannot be introduced as deep.

Type and Orientation of the Bevel of the Needle

To improve safety of irrigation and prevent extrusion of the irrigant through the apical foramen, some needles release the solution via lateral openings and have a closed, safe-ended tip. The orientation of the bevel is crucial to produce a turbulence effect on the dentinal wall of the canal. Side-vented and double side-vented needles lead to maximum shear stress concentrated on the wall facing the outlet (the proximal outlet for the double side-vented).[67]

Irrigants

An optimal irrigant would have all of the characteristics considered beneficial in endodontics but none of the negative or harmful properties. Presently, no solution can be regarded

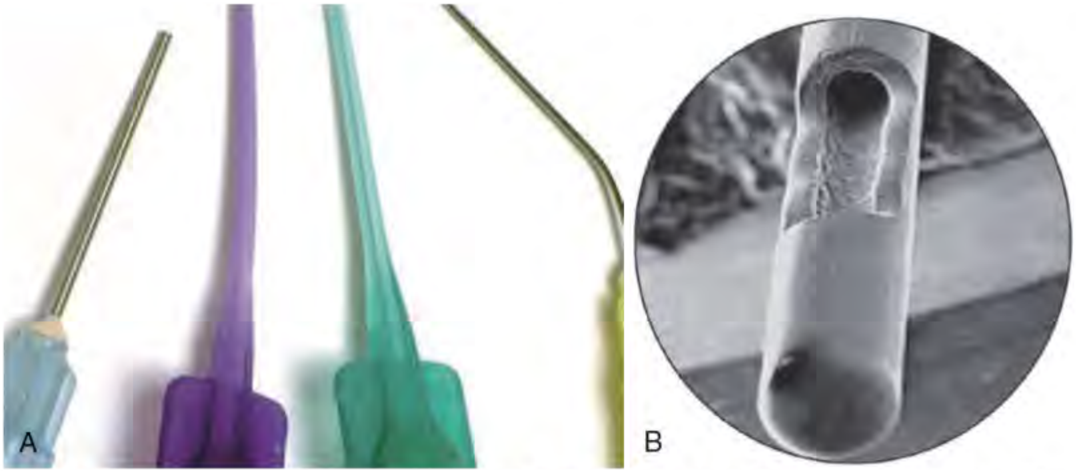


FIG. 6-53. A, Various types of needles for root canal irrigation. Shown are examples with open end and closed end, side vented. These are manufactured from plastic and stainless steel. B, SEM image of 30 gauge safety needle. (Courtesy Dr. F. Tay.)

BOX 6-5

Benefits of Using Irrigants in Root Canal Treatment

- Removal of particulate debris and wetting of the canal walls
- Destruction of microorganisms
- Dissolution of organic debris
- Opening of dentinal tubules by removal of the smear layer
- Disinfection and cleaning of areas inaccessible to endodontic instruments

BOX 6-6

Properties of an Ideal Irrigant for Root Canal Treatment

An ideal irrigant should do the following:

- Be an effective germicide and fungicide
- Be nonirritating to the periapical tissues
- Remain stable in solution
- Have a prolonged antimicrobial effect
- Be active in the presence of blood, serum, and protein derivatives of tissue
- Have low surface tension
- Not interfere with repair of periapical tissues
- Not stain tooth structure
- Be capable of inactivation in a culture medium
- Not induce a cell-mediated immune response
- Be able to completely remove the smear layer, and be able to disinfect the underlying dentin and its tubules
- Be nonantigenic, nontoxic, and noncarcinogenic to tissue cells surrounding the tooth
- Have no adverse effects on the physical properties of exposed dentin
- Have no adverse effects on the sealing ability of filling materials
- Have a convenient application
- Be relatively inexpensive

as optimal. However, combined use of selected irrigation products greatly contribute to successful outcome of treatment (Box 6-5 and Box 6-6).

Sodium Hypochlorite

NaOCl is the most commonly used irrigating solution[332] because of its an antibacterial capacity and the ability to dissolve necrotic tissue, vital pulp tissue, and the organic components of dentin and biofilms in a fast manner.[453]

NaOCl solution is frequently used as a disinfectant or a bleaching agent. It is the irrigant of choice in endodontics, owing to its efficacy against pathogenic organisms and pulp digestion, and satisfies most of the preferred characteristics stated earlier.[332]

History

Hypochlorite was first produced in 1789 in France. Hypochlorite solution was used as a hospital antiseptic that was sold under the trade names Eusol and Dakin's solution. Dakin recommended NaOCl as a buffered 0.5% solution for the irrigation of wounds during World War I.[114] Coolidge[108] later introduced NaOCl to endodontics an intracanal irrigation solution.[575]

Mode of Action

When sodium hypochlorite contacts tissue proteins, nitrogen, formaldehyde, and acetaldehyde are formed. Peptide links are fragmented and proteins disintegrate, permitting hydrogen in the amino groups (-NH-) to be replaced by chlorine (-NCl-) forming chloramines; this plays an important role for the antimicrobial effectiveness. Necrotic tissue and pus are dissolved and the antimicrobial agent can better reach and clean the infected areas.

In 2002 Estrela reported that sodium hypochlorite exhibits a dynamic balance (Fig. 6-54)[142]:

1. Saponification reaction: Sodium hypochlorite acts as an organic and fat solvent that degrades fatty acids and transforms them into fatty acid salts (soap) and glycerol (alcohol), reducing the surface tension of the remaining solution.
2. Neutralization reaction: Sodium hypochlorite neutralizes amino acids by forming water and salt. With the exit of hydroxyl ions, the pH is reduced.
3. Hypochlorous acid formation: When chlorine dissolves in water and it is in contact with organic matter, it forms

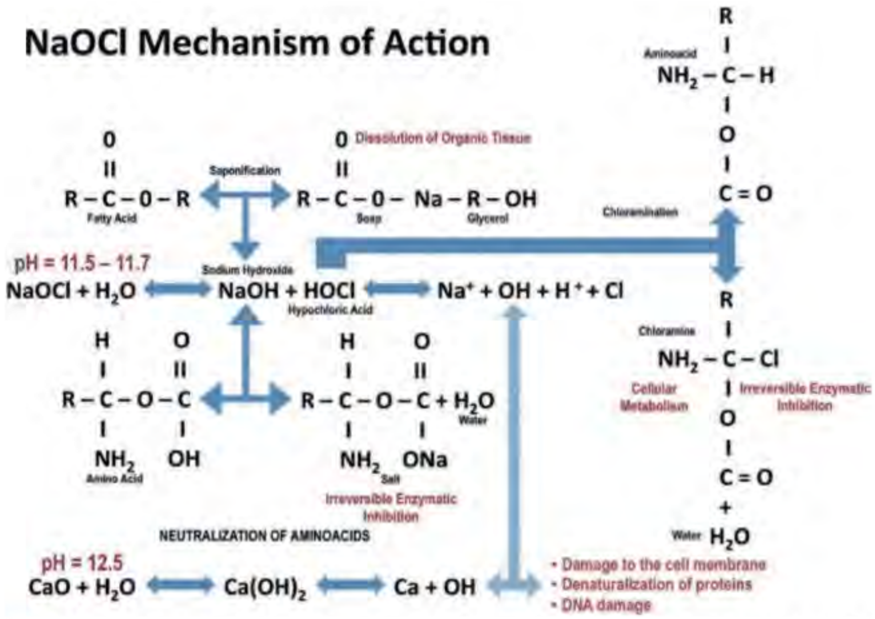


FIG. 6-54 Schematic diagram of the mechanism of action of NaOCl with the main interactions and properties highlighted. (Courtesy Dr. A. Manzur.)

hypochlorous acid. It is a weak acid with the chemical formula HClO that acts as an oxidizer. Hypochlorous acid ($HOCl^-$) and hypochlorite ions (OCl^-) lead to amino acid degradation and hydrolysis.

4. Solvent action: Sodium hypochlorite also acts as a solvent, releasing chlorine that combines with protein amino groups (NH) to form chloramines (chloramination reaction). Chloramines impede cell metabolism; chlorine is a strong oxidant and inhibits essential bacterial enzymes by irreversible oxidation of SH groups (sulfydryl group).[142]
5. High pH: Sodium hypochlorite is a strong base (pH > 11). The antimicrobial effectiveness of sodium hypochlorite, based on its high pH (hydroxyl ions action), is similar to the mechanism of action of calcium hydroxide. The high pH interferes in cytoplasmic membrane integrity due to irreversible enzymatic inhibition, biosynthetic alterations in cellular metabolism, and phospholipid degradation observed in lipidic peroxidation.[142]

Allergic Reactions to Sodium Hypochlorite

Although few reports have been published on allergic reactions to NaOCl,[144,198] real allergies to NaOCl are unlikely to occur, as both Na and Cl are essential elements in the physiology of the human body. It must be remembered that the hypochlorous acid (active component of the sodium hypochlorite) is a chemical substance that is elaborated by neutrophils in the process of phagocytosis; it may create local tissue damage when it is produced in excess (liquefaction necrosis: purulent exudate) but does not cause allergic responses. Nevertheless, hypersensitivity and contact dermatitis may occur in rare situations. A case report describes a serious chemical burn in an endodontist's eye caused by accidental contact with 3.5% NaOCl used as an irrigant during root canal.[403]

When hypersensitivity to NaOCl is suspected or confirmed, chlorhexidine should not be used either because of its chlorine content. For individuals who genetically have more possibilities than the normal population to generate allergies to multiple elements (allergies to food or to latex), a skin test

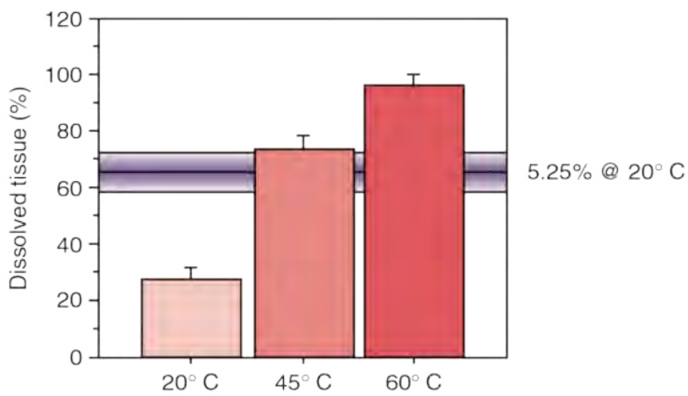


FIG. 6-55 Effect of heating on the ability of 0.5% sodium hypochlorite (NaOCl) to dissolve pulp tissue: NaOCl heated to 113° F (45° C) dissolved pulp tissue as well as the positive control (5.25% NaOCl) did. When the NaOCl was heated to 140° F (60° C), almost complete dissolution of tissue resulted. (Modified from Sirtes G, Waltimo T, Schaetzle M, Zehnder M: The effects of temperature on sodium hypochlorite short-term stability, pulp dissolution capacity, and antimicrobial efficacy, *J Endod* 31:669, 2005.)

for both NaOCl and CHX may be indicated. The use of an alternative irrigant with high antimicrobial efficacy, such as iodine potassium iodide, should be considered, assuming there is no known allergy to that irrigant. Solutions such as alcohol or tap water are less effective against microorganisms and do not dissolve vital or necrotic tissue; however, $Ca(OH)_2$ could be used as a temporary medicament because it dissolves both vital and necrotic tissue.[18,207]

Temperature

Increasing the temperature of low-concentration NaOCl solutions improves their immediate tissue-dissolution capacity (Fig. 6-55).[575] Furthermore, heated hypochlorite solutions remove organic debris from dentin shavings more efficiently. Bactericidal rates for NaOCl solutions, the capacity of human pulp dissolution, and increased efficacy were detailed in several

FIG. 6-56 Device for heating syringes filled with irrigation solution (e.g., sodium hypochlorite) before use. (Courtesy Vista Dental Products, Racine, WI.)

studies.[475] There are various devices to preheat NaOCl syringes (Fig. 6-56); however, it was demonstrated that as soon as the irrigant touches the root canal system, the temperature reaches the body temperature.[579] Therefore, some authors recommend in situ heating of NaOCl. This can be done by activating ultrasonic or sonic tips to the NaOCl inside the root canal for a couple of minutes (see irrigation timings, discussed later). Macedo and colleagues stated that the efficacy of NaOCl on dentin is improved by refreshment, ultrasonic activation, and exposure time.[307] In this investigation, a 10° C temperature rise during ultrasonic activation was insufficient to increase the reaction rate. However, no clinical studies are available at this point to support the use of heated NaOCl.[42,104]

Concentrations

NaOCl is used in concentrations between 0.5% and 6% for root canal irrigation. Controversy exists over recommended concentrations of sodium hypochlorite during root canal treatment. Some in vitro studies have shown that NaOCl in higher concentrations is more effective against *Enterococcus faecalis* and *Candida albicans*.[177,395,547] In contrast, clinical studies have indicated both low and high concentrations to be equally effective in reducing bacteria from the root canal system.[87,111] NaOCl in higher concentrations has a better tissue-dissolving ability.[204] However, in lower concentrations when used in high volumes it can be equally effective.[336,470] Higher concentrations of NaOCl are more toxic than lower concentrations.[491] However, due to the confined anatomy of the root canal system, higher concentrations have successfully been used during root canal treatment, with a low incidence of mishaps.

In summary, if lower concentrations are to be used for intracanal irrigation, it is recommended that the solution be used in higher volume and in more frequent intervals to compensate for the limitations in effectiveness.[470]

Instrumentation coupled with an antimicrobial irrigant, such as NaOCl, has been shown to yield more negative cultures than instrumentation alone.[86,323,364,372,463] However, even with the use of NaOCl, removal of bacteria from the root canal systems following instrumentation remains an elusive goal.

Grossman observed pulp tissue dissolution capacity and reported that 5% sodium hypochlorite dissolved this tissue in between 20 minutes and 2 hours.[185] The dissolution of bovine pulp tissue by sodium hypochlorite (0.5, 1.0, 2.5, and 5.0%) was studied in vitro under different conditions.[142] The study yielded the following conclusions:

1. The velocity of dissolution of the bovine pulp fragments was directly proportional to the concentration of the sodium hypochlorite solution and was greater without the surfactant;
2. variations in surface tension, from beginning to end of pulp dissolution, were directly proportional to the concentration of the sodium hypochlorite solution and greater in the solutions without surfactant. Solutions without surfactant presented a decrease in surface tension and those with surfactant an increase;
3. in heated sodium hypochlorite solutions, dissolution of the bovine pulp tissue was more rapid;
4. the greater the initial concentration of the sodium hypochlorite solutions, the smaller was the reduction of its pH.[142]

Time

There is conflicting evidence regarding the time course of the antibacterial effect of NaOCl.[42,195] In some articles hypochlorite is reported to kill the target microorganism in seconds, even at low concentrations, whereas other reports have published considerably longer times for the killing of the same species.[185] Such differences are likely a result of several factors: the presence of organic matter during experiments has a detrimental effect on the antibacterial activity of NaOCl. Haapasalo and colleagues showed that the presence of dentin caused marked delays in the killing of *Enterococus faecalis* by 1% NaOCl.[193] Morgental and colleagues reported similar findings.[337]

Many of the earlier studies were performed in the presence of an unknown amount of organic matter. When such confounding factors are eliminated, it has been shown that NaOCl kills the target microorganisms rapidly even at low concentrations of less than 0.1%.[195,539] However, in vivo the presence of organic matter (inflammatory exudate, tissue remnants, and microbial biomass) consumes NaOCl and weakens its effect. Therefore, continuous replenishing of irrigation solution and allowing sufficient contact time are important factors for the effectiveness of NaOCl.[195]

The chlorine ion, which is responsible for the dissolving and antibacterial capacity of NaOCl, is unstable and consumed rapidly during the first phase of tissue dissolution, probably within 2 minutes,[336] which provides another reason for continuous replenishment. This should especially be considered in view of the fact that rotary root canal preparation techniques have expedited the shaping process. The optimal time that a hypochlorite irrigant at a given concentration needs to remain in the canal system is an issue yet to be resolved.[575]

Toxicity

If inadvertently NaOCl is extruded through the apex, severe accidents may occur (Fig. 6-57, A-C). It is important to recognize the symptoms and act accordingly. After an accident with NaOCl, the following can be expected: severe pain, edema of neighboring soft tissues, possible extension of edema over the injured half of face and upper lip, profuse bleeding from root canal, profuse interstitial bleeding with hemorrhage of skin and mucosa (ecchymosis), chlorine taste and irritation of throat after injection into maxillary sinus, secondary infection possible, and reversible anesthesia or paresthesia is possible. To manage these lesions, the clinician should inform the patient and control pain with local anesthesia and analgesics.

FIG. 6-57 Toxic effect of sodium hypochlorite on periradicular tissues. After root canal treatment of tooth #3, the patient reported pain. **A**, On a return visit, an abscess was diagnosed and incised. **B**, Osteonecrosis was evident after 3 weeks.

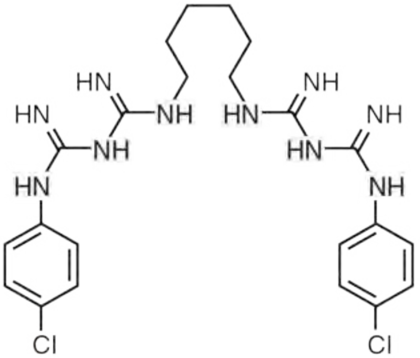


FIG. 6-58 Schematic drawing of the chlorhexidine molecule.

The application of extraoral cold compresses to reduce swelling is also effective. After 1 day, warm compresses and frequent warm mouth rinses for stimulation of local systemic circulation should be used. Patients should be recalled daily to monitor recovery. The use of antibiotics is not obligatory and is recommended only in cases of high risk or evidence of secondary infection. The administration of antihistamine is also not obligatory, and the use of corticosteroids is controversial. Further endodontic therapy with sterile saline or chlorhexidine as root canal irrigants and referral to a hospital in case of worsening symptoms were suggested.[260]

Chlorhexidine

History

Chlorhexidine (CHX) was developed in the UK and first marketed as an antiseptic cream.[148] It has been used for general disinfection purposes and the treatment of skin, eye, and throat infections in both humans and animals.[148,294] It has been used as an irrigant and medicament in endodontics for more than a decade.[309,333,363]

Molecular Structure

CHX is a strongly basic molecule with a pH between 5.5 and 7 that belongs to the polybiguanide group and consists of two symmetric four-chlorophenyl rings and two bisbiguanide groups connected by a central hexamethylene chain. CHX digluconate salt is easily soluble in water and very stable[184] (Fig. 6-58).

Mode of Action

Chlorhexidine, because of its cationic charges, is capable of electrostatically binding to the negatively charged surfaces of bacteria,[117] damaging the outer layers of the cell wall and rendering it permeable.[214,229,228] CHX is a wide-spectrum antimicrobial agent, active against gram-positive, gram-negative bacteria and yeasts.[129]

Depending on its concentration, CHX can have both bacteriostatic and bactericidal effects. At high concentrations, CHX acts as a detergent; and exerts its bactericidal effect by damaging the cell membrane and causes precipitation of the cytoplasm. At low concentrations, CHX is bacteriostatic, causing low molecular-weight substances (i.e., potassium and phosphorus) to leak out without the cell being permanently damaged.[43]

Substantivity

Because of the cationic nature of the CHX molecule, it can be absorbed by anionic substrates such as the oral mucosa and tooth structure.[308,312,414,527] CHX is readily adsorbed onto hydroxyapatite and teeth. Studies have shown that the uptake of CHX onto teeth is reversible.[222] This reversible reaction of uptake and release of CHX leads to substantive antimicrobial activity and is referred to as *substantivity*. This effect depends on the concentration of CHX. At low concentrations of 0.005% to 0.01%, only a constant monolayer of CHX is adsorbed on the tooth surface, but at higher concentrations (>0.02%), a multilayer of CHX is formed on the surface, providing a reservoir of CHX that can rapidly release the excess into the environment as the concentration of CHX in the surrounding environment decreases.[139] Time and concentration of CHX can influence the antibacterial substantivity, and the conclusions are inconsistent. Some studies demonstrated that 4% CHX has greater antibacterial substantivity than 0.2% after a 5-minute application.[333] Other studies stated that CHX should be left for more than 1 hour in the canal to be adsorbed by the dentin.[291] Komorowski and colleagues suggested that a 5-minute application of CHX did not induce substantivity, so dentin should be treated with CHX for 7 days.[265] However, when Paquette and Malkhassian,[364] in their in vivo study, medicated the canals with either liquid or gel forms of CHX for 1 week, neither of them could achieve total disinfection. Therefore, residual antimicrobial efficacy of CHX in vivo still remains to be demonstrated.

Cytotoxicity

CHX is normally used at concentrations between 0.12% and 2%. Löe and colleagues[294] demonstrated that at these concentrations, CHX has a low level of tissue toxicity, both locally and systemically. When 2% CHX was used as a subgingival irrigant, no apparent toxicity was noted on gingival tissues.[295,488] Additionally, CHX rinses have been suggested to promote healing of periodontal wounds after surgery.[24] These reports were the basis of many studies that assumed that CHX will be tolerated on periapical tissues with a similar response than in the gingival tissues.[245] When compared CHX and NaOCl into subcutaneous tissues of guinea pigs and rats, an inflammatory reaction developed; however, the toxic reaction from CHX was less than that of NaOCl.[352,571] Moreover, a reduced incidence of alveolar osteitis was found when CHX was applied as a rinse in the extraction sites of the third molars on the day of surgery and several days after.[91] Allergic and anaphylactic reactions to CHX were reported in only a few articles.[166,351] It is important to mention that patients that are allergic to NaOCl may be also allergic to CHX.

On the other hand, some controversial results were found. Some studies demonstrated that CHX is cytotoxic to some lines of cultured human skin fibroblasts.[219] It has been reported that CHX has a higher cytotoxicity profile than povidone iodine when studied in osteoblastic human alveolar bone.[88] Also, when CHX was injected in the hind paw of mice, it could induce severe toxic reactions.[149]

Finally, when CHX is mixed with NaOCl, parachloroaniline (PCA) is formed.[46] The toxicity level of CHX on periapical tissues when applied in the root canals, especially with other irrigants, merits further investigation.

Chlorhexidine as an Endodontic Irrigant

CHX has been extensively studied as an endodontic irrigant and intracanal medication, both in vivo[35,292,311,364,564] and in vitro.[41,44,45,141,245,265,273,281,282,469,471,506,540,574]

The antibacterial efficacy of CHX as an irrigant is concentration dependent. It has been demonstrated that 2% CHX has a better antibacterial efficacy than 0.12% CHX in vitro.[45] When comparing with the effectiveness with NaOCl, controversial results can be found. NaOCl has an obvious advantage over CHX with the dissolution capacity of organic matter that CHX lacks; therefore, even though in vitro studies suggest some advantages with the use of CHX, as soon as organic and dental tissue is added, NaOCl is clearly preferable.

The antibacterial effectiveness of CHX in infected root canals has been investigated in several in vivo studies. Investigators reported that 2.5% NaOCl was significantly more effective than 0.2% CHX when the infected root canals were irrigated for 30 minutes with either of the solutions.[409]

In a controlled and randomized clinical trial, the efficacy of 2% CHX liquid was tested against saline using culture technique. All the teeth were initially instrumented and irrigated using 1% NaOCl. Then either 2% CHX liquid or saline was applied as a final rinse. The authors reported a further reduction in the proportion of positive cultures in the CHX group. Their results showed a better disinfection of the root canals using CHX compared to saline as a final rinse.[574]

The antibacterial efficacy of 2% CHX gel was tested against 2.5% NaOCl in teeth with apical periodontitis, with the bacterial load assessed using a real-time quantitative polymerase chain reaction (RTQ-PCR) and colony forming units (CFUs). The bacterial reduction in the NaOCl group was significantly greater than that for the CHX group when measured by RTQ-PCR. Based on culture technique, bacterial growth was detected in 50% of the CHX group cases compared to 25% in the NaOCl group.[540] On the other hand, another study based on this culture technique revealed no significant difference between the antibacterial efficacy of 2.5% NaOCl and 0.12% CHX liquid when used as irrigants during the treatment of infected canals.[469,471]

In a systematic review, Ng and colleagues demonstrated that abstaining from using 2% CHX as an adjunct irrigant to NaOCl was associated with superior periapical healing.[345] Unlike NaOCl, CHX lacks a tissue-dissolving property. Therefore, NaOCl is still considered the primary irrigating solution in endodontics.

Chlorhexidine as an Intracanal Medication

CHX as intracanal medication has been the focus of many in vitro[38,128,265,281,468] CHX used as intracanal medicament has at least as good or even better antimicrobial efficacy than $Ca(OH)_2$.[468] and it was shown to be very effective in eliminating a biofilm of *E. faecalis*.[288]

When in vivo studies are analyzed,[35,115,123,140,292,311,364,580] some controversial results were found. On one hand, CHX, inhibits experimentally induced inflammatory external root resorption when applied for 4 weeks.[292] In infected root canals, it was shown to reduce bacteria as effectively as $Ca(OH)_2$ when applied for 1 week.[34] Because of its substantivity, CHX has the potential to prevent bacterial colonization of root canal walls for prolonged periods of time.[245,265] It was demonstrated that its effect depended on the concentration of CHX but not on its mode of application, which may be as a liquid or gel.[44]

In vivo, results can be different; one of the reasons for this is that researchers[193] developed an experimental model using dentin powder particles to investigate the possible inactivation of some antibacterial medicaments when they come in contact with dentin. They showed that dentin powder had inhibitory effects on all medicaments tested. The effect was dependent on the concentration of the medicament and the duration of contact. The effect of $Ca(OH)_2$ was totally abolished by the presence of dentin powder. The effect of 0.05% CHX and 1% NaOCl was reduced but not totally eliminated by the presence of dentin. No inhibition could be measured when full-strength solutions of CHX and IKI were used.

An in vivo investigation assessed the antibacterial efficacy of three different intracanal medications: camphorated paramonochlorophenol, $Ca(OH)_2$, and 0.12% CHX liquid by applying them for 1 week in single-rooted teeth of patients with apical periodontitis. The proportions of positive cultures were not significantly different among the tested medications, but they were slightly lower in teeth medicated with CHX (0.12%) liquid than those medicated with camphorated paramonochlorophenol or $Ca(OH)_2$.[35] Another in vivo study evaluated antibacterial effectiveness of 2% CHX liquid as an intracanal medication in teeth with apical periodontitis. The authors concluded that a moderate increase in bacterial counts during a medication period of 7 to 14 days that was similar to outcomes seen and reported for $Ca(OH)_2$ by Peters and colleagues.[364, 372] On the other hand, an alternative investigation[311] demonstrated no significant differences among the medication groups. Intracanal medication with $Ca(OH)_2$, 2% CHX gel, or a mixture of $Ca(OH)_2$/CHX applied for 7 days did not reduce the bacterial concentration beyond what was achieved after chemomechanical preparation using 1% NaOCl. Other research showed that a final rinse with MTAD and medication with 2%CHX gel, did not reduce bacterial counts beyond levels achieved by a chemomechanical preparation using NaOCl.[310]

Chlorhexidine Mixed with Calcium Hydroxide

To enhance the properties of both CHX and $Ca(OH)_2$, their combination was analyzed in several in vitro and in vivo studies. The high pH of $Ca(OH)_2$ was unaffected when combined with CHX.[46] However, the results have not been conclusive. Some in vitro studies have reported an improved antibacterial action when both agents were combined,[45,145,575] whereas other studies reported contradictory results.[199]

The combination of CHX and $Ca(OH)_2$ showed good antimicrobial properties when tested in animal studies.[480] When studied in vivo in patients with apical periodontitis, the results showed similar antibacterial efficacy of each medicament alone or in combination.[311] In another clinical study, when 0.12% CHX was used during cleaning and shaping and an intracanal medication with $Ca(OH)_2$/0.12% CHX was left in the canals for 7 days, it was found that using 0.12% CHX solution as an irrigant significantly reduced the number of intracanal bacteria, but it failed to render the canals bacteria free.[465] Therefore, it seems that the usefulness of mixing $Ca(OH)_2$ with CHX remains controversial.

Chlorhexidine and Coronal Penetration of Bacteria

Several studies analyzed the property of antibacterial substantivity and bacterial penetration.[178] It was demonstrated that placement of intracanal medication delays bacterial penetration because of the physical barrier alongside the antibacterial action of the medicament. Gomes and colleagues,[178] in a laboratory study, investigated the time required for recontamination of the root canal system of teeth with coronal restorations medicated with $Ca(OH)_2$, 2% CHX gel, or a combination of both and concluded that if medication is present, retardation of microorganism invasion was seen. Overall, because of its substantivity, CHX as an intracanal medicament/irrigant may delay the coronal recontamination of the root canal system, but more in vivo studies are needed to corroborate these results.

Interaction between CHX, NaOCl, and EDTA

NaOCl and CHX when in contact produce a change of color and a precipitate (Fig. 6-59, *A* and *B*). The reaction is dependent of the concentration of NaOCl. The higher the concentration of NaOCl, the more precipitate is generated in the presence of 2% CHX.[46] Furthermore, concerns have been raised that the color change may have some clinical relevance because of staining, and the resulting precipitate might interfere with the seal of the root obturation. Basrani and colleagues evaluated the chemical nature of this precipitate and reported the formation of 4-chloroaniline (PCA).[46] Furthermore, a study using time-of-flight secondary ion mass spectrometry (TOF-SIMS) analysis shows the penetration of PCA inside dentinal tubules. PCA has been shown to be toxic in humans with short-term exposure, resulting in cyanosis, which is a manifestation of methemoglobin formation. The combination of NaOCl and CHX causes color changes and formation of a possibly toxic insoluble precipitate that may interfere with the seal of the root obturation. Alternatively, the canal can be dried using paper points before the final CHX rinse.[575]

The combination of CHX and EDTA produces a white precipitate, so a group of investigators [399] did a study to determine whether the precipitate involves the chemical degradation of CHX. The precipitate was produced and redissolved in a known amount of dilute trifluoroacetic acid. Based on the results, CHX was found to form a salt with EDTA rather than undergoing a chemical reaction.

Chlorhexidine and Dentin Bonding

Researchers evaluated the effect of CHX on resin-dentin bond stability ex vivo.[90] They concluded that autodegradation of collagen matrices can occur in resin-infiltrated dentin, but this may be prevented by the application of a synthetic protease inhibitor such as CHX.[90] Because of its broad-spectrum matrix metalloproteinase (MMP)-inhibitory effect, CHX may significantly improve resin-dentin bond stability.[90]

Allergic Reactions to Chlorhexidine

Allergic responses to CHX are rare, and there are no reports of reactions following root canal irrigation with CHX.[27,235] Several studies have reported the sensitization rate to be approximately 2%.[268] However, some allergic reactions such as anaphylaxis, contact dermatitis, and urticaria have been reported following direct contact to mucosal tissue or open wounds.[134,388,451,479]

Decalcifying Agents

Debris is defined as dentin chips or residual vital or necrotic pulp tissue attached to the root canal wall. Smear layer was defined by the American Association of Endodontists in 2003 as a surface film of debris retained on dentin or another surface after instrumentation with either rotary instruments or endodontic files; it consists of dentin particles, remnants of vital or necrotic pulp tissue, bacterial components, and retained irrigants. Although it has been viewed as an impediment to irrigant penetration into dentinal tubules (Fig. 6-60), there is

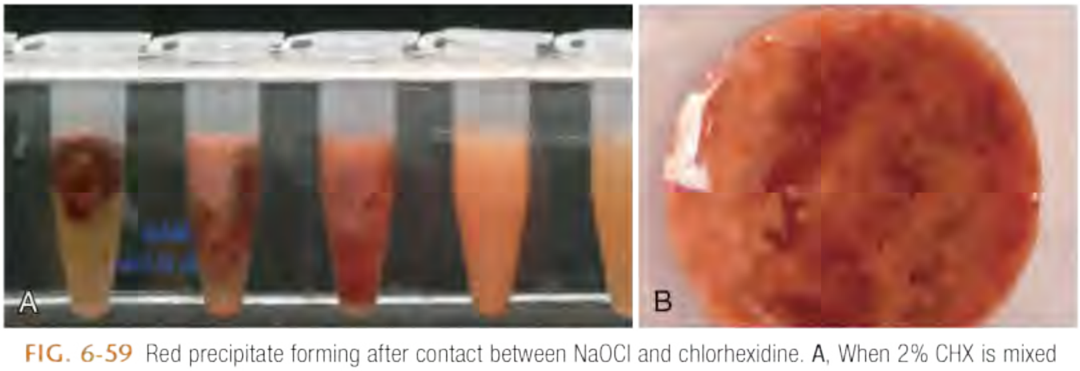


FIG. 6-59 Red precipitate forming after contact between NaOCl and chlorhexidine. **A**, When 2% CHX is mixed with different concentration of NaOCl, a change of color and precipitate occurs. The higher the concentration of NaOCl, the larger is the precipitate formation. **B**, Detail of the interaction between 2% CHX and 5%NaOCl.

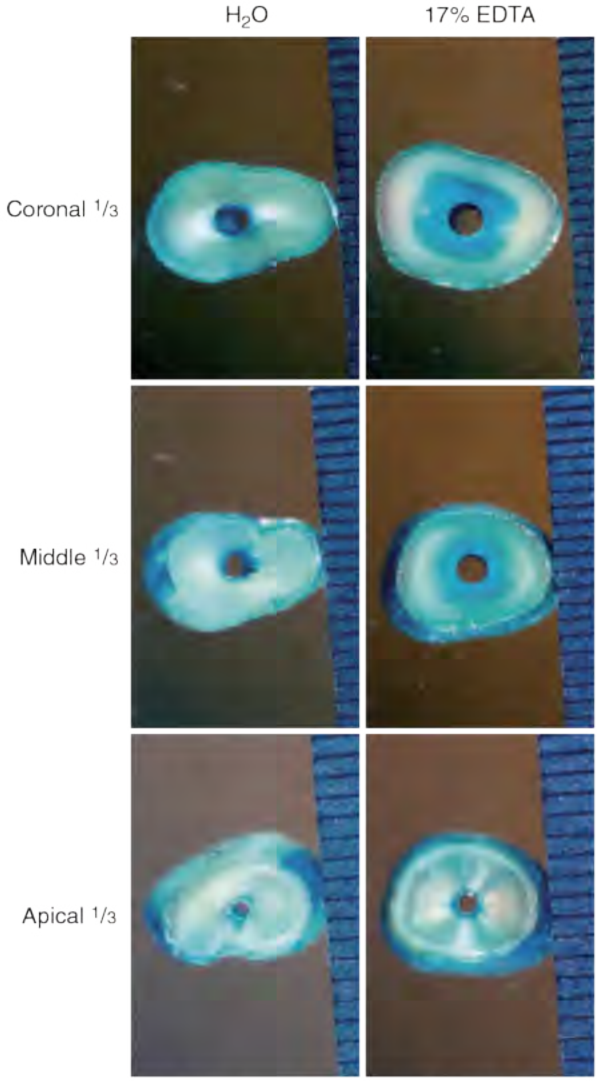


FIG. 6-60 Penetration of irrigants into dentinal tubules after root canal preparation with different dentin pretreatments. *Left column,* Irrigation with tap water and then with blue dye. *Right column,* Smear layer is removed with 17% EDTA, applied in high volume and with a 30-gauge needle, followed by irrigation with blue dye. Note the comparable diffusion of dye in the apical sections, whereas dye penetrated deeper into the dentin in the two coronal sections.

still a controversy about the influence of smear layer on the outcome of endodontic treatment. Some researchers emphasize the importance on removing the smear layer to allow irrigants, medications, and sealers to penetrate dentinal tubules and improve disinfection. On the other hand, other researchers focused on keeping the smear layer as a protection for bacterial invasion, apical and coronal micro leakage, bacterial penetration of the tubules, and the adaptation of root canal materials. The majority of the conclusions on smear layer are based on in vitro studies. A clinical study by Ng and colleagues[345] found that the use of EDTA significantly increased the odds of success of retreatment cases twofold.

Ethylenediamine Tetra-Acetic Acid

Ethylenediamine tetra-acetic acid, widely abbreviated as EDTA, is an aminopolycarboxylic acid and a colorless, water-soluble solid EDTA is often suggested as an irrigation solution because it can chelate and remove the mineralized portion of the smear

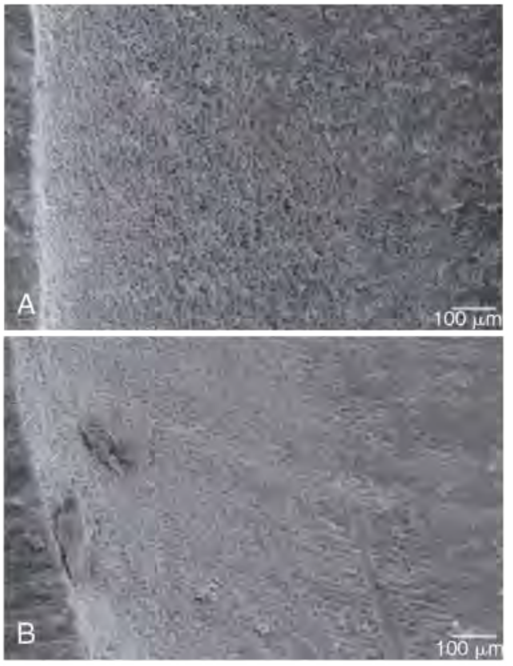


FIG. 6-61 Example of canals with minimal smear layer. **A,** Middle third after irrigation with 17% ethylenediaminetetraacetic acid (EDTA) and 2.5% sodium hypochlorite (NaOCl). **B,** Apical third with some particulate debris.

layer (Fig. 6-61). It is a polyaminocarboxylic acid with the formula $[CH_2N(CH_2CO_2H)_2]_2$. Its prominence as a chelating agent arises from its ability to sequester di- and tricationic metal ions such as Ca^{2+} and Fe^{3+}. After being bound by EDTA, metal ions remain in solution but exhibit diminished reactivity.[494]

History

The compound was first described in 1935 by Ferdinand Munz, who prepared the compound from ethylenediamine and chloroacetic acid. Chelating agents were introduced into endodontics as an aid for the preparation of narrow and calcified root canals in 1957 by Nygaard-Østby.[232] Today, EDTA is mainly synthesized from ethylenediamine (1,2-diaminoethane), formaldehyde (methanal), and sodium cyanide.[232,494]

Mode of Action

On direct exposure for extended time, EDTA extracts bacterial surface proteins by combining with metal ions from the cell envelope, which can eventually lead to bacterial death.[232] Chelators such as EDTA form a stable complex with calcium. When all available ions have been bound, equilibrium is formed and no further dissolution takes place; therefore, EDTA is self-limiting.[232]

Applications in Endodontics

EDTA alone normally cannot remove the smear layer effectively; a proteolytic component, such as NaOCl, must be added to remove the organic components of the smear layer.[176] For root canal preparation, EDTA has limited value alone as an irrigation fluid.[176] EDTA is normally used in a concentration of 17% and can remove the smear layers when in direct contact with the root canal wall for less than 1 minute. Even though EDTA has self-limited action, if it is left in the canal for longer or NaOCl is used after EDTA, erosion of dentin has been demonstrated (Fig. 6-62).

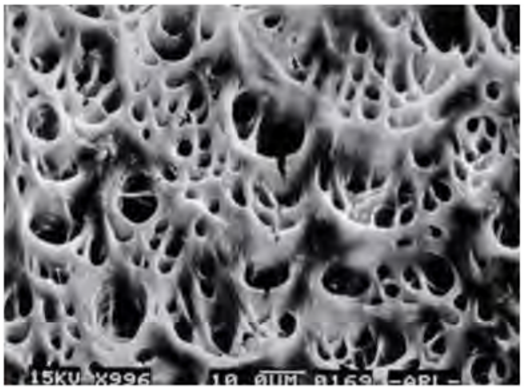


FIG. 6-62 Scanning electron microscope (SEM) image of root canal dentin exposed to 2 minutes of EDTA.

FIG 6-63 Container with BioPure MTAD. (Courtesy Dentsply Tulsa Dental Specialties, Tulsa, OK.)

Although citric acid appears to be slightly more potent at similar concentration than EDTA, both agents show high efficiency in removing the smear layer. In addition to their cleaning ability, chelators may detach biofilms adhering to root canal walls.[188] This may explain why an EDTA irrigant proved to be highly superior to saline in reducing intracanal microbiota despite the fact that its antiseptic capacity is relatively limited.[188] Antiseptics such as quaternary ammonium compounds (EDTAC) or tetracycline antibiotics (MTAD) (see the discussion on the combination of irrigants, presented later) have been added to EDTA and citric acid irrigants, respectively, to increase their antimicrobial capacity. The clinical value of this, however, is questionable. EDTAC shows similar smear-removing efficacy as EDTA, but it is more caustic.

The effect of chelators in negotiating narrow, tortuous, calcified canals to establish patency depends on both canal width and the amount of active substance available, since the demineralization process continues until all chelators have formed complexes with calcium.[232,452,577] Therefore, studies should be read with cautious because one study can show demineralization up to a depth of 50 μ m into dentin,236 but other reports demonstrated significant erosion after irrigation with EDTA.[519]

A comparison of bacterial growth inhibition showed that the antibacterial effects of EDTA were stronger than citric acid and 0.5% NaOCl but weaker than 2.5% NaOCl and 0.2% CHX.[467] EDTA had a significantly better antimicrobial effect than saline solution. It exerts it strongest effect when used synergistically with NaOCl, although no disinfecting effect on colonized dentin could be demonstrated.[212]

Interaction of EDTA and NaOCl

Investigators studied the interactions of EDTA with NaOCl.[183] They concluded that EDTA retained its calcium-complex ability when mixed with NaOCl, but EDTA caused NaOCl to lose its tissue-dissolving capacity, with virtually no free chlorine detected in the combinations. Clinically, this suggests that EDTA and NaOCl should be used separately. In an alternating irrigating regimen, copious amounts of NaOCl should be administered to wash out remnants of the EDTA. In modern endodontics, EDTA is used once the cleaning and shaping is completed for around 1 minute. It can be activated with ultrasonic activation for better penetration in dentinal tubules. It should be taken into consideration that an increase in the temperature of EDTA is not desirable. Chelators have a temperature range within which they work best. When EDTA is heated from 20° to 90°, the calcium binding capacity decreases.[576]

HBPT

HEBP (1-hydroxyethylidene-1, 1-bisphosphonate; also called etidronic acid) is a weak chelator.[575] It is a potential alternative to EDTA because it has no short-term reactivity with NaOCl. It can be used in combination with NaOCl without affecting its proteolytic or antimicrobial properties.[575] It is nontoxic,[26,125] and it is used in medicine to treat bone diseases.[362]

Combination of Irrigants and Added Detergent

Surface Tension

Irrigants with low surface tension have better wettabilty, and it is assumed that they may penetrate better in dentinal tubules and anatomic irregularities. Detergents (e.g., Tween 80) are added to irrigants to lower their surface tension. However, Boutsioukis and Kishen did not find support for this rationale,[65] perhaps because the effect of surface tension is important only at the interface between two immiscible fluids (e.g., between irrigant and an air bubble, but not between irrigant and dentinal fluid). Studies have also confirmed that surfactants do not enhance the ability of NaOCl to dissolve pulp tissue[251] or the efficacy of common chelators to remove calcium or smear layer.[65,125,300,577]

BioPure MTAD and Tetraclean

Two new irrigants based on a mixture of antibiotics, citric acid, and a detergent have been developed. These irrigants are capable of removing both the smear layer and organic tissue from the infected the root canal system.[520] MTAD (Fig. 6-63), introduced by Torabinejad and Johnson at Loma Linda University in 2003,[520] is an aqueous solution of 3% doxycycline, a broad-spectrum antibiotic; 4.25% citric acid, a demineralizing agent; and 0.5% polysorbate 80 detergent (Tween 80).[520] It is mixed as a liquid and powder prior to use. MTAD has been recommended in clinical practice as a final rinse after completion of conventional chemomechanical preparation.[48,248,457,458,520,521]

Tetraclean (Ogna Laboratori Farmaceutici, Muggio, Italy) is a combination product similar to MTAD. The two irrigants differ in the concentration of antibiotics (doxycycline 150 mg/5 ml for MTAD and 50 mg/5 ml for Tetraclean) and the kind of detergent (Tween 80 for MTAD, polypropylene glycol for Tetraclean).

Mode of Action

All tetracyclines are derivatives of four ringed nuclei that differ structurally in regard to the chemical groups at the 2, 5, 6, and

7 positions. These derivatives exhibit different characteristics such as absorption, protein binding, metabolism, excretion, and degree of activity against susceptible organism.[210] Tetracyclines inhibit protein synthesis by reversibly binding to the 30S subunit of bacterial ribosome in susceptible bacteria. It is effective against *Aa. capnocytophaga*, *P. gingivalis*, and *P. intermedia* and affects both gram-positive and gram-negative (more gram-negative effect) types. Tetracycline is a bacteriostatic antibiotic, but in high concentrations, tetracycline may also have a bactericidal effect. Doxycycline, citric acid, and Tween 80 together may have a synergistic effect on the disruption of the bacterial cell wall and on the cytoplasmic membrane.

Smear Layer Removal

In two studies, the efficacy of MTAD or EDTA in the removal of the smear layer was confirmed, but no significant difference between these two solutions was reported.[507,508]

Antibacterial Efficacy

Earlier in vitro research on MTAD showed its antimicrobial efficacy over conventional irrigants.[118,267,507,508,521] Torabinejad and colleagues found that MTAD was effective in killing *E. faecalis* up to 200× dilution.[117] Shabahang and Torabinejad showed that the combination of 1.3% NaOCl as a root canal irrigant and MTAD as a final rinse was significantly more effective against *E. faecalis* than the other regimens.[458]A study using extracted human teeth contaminated with saliva showed that MTAD was more effective than 5.25% NaOCl in disinfection of the teeth. In contrast to the previously mentioned studies, later research suggested less than optimal antimicrobial activity of MTAD.[170,248,258] Krause and colleagues,[267] using bovine tooth sections, showed that 5.25% NaOCl was more effective than MTAD in disinfection of dentin disks inoculated with *E. faecalis*.[458,468]

Clinical Trials

Malkhassain and colleagues, in a clinical controlled trial of 30 patients, reported that the final rinse with MTAD did not reduce the bacterial counts in infected canals beyond levels achieved by a chemomechanical preparation using NaOCl alone.[310]

Protocol for Use

MTAD was developed as a final rinse to disinfect the root canal system and remove the smear layer. The effectiveness of MTAD to completely remove the smear layer is enhanced when a low concentration of NaOCl (1.3%) is used as an intracanal irrigant before placing 1 ml of MTAD in a canal for 5 minutes and rinsing it with an additional 4 ml of MTAD as the final rinse.[457]

QMiX

QMiX was introduced in 2011; it is one of the new combination products introduced for root canal irrigation (Fig. 6-64). It is recommended to be used at the end of instrumentation, after NaOCl irrigation. According to the patent[194] QMix contains a CHX-analog, Triclosan (N-cetyl-N,N,N-trimethylammonium bromide), and EDTA as a decalcifying agent; it is intended as antimicrobial irrigant as well as an agent to remove canal wall smear layers and debris.

Protocol

QMiX is suggested as a final rinse. If sodium hypochlorite was used throughout the cleaning and shaping, saline can rinse out NaOCl to prevent the formation of PCA.

FIG 6-64 QMiX 2in1. Combination of C, EDTA and detergent. QMiX irrigating solution is a single solution used as a final rinse after bleach for one-step smear layer removal and disinfection. (Courtesy Dentsply Tulsa Dental Specialties, Tulsa, OK.)

Smear Layer Removal

Stojic and colleagues investigated the effectiveness of smear layer removal by QMiX using scanning electron microscopy.[500] QMiX removed smear layer equally well as EDTA. Dai and colleagues examined the ability of two pH versions of QMiX to remove canal wall smear layers and debris using an open canal design.[113] Within the limitations of an open-canal design, the two experimental QMiX versions are as effective as 17% EDTA in removing canal wall smear layers after the use of 5.25% NaOCl as the initial rinse.

Antibacterial Efficacy and Effect on Biofilms

Stojic and colleagues assessed,[500] in a laboratory experimental model, the efficacy of QMiX against *Enterococcus faecalis* and mixed plaque bacteria in planktonic phase and biofilms. QMiX and 1% NaOCl killed all planktonic *E. faecalis* and plaque bacteria in 5 seconds. QMiX and 2% NaOCl killed up to 12 times more biofilm bacteria than 1% NaOCl ($P < .01$) or 2% CHX ($P < .05$; $P < .001$). Wang and colleagues compared the antibacterial effects of different disinfecting solutions on young and old *E. faecalis* biofilms in dentin canals using a novel dentin infection model and confocal laser scanning microscopy.[548] Six percent NaOCl and QMiX were the most effective disinfecting solutions against the young biofilm, whereas against the 3-week-old biofilm, 6% NaOCl was the most effective followed by QMiX. Both were more effective than 2% NaOCl and 2% CHX. Morgental and colleagues showed that QMiX was less effective than 6% NaOCl and similar to 1%NaOCl in bactericidal action.[337] According to their in vitro study, it appears that the presence of dentin slurry has the potential to inhibit most current antimicrobials in the root canals system,

Moreover, Ordinola and colleagues found that several endodontic irrigants containing antimicrobial compounds such as chlorhexidine (QMiX), cetrimide, maleic acid, iodine compounds, or antibiotics (MTAD) lacked an effective antibiofilm activity when the dentin was infected intraorally.[353] The irrigant solutions 4% peracetic acid and 2.5% to 5.25% sodium hypochlorite decreased significantly the number of live bacteria in biofilms, providing also cleaner dentin surfaces ($P < .05$). They concluded that several chelating agents containing antimicrobials could not remove or kill significantly biofilms developed on intraorally infected dentin, with the exception of sodium hypochlorite and 4% peracetic acid. Dissolution ability is mandatory for an appropriate eradication of biofilms attached to dentin.

Clinical Trials

The efficacy and biocompatibility of QMiX was demonstrated via nonclinical in vitro and ex vivo studies. Further clinical research from independent investigators is needed to corroborate the findings.

Iodine Potassium Iodide

Iodine potassium iodide (IKI) is a root canal disinfectant that is used in concentrations ranging from 2% to 5%. IKI kills a wide spectrum of microorganisms found in root canals but shows relatively low toxicity in experiments using tissue cultures.[491] Iodine acts as an oxidizing agent by reacting with free sulfhydryl groups of bacterial enzymes, cleaving disulfide bonds. *E. faecalis* often is associated with therapy-resistant periapical infections (see Chapter 15), and combinations of IKI and CHX may be able to kill $Ca(OH)_2$-resistant bacteria more efficiently. One study evaluated the antibacterial activity of a combination of $Ca(OH)_2$ with IKI or CHX in infected bovine dentin blocks.[473] Although $Ca(OH)_2$ alone was unable to destroy *E. faecalis* inside dentinal tubules, $Ca(OH)_2$ mixed with either IKI or CHX effectively disinfected dentin. Others demonstrated that IKI was able to eliminate *E. faecalis* from bovine root dentin when used with a 15-minute contact time.[32] An obvious disadvantage of iodine is a possible allergic reaction in some patients. Although iodine is not generally considered an allergen, some patients are hypersensitive to this compound and may be considered to have an iodine “allergy.”

Intracanal Medication

When treatment cannot be completed in one appointment (see Chapters 3 and 14), the surviving intracanal bacteria proliferate between appointments.[85,546] Therefore, an intracanal medication that will restrict bacterial regrowth, supply continued disinfection, and create a physical barrier can be advantageous.

Calcium Hydroxide

Calcium hydroxide is the most popular intracanal medication in use. Hermann introduced it in 1920.[215,216] Although its use was well documented for its time, evidence of its efficacy in clinical endodontics is controversial. A series of articles promoted the antibacterial efficacy of $Ca(OH)_2$ in human root canals.[85,87] Subsequent studies substantiated these reports,[354,477] and the routine use of $Ca(OH)_2$ as an interappointment intracanal medicament became widespread.[429]

However, newer clinical studies and systematic reviews failed to show a clear benefit of $Ca(OH)_2$ to further eliminate bacterial from the root canal.[372,429] $Ca(OH)_2$ mostly is used as slurry of $Ca(OH)_2$ in a water base; at body temperature, less than 0.2% of the $Ca(OH)_2$ is dissolved into Ca^{++} and OH^- ions. Because $Ca(OH)_2$ needs water to dissolve, water should be used as the vehicle for the $Ca(OH)_2$ paste. In contact with air, $Ca(OH)_2$ forms calcium carbonate ($CaCO_3$). However, this is an extremely slow process and of little clinical significance. $Ca(OH)_2$ paste, with a significant amount of calcium carbonate, feels granular because the carbonate has a very low solubility.[422,477]

$Ca(OH)_2$ is a slow-acting antiseptic; direct-contact experiments in vitro show that a 24-hour contact period is required for complete killing of enterococci.[422,477] Another study of 42 patients found that NaOCl canal irrigation reduced the bacteria level by only 61.9%, but use of $Ca(OH)_2$ in the canals for 1 week resulted in a 92.5% reduction.[463] These researchers concluded that $Ca(OH)_2$ should be used in infected cases to more predictably obtain disinfection.

In addition to killing bacteria, $Ca(OH)_2$ has the beneficial ability to hydrolyze the lipid moiety of bacterial lipopolysaccharides (LPS), thereby inactivating the biologic activity of the lipopolysaccharide and reducing its effect.[424,423] This is a desirable effect because dead cell wall material remains after the bacteria have been killed and can continue to stimulate inflammatory responses in the periradicular tissue.

The main characteristics of $Ca(OH)_2$ include limited solubility, high pH, use as a broad-spectrum antimicrobial agent, and the ability to sustain antimicrobial action for long periods.

Other Uses of $Ca(OH)_2$

Long-term calcium hydroxide treatment can be used to induce apexification of the immature tooth with pulpal necrosis before placing an obturation material such as gutta-percha in the root canal system.[155] Also, in cases where revascularization is desired, $Ca(OH)_2$ can be used instead of antibiotic pastes (for more details, see the discussion presented later in the chapter and Chapter 10).

Clinical Protocol

Calcium hydroxide should be in contact with the tissue to act. $Ca(OH)_2$ powder may be mixed with sterile water or saline and placed into the canal with using a lentulo paste filler.[371] Alternatively, the mix may be applied from sterile, single-dose packages (e.g., Calasept [J.S. Dental, Ridgefield, CT], Calcijet [Centrix, Shelton, CT], and DT Temporary Dressing [Global Dental Products, North Bellmore, NY]) (Fig. 6-65). The mixture should be thick to carry as many $Ca(OH)_2$ particles as possible; however, it should not be overdried to retain enough moisture and to promote continued dissociation with a resulting high pH. For maximum effectiveness, the root canal should be filled homogeneously to the working length.

Limitations of Calcium Hydroxide

There are some concerns regarding the use of $Ca(OH)_2$. The handling and proper placement of $Ca(OH)_2$ present a challenge to the average clinician.[296,474] Moreover, the removal of $Ca(OH)_2$ is frequently incomplete,[306] resulting in a residue covering 20% to 45% of the canal wall surfaces, even after copious irrigation with saline, NaOCl, or EDTA.[276] Residual $Ca(OH)_2$ can shorten the setting time of zinc oxide eugenol–based endodontic sealers.[315] Most notably, it may interfere with the seal of the root filling and compromise the quality of treatment. An additional concern is that $Ca(OH)_2$ is not totally effective against several endodontic pathogens, including *E. faecalis* and *Candida albicans*.[547] The ability of $Ca(OH)_2$ to completely eradicate bacteria from the root canal has been questioned. For example, in vitro studies have shown that dentin can inactivate the antibacterial activity of $Ca(OH)_2$,[193,393] and one clinical study has shown that the number of bacteria-positive canals actually increased after $Ca(OH)_2$ medication.[372] Other studies have also indicated that $Ca(OH)_2$ could not predictably eliminate bacteria or that cultures changed from negative to positive after $Ca(OH)_2$ placement.[372,546]

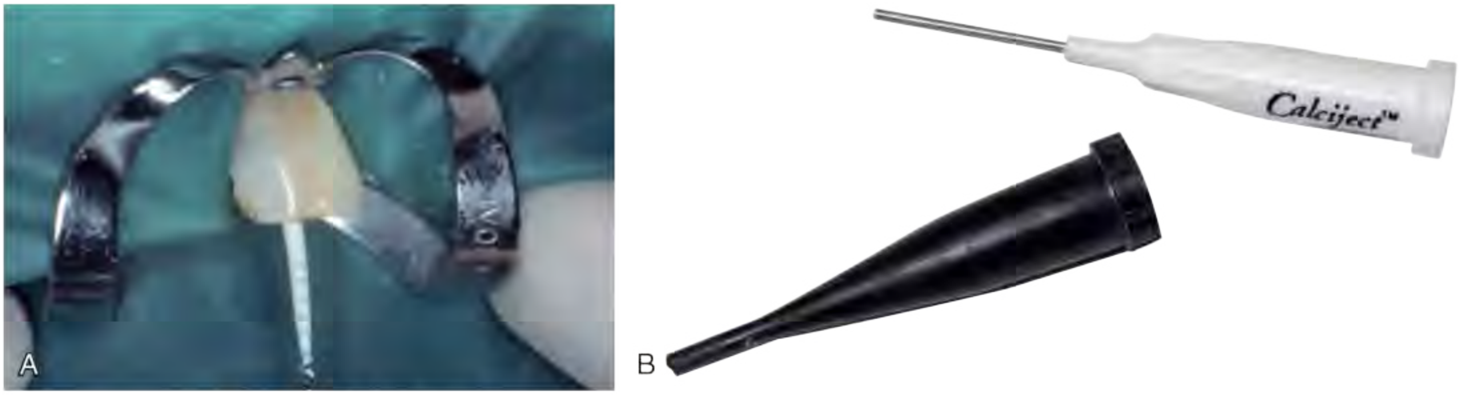


FIG. 6-65 **A,** Application of calcium hydroxide paste in the canal with a lentulo spiral. **B,** Calciject is a calcium hydroxide prefilled, easy-to-use, single-dose syringe system. Centrix NeedleTube cartridges can be used for direct syringe injection into the root canal. (*A,* Courtesy Dr. S. Friedman. *B,* Courtesy Centrix, Shelton, CT.)

When different studies report inconsistent results, a systematic review and meta-analysis technique can clarify conflicting research data and the current state of knowledge regarding specific issues. Therefore, based on the current best available evidence, $Ca(OH)_2$ has limited effectiveness in eliminating bacteria from human root canals when assessed by culture techniques. The quest for better antibacterial protocols and sampling techniques must continue to ensure that bacteria can be been reliably eradicated prior to obturation.

Phenolic Preparations

Phenol (C_6H_5OH) and phenolic preparation used to be commonly used intracanal medicament in endodontics. It was thought that because of their volatile properties, they could penetrate dentinal tubules and anatomic irregularities. However, later it was demonstrated that these compounds have a short life span, and their volatility can diffuse through the temporary fillings and also through the periapical tissue causing toxicity. Despite the severe toxicity of phenolic preparations, derivatives of phenol, such as paramonochlorophenol (C_6H_4OHCl), thymol ($C_6H_3OHCH_3C_3H_7$), and cresol ($C_6H_4OHCH_3$), remain available. Currently, $Ca(OH)_2$ or no medication is preferred.[167] Phenol is a nonspecific protoplasm poison that has an optimal antibacterial effect at 1% to 2%. Many dental preparations use much too high a concentration of phenol (e.g., in the range of 30%).[167] At such a concentration, the antimicrobial effect in vivo is lower than optimal and of very short duration.[326] Derivatives of phenol are stronger antiseptics and more toxic than phenol. Phenolic compounds are available as camphorated solutions.[491,492] Camphorated solutions result in a less toxic phenolic compound because they slow the release of toxins to the surrounding tissues. Studies in vitro have shown that phenol and phenol derivatives are highly toxic to mammalian cells, and their antimicrobial effectiveness does not sufficiently balance their toxicity.[491,492] Phenols are ineffective antiseptics under clinical conditions.[85,137]

Formaldehyde

Formaldehyde, used as formocresol, is highly toxic, mutagenic, and carcinogenic; however, it has been used extensively in endodontic therapy.[284] These formulations are still being recommended for use in pediatric dentistry when treating deciduous teeth. The formaldehyde component of formocresol may vary substantially between 19% and 37%. Tricresol formalin, another formaldehyde preparation, contains 10% tricresol and 90% formaldehyde.[284] All of these preparations have a formaldehyde content well above the 10% normally used for fixation of pathologic specimens. Formaldehyde is volatile and releases antimicrobial vapors when applied to a cotton pellet for pulp chamber disinfection. All formaldehyde preparations are potent toxins with an antimicrobial effectiveness much lower than their toxicity.[492,493] There is no clinical reason to use formocresol as an antimicrobial agent for endodontic treatment, based on what is known at this time. The alternatives are better antiseptics with significantly lower toxicity.[492,493]

Halogens

Chlorinated solutions have been used for many years to irrigate root canals. They are also used as intracanal dressings in the form of chloramine-T, an *N*-chloro-tosylamide sodium salt. Iodine, in the form of IKI, is a very effective antiseptic solution with low tissue toxicity. IKI is an effective disinfectant for infected dentin and can kill bacteria in infected dentin in 5 minutes in vitro.[422] IKI releases vapors with a strong antimicrobial effect. The solution can be prepared by mixing 2 g of iodine in 4 g of potassium iodide; this mixture then is dissolved in 94 ml of distilled water. Tincture of iodine (5%) has proved to be one of the few reliable agents for disinfecting rubber dam and tooth surfaces during the preparation of an aseptic endodontic workfield.[334]

Chlorhexidine

CHX is also used as an intracanal medication and was discussed extensively earlier in this chapter.

Steroids

Steroids have been used locally, within the root canal system, to reduce pain and inflammation. Ledermix (Riemser Arzneimittel AG, Insel Riems, Germany) is a commercially available product that was developed about 1960 by Prof. André Schroeder.[450] The active ingredients are the potent anti-inflammatory corticoid triamcinolone acetonide in combination with the broad-spectrum antibiotic demeclocycline. It is an intracanal medicament paste popularly used in some countries. Ledermix paste has been advocated as an initial dressing, particularly if the patient presents with endodontic symptoms.[450] Ledermix paste contains triamcinolone acetonide as an anti-inflammatory agent, at a concentration of 1%.[261] The clinical effect is a rapid relief of pain associated with acute inflammatory conditions of the pulp and periodontium.

Ledermix paste is a nonsetting, water-soluble paste material for use as root canal medicament or as a direct or indirect pulp-capping agent. The mechanism of action of this substance is based on inhibition of the ribosomal protein synthesis in the bacteria. The release and dentin diffusion characteristics of triamcinolone from Ledermix paste when used as a root canal medicament have been investigated under different conditions.[1-3] Collectively, these studies show that triamcinolone is released from Ledermix paste in the root canal and can reach the systemic circulation via diffusion through dentinal tubules, lateral canals, and the apical foramen. Also, because of its root resorption inhibition property, it was tested for replanted teeth in dogs. The results showed that the groups treated with Ledermix, triamcinolone, and demeclocycline had significantly more favorable healing and more remaining root structure than the group filled with gutta-percha and sealer (positive control).[95]

Triple-Antibiotic Paste

The triple-antibiotics regimen, composed of metronidazole, ciprofloxacin, and minocycline, was first tested[430] for its effectiveness against *Escherichia coli*–infected dentin in vitro. The same research group also tested its bactericidal efficacy against microbes from carious dentin and infected pulp. They found that the mixture of antibiotics is sufficiently potent to eradicate the bacteria.[511] The clinical effectiveness of the triple-antibiotic paste in the disinfection of immature teeth with apical periodontitis has been reported.[557] One potential concern of using an intracanal antibiotic paste is that it may cause bacterial resistance. Additionally, intracanal use of minocycline can cause tooth discoloration, creating potential cosmetic complications. For this reason, a dual paste (metronidazole, ciprofloxacin) and, alternatively, abandonment of this protocol in favor of $Ca(OH)_2$ have been considered.[279] Another reason for such a change could be the reported high toxicity to stem cells of paste prepared from antibiotic powder.[418]

Bioactive Glass

Research is under way in the use of bioactive glass as an intracanal medicament. In one study,[578] the glass used was composed of 53% SiO_2 (w/w), 23% Na_2O, 20% CaO, and 4% P_2O_5 and was prepared from reagent-grade Na_2CO_3, $CaHPO_4$, $2H_2O$, $CaCO_3$, and Belgian sand. When used in root canals, bioactive glass was found to kill bacteria, but the mechanism of action was not pH related, and dentin did not seem to alter its effect.[578] Some newer obturating materials (e.g., Resilon; Pentron Clinical Technologies, Wallingford, CT) contain bioactive glass.

Lubricants

In root canal treatment, lubricants are mostly used to emulsify and keep in suspension debris produced by mechanical instrumentation. Although irrigation solutions serve as lubricants for hand instrumentation, special gel-type substances are also marketed. Two of these are wax-based RC-Prep, which contains EDTA and urea peroxide, and glycol-based Glyde. Another purported function of lubricants is to facilitate the mechanical action of endodontic hand or rotary files. A study evaluating the effects of lubrication on cutting efficiency found that tap water and 2.5% NaOCl solutions increased cutting efficiency compared with dry conditions.[572] The authors of this study cited the ability of an irrigant to remove debris as the factor for the increased efficiency. Similarly, a reduction of torque scores was found when canals in normed dentin disks were prepared with ProFile and ProTaper instruments under irrigation, but the use of a gel-type lubricant resulted in similar torques as in dry, nonlubricated canals.[61,376]

In summary, irrigation is an indispensable step in root canal treatment to ensure disinfection. NaOCl is the irrigant of choice because of its tissue-dissolving and disinfecting properties. EDTA or other chelators should be used at the end of a procedure to remove the smear layer, followed by a final flush with NaOCl for 1 minute for maximum cleaning efficiency and to minimize dentin erosion. This strategy also minimizes inactivation of NaOCl by chemical interactions.

Disinfection Devices and Techniques

Syringe Delivery

Application of an irrigant into a canal by means of a syringe and needle allows exact placement, replenishing of existing fluid, rinsing out of larger debris particles, as well as allowing direct contact to microorganisms in areas close to the needle tip. In passive syringe irrigation, the actual exchange of irrigant is restricted to 1 to 1.5 mm apical to the needle tip, with fluid dynamics taking place near the needle outlet.[66,575] Volume and speed of fluid flow are proportional to the cleansing efficiency inside a root canal.[66] Therefore, both the diameter and position of the needle outlet determine successful chemomechanical debridement; placement close to working length is required to guarantee fluid exchange at the apical portion of the canal, but close control is required to avoid extrusion.[66,224,322] Therefore, the choice of an appropriate irrigating needle is important Although larger-gauge needles allows a quicker and larger amount of fluid exchange, the wider diameter does not allow cleaning of the apical and narrower areas of the root canal system (see irrigation dynamics earlier in this chapter) (see Fig. 6-7). Excess pressure or binding of needles into canals during irrigation with no possibility of backflow of the irrigant should be avoided under all circumstances[231] to prevent extrusion into periapical spaces. In immature teeth with wide apical foramina or when the apical constriction no longer exists, special care must be taken to prevent irrigation extrusion and potential accidents.[111]

There are different sizes and types of irrigation needles. The size of the irrigation needle[101] should be chosen depending on the canal size and taper.[89,328,347] Most root canals that have not been instrumented are too narrow to be reached effectively by disinfectants, even when fine irrigation needles are used (see Figs. 6-7 and 6-52). Therefore, effective cleaning of the root canal must include intermittent agitation of the canal content with a small instrument[320,535] to prevent debris from accumulating at the apical portion of the root canal (see Fig 6-47).

Preparation size[328] and taper[105] ultimately determine how close a needle can be placed to the final apical millimeters of a root canal. Open-ended needles are recommended over the end open needles to prevent extrusion of the irrigant. Some needles and suction tips may be attached to the air/water syringe to increase both the speed of irrigant flow and the volume of irrigant. Examples include the Stropko Irrigator (Vista Dental Products), which is an adapter that connects to the air/water syringe and accepts standard Luer-lock needle tips for irrigant removal and application as well as air-drying.

Manually Activated Irrigation

Liquid placed inside the root canal more effectively reaches crevices and mechanically untouched areas if it is agitated inside the root canal. Corono-apical movements of the irrigation needle,[231] stirring movements with small endodontic instruments,[320,535] and manual push-pull movements using a fitted master gutta-percha cone have been recommended.[225]

Other than conventional irrigation, additional techniques for endodontic disinfection have been proposed and tested, including laser systems and gaseous ozone. Several new devices for endodontic irrigation or disinfection have been introduced, among which are the EndoActivator System (Dentsply Tulsa Dental Specialties), passive ultrasonic irrigation, EndoVac (Discus Dental Inc., Culver City, CA), the Safety-Irrigator (Vista Dental Products, Racine, WI), the Self-adjusting File (discussed earlier), photoactivation disinfection, and ozone. These new devices use pressure, vacuum, oscillation, or a combination with suction.

Sonically Activated Irrigation

The EndoActivator System uses safe, noncutting polymer tips in an easy-to-use subsonic hand piece to quickly and vigorously agitate irrigant solutions during endodontic therapy (Fig. 6-66).

In one study,[130] the safety of various intracanal irrigation systems was analyzed by measuring the apical extrusion of irrigant. The authors concluded that EndoActivator had a minimal statistically insignificant amount of irrigant extruded out of the apex in comparison with manual, ultrasonic, and Rinsendo (Dürr Dental, Bietigheim-Bissingen, Germany) groups.[130]

When cleanliness of the root canal walls was analyzed, [421] investigators suggested that both passive sonic or ultrasonic irrigation rendered root canals significantly cleaner than manual preparation in comparison with manual syringe irrigation.[82,533] When comparing sonic with ultrasonic irrigation, the results can be controversial. The majority of the studies benefit ultrasonic irrigation.[246,421] The difference lies in the oscillating movements: sonic devices range between 1500 Hz and 6000 Hz, and ultrasonic equipment requires vibrations greater than 20,000 Hz.[246,302,497] If sonic devices are left in the canal for longer periods of time, better cleaning effects can be found. Sonic or ultrasonic irrigation may be carried out with activated smooth wires or plastic inserts, endodontic instruments, or activated irrigation needles. Examples include EndoSonor (Dentsply Maillefer) and EndoSoft ESI (EMS Electro Medical Systems, Nyon, Switzerland) inserts, IrriSafe (Acteon Satelec), the EndoActivator System (Dentsply Tulsa Dental Specialties), and the Vibringe sonic syringe (Vibringe B.V., Amsterdam, Netherlands). Inadvertent cavitation of root canal walls has not been observed with sonic activation of instruments.[320]

Passive Ultrasonic Irrigation

Richman was the first to introduce ultrasonic devices in endodontics.[405] The files are driven to oscillate at ultrasonic frequencies of 25 to 30 kHz to mechanically prepare the root canal walls.[543,544] (See the discussion presented earlier in this chapter for more details.) It has been shown that ultrasonically driven files are effective to activate the irrigation liquids inside the root canal system by inducing acoustic streaming and cavitation.

Two types of ultrasonic irrigation have been described in the literature: one where irrigation is combined with simultaneous ultrasonic instrumentation (UI) and another without simultaneous instrumentation, called *passive ultrasonic irrigation* (PUI).[8,554] During UI, the file is intentionally brought into contact with the root canal wall. But because of the complex canal anatomy, the UI will never contact the entire wall and it may result in uncontrolled cutting of the root canal walls without effective disinfection.[8,373,560] In a study by Macedo,[307] instrument oscillation frequency, ultrasonic power, and file taper determined the occurrence and extent of cavitation. Some degree of cavitation occurred between the file and canal surface and reached lateral canals and isthmuses.

Passive ultrasonic irrigation (PUI) was first described by Weller and colleagues[554] The term *passive* is related to the noncutting action of the ultrasonically activated file.[8] PUI relies on the transmission of acoustic energy from an oscillating file or smooth wire to an irrigant in the root canal.

PUI should be introduced in the canal once that the root canal system has a final apical size and taper. A fresh solution of irrigant should be introduced and a small file or smooth wire (for example, size #15) is ultrasonically activated. Because the root canal has already been shaped, the file or wire can move more freely,[416,534,535] and the irrigant can penetrate into the apical part of the root canal system,[269] with the cleaning effect being more significant.[301] Using this noncutting methodology, the potential to create aberrant shapes within the root canal are reduced to a minimum. Obviously, a file larger than a #15 or #20 will require a wide root canal to reduce oscillation dampening by wall contact.

Ultrasonic activation of the irrigant seems to improve debridement of the root canal system in vitro, and the results in vivo present some controversy. Therefore, objective guidelines regarding their risks and benefits have not been ascertained.[286,575] Ultrasonic activation of the irrigant can be intermittent or continue. The ProUltra PiezoFlow (Dentsply Tulsa Dental Specialties) has been introduced to irrigate and activate the liquids at the same time. The device consists mainly of an ultrasonically energized needle connected to a reservoir of sodium hypochlorite (NaOCl). This continuous ultrasonic irrigation (CUI) system allows simultaneous continuous irrigant delivery and ultrasonic activation; unlike PUI,

FIG. 6-66 The EndoActivator, a sonic frequency system. (Courtesy Dentsply Tulsa Dental Specialties, Tulsa, OK.)

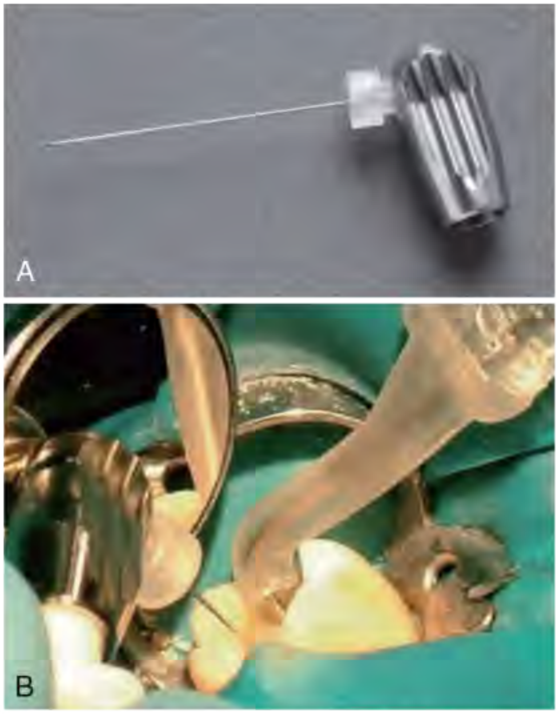


FIG. 6-67 The EndoVac system: magnification of the closed-ended microcannula (**A**), and clinical view of the EndoVac system combined with the Safety-Irrigator (**B**). (*A,* Courtesy Discus Dental Inc., Culver City, CA. *B,* Courtesy Dr. A. Azarpazhooh.)

it does not require the intermittent replenishment of irrigant between ultrasonic file activations. Research shows better elimination of debris and better penetration of irrigant into dentinal tubules.[6,93,247]

Negative Apical Pressure

Another approach to afford better access of irrigation solution to the apical portion of the canal is so-called negative-pressure irrigation (Fig. 6-67). Here, irrigant is delivered into the access chamber, and a very fine needle connected to the dental unit's suction device is placed into the root canal. Excess irrigant from the access cavity is then transported apically and ultimately removed via suction. First, a macrocannula, equivalent to an ISO size #55, .02 taper instrument, removes coronal debris. Subsequently, a microcannula, equivalent to a size #32, .02 taper, removes particles lodged close to working length. Such a system is commercially available (EndoVac, Discus Dental) and may prove a valuable adjunct in canal disinfection.[348] One of the main characteristics of the system is the safety. Many studies proved that EndoVac will not extrude irrigation solution through the apex. On the other hand, because the irrigation is deposited in the coronal area, the irrigant flow in the apical last millimeters of the canal is very passive, and some concerns were expressed that flow is laminar and passive in the apical region. In one study, the apical negative pressure mode of irrigation generated the lowest wall shear stress.[96]

Another device that makes use of pressure-suction technology is the RinsEndo system (Dürr Dental, Bietigheim-Bissingen, Germany). It aspirates the delivered rinsing solution into an irrigation needle that is placed close to working length and at the same time activates the needle with oscillations of 1.6 Hz amplitude.[69,322]

FIG. 6-68 The Safety-Irrigator. (Courtesy Vista Dental Products, Racine, WI.)

FIG. 6-69 The GentleWave system. The system uses multisonic energy to develop a broad section of waves within the irrigation solution to clean inside the roots canal system. It has two main components: a handpiece and a console (shown in figure). (Courtesy Sonendo, Inc, Laguna Hills, CA.)

Safety-Irrigator

The Safety-Irrigator (Vista Dental Products) is an irrigation/evacuation system that apically delivers the irrigant under positive pressure through a thin needle containing a lateral opening and evacuates the solution through a large needle at the root canal orifice (Fig. 6-68). The Safety-Irrigator features a large coronal evacuation tube, enabling the user to safely irrigate and evacuate simultaneously. It fits any standard Luer-lock syringe. Designed to limit risk of NaOCl accidents, this "negative-pressure" irrigation device comes fully assembled and fitted with a side-vented irrigating needle for added safety. This system was tested in vitro to evaluate the removal of dentin debris from artificially made grooves in standardized root canals and showed that there was no significant difference among the manual dynamic activation (MDA) with a nontapered gutta-percha cone, the Safety Irrigator, and the apical negative pressure irrigation. These techniques produced better cleaning efficacy than syringe irrigation ($P < .005$) but significantly worse than MDA with a tapered cone ($P < .05$). Continuous ultrasonic irrigation was significantly better than all the other techniques tested in this study ($P < .001$).[247]

Gentle Wave System

Sonendo Inc. develops a so-called multisonic cleaning technology (Gentle Wave, Fig. 6-69) that only requires pulp chamber access. This system is noninstrumentational and being tested clinically with, according to the company, promising results. It appears to have the potential to reach inaccessible canal areas with significantly more cleaned surface than other systems. A first in vitro study shows the potential of the system to debride better than conventional needle irrigation or ultrasonically activated irrigation.[197]

Laser-Activated Irrigation

Lasers are widely used in dentistry and include diode, Nd:YAG, erbium, and CO_2, which produces radiation in both the near- and far-infrared electromagnetic spectrum.[186] Laser devices have been proposed to improve the efficacy of irrigants.[186] Lasers have been studied for their ability to clean and effectively disinfect root canals. The Er:YAG laser wavelength (2940 nm) has the highest absorption in water and a high affinity to hydroxyapatite, which makes it suitable for use in root canal treatment.[107]

Laser energy may be used to activate irrigant solutions in different ways—for example, at a molecular level, as in photo-activated disinfection (PAD), or at a bulk flow level, as in laser-activated irrigation (LAI). Several studies in vivo and ex vivo have indicated that laser activated irrigation is promising for removing smear layer[168] and dentin debris[121,122] in less time than PUI. The mechanism of action[56] is based on the generation of a secondary cavitation effect with expansion and successive implosion of fluids.[56]

These results are in agreement with data related to a new erbium laser technique that used a photon-induced photoacoustic streaming (PIPS) of irrigants. In that technique, the laser tip is placed into the coronal access opening of the pulp chamber only and is kept stationary without advancing into the orifice of the canal.[132] The use of a newly designed tapered and stripped tip with specific minimally ablative laser settings is required, resulting in low energy (20 mJ), a pulse repetition rate of 15 Hz, and a very short pulse duration (50 μs). The difference in laser penetration and bacterial killing is attributed to the difference in the degree of absorption of different wavelengths of light within the dentin. Bergmans and colleagues concluded in their in vivo study that the Nd:YAG laser irradiation is not an alternative but a possible supplement to existing protocols for canal disinfection, as the properties of laser light may allow a bactericidal effect beyond 1 mm of dentine.[49] Endodontic pathogens that grow as biofilms, however, are difficult to eradicate even upon direct laser exposure.[65]

Photoactivation Disinfection

Photodynamic therapy (PDT) or light-activated therapy (LAT) may have endodontic applications because of its antimicrobial effectiveness.[203] In principle, antimicrobial photodynamic therapy (APDT) is a two-step procedure that involves the introduction of a photosensitizer (step 1: photosensitization of the infected tissue) followed by light illumination (step 2: irradiation of the photosensitized tissue) of the sensitized tissue, which would generate a toxic photochemistry on the target cell, leading to cell lysis. Each of these elements used independently will not have any action, but together they have a synergism effect to produce antibacterial action. Indeed, in vitro experiments showed promising results when used as an adjunct disinfected device. Shresta and Kishen concluded that the tissue inhibitors existing within the root canal affected the antibacterial activity of PDT at varying degrees,[462] and further research is required to enhance their antimicrobial efficacy in an endodontic environment.

Antibacterial Nanoparticles

Nanoparticles are microscopic particles with one or more dimensions in the range of 1 to 100 nm. Nanoparticles are recognized to have properties that are unique from their bulk or powder counterparts. Antibacterial nanoparticles have been found to have a broad spectrum of antimicrobial activity and a far lower propensity to induce microbial resistance than antibiotics. Such nanoparticles in endodontics are being studied in different ways, such as mixed with irrigants, photosensitizer, and sealers.[259] Currently, the consensus is that the successful application of nanoparticles in endodontics will depend on both the effectiveness of antimicrobial nanoparticles and the delivery method used to disperse these particles into the anatomic complexities of the root canal system.

Superoxidized Water

Superoxidized water,[191] also called electrochemically activated water[313,481] or oxidative potential water,[208,455] is effectively saline that has been electrolyzed to form superoxidized water, hypochlorous acid, and free chlorine radicals. It is commercially available as Sterilox (Sterilox Technologies, Radnor, PA). This solution is nontoxic to biologic tissues yet able to kill microorganisms. The solution is generated by electrolyzing saline solution, a process no different than that used in the commercial production of NaOCl.[154] The difference, however, is that the solution accumulating at the anode is harvested as the anolyte and that at the cathode as the catholyte. These solutions display properties that are dependent on the strength of the initial saline solution, the applied potential difference, and the rate of generation. The technology that allows harvesting of the respective solutions resides in the design of the anode and the cathode and originates either in Russia (electrochemically activated water) or in Japan (oxidative potential water).[312,313] Although the solutions bear different names, the principles in the manufacturing process appear to be similar.

The use of superoxidized water is sparsely described in the endodontic literature but shows early promise. The solutions from both technologies have been tested for their ability to debride root canals,[208,313] remove smear layer,[455,481] and kill bacteria[223] and bacterial spores.[297] Results are favorable and show biocompatibility with vital systems.[237]

Anolyte and catholyte solutions generated from one such technology (Radical Waters Halfway House 1685, South Africa) have shown promise as antibacterial agents against laboratory-grown, single-species biofilm models.[169] Such solutions have been recommended as suitable for removing biofilms in dental unit water lines[312] and have even been marketed for this purpose. Cautious clinicians may prefer to wait for more studies to demonstrate safety and efficacy under ordinary clinical setting conditions before adopting newer, less tested irrigating solutions.

CRITERIA TO EVALUATE CLEANING AND SHAPING

Well-Shaped Canals

The main aims of canal shaping are to directly remove tissues and microbial irritants and to provide sufficient geometrical space for subsequent obturation (see Table 6-2). To achieve these goals, the prepared canal should include the original canal (see the red areas in Fig. 6-4); there should be an apical narrowing and the canal should be tapered. These concepts were popularized by Schilder[445] and are still maintained today.[17,258]

Therefore, a well-shaped canal is defined more specifically by the absence of procedural errors (discussed later) and the achievement of disinfection; more recently another element was added to this equation, the retention of as much tooth structure as feasible.[172]

A clinician can often determine whether a canal is adequately shaped by examining radiographs and relying on clinical experience—for example, when fitting a cone. At this time the feel would be of tug-back, a slight resistance to pull; a radiograph should show a symmetrical canal-shape lateral of the cone, the presence of an intact apical narrowing, and no thinned-out radicular wall sections.

Using magnification, clinicians should inspect the canal orifice and the coronal third of each shaped canal for clean canal walls.[367] Immediately after irrigation with sodium hypochlorite, an absence of visible turbidity and effervescence should be noted. If present, these phenomena, along with visible deposits on the canal walls, are indicative of organic matter still in suspension or adherent to the radicular walls.

Signs of Mishaps

Instrument Fracture

Most reports suggest that manual endodontic file fracture or rotary instrument fracture occur at a rate of approximately 1% to 6% and 0.4% to 5%, respectively.[365,495,531] Such fractures are untoward events and perceived as such by clinicians.[55] Evidently, retained instrument fragments limit access of disinfecting irrigants to the root canal system, possibly impeding sufficient elimination of microorganisms.[196] However, the current clinical evidence does not suggest that the presence of a retained instrument must result in a significantly higher rate of failing root canal treatments when done by specialists.[495]

In general, instruments used in rotary motion break into two distinct modes: torsional and flexural.[374,431,530] Torsional fracture occurs when an instrument tip is locked in a canal while the shank continues to rotate, thereby exerting enough torque to fracture the tip. This also may occur when instrument rotation is sufficiently slowed in relation to the cross-sectional diameter. In contrast, flexural fracture occurs when the cyclic loading leads to metal fatigue. This problem precludes the manufacture of continuously rotating stainless steel endodontic instruments, because steel develops fatal fatigue after only a few cycles.[454] NiTi instruments can withstand several hundred flexural cycles before they fracture,[201,285,394,530,567] but they still can fracture in the endodontic setting after a low (i.e., below 10,000) number of cycles.[97]

Repeated loading and cyclic fatigue tests for endodontic instruments are not described in pertinent norms. Initially, rotary instruments such as Gates-Glidden burs and Peeso reamers were tested with a superimposed bending deflection.[68] In GG burs, a 2-mm deflection of the instrument tip resulted in fatigue life spans ranging from 21,000 revolutions (size #1 burs) to 400 revolutions (size #6 burs).[68] In another study, stainless steel and NiTi hand files were rotated to failure in steel tubes with an acute 90-degree bend and an unspecified radius.[454] Under these conditions, size #40 stainless steel instruments fractured after fewer than 20 rotations, whereas various NiTi files of the same size withstood up to 450 rotations.

Cyclic fatigue was also evaluated for ProFile .06 taper instruments using a similar device.[567,568] The number of rotations to failure for unused control instruments ranged from 1260 (size #15 files) to 900 (size #40 files). These scores did not change when the instruments were tested under simulated clinical conditions such as repeated sterilization and contact with 2.5% NaOCl. Subsequently, control instruments were compared with a group of instruments used in the clinical setting in five molar cases[568]; again, no significant differences were found in resistance to cyclic fatigue.

One study used a different testing method involving tempered metal cylinders with radii of 5 mm and 10 mm that produced a 90-degree curve.[201] The researchers reported fatigue fractures for size #15, .04 taper ProFile instruments after about 2800 cycles with the 10 mm cylinders. In size #40, .04 taper ProFile instruments, fractures occurred after about 500 cycles with the 5-mm cylinders. In comparison, size #15, .06 taper ProFile instruments also failed after about 2800 revolutions with the 10-mm cylinders, but failure occurred in size #40, .06 taper ProFile specimens after only 223 cycles with the 5-mm cylinders.

Rotary NiTi instruments with larger tapers and sizes consistently fractured after fewer rotations,[390] and although the radius of the curves was halved, fatigue life was reduced by 400%. Another investigation reported similar results for selected HERO instruments,[201] and the findings were confirmed by other tests on GT rotary instruments. Size #20, .06 taper GT files failed after 530 rotations in a 90-degree curve with a 5-mm radius; size #20, .12 taper GT files failed after 56 rotations under the same conditions.[378]

Reuse of rotary instruments depends on safety, specifically on assessment of fatigue and also the potential to properly clean NiTi surfaces.[36,63,350,357,460,486,489,525] Specific instruments perform differently in this regard, as fatigue depends more on the amount of metal in cross section at the point of stress concentration[182,523] than on the specifics of instrument design.[98]

On the other hand, manufacturers constantly claim that their instrument has been equipped with design elements that render it more fatigue resistant. For example, LightSpeed LSX is manufactured without a milling process. However, no data have been published regarding its fatigue resistance. GTX is manufactured from a novel NiTi alloy, M-Wire, to increase its fatigue resistance.[249] However, investigators could not confirm these findings.[266] Similarly, another study did not find the Twisted File,[277] which is not milled and hence thought to be fatigue resistant,[163] to perform better than conventionally manufactured ProFile rotaries. Another feature, electropolishing (discussed earlier), does not appear to confer a significantly increased fatigue resistance to EndoSequence[277,401] and RaCe.[523,525,565] One possible reason for these variable outcomes is the different testing environments used in vitro[100]; clinically, even greater variability is to be expected.

Attempts have been made to use tests according to norms and specifications described for stainless steel hand instruments such as K-files and Hedström files,[239] as no comparable norms exist for instruments used in continuous rotary motion. Consequently, a number of models have been devised to assess specific properties of NiTi rotary instruments, including torque at failure, resistance against cyclic fatigue, and others

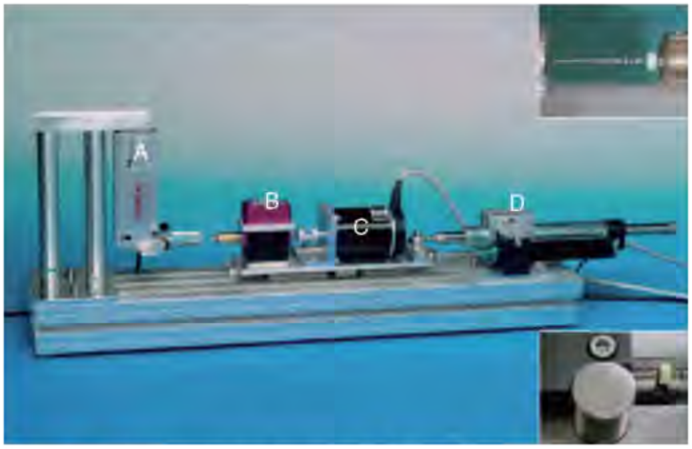


FIG. 6-70 Testing platform for analysis of various factors during simulated canal preparation with rotary endodontic instruments. Labeled components are a force transducer (A), a torque sensor (B), a direct-drive motor (C), and an automated feed device (D). For specific tests, a cyclic fatigue phantom or a brass mount compliant with ISO No. 3630-1 *(insets)* may be attached.

(Fig. 6-70). These systems may simultaneously assess torque at failure, working torque axial force, and cyclic fatigue.

According to the norms mentioned previously, torque at failure is recorded with the apical 3 mm of the instrument firmly held in the testing device while the instrument's handle is rotated. A wide variety of rotary NiTi endodontic instruments have been tested in this way—for example, ProFile NiTi rotary files in ISO sizes #25, #30, and #35 (.04 taper) fractured at 0.78, 1.06, and 1.47 Ncm, respectively.[503]

Investigators reported similar scores when instruments were forced to fracture in plastic blocks with simulated curved canals.[504] In a different setup, GT rotary instruments (size #20, .06 taper to size #20, .12 taper) fractured at 0.51 and 1.2 Ncm, respectively.[378] These values are somewhat lower than data obtained from the same but slightly modified torque bench,[254] pointing to the importance of experimental conditions for torque and fatigue measurements.

Compared with NiTi instruments with tapered flutes, LightSpeed instruments had lower torque to fracture (0.23 to 2 Ncm).[318] No such data are currently available for LightSpeed LSX.

When analyzing clinical factors involved in instrument fracture, one must consider both torsional load and cyclic fatigue.[431] However, these are not separate entities, especially in curved canals.[64] Working an instrument with high torque may lower resistance to cyclic fatigue.[161] Conversely, cyclic prestressing has been shown to reduce the torsional resistance of ProTaper finishing files,[530] as well as K3[31] and MTwo.[390] Also, cyclic fatigue occurs not only in the lateral aspect when an instrument rotates in a curved canal but also axially when an instrument is bound and released by canal irregularities.[54]

The torque generated during canal preparation depends on a variety of factors, and an important one is the contact area.[57] The size of the surface area contacted by an endodontic instrument is influenced by the instrumentation sequence or by the use of instruments with different tapers.[448] A crown-down approach is recommended to reduce torsional loads (and thus the risk of fracture) by preventing a large portion of the tapered rotating instrument from engaging root dentin (known as *taper lock*).[57,569]

The clinician can further modify torque by varying axial pressure, because these two factors are related448 (see Fig. 6-20). In fact, a light touch is recommended for all current NiTi instruments to avoid forcing the instrument into taper lock. The same effect might occur in certain anatomic situations, such as when canals merge, dilacerate, and divide.

The torsional behavior of NiTi rotary endodontic instruments cannot be described properly without advanced measurement systems and a new set of norms. However, the clinician must be able to interpret correctly the stress-strain curves for all rotary NiTi instruments used in the clinical setting to be able to choose an appropriate working torque and axial force.

Therefore, a careful evaluation should be performed before the attempt is made to remove any retained fragment (see Fig. 6-25). In fact, Ward and colleagues suggested that any attempt of fragment removal be made only when the fragment is located coronal of a significant root canal curve and thus visible with the aid of magnification.[549]

There are sophisticated means and strategies to remove retained fragments, which are described in detail in Chapter 19.

Of note, assessment of physical parameters governing rotary root canal preparation was considered crucial because NiTi rotary in vitro had increased risk of fracture compared with K-files. Some clinicians also describe instrument fracture as a main issue for concern.[55]

In a study using plastic blocks, as many as 52 ProFile Series 29 instruments became permanently deformed.[515] Three fractures were reported in a subsequent study on ISO-norm ProFile taper .04 instruments, and three other instruments were distorted.[75] An even higher fracture incidence was shown in a study on rotary instruments used in plastic blocks in a specially designed testing machine.[509] These findings were supported by two studies in which high fracture incidences were reported for LightSpeed and Quantec rotary instruments used in a clinical setting.[33,431]

On the other hand, as stated previously, a retrospective clinical study suggested similar outcomes with and without retained instrument fragments[495]; moreover, others' experience suggests that the number of rotary instrument fractures is lower than previously estimated.[126,262,558] Removal of such fragments is possible in many situations, but there is also the potential for further damage (e.g., perforation) rather than successful removal.[502,558] Consequently, a benefit-versus-risk analysis should be carried out prior to attempts to remove NiTi instrument fragments to address the reasons and the clinical consequences of instrument fracture.

Canal Transportation

Perhaps the most frequent adverse outcomes during canal shaping are aberrations from the original canal path. Much has been written on the appearance of such aberrations using labels as zip and elbow formation, ledging, perforation, stripping, and others.[553]

Canal transportation is at the root of all these clinical problems and may be defined as "the removal of canal wall structure on the outside curve in the apical half of the canal due to the tendency of files to restore themselves to their original linear shape during canal preparation."[17]

As files tend to straighten in the canal, transportation typically occurs toward the inner (or convex) radicular wall at midroot. Such a shift of the canal axis during shaping results in excessive loss of dentin and may ultimately result in perforation, whereas apical transportation may lead to zipping or apical perforation (see Fig. 6-40).

Conceptually, any canal preparation will shift the canal axis, which is often determined as the center of gravity in cross sections. It has been held that a transportation of about 100 to 150 μm may be clinically acceptable.[233]

If canal transportation has led to ledge formation, subsequent instruments will bypass the area of the ledge only when adequately precurved. In case of rotary instrumentation, hand-operated instruments of comparable size are then recommended (Fig. 6-71).

Perforation

As indicated earlier, perforation may be the ultimate result of canal transportation when it occurs within the root canal system. Other perforations are those in the access cavity; a discussion of access cavity preparation may be found in Chapter 5. Obviously, the preparation of mineralized canals requires advanced operator skills and is facilitated by magnification (Fig. 6-72).

Three types of perforations can be defined: strip perforations that occur toward the furcation in multirooted teeth (also known as *"danger zones"*[15]), perforations associated with canal curvatures, and perforations though the apical foramen.

Blockage

A canal may become impassable during the process of cleaning and shaping due to two distinct, but often connected, occurrences. A ledge is a dentinal shelf that is created by shaping instruments that straighten and dig into the convex side of the canal wall. In less severe cases, ledges can be corrected and smoothed out with precurved instruments. This condition may lead to false paths and impede optimal obturation when working length cannot be reached with master cones.

A blockage refers mainly to a root canal area that is filled with densely compacted debris or collagenous pulp remnants (see Fig. 6-39). It may also be caused by other obstacles such as a fractured files or remnants of a preexisting coronal or radicular filling materials. Clinically the presence of ledge or block is signaled by the inability of a straight flexible instrument to penetrate deeper into the root canal; however, this needs to be differentiated from a small or mineralized canal, which causes longer portions of the instrument's cutting flutes to bind.

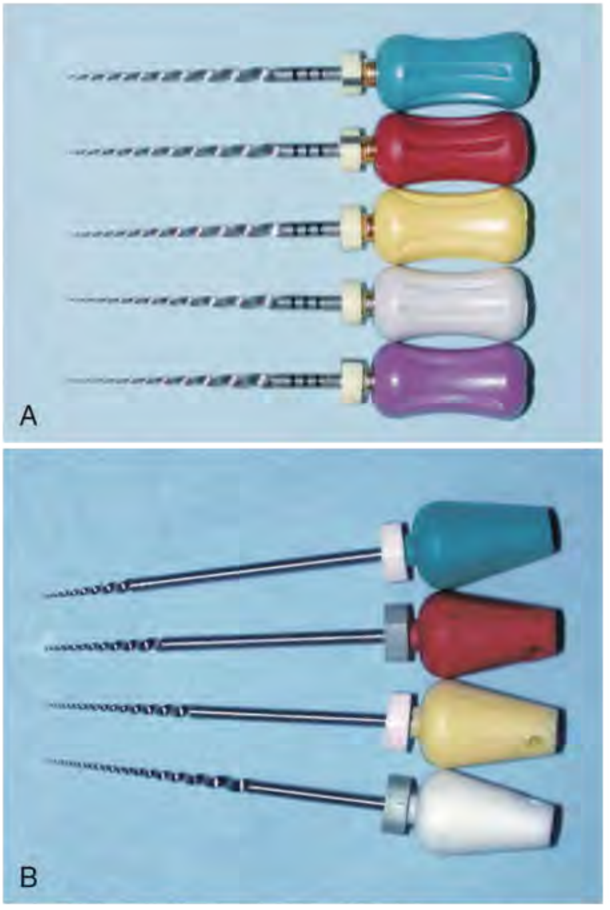


FIG. 6-71 Instruments with increased taper that can be used by hand. A, ProTaper instruments with special handles attached to rotary instrument shanks. B, GT hand instruments.

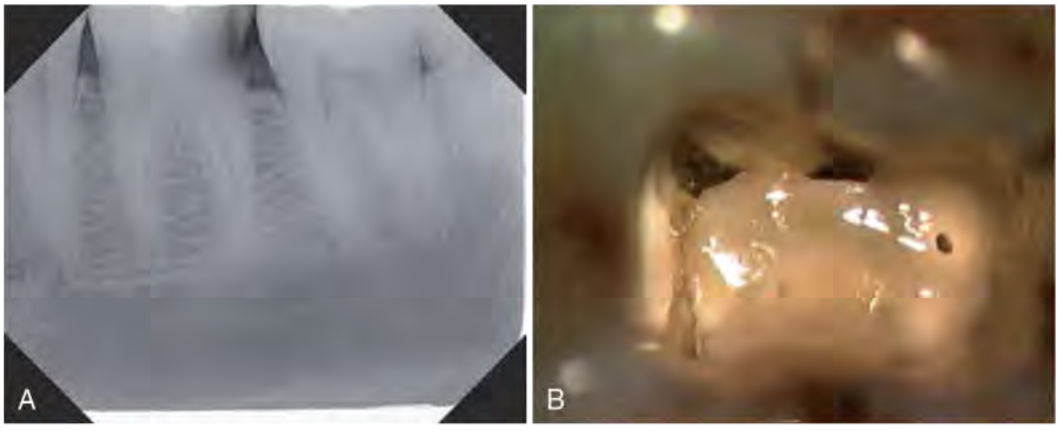


FIG. 6-72 Evidence of coronal hard-tissue deposition. A, Periapical radiograph of tooth #19 shows evidence of reduced coronal and radicular pulp space. B, Intraoral photograph, taken through an operating microscope (×25), of access cavity of the tooth shown in A; note the calcific metamorphosis.

Obviously, such a blockage prevents the apical canal portion from being disinfected. For details of strategies to deal with ledge and blockage, please refer to Chapter 19.

Another reason for a perceived blockage may be an abrupt canal curvature.

SAMPLE PROTOCOL FOR CONTEMPORARY CLEANING AND SHAPING PROCEDURES

- Using well-angulated preoperative radiographs, analyze case difficulty under well-established parameters.
- Place rubber dam and estimate working length.
- Prepare a conservative access cavity sufficient to reveal all root canal orifices.
- Scout canals with a #10 K-file in the presence of a lubricant.
- If the selected series of rotary instruments advances easily to the estimated working length (WL), confirm patency and determine WL using an electronic apex locator.
- If the instruments meet resistance and the file does not progress gently to WL, use a dedicated NiTi instrument; it is prudent to modify the orifice to create a coronal receptacle for the subsequent rotaries. Negotiate, confirm patency, and determine WL.
- Create a reproducible glide path to WL with appropriate instruments.
- Irrigate with sodium hypochlorite throughout the shaping procedure.
- Advance the selected series of rotary instruments (based on canal anatomy) passively in the presence of sodium hypochlorite to shape the middle third. When shaping canals that have a larger buccal-lingual dimension, consider shaping as two canals.
- Clean cutting flutes routinely upon removal, and remove debris with an alcohol-moistened gauze. If the selected rotary does not progress easily, remove irrigant, recapitulate with a #10 K-file, and choose a different, often smaller, instrument.
- Use copious irrigation, and reverify canal patency and working length throughout and upon completion of shaping. Gauge the size of the foramen with an appropriate hand file.
- Protocol for irrigation:
  - Irrigate using copious amounts of sodium hypochlorite.
  - Activate the irrigant.
  - Select irrigation solution for smear layer management.
  - Perform the final irrigation.
- Dry the canal thoroughly and obturate with a technique that promotes a three-dimensional fill.
- Restore the endodontically treated tooth in a timely manner.

SUMMARY

Cleaning and shaping are important, interdependent steps in root canal treatment. Cleaning, as demonstrated by an intracanal surface free of smear layer, can be done only after root canals have been sufficiently enlarged to accommodate adequate irrigation needles. Canal preparation is optimized when mechanical aims are fulfilled and enlargement is acceptable; such aims include avoiding both significant preparation errors and weakening of the radicular structure, which can result in fractures.

Taken together and performed to a high standard, the procedures described in this chapter lay the foundation for biologic success in both straightforward (Fig. 6-73) and more

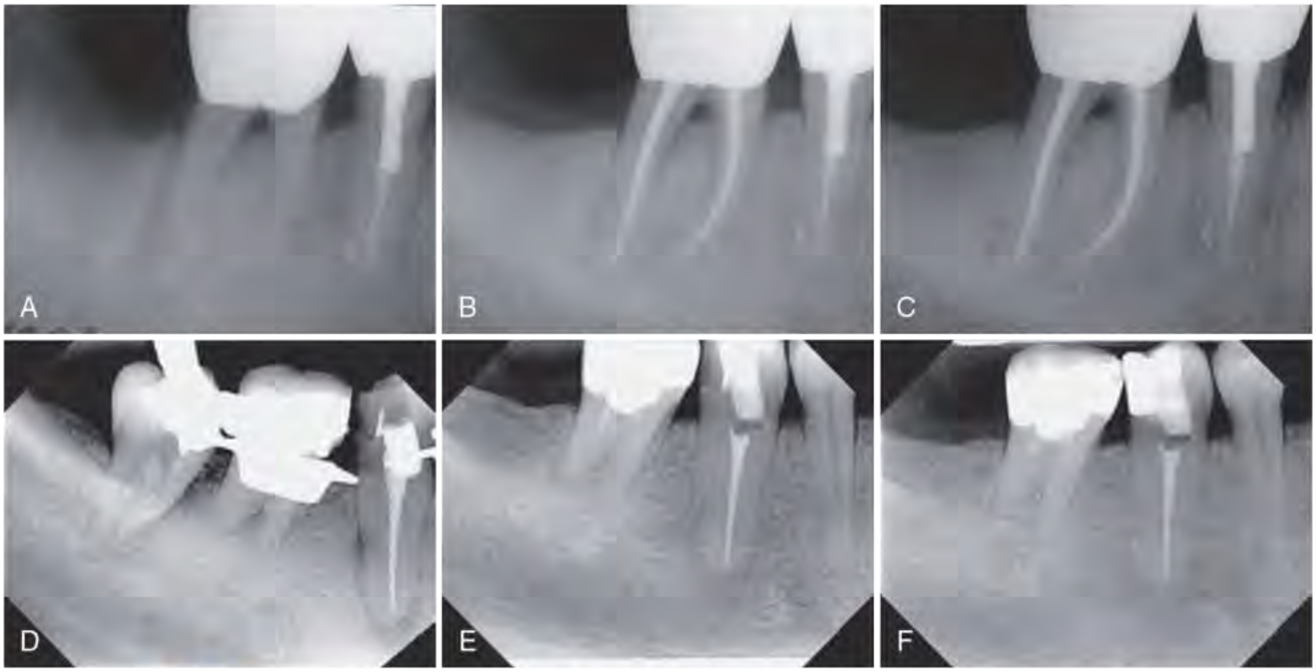


FIG. 6-73 Clinical cases treated according to the principles detailed in this chapter. A, Pretreatment radiograph of tooth #30 with a periradicular lesion. B, Postobturation radiograph. C, Two-year follow-up radiograph shows osseous healing. D, Immediate postobturation radiograph of tooth #29 shows both a periapical and a lateral osseous lesion. E-F, One-year and three-year follow-up radiographs show progressing osseous healing. Note the imperfect obturation of tooth #30.

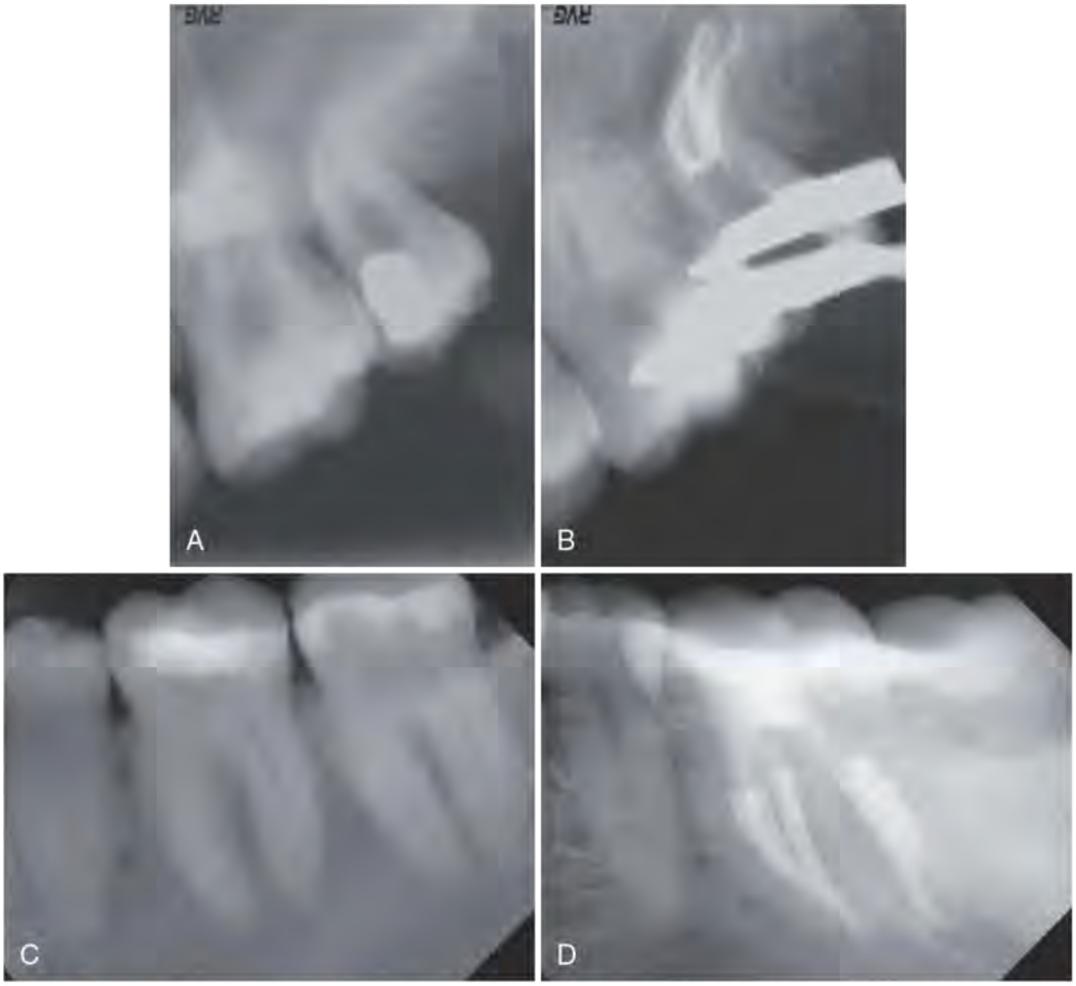


FIG. 6-74 Complicated clinical cases treated with hybrid techniques. **A**, Pretreatment radiograph of tooth #16 indicates laceration and significant curvature of all roots. **B**, Posttreatment radiograph shows multiple planes of curvature. **C**, Pretreatment radiograph of tooth #19, which was diagnosed with irreversible pulpitis. **D**, Angulated posttreatment radiograph shows three canals in the mesiobuccal root canal system, all of which were prepared to apical size #50. (*A-B,* Courtesy T. Clauder. *C-D,* Courtesy Dr. H. Walsch.)

complicated (Fig. 6-74) clinical cases. Recall radiographs confirm favorable outcomes or biologic success (i.e., prevention or healing of periradicular periodontitis) over the years. Similarly, adherence to the principles discussed leads to predictable outcomes for root canal treatments.

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Cervical Level Biological Repair of the Access Opening after Regenerative Endodontic Procedures: Three Cases with the Same Repair Pattern

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ABSTRACT

Introduction: This article describes the regenerative endodontic procedures applied in 3 cases of maxillary incisor necrosis that resulted in continuous root development, dentinal wall thickening, and cervical level biological repair of the access openings that was verified radiographically in 2 cases and clinically in 1 case. **Methods:** Three maxillary central incisors in 2 different patients were rendered necrotic after having dentin enamel fracture traumatic dental injuries. All teeth were treated with single- or multiple-visit regenerative endodontic procedures. **Results:** The 5- and 9-year follow-up evaluations revealed similar continuous root development, dentin wall thickening, and hard tissue biological repair of the wide access cavities. In the 9-year follow-up case, the calcium silicate cement was removed because of unacceptable discoloration. The hard tissue biological repair was visualized under the microscope and checked for its continuity with the axial walls, its resistance to displacement, and the presence of possible gaps. The repair tissue seemed to be yellowish in appearance with some brown niches of irregular texture, did not have detectable gaps, was firmly connected with the axial dentinal walls through a demarcated white line, and resisted all displacement forces applied. The tooth was restored with bonded composite resin restoration after internal bleaching. The 10-year follow-up revealed satisfactory esthetics and uneventful soft and hard tissue healing. **Conclusions:** Cervical-level hard tissue repair of the access opening after the application of regenerative endodontic procedures in necrotic immature maxillary incisors might reinforce the weakened tooth structure to a great extent and warrants further investigation. *(J Endod 2019;45:1219–1227.)*

KEY WORDS

Apical repair; cervical level access repair; dental trauma; healing pattern; regenerative procedures

SIGNIFICANCE

The cervical level biological repair of the access opening in necrotic immature teeth might be feasible after regenerative endodontic procedures. A regenerative protocol that can induce such a healing pattern might strengthen the immature tooth and warrants further scientific investigation and modulation.

Occasionally, traumatic dental injuries or carious lesions in children and adolescents may render the pulp of the developing teeth infected and necrotic. Pulp necrosis results in the cessation of maturation and further root development, leaving the tooth weakened and prone to fracture. In such teeth conventional endodontic treatment procedures are challenging[1]. The deeper and heavier bacterial penetration of the young dentin[2] as well as the absence of an apical stop renders the disinfection and the root canal obturation of these teeth difficult and unpredictable, respectively. Moreover, the defective crown to root ratio, the thin dentinal walls, and especially the wide access cavity that is required to treat these cases render these teeth susceptible to fracture especially when either long-term apexification modalities[3] or one-step apical barrier techniques are opted[4,5].

For long-term apexification, the aim is to induce a hard tissue biological apical closure after long-term medication with calcium hydroxide[1]. The unpredictable nature of the apical closure, the long timespan of the entire treatment, and the risk of tooth fracture after the wide access cavity preparation and the long-term use of calcium hydroxide made the endodontic community search for alternative techniques.

With the introduction of mineral trioxide aggregate (MTA)[6], one-step apical barrier techniques rapidly became very popular. The rationale of one-step MTA apexification procedure is to establish an artificial biocompatible apical stop against which immediate root canal filling and restoration can be achieved[1].

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Apexification protocols with MTA offered the advantage of shortened treatment time and improved patient compliance, but most of all they facilitated the rapid placement of a bonded restoration for the fragile immature root[1]. Although advances with MTA and bonded restorations went some way toward a better outcome, both apexification methods required a wide access cavity preparation that weakened and destabilized the tooth structure further[7] and condemned the immature roots to the cessation of further root development[8,9]. Moreover, the dental tissues removed from the cervical level of the roots during wide access cavity preparation could only be restored with artificial materials and not repaired or regenerated. Thus, the problem of strengthening the immature root had remained largely unsolved[10].

Recently, revitalization procedures were introduced for the induction of continued root development and dentin wall thickening of the necrotic immature root that might strengthen the tooth structure[8,11]. Although the biological goals of these procedures can be achieved, the outcome of the treatment is not always predictable[12], and the strengthening effect of the different healing patterns reported is questionable[13]. With unpredictable and questionable outcomes, clinicians are reluctant to incorporate regenerative endodontic procedures in their everyday practice, and they ask for more evidence and better biological outcomes[14,15].

The aim of this article is to report the regenerative endodontic procedures followed in 3 cases of maxillary incisor immature tooth necrosis that resulted not only in continued root development and dentin wall thickening but also in formation of a cervical level hard tissue biological repair of the access cavity in close continuity with the axial walls, as verified clinically in 1 case. A regenerative protocol that can induce such a healing pattern might strengthen the immature root and deserves further scientific investigation.

CASE REPORTS 1 AND 2

A 9-year-old male patient was referred for evaluation and possible treatment of teeth 8 and 9. In the dental history it was reported that the patient had an impact injury after a fight with his brother 6 months earlier, and both teeth suffered an enamel-dentin fracture with no pulp involvement. Both teeth remained asymptomatic, and no treatment was sought since then. A week before presenting to the endodontic postgraduate clinic (School of Dentistry, NKUA, Athens, Greece), both teeth became painful, and a swelling in the anterior area of the maxilla developed. The patient had then sought treatment at the emergency clinic of the Pediatric Hospital, where an access opening at tooth 9 was performed. At the time of the appointment both teeth were painful on percussion and palpation. Clinical examination revealed a vestibular intraoral fluctuant swelling associated with tooth 8 and a sinus tract stoma associated with tooth 9 (Fig. 1*A*). The access opening of tooth 9 had been sealed with a temporary filling material (Fig. 1*B*). Periodontal probing was within normal limits. No reaction was recorded on thermal and electrical sensibility tests. After fistula tracing with a gutta-percha point, the radiographic examination revealed periapical radiolucencies associated with teeth 8 and 9. Both teeth showed immature root formation (root length, apical closure, and decreased root canal dentin thickness) (Fig. 2*A*). A diagnosis of pulpal necrosis with acute apical abscess and previously initiated treatment with chronic apical abscess was established for teeth 8 and 9, respectively. After presenting and discussing all treatment alternatives with the patient's guardian, a decision was made to attempt revitalization endodontic procedures for both immature necrotic maxillary incisors by using an identical treatment protocol. An informed consent was obtained.

The following revitalization protocol was used.

First Visit

- The patient was anesthetized by using buccal infiltration anesthesia without vasoconstrictors (3% mepivastesin; 3M ESPE, St Paul, MN).
- The rubber dam was placed and stabilized with Wedjets (Coltene, Altstätten, Switzerland). The operation field was disinfected by using 2% chlorhexidine scrub.
- The pulp cavities were accessed with a sterile diamond bur (Endo-Access Bur; Dentsply Maillefer, Ballaigues, Switzerland), and the contaminated content of both canals was rinsed away with copious sterile saline irrigation through a slotted end needle.
- The working length was estimated with a working length radiograph and an ISO 100 K-file. The file was placed coronal to the length estimated from the preoperative periapical radiograph (to avoid damage to the apical papilla).
- No further instrumentation of the root canal walls was performed.
- The wide canals of both teeth were rinsed with 10 mL of 1.5% NaOCl solution through a 27-gauge slotted end needle fitted 2 mm short of working length.
- The canals were dried with capillary suction fitted 2 mm short of working length.
- A double antibiotic mixture powder containing equal parts of ciprofloxacin and metronidazole had been prepared by the compound pharmacy. The powder had been kept in the refrigerator. Just before use, the powder was mixed with sterile water to a slurry consistency (approximately 1000 mg/mL solution is needed to create a pasty slurry consistency) and placed inside both canals with a lentulo spiral rotating 2 mm short of working length.
- Both teeth were provided with glass ionomer as temporary restorative material (Fuji IX GP; GC America, Ilsip, IL).
- The patient was scheduled for another visit after 2 weeks.

On clinical examination at the second visit both teeth were asymptomatic, with the vestibular intraoral swelling and the sinus tract resolved (Fig. 1*C*).

Second Visit

- Anesthesia and rubber dam isolation were performed as in the first visit.
- The temporary restorations were removed from both teeth with a sterile diamond bur, and the double antibiotic mix was rinsed away with copious sterile saline irrigation through a slotted end needle.
- The root canals were rinsed with 20 mL of 1.5% NaOCl solution through a 27-gauge slotted end needle fitted 2 mm short of working length.
- The canals were dried with capillary suction fitted 2 mm short of working length.
- The Endo-Vac macro-cannula (Kerr Dental, Bioggio, Switzerland) was fitted 1 mm short of working length, and negative pressure irrigation with 10 mL of 1.5% NaOCl was performed in each tooth.
- The canals were flooded with 1.5% NaOCl and left inside the canals non-agitated for 30 minutes.
- The canals were dried with capillary suction from the NaOCl solution and were flooded with 17% EDTA through an Endo-Vac macro-cannula fitted in working length.
- The EDTA 17% was left for 10 minutes and then rinsed away with sterile water.
- The canals were dried with capillary suction fitted 2 mm short of working length.
- Bleeding was induced by mechanical irritation of the periapical tissues and rotational movement of a sterile apically pre-curved size 40 K-file.
- The canals were allowed to fill with blood to the level 2 mm below the cementoenamel

FIGURE 1 – (*A*) Preoperative buccal clinical view of maxillary anterior teeth. (*B*) Preoperative occlusal view of maxillary anterior teeth. (*C*) Buccal clinical view of teeth 8 and 9 after 2 weeks with DAP dressing. (*D*) Four-month follow-up clinical buccal view of teeth 8 and 9. (*E*) Five-year follow-up buccal clinical view of maxillary anterior teeth. (*F*) Five-year follow-up palatal clinical view of maxillary anterior teeth.

junction and waited for 15 minutes for a clot to be formed.

- An MTA barrier of 4-mm thickness (MTA Angelus, Londrina Brazil) was placed over each blood clot with an MTA applicator.
- The MTA material was adapted over the blood clot with a micro-brush and a dry sterile cotton pellet.
- MTA material was protected with injectable gutta-percha, and the MTA remnants were removed with a grit blast of bisodium carbonate sandblasting.
- The access cavities were rinsed with water, the gutta-percha plug was removed with an excavator, and both teeth were restored with glass ionomer (Fuji IX GP).
- A postoperative radiograph was taken to be used as baseline for future evaluations (Fig. 2*B*).
- The patient was referred for the restoration of both teeth with composite resin.

The patient returned for the scheduled follow-up appointment 4 months later. The clinical (Fig. 1*D*) and radiographic evaluations (Fig. 2*C*) revealed asymptomatic maxillary central incisors with resolution of the periapical pathosis and signs of continued root maturation. The cervical discoloration resulting from the MTA material was minimal and had been masked sufficiently with the composite resin restorations.

The 5-year follow-up clinical evaluation revealed healthy soft and hard tissues and favorable esthetics (Fig. 1*E* and *F*). The radiographic examination revealed a characteristic healing pattern with complete periapical healing, hard tissue repair of the access cavity in contact with the MTA coronal barrier, continuous root development, dentinal wall thickening, and apical closure (Fig. 2*D*–*F*). No response to electric vitality testing was recorded.

CASE REPORT 3

An 8-year-old female patient was referred for evaluation and possible treatment of tooth 9. In the dental history it was reported that the patient had an impact injury after a bicycle accident 6 months earlier, and both maxillary central incisors suffered a dentin-enamel fracture with no pulp involvement. Both teeth were restored with composite resin restorations by the pediatric dentist and had remained asymptomatic since then. A week before presenting to the clinic, tooth 9 was rendered painful, and a swelling developed. The patient had then sought treatment at the emergency clinic of the Pediatric Hospital, where antibiotics were administered for 1 week (500 mg amoxicillin every 8 hours) without any other intervention. At the time of the appointment the antibiotics regimen was completed, but the tooth was still slightly percussion and palpation painful. Clinical examination revealed a vestibular intraoral swelling associated with tooth 9 (Fig. 3*C*). Periodontal probing was within normal limits. No reaction was recorded on thermal and electrical sensibility tests only for tooth 9. The radiographic examination revealed periapical radiolucency associated with the immature

FIGURE 2 – (*A*) Preoperative periapical radiograph of teeth 8 and 9. (*B*) Postoperative periapical radiograph of teeth 8 and 9 after completion of regenerative procedures. (*C*) Four-month follow-up periapical radiograph of teeth 8 and 9 indicating periapical healing. (*D*) Five-year follow-up periapical radiograph of tooth 8 indicating characteristic healing pattern. (*E*) Five-year follow-up periapical radiograph of tooth 9 indicating identical characteristic healing pattern. (*F*) Clinical view radiograph of characteristic healing patterns consisting of periapical lesion healing, hard tissue bridging in contact with MTA, dentin wall thickening, continued root development, and apical closure.

tooth 9 (Fig. 3*A*). A diagnosis of pulpal necrosis with acute apical abscess was established. After presenting and discussing all treatment alternatives with the patient's parents, a decision was made to attempt revitalization endodontic procedures for the immature necrotic maxillary incisor. A signed informed consent was obtained.

Revitalization Protocol

- The patient was anesthetized by using buccal infiltration anesthesia without vasoconstrictors (3% mepivastesin; 3M ESPE).
- The rubber dam was placed and stabilized with Wedjets. The operation field was disinfected by using 2% chlorhexidine scrub.
- The pulp cavity was accessed with a sterile diamond bur (Endo-Access Bur; Dentsply Maillefer). After accessing the wide canal, purulent drainage was noticed (Supplementary Video 1). The tooth was left to drain until the drainage became hemorrhagic and ceased. The contaminated content of the wide canal was rinsed away with copious sterile saline irrigation through a slotted end irrigation needle.
- The working length was estimated with a working length radiograph with an ISO 100 K-file.
- No further instrumentation of the root canal walls was performed.
- The wide canal was rinsed with 20 mL of 1.5% NaOCl solution through a 27-gauge slotted end needle fitted 2 mm short of working length.
- The canal was dried with capillary suction fitted 2 mm short of working length.
- The Endo-Vac macro-cannula was fitted 1 mm short of working length, and negative pressure irrigation with 20 mL of 1.5% NaOCl was performed.
- The canals were flooded with 1.5% NaOCl and left inside the canals non-agitated for 30 minutes.

FIGURE 3 – (*A*) Preoperative periapical radiograph of tooth 9. (*B*) Postoperative periapical radiograph of tooth 9. (*C*) Preoperative clinical image of the buccal infection. (*D*) One-year follow-up periapical radiograph showing periapical lesion healing. (*E*) Three-year follow-up periapical radiograph showing periapical lesion healing, continuous root development, dentin wall thickening, and cervical level hard tissue biological repair of the access opening. (*F* and *G*) Eight-year follow-up clinical image and periapical radiograph during the orthodontic treatment.

- The canal was dried with capillary suction from the NaOCl solution, and it was flooded with 17% EDTA through an Endo-Vac macro-cannula fitted in working length.
- The EDTA 17% was left for 10 minutes and then rinsed away with sterile water.
- The canal was dried with capillary suction fitted 2 mm short of working length.
- Bleeding was induced by mechanical irritation of the periapical tissues and rotational movement of a sterile apically pre-curved size 40 K-file.
- The canal was allowed to fill with blood to the level 2 mm below the cementoenamel junction and waited for 15 minutes for a clot to be formed.
- An MTA barrier of 4-mm thickness (MTA Angelus) was placed over the blood clot with an MTA applicator.
- The MTA material was adapted over the blood clot with a micro-brush and a dry sterile cotton pellet.
- MTA material was protected with injectable gutta-percha, and the MTA remnants were removed with a grit blast of bisodium carbonate sandblasting.
- The access cavity was rinsed with water, the gutta-percha plug was removed with an excavator, and the tooth was temporarily restored with glass ionomer (Fuji IX GP). A radiograph was taken to evaluate the coronal plug (Fig. 3*B*).
- The patient was scheduled 14 days later for evaluation and permanent composite resin restoration.

The patient returned for the scheduled follow-up appointment 14 days later. The clinical evaluation revealed an asymptomatic maxillary central incisor, but the sinus tract was still present. The temporary restoration was removed, and the MTA was checked for proper setting. The dentin in contact with MTA had been rendered grey. The discoloration was removed in part with a diamond bur, and the tooth was restored with composite resin. The patient was recalled after 1 month for a detailed clinical evaluation of the tooth. The sinus tract had been resolved, and the tooth was asymptomatic and functional. Periodontal probing was within normal limits. No radiograph was taken, and the patient was scheduled for long-term clinical and radiologic follow-ups. The 1-, 3-, and 8-year follow-up radiographs revealed continuous root development, dentin wall thickening, and hard tissue biological closure of the access cavity over time (Fig. 3*D*, *E*, and *G*). The clinical evaluation at the 8-year follow-up examination revealed healthy soft tissues and a grey cervical discoloration (Fig. 3*F*). The tooth had been subjected to orthodontic movement. After the removal of the orthodontic appliances, a decision was made to manage the discoloration (Fig. 4*A* and *C*). The tooth was isolated with rubber dam, and the composite resin was removed, exposing the calcium silicate cement underneath. The discoloring cement was removed with ultrasonics under microscopic visualization, and the hard tissue biological repair of the access cavity was exposed. The repair tissue was yellowish with some brown niches and seemed irregular and firmly connected with the axial walls through a well-demarcated white line (Fig. 4*D* and *F*). A periodontal probe was used to assess the stability of the hard tissue bridge to displacement forces. The hard tissue seemed compact and stable (Supplementary Video 2). A self-etching bonding agent (One coat; Coltene) was used over the repaired access cavity, and a thin layer of flowable composite (Brilliant; Coltene) was placed. Internal bleaching was performed with 35% hydrogen peroxide gel (Opalescence Endo; Ultradent Products, Inc, South Jordan, UT) for 5 days. The tooth was restored with composite resin. The 10-year follow-up clinical and radiographic evaluations revealed healthy tissues and satisfactory esthetic result (Fig. 4*B* and *E*).

FIGURE 4 – (*A*) Nine-year follow-up radiograph after completion of orthodontic movement. (*B*) Ten-year follow-up periapical radiograph showing periapical tissue healing, continuous root development, and cervical level hard tissue repair of the access opening. (*C*) Nine-year follow-up clinical view of the greyish cervical discoloration. (*D* and *F*) Clinical images of cervical level biological hard tissue repair of access opening; original magnification, $\times$16 and $\times$20, respectively. (*E*) Ten-year follow-up clinical image showing favorable esthetic result.

DISCUSSION

The strengthening of immature necrotic teeth is considered a major challenge in dentistry. Incompletely formed teeth with thin dentin walls have been shown to experience higher incidences of cervical root fracture, which lead to reduced long-term overall prognosis. Faced with these situations, clinicians have attempted to use bonded composite restorations and fiber posts to reinforce the remaining roots[16]. Although apexification procedures with bonded composite restorations and fiber posts offered favorable outcomes[17], the replacement of missing tissues with artificial means cannot possibly compete with the biological replacement of the missing tissues with natural dental structures.

Recently, regenerative endodontic procedures were introduced to restore the damaged tissues and strengthen the immature necrotic teeth. Regenerative endodontic procedures are defined as biologically based procedures aiming at the elimination of the infection (primary goal, essential), continuous root development/dentin wall thickening (secondary goal, desirable), and regeneration of the pulpal-dentinal complex within a previous empty but infected root canal space (tertiary goal)[18]. Irrespective of the regenerative objectives that can be accomplished, all regenerative protocols require a wide access cavity to gain access to the wide canal. Usually this access cavity is restored at the cervical level of the root with biocompatible/bioactive calcium silicate cement combined with a composite resin restoration. The coronal placement of the calcium silicate cement in regenerative endodontic procedures precludes the use of fiber posts and might hinder the reinforcement of the immature tooth at the cervical level.

Interestingly enough, most of the regenerative literature focused on the continuous root development and the dentin wall thickening potential of the different regenerative protocols to strengthen the root, and little attention was given to the cervical area.

Although the biological repair of the access cavity in the cervical root level with hard tissue bridge is reported among the favorable outcomes of regenerative endodontic procedures[9,19], it is not included in the goals of regenerative endodontic procedures. However, cervical level access opening repair might be a more important biological outcome than continuous root development and dentin wall thickening, leading to true strengthening of the immature teeth.

In this article, we report the regenerative protocols applied in 3 cases of immature maxillary incisor necrosis that, in addition to continuous root development and dentin wall thickening, also resulted in hard tissue repair of the wide access cavities after 5- and 9-year follow-up periods. In the last case, the cervical MTA plug was removed because of esthetic reasons. The hard tissue biological repair was visualized under the microscope and checked for its continuity with the axial walls, its resistance to displacement, and the presence of defects. The repair tissue seemed to be yellowish in appearance with some brown niches, of irregular texture, firmly connected with the axial dentinal walls through a demarcated white line, and resisted all displacement forces applied. This tissue is suggested to provide true fortification of the immature root and might be more important biological outcome than continuous root development and dentin wall thickening.

On the basis of the best available evidence, a protocol that provides the most favorable outcome has yet to be determined[20]. This is attributed to the high variability of the clinical protocols applied during regenerative endodontic procedures[21]. Even similar regenerative protocols applied by the same operator in the same patient have been reported to result in different biological outcomes[12] or induce different healing patterns[13]. Patterns of healing might differ according to the nature of the initial injury and the timing before intervention. Moreover, the patterns of healing can differ according to tooth type, stage of root maturation, type of coronal barrier, disinfection protocol used, and type of intracanal dressing in multiple-visit cases[13].

Although antibiotics were used as intermediate dressing for most multiple-visit published case reports, recent publications advocate the use of calcium hydroxide[20,22,23]. Recently, the European Society of Endodontology published a position statement on revitalization procedures suggesting that the use of antibiotics should be replaced with calcium hydroxide interim dressing[18].

The main concerns for the use of antibiotic pastes during revitalization procedures are treatment-related (crown discoloration, stem cell toxicity, fracture resistance, reduction of dentin) and patient-related (sensitization, bacterial resistance). With regard to the stem cell toxicity, an *in vitro* study has demonstrated that concentrations of triple antibiotic paste, modified triple antibiotic paste, or a double antibiotic paste (DAP) exceeding 1–6 mg/mL were detrimental to stem cells from the apical papilla when in direct contact[24]. Indeed, this raises some concerns when highly concentrated pasty polyantibiotic mixtures are used. However, for calcium hydroxide dressings, although they exert some antibacterial effects in the root canal system, their antibacterial and anti-biofilm effects remain controversial[25,26]. Recently, there is growing evidence that the most important reason for regenerative failure is persistent biofilm infection, and that improvement of disinfection procedures could shift failing regenerative cases to favorable healing patterns[27]. In the regenerative protocol described in cases 1 and 2, a double antibiotic simple mixture was used to a pasty slurry consistency (approximately 1000 mg/mL solution) that is considered toxic for the stem cells. However, the possible benefit of improved disinfection outweighed the risks of DAP toxicity to the stem cells from the apical papilla. Moreover, the risk was minimized by controlling the level of the placement of the DAP and avoiding extrusion of the antibiotic and direct contact with the cells in their apical niches. Inside the canal space the most detrimental factor is effective disinfection and not the toxicity to stem cells that are not yet there. Removal of all antibiotic paste remnants and dentin conditioning before scaffolding are essential steps to shift the intracanal environment to an environment friendly to cell growth and differentiation after the use of antibiotics.

In the present article, both multiple-visit and single-step protocols resulted in favorable biological repair consisting of continuous root development, dentinal wall thickening, and biological repair of the radicular access opening that might account for the true fortification of the necrotic immature teeth.

CONCLUSIONS

The biological repair of the access cavities observed here is suggested to be as important as continuous root development and dentin wall thickening for the long-term prognosis of regenerative endodontic procedures. A regenerative protocol that can induce such a healing pattern might strengthen the immature root and deserves further scientific investigation and modulation.

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The authors deny any conflicts of interest related to this study.

SUPPLEMENTARY MATERIAL

Supplementary material associated with this article can be found in the online version at www.jendodon.com (https://doi.org/10.1016/j.joen.2019.07.003).

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Case Sharing

Case from Dr.Alla Oussama

The case is about an upper right second premolar.
Yes, as you see there is no rubberdam.
I'm sorry for the awful image, the patient have a severe Gag reflexe he couldn't tolerate the presence of the clamp nor the rubberdam, even the suction tip when its a little deep, so I was forced to remove it.
WL was determined,K10 till working length, orifice opening use the fanta orifice opener from Fanta AF F ONE.
Glide Path using 10/04 from Navigator Evo, precurved k15 till WL → precurved k20 till working length → Fanta AF F one 20/06 till WL
I'm so amazed by the flexibility and the preparation ability of Fanta files
I hope you like this case.
A special to my friend William Ha, always in help , as I tell him, he is a true endodontic encyclopedia.

Case from Dr. Anand Poly Dental Care Jhansi

A 32 year-old male referred patient reported to our clinic, with the chief complaint of pain in relation to lower right back tooth region.
Clinical examination revealed mandibular right first molar having faulty restoration.
*The tooth was tender on percussion.
The radio-graphic examination revealed the faulty restoration involving distal pulp horn,

with periodontal ligament widening. Apart from these findings, A sharp curvature in the apical-third region of the tooth was observed on the radio-graph.

A diagnosis of chronic irreversible pulpitis was established and the endodontic treatment was planned followed by full coverage restoration of the tooth.

The apical portions of the canals were prepared using short amplitude filing. Special attention was given on frequent_irrigation of the root canal and recapitulation was done to avoid blockage by dentinal debris and to remove the necrotic remnants of the pulp tissue.

Final cleaning and shaping was carried out using Fanta S One Rotary files

After All cleaning protocols,

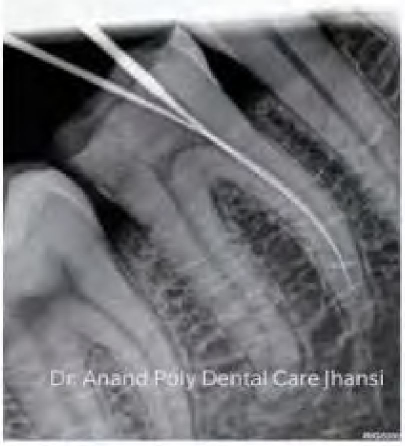
We prepared distal with 25 -6% tapered

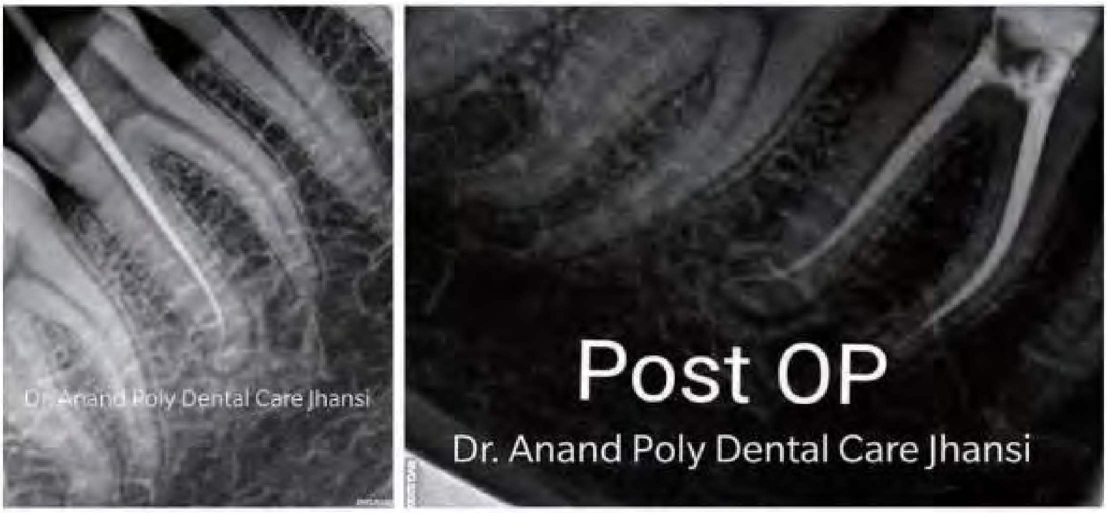
Mesial and Distal with 4% tapered

By using #fantasone rotatary files

For obturation, cement we recommend is seal apex

For vertical condensation we use waldent obturation pen.





Case from Dr. Mohamad Saad

Patient 70 age with recurrent buccal fistula related to tooth # 46 by GP tracing ...showing failed old RCT 10 Yrs ago....
Treatment plan: Re-RCT with explanation of all scenarios to the patient...
Access done through the old Amalgam restoration.
GP removed and the distal canal only becomes patent to the full working length with sharp curve apically..but the two mesial showing total calcification from the mid root to the apex!...
Trials to open these canals all failed, So I decide to disinfect these canals more than usual .... with CHX gel medication ....
Unfortunately I broke RF # 35 .04 in the distal canal ....with failure of all means of bypassing or retrieval....also the disinfection with CHX gel for 3 days ....
Obturation with EndoSeal MTA sealer and WVC obturation...
After 3 days of starting the RCT the buccal tract closed and this is one year follow up...with disappearance of the chronic lesion under the distal root ....

Case from Dr. Mohamad Saad

Patient came with acute abscess related to tooth # 35 with FAILD OLD RCT ...
I&D for emergency pain relief (No ABs)

In next day about 70 % of the abscess was resolved

In the third day I started the RE-RCT ....BUT WITH FAILURE TO NEGOTIATE THE APICAL BIFID CANALS (ledge or irregular pathway)

I start using an aqueous gel with S manual files (pre-curved) once I got the catch I proceeded with FANTA C files.....the CL & SH done with a mix of Azure and FANTA S files ...

Obturation done with BC sealer and vertical compaction...

Case from Dr. Mohamad Saad

Male patient 78 Yrs old Asked to restore his tooth # 48 and keep it in function without pain!

Patient motivation, attitude and needs are very important....

The preoperative x ray was caught in 2016, but now showing chronic apical periodontitis with sinus tract!!

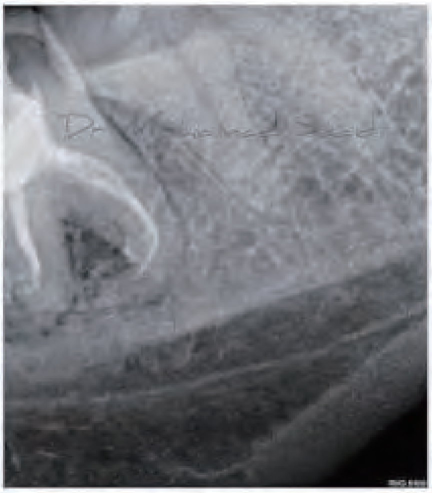
The WL in both roots is 22 mm but due to vertical angle may look shorter!!

Thanks to FANTA C files with lubricant gel !! Then FANTA AF F one # 20, 25 0.04 ....

A Bio-C sealer was used with vertical compaction....


preoperative


Master
Dr Mohamad Saad


Dr Mohamad Saad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From Orifice To Apex

Reading club

PRINCIPLES OF CLEANING AND SHAPING

ENDODONTIC INSTRUMENTS

STEPS OF CLEANING AND SHAPING

WWW.FANTA-DENTAL.COM