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Innovations in Shaping and Cleaning the Root Canal System

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CHAPTER 1: The Problem

Numbers concerning endodontics are growing rapidly year after year (in the US it has gone from 6 million endodontically treated teeth in 1969 to over 25 million estimated (1-2) and the trend is constantly changing.

Although the clinical endodontics is a specialty anything but limited, which includes a large number of interventions, we will focus on the treatment of the pulp and of the root canal system (with or without pathology periradicular), which, if properly executed, it allows patients to maintain their natural teeth and maintain aesthetics and function.

As described by Schilder (3), Weine(4), Bence (5) and the entire literature, three key moments can be identified in the endodontic treatment:

- DIAGNOSTIC PHASE, prime mover of any subsequent medical strategy, which identifies the cause of the disease and formulates a plan of targeted treatment;
- CLEANING & SHAPING PHASE, comprising cleaning and shaping of the root canals: the content of canals is removed and the canal space so shaped as to be able to receive a filling three-dimensional;
- OBTURATION PHASE, in which the root canal system, previously prepared, is filled with inert material that ensures an airtight seal.

The achievement of endodontic success is closely tied to the careful execution of these three phases.

Over time, the approach to the preparation of the root canal space has undergone a rapid evolution.

It has gone from a mechanical preparation, extended to a limited portion of the root canal aim to the introduction of the medication and/or the possible fillings, to a biomechanical preparation extended to the whole root canal, which provides for the removal of waste pulp, till the currently adopted chemo-mechanical preparation, , which also uses irrigating solutions.

The canal chemo-mechanical preparation was born with two aims: the "cleansing" of the canal system and the "shaping of the main root canal", moments that are a sine qua non for the achievement of predictable and long lasting theraphy.

The cleansing has the aim to remove and neutralize potentially pathogens that colonize the root canal system: bacteria and their products, organic and inorganic debris, the vital pulp, products of saliva, blood, etc.

It is obtained by the mechanical action promoted by the work of root canal instruments and through the flow of irrigants; the irrigant solutions, in a variable degree, depending on their chemical composition, act with a solvent action on organic and inorganic residues, and eith an antimicrobial activity.

The shaping, has as its ultimate goal to give to the root canal a shape and a size suitable to allow its obturation (6).

Reasoning by abstract, cleansing would not require a precise shape or a calibrated dimensions: for clean and decontaminate the root canal system would be sufficient a generic widening of the space to permit both easy and comfortable access to the cutting action of root canal instruments and the introduction of irrigants.

Then, how much should be enlarged each root canal as a function of cleansing?

Or what is the amount of dentine to be removed to allow a mechanical debridement of the main root canals to the apical region?

Therefore there is no precise rule and express opinions in literature a fundamental disagreement.

Without entering into the merit of specific quotations, on the one hand there are those who support the need to always carry a working length instruments with ISO size than # 60 to thoroughly cleanse and detoxify the apical third (7); on the other there are those who support the need to maintain the size of the apical diameter as smaller as possible (8).

Basically we could say that the original diameter of the root canal should influence the choices.

But also published studies on the anatomy of the apical region show values often quite divided on the average diameters (9-11), which in addition are significantly variable depending of 'individual, of dental element and its root; so each case has its own story.

A fact that greatly widen the root canal means to weaken the tooth structure.

The instrumentation remains one of the most difficult tasks in

endodontic therapy.
A number of terms have been used for this step of the treatment in the literature including instrumentation, preparation, enlargement, and shaping.
The main goals of root canal preparation are the prevention of periradicular disease and/or promotion of healing in cases where disease already exists through:

- Removal of vital and necrotic tissue from the main root canal(s).
- Creation of sufficient space for irrigation and medication.
- Preservation of the integrity and location of the apical canal anatomy.
- Avoidance of iatrogenic damage to the canal system and root structure.
- Facilitation of canal filling.
- Avoidance of further irritation and/or infection of the periradicular tissues.
- Preservation of sound root dentine to allow long- term function of the tooth.

Techniques for root canal devising include manual preparation, automated root canal preparation, sonic and ultrasonic preparation, use of laser systems, and NITs.

Challenges of root canal preparation

Anatomical factors

Different anatomical and histological studies have demonstrated the complexity of the anatomy of the root canal system, including a broad variation in number, length, curvature and diameter of root canals; the complexity of the apical anatomy with accessory canals and ramifications; communications between the canal space and the lateral periodontium and the furcation area (12–15). This complex anatomy must be considered as one of the major challenges in root canal.

Iatrogenic damage caused by root canal preparation

Several Authors (16-18) described the potential iatrogenic vitiation that can happen to roots during preparation with conventional steel instruments and included several distinct preparation errors:

Zip

The Zipping of a root canal is the result of the proneness of the instrument to straighten inside a curved root canal. This results in over-enlargement of the canal along the outer side of the curvature and under-preparation of the inner aspect of the curvature at the apical end point. The main axis of the root canal is transported, so that it deviates from its original axis. Therefore, the terms used to describe this type of irregular defect are also straightening, deviation, transportation. The terms 'teardrop' and 'hour-glass shape' are used similarly to describe the resulting shape of the zipped apical part of the root canal.

Elbow

The creation of an 'elbow' is associated with zipping and describes a narrow region of the root canal at the point of maximum curvature as a result of the irregular widening that occurs coronally along the inner aspect and apically along the outer aspect of the curve. The irregular conicity and insufficient taper and flow associated with elbow may jeopardize cleaning and filling the apical part of the root canal.

Ledging

The ledging of the root canal may happen as the result of preparation with inflexible instruments with a sharp, inflexible cutting tip particularly when used in a rotational motion. The ledge will be found on the outer side of the curvature as a platform, which may be difficult to bypass as it frequently is associated with obstruction of the apical part of the root canal. The occurrence of ledges was related to the degree of curvature and design of instruments (19–21).

Perforation

The perforations of the root canal may take place as a result of preparation with inflexible implements with a sharp cutting tip when used in a rotational motion. Perforations are associated with the wrecking of the root cementum and irritation and/or infection of the periodontal ligament and are difficult to seal. The incidence of perforations in clinical treatment as well as in experimental studies has been reported as rangingfrom 2.5 to 10% (22-26). A consecutive clinical problem of perforations is that a part of the original root canal will remain underprepared if it is not possible to regain access to the original root canal apically of the perforation.

Strip perforation

The result of Strip perforations from over-preparation and straightening along the inner aspect of the root canal curvature are again associated with destruction of the root cementum and irritation of the periodontal ligament and are difficult to seal. The radicular walls to the furcal aspect of roots are often extremely thin and were as a consequence termed 'danger zones'.

Outer widening

Bryant et al. (27) reported that 'outer widening' describes an over-preparation and straightening along the outer side of the curve without displacement of the apical foramen. This phenomenon until now has been noticed only following preparation of simulated canals in resin blocks.

Apical blockage

Apical blockage of the root canal occurs as a result of packing of tissue or debris and results in a loss of working length and of root canal patency. As a consequence complete disinfection of the most apical part of the root canal system is nonviable.

Damage to the apical foramen

Displacement and enlargement of the apical foramen may happen as a result of incorrect determination of working length, straightening of curved root canals, over-extension and over-preparation. As a consequence irritation of the periradicular tissues by extruded irrigants or filling materials may occur because of the loss of an apical stop. Clinical consequences of this manifestation are reviewed elsewhere in this issue.

Besides these 'classical' preparation errors insufficient taper (conicity) and flow as well as under- or over- preparation and over- and under- extension have been referred to in the literature.

Traditional shaping techniques

While each technique could, at least theoretically, produce the same final shaping effect, each method presents peculiarities that make it ideal for the instrumentation of a specific region of the canal and by means of a precise sequence (28). Over time the instrumentation techniques have been extensively modified, added of contributions and revisions and, sometimes, they have lost much of their identity.

Often new techniques have been introduced as a synthesis of concepts from the past and belonging to previous techniques, and original insights. Two different orientations about cleansing and shaping of the root canals have emerged mainly over the years. The first one aim to start preparing from the apex, with thin instruments, and then work towards apical-coronal with progressively larger instruments ("step-back" or "serial" technique).

The second, by contrast, plans to begin preparation from chamber orifice with larger instruments, and then gradually progress towards the apex with increasingly smaller instruments ("step-down or "crown-down" technique). Each of these methods of preparation of the root canal allows to preserve, to a greater or lesser extent, a degree of centering of the root canal and to obtain a conical preparation.

Over the years the crown-down technique has taken over, but, above all, it has gone from a shape obtained by the action in progressive sequences of different instruments, to the possibility of obtaining the final shape by the action of a single instrument capable of reproducing its shape within the root canal.

Types of hybrid approach are, then, came to light from the mixture of the two methods in an attempt to benefit from the advantages of both techniques.

The technique, whatever it is, must take into account the need to avoid complications such as blocks, nicks apical transport apex, forming drop, deformation or perforations (29).

Standardized (Ingle, 1961)

Over the years, the concept of the ideal shape of the canal preparation is progressively changed.

Once the suggested shape foresaw circular section and limited taper (the instruments on the market had fixed taper .02): the walls seemed almost parallel, and the result was similar to an obelisk. Only the apical portion had a conicity corresponding to 75 ° of amplitude characteristic of the tip of the instruments used to shape.

The standard technique aim to bring to the same working length, all of the instruments introduced in the root canal system: the shape will be given transferring to the root canal the intrinsic form of the instruments used for shaping. Precisely for the logic according to which it proceeds, this approach can also be defined as "single length technique" that has recently regained popularity with the introduction of rotary Ni-Ti instruments as ProTaper® (Dentsply Maillefer, Ballaigues, Switzerland) and Mtwo® (Sweden & Martina, Padova, Italy).

It starts with the scouting of the root canal through the smaller file brought to working length through a movement called winding watch; after which it continues by introducing, in succession, those of greater diameter, always at working length and always with the same movement. Conceptually the final shape will be given by the last instrument used (also called Master Apical File, MAF).

The ISO standardization of manual stainless steel instruments, was placed at the base of this model of ideal form.

It has constituted, in fact, the premise of a technique of integrated endodontic preparation (an instrument of medium or large size that is rotated within a root canal, giving rise to a preparation almost cylindrical, often rectilinear and eccentric, with accentuated enlargement of the region apical) and shutter speed (by means of a cone "master", "standardized" in fact, also nearly cylindrical, comparable to the diameter of the instrument used to prepare the root canal). However, the effectiveness of this technique is adversely affected mainly by two factors: first, the root canals (especially those with accentuated curvatures) shaped with the standardized technique, often are widened more than expected by the diameter of the last instrument used (30, 31); second, optimal compaction of gutta-percha in a root canal with so small taper (.02 or so) is difficult or almost impossible (32, 33)

Step-Back (Clem, Wayne 1969-1974)

Starting from the need of an enlargement greater than what can be obtained through the standardized technique Clem (34) Weine (35) introduced the step-back technique (also called telescopic (36) as its performance in apical-coronal sense recalls the shape of an open telescope). This procedure needed a gradual reduction of the working length during the treatment, usually of 0.5 - 1 mm with the progressive use of larger diameter instruments, producing a conicity of 0.5 - 0.10.

The gradual reduction in the working length, when instruments were used larger and more rigid, also reduced the incidence of errors during the preparation, especially the curved root canals.

Initially Clem (34) described the step-back technique for curved canals in teeth of adolescents, such as the creation of a single bottleneck at the point of transition between the straight portion and the curve of the root canal.

After the classic work of Schilder (37) on cleaning and shaping the root canals, the recommended form of preparation has been renewed, in the shape of a truncated tapered cone continuous in the apical-coronal sense, with the smallest diameter at the level of the apical constriction and the larger diameter at the level of the chamber orifice. One suggested by Schilder and defined "preparation serial" recommended an extension until the apical constriction with ISO files # 30 - # 35, progressively reducing the working length of the following instruments: the resulting form appeared uniformly tapered, so similar to those achieved through step-back technique.

A conical preparation follows the original shape of the root canal, and then allows to enlarge it, without deforming it

It also shows greater effectiveness in the removal of debris with respect to a preparation in almost parallel walls, as it allows a more rapid and convenient penetration of irrigants, and a greater space for their flush.

With the advent of rotary NiTi a new concept was introduced: the tapered end of the root canal can be obtained with a single instrument (precisely "to increased taper "), carving dentin of the canal walls, its own form.

The validity of Schilder's mechanical principles was underlined by Buchanan (29) reiterating that a conical preparation is best to allow the filling obturation.

Crown Down Technique (Marshall , 1980)

The first author who proposed an coronoapical approach was Talbot (38) that in the last century had pointed this kind of root canal instrumentation as the most sensible, especially in the most difficult with curved and narrow canals.

However, despite the early introduction in endodontics, it is only more recently that the coronoapical approach rose to prominence among the endodontists.

The introduction of the first mechanized system which provided for a crown-down approach is due to Dr. Riitano (39)

The " three-time technique ", as he called it, was based, in fact, on the use of particular instruments which worked in coronoapical direction (the RiSpi, made together with Dr. Spina and made by Micro-Mega).
The three-time technique, it provided, in fact, after the scouting of the root canal and the elimination of coronal interferences, the preparation of the coronal and middle thirds and only in the last instance the preparation of the apical third. The root canal is ideally divided into three zones, to be prepared in three steps: coronal, middle and apical.
Of particular interest is the operative concept of rectification of the first two-thirds of the root canal, which is obtained with a correct design of the access cavity and which allows the elimination of coronal interferences of enamel and dentin and grants a correct approach to the middle third of the canal.

The purpose of this procedure is, according to Riitano, to promote the insertion of instruments as straight as possible, in the apical third; in this way we can avoid that any interferences condition the working part or the stem of the instrument, forcing the tip against the dentinal walls, with the risk of incurring in iatrogenic errors (such as steps, perforations or transport of the foramen).

While these interference are not perceived by the smaller instruments that, by virtue of their flexibility, they can quite easily follow the course of the canal to the apex, they are very dangerous in large ones (with # 20 - # 25 tip diameter), since the increased stiffness the instrument tends to download more tensions at the tip (as a result of the increased elastic recoil).

The apical preparation as the final moment, is consequential and logical: instruments prepare the most complex part of the canal only at the end, after clearing all the interference of the first two-thirds that could have hindered a proper instrumentation of the apical third.

The fact that this technique is the ideal approach to the root canal system , is arrived in the last two decades, in which this method has been used with both manual and mechanical instrumentation.

The ideas expressed by Riitano, in fact, have been taken up by Marshall and Pappin (40) in 1980 that revived the technique calling it Crown-Down
(The first description of the crown-down preparation when large files were used to enlarge the coronal portion of the canal and then progressively smaller instruments were used to

prepare the apical portion, can be found in the thesis of J. Pappin (41)).
Initially, Marshall & Pappin (40) recommended a "Crown-Down Pressureless Preparation" in which they were used larger files in the coronal two-thirds of the root canal , and then move on, proceeding towards the apex, with progressively smaller files in "crown-down" , up to the working length.

The crown-down technique, in essence, promotes a coronoapical progression that guarantees the elimination of the preliminary coronal interferences that hinder access to the apical portion, unlike the step-back technique in which the apical third, instead, is prepared first.

Balanced Force Technique (Roane, 1985)

This approach, reported by Roane & Sabala in 1985 (42, 43), was originally associated with specially conceived stainless-steel or NiTi K-file instruments (Flex-R-Files) with adapted tips in a stepdown manner. Instruments are introduced into the root canal with a clockwise motion and apical advancement (placement phase), followed by a counterclockwise rotation with adequate apical pressure (cutting phase). The final removal phase is then performed with a clockwise rotation and withdrawal of the file from the root canal. Apical preparation is recommended to larger sizes than with other manual techniques, e.g., to size #80 in straight canals and #45 in curved canals. The main advantages of the Balanced force technique are good apical control of the file tip as the instrument does not cut over the complete length, good centring of the instrument because of the non-cutting safety tip, and no need to pre-curve the instrument (44).

Copious articles (48-56) described good results for the preparation of curved canals without or with only minimum of straightening. However, others reported a relatively high incidence of procedural problems such as root perforations (57) or instrument fractures (58). The amount of apically extruded debris was less than with stepback or ultrasonic techniques (59-61), the apical region showed good cleanliness (62). Varying outcomes were reported for the amount of dentine removed; in one study the Balanced force technique performed best compared with the stepback technique (63), while in another study more dentine was removed 1 mm from the apex when using the stepback technique (64). When used in a double-flared sequence canal area after shaping was larger than after preparation with Flexogates or Canal Master U-instruments (65). Post-instrumentation area was also greater in comparison with Lightspeed preparation (66), following ultrasonic preparation or rotary Canal Master preparation and equal to hand preparation using the stepback technique (45). A comparison of NiTi K-files used in Balanced forces motion to current rotary instrument systems indicated similar shaping abilities (46). However, some earlier reports had indicated significantly more displacement of the root canal centres, suggesting straightening (66, 67).

Cleanliness was rated of higher quality compared with the crowndown pressureless and stepback techniques (68). The Balanced force technique necessitated more working time than preparation with GT Rotary, Lightspeed or ProFile NiTi instruments (56, 67).

Irrigation

Instrumentation of the root canal system must always be supported by irrigation capable of removing pulp residue and dentin debris. Without irrigation, the build up of this debris causes instruments to rapidly become ineffective. Several irrigating solutions also have antimicrobial activity and kill bacteria and yeasts when exposed with them. Endodontic microbes dwell within the entire root canal area as surface-adherent biofilms. In order to simulate this in vivo situation, a variety of in vitro biofilm models are at the present time being used in endodontic research, for example, to study how irrigation and instrumentation can kill biofilm bacteria and wipe off these biofilms. Factors that remain a challenge with irrigants include deficient penetration, limited tissue-dissolving ability, and exchange in the highly complex root canal anatomy. The most favourable irrigation is based on research using reliable, reproducible, and standardized irrigation models that closely replicate in vivo scenarios in order to estimate safe and effective irrigation.

The ambition of endodontic therapy is the removal of all vital or necrotic tissue, microorganisms, and microbial by-products from the root canal system. However this may be achieved through chemomechanical debridement (68), it is difficult to predictably reach this aim (69-71) because of the intricate structure of the root canal anatomy and the resistance of microbial biofilms (72-74). Instrumentation of the root canal system must on all occasions be supported by irrigation capable of removing remnants of pulp tissue and other loose material. The effectiveness of an irrigation system is dependent not only on its ability to provide the irrigant to the apical and non-instrumented regions of the canal space, but also on the

ability to create a current strong enough to carry the debris away from the canal systems (75-79), to dissolve both organic and inorganic matter, and to kill microorganisms. Irrigating solutions are constantly modified and further broadened to improve their properties. However, there is currently no unique irrigant that meets all of the requirements for an optimal irrigating solution (80-91).
Byström & Sundqvist (92) found that mechanical instrumentation and irrigation with saline significantly lessened the number of bacteria in the root canal. However, in half of the cases, bacteria still remained in the canals after four treatments, and it was concluded that the supporting action of a disinfectant is necessary for the successful extermination of living bacteria. The mechanical instrumentation of root canals has been deemed one of the most important phases in endodontic treatment. In a study by Dalton et al. (93), the investigators prepared root canals, irrigated with saline solution, specimen of microorganisms from the canals before, during, and after instrumentation were sampled, and counted the culturable bacteria CFUs) at each stage of the treatment. The outcome showed that progressive filing reduced the number of bacteria regardless of whether rotary or stainless-steel hand instrumentation was used. However, no technique

resulted in bacteria-free canals. These finding were also confirmed by Siqueira et al. (94) who found that instrumentation combined with saline irrigation mechanically removed more than 90% of the bacteria in the root canal. The same group later reported that sodium hypochlorite (NaOCl) solutions (1%, 2.55%, and 5.25%) were significantly more successful than saline in reducing the number of bacteria in the main root canal (95).

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CHAPTER 2: Shaping concepts evolution

Talking about endodontic instruments, the most significant change in recent times has come with the introduction of nickel-titanium alloys (Ni-Ti alloys).

Endodontics has opened its doors to the nickel-titanium since 1988, with the pioneering studies of Walia et al. (1) on prototypes of files obtained from the manual processing of orthodontic wires produced made of this alloy. From then on, after more than a century of dedicated steel instruments in the endodontic field, the Ni-Ti has officially entered the stage, representing a real revolution especially regarding the production of rotary instruments. The change from manual to rotary constituted a must as natural: is justified by the fact that the use of rotary instruments, promoted by special motors with a precise speed control (and possibly also of torque), it allows fully exploiting the super-elasticity of the alloy.
This characteristic is manifested in a considerable and reversible elastic deformation, which subjecti the instrument to an almost constant effort.
The shaping process is facilitated both by virtue of the greater flexibility of the Ni-Ti alloy in curved canals, both to the increased cutting ability resulting from the continuous motion.

To the greater effectiveness and speed of the procedures the advantage of a preparation properly centered in the root canal is added by virtue of the lesser elastic recovery (typical of the steel), which results in a reduced tendency to deformation of root canal anatomy (2) .

The first NiTi rotary instruments (Nickel-Titanium Rotary, NTR) were developed between 1993 and 1994 by J. Mc Spadden and Ben Johnson and marketed with the name of ProFile (Tulsa Dental Products);in the following years a large number of specialists and not, begun to adopt mechanical instruments for clinical practice, decreeing their international success (3). This was only the beginning. Over time, many NiTi products were launched on the market, and the public interest was not limited to a purely commercial context, but also extensively involved literature.

Studies on the properties and performance of these instruments became an area of intensive research: in fact, since their introduction in 1993 until January 2007, Pubmed could count more than 350 scientific papers on various aspects of these instruments.

Of course, for getting this overwhelming wave of progress, the support of the industry was obliged too.

The traditional manufacturing processes for torsion, in fact, at least initially, were not suitable to the realization of such instruments, for that reason it was necessary to design and build the appropriate computerized equipment capable of working rough Nickel -titanium threads so as to confer them increasingly complex drawings and a better performance compared to traditional endodontic files.

Through these innovative equipment, achieve new instruments with complex has been possible and, at the same time, introduce the concept of increased taper, compared to the traditional ISO .02.

In fact, before the advent of the Ni-Ti alloy, instruments for endodontic shaping were normally used by hand and made of stainless steel with a standard taper .02 ,: they increased diameter of 0.02 mm for every millimetre, proceeding from the tip up to the end of the active part, 16 mm long 80. The clinical use of these instruments required, the scalar use of them: each instrument was brought to different lengths within the root canal, to achieve a funnel-shaped canal clinically effective and accordingly to achieve adequate conicity of preparation.

Everything required great clinical experience by the operator, but especially long times and a large number of instruments, by virtue of the fact that preparations with standard taper (.02) were insufficient to ensure a valid shaping for cleaning and the final root filling.

The other innovation, made possible by the use of sophisticated computerized equipment in the production process for turning (or slot) concerns the opportunity to vary the design of the instrument, both in terms of cross section of that trend and orientation of the coils (4, 5).

This innovation has contributed to the introduction of more technologically advanced instruments, greatly performing in terms of cutting ability, and able to resist to higher physical stresses.

What are the advantages of the nickel-titanium over steel justifying the thousands of pages of scientific papers published, the efforts of legions of engineers and rising inventory costs incurred by operators to use these instruments?

The undisputed advantages, can be summarized in three basic points (6-8):

1. Speeding up of the operational procedures: the traditional manual techniques based on the use of stainless steel instruments included the use of a large number of files and steps. The particular cutting efficiency of the Ni-Ti instruments and the introduction of increased taper allowed to reduce considerably the number of necessary instruments for shaping

a tronco-conical canal and then to spend less time for achieve these objectives (9, 10).

2. Simplification of the operational procedures: the technique is simpler and immediate than the traditional ones, precisely because of the flexibility of the Ni-Ti alloy and the use of the continuous motion (11). The instrumentation is simplified also because there is less need to pre-bend the files in more complex canals. These benefits, together with the reduction in the number of instruments necessary to shape the root canal, and the relative recaps, translates into a reduction of iatrogenic errors (false roads, steps and transport root canal). The quality, expressed in terms of centering ability, draws its advantages: a greater respect of the original trajectories and an effective cleansing of the endodontic space. Substantially fewer steps mean, in theory, less chance of error.

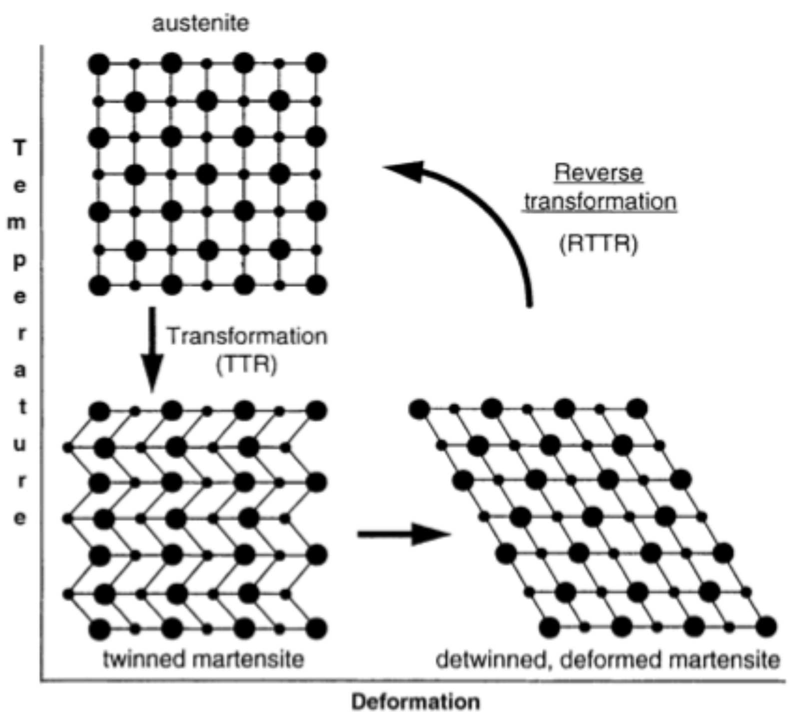
3. Predictability and effectiveness of treatment: the increased taper of the instruments in Ni-Ti can reach transverse more adequate preparation diameters. Greater diameters of preparation improves the ability of mechanical removal of contaminants, and at the same time they increase the area on which the irrigating solutions are able to carry out their chemical action granting their spreading to the apical region.

In fact, the apical penetration of irrigants is incremented by a valid flaring of the root canals, as well as the procedures of root canal filling are simplified and made more predictable if the root canal is properly shaped (12).

Ni-Ti Systems

Metallurgical aspects

The nickel–titanium alloys used in root canal treatment contain approximately 56% (wt) nickel and 44% (wt) titanium. In some NiTi alloys, a small percentage (<2% wt) of nickel can be substituted by cobalt. The resultant combination is a one-to-one atomic ratio (equiatomic) of the major components and, as with other metallic systems, the alloy can exist in various crystallographic forms.



The generic term for these alloys is 55- Nitinol; they have an inherent ability to alter their type of atomic bonding which causes unique and significant changes in the mechanical properties and crystallographic arrangement of the alloy. These changes occur as a function of temperature and stress. The two unique features that are of relevance to clinical dentistry occur as a result of the austenite to martensite transition in the NiTi alloy; these characteristics are termed *shape memory* and *super-elasticity*

Nitinol belongs to a category of alloys called “shape memory alloys” that have some extraordinary qualities. NiTi behaves like two different metals, as it may exist in one of two crystalline forms. The alloy normally exists in an austenitic crystalline phase that transforms to a martensitic structure on stressing at a constant temperature. In this martensitic phase only a light force is required for bending. If the stress is released, the structure re- covers to an austenitic phase and its original shape. This phenomenon is called a stress-induced thermoelastic transformation.

Nickel–titanium alloy production is a very complex process that consists of:

- vacuum melting/casting

- press forging
- rotary swaging
- rod/wire rolling

In the past, NiTi alloys with near stoichiometric composition have been produced satisfactorily by both arc and induction melting methods. One of the problems encountered with arc-melting was that it required multiple remelts to ensure chemical homogeneity; however, importantly this process produces only minimum contamination of the alloy. Current manufacture involves the use of vacuum induction melting in graphite crucibles that ensures effective alloy mixing by simple means, with slight carbon contamination in the melt forming TiC The presence of oxide impurities does not effect the unique properties of 55-Nitinol, as these appear to be evenly distributed within the NiTi matrix.

The manufacture of NiTi endodontic instruments is more complex than that of stainless steel instruments, as the files have to be machined rather than twisted. The super-elasticity of the alloy means that it cannot maintain a spiral as the alloy undergoes no permanent deformation. Attempts to twist instruments in a conventional way would probably result in instrument fracture. The instrument profile (design) has to be ground into the Nitinol blanks. Further difficulties during production include elimination of surface irregularities (milling marks) and metal flash (roll-over) on the cutting edges that may compromise the cutting ability of these instruments and potentially cause problems with corrosion.

The composition of Nitinol used to construct endodontic instruments is 56% (wt) nickel and 44% (wt) titanium. Although only one manufacturer (Dentsply, Maillefer Instruments SA, Ballaigues, Switzerland) has released the absolute composition and manufacturing details of the nickel–titanium used to construct their instruments, it would appear that this is the only alloy composition that can utilize the super-elastic properties of the alloy.

It is possible to vary the composition of NiTi alloy in order to give rise to wires with two different characteristics; either to be a super-elastic alloy or to have the shape memory property. The differences between the alloys are in their nickel content and the transitional temperature range for the given alloy. Various parameters affect the transformation temperature; a decrease in the trans- formation temperature occurs with an increase in nickel content or by substituting trace elements such as cobalt as discussed previously, whilst an increase in annealing temperature increases the transformation temperature. Ideally, for the manufacture of root canal instruments the ultimate tensile strength of the alloy should be as high as possible to resist separation, whilst the elongation parameters must be suitable for instrument flexibility, thereby decreasing canal transportation, and to allow high resistance to fatigue.

Shaft and tip design

In addition to variation in taper, the existing NiTi systems have different designs of blades, grooves and tip. The resultant dissimilarity of rake angle, degree of twist, groove spacing and cutting or non-cutting tip, complicates the clinician's choice of instruments.

The shaft design of NiTi instruments is tailored to be used in a rotary handpiece. Most systems have simply one of two possible designs to prevent the instrument from screwing and binding in the canal wall. The first design incorporates a dissimilar helical angle pattern for the cutting blades. For the other design, a space remains without being ground between each groove, providing a "radial land area". Without a blade projecting outward from the middle of the shaft, this flat area prevents the instrument from locking in the dentin and cutting occurs through a planing rather than a cutting action (13).

Rotary files with radial land areas are further subdivided depending on the shape of the grooves, U-shaped or L-shaped, resulting in a U-type or H-type file. The U-type file is constructed by grinding three equally spaced U- shaped grooves around the shaft of a tapered wire, whereas the H-type file consists of a single L-shaped groove (Hedström type) produced in the same way.

Cleaning ability

Even though studies on various NiTi instruments in the last years have focused on centring ability, maintenance of root canal curvature, or working safety of these new rotary systems, only relatively little information is available on their cleaning ability. It should be mentioned that the term 'canal cleaning' is usually used for the adeptness to remove particulate debris from root canal walls with cleaning and shaping procedures. This property often has been determined using scanning electron micrographs.
Throughout the many studies in literature (14-17) no completely cleaned root canals could be found regardless of the NiTi system investigated. Whereas most of the debris was removed, different degrees of smear layer were found in all root canals. Cleanliness uniformly decreased from the coronal to the apical third of the root canals, instruments with actively

cutting blades showed better cleanliness than files with radial lands.

As a conclusion it may be stated, that

- the use of NiTi instruments results in less straightening and better centred preparations of curved root canals,
- the use of NiTi instruments alone does not result in complete cleanliness of the root canal walls,
- cleanliness dininishes from the coronal to the apical part of the root canal,
- when used according to the manufacturers' guidelines NiTi instruments seem to be safe to use,
- the use of instruments with safety tips seems to be preferable with respect to working safety,
- the use of a special motor with constant speed, low torque and torque-control is recommended.

Ni-Ti Instruments Failure

The introduction of rotary nickel-titanium alloy (Nickel Titanium Rotary, NTR) has been a real revolution in endodontics. It is well established that the NiTi instruments offer many advantages in the preparation of the root canals (12, 18-20). The use of Ni-Ti exhibits, however, a constant threat, represented by a higher risk of fracture than steel.

The reason why many operators, though attracted, are reluctant to step in NiTi instruments was the fear of intracanal instrument fracture (12), altough the incidence is considered low.

Parashos (21) in a study examined 7159 instruments obtained from 14 endodontists from 4 countries found an incidence of fracture average of about 5% (of which 70% for fatigue).

Sonntag(18)considers a fracture index less than 2.5% clinically acceptable. Di Fiore (22), in a more recent study in which 11 graduated students have treated 3,181 channels with 6,661 rotary instruments from many different manufacturers, found an average of 0.39% of fracture.

The main causes of failure of the instruments in Ni-Ti are represented by the "torsional fracture" and the "cyclic fatigue fracture".

The torsional fracture must be considered that the tool in rotation is normally subjected to torsional loading, due to 'cutting action that its blades exert on the canal wall: if this load increases, one can determine the deformation and then the subsequent fracture of the instrument (23).

An accidental locking of the tip, or another part of the instrument, may cause a sudden and excessive torsional stress, that could determine the fracture. In fact, the tip, or any other portion of the instrument, remains locked within the channel while the rest of the instrument continues to rotate; the elastic limit of the metal is exceeded and therefore develops an irreversible plastic deformation, followed by fracture.

Fracture can happen without any visible signs of previous permanent deformation, apparently within the elastic limit of the instrument (24-26) Visible inspection, therefore, is not a reliable method for evaluating the used NiTi instruments. Another concern is that tests for physical properties, as detailed in the ADA Specification No. 28, are not useful because they are conducted in a static mode and do not consider canal geometry. NiTi engine-driven rotary systems require that the instruments be activated before insertion into the canal, where it mostly operates in flexed conditions. The phenomenon of repeated cyclic metal fatigue may be the most important factor in instrument separation(27-30) When instruments are placed in curved canals, they deform and stress occurs within the instrument. Being half of the instrument shaft on the outside of the curve in tension, the half on the inside is in compression. As a result, each rotation causes the instrument to undergo one complete tension-compression cycle. Clearly, stress levels are the greatest in the area of curvature (31). More severe bends create greater stress and larger, stiffer instruments will experience greater stress than smaller instruments when confined to the same curved canal shape (31). Taking in consideration cycle fatigue as a contributor to instrument failure, larger instruments should not be considered safer or stronger in clinical practice (30-32). The torsional loading happening during a rotational use is another variable to consider. The amount of torque applied on the instrument mainly depends on the file manipulation and its design. The crown-down technique generates lower torque and lower vertical forces, although these detections also depend on the shape of the individual canals (33, 34). In another study,(35) the same author demonstrated that the areas of contact with dentin are positioned at or close of the tip of the ProFile 0.04 taper file. For the ProFile 0.06 tapered files, however, the location of friction areas never involved the tip of the instrument.

The file design has its influence on torsional loading because cutting blades could act as stress concentrators, potentially resulting in more rapid crack initiation. The radial land areas, however, contribute to the strength of the instrument by the relative large peripheral mass. Furthermore, the effect of instrument design is an area of concern, particularly with the introduction of non-standardized tapered NiTi instruments. The greater taper enlarges the diameter of the instrument at the coronal curvature, compared with the apical area, therefore resulting in higher stress (30)

Due to its broad range of elastic deformation, NiTi alloy may be toiled much further than stainless steel before it is permanently deformed. Resistance to fracture, however, measured as angular deflection before fracture, is lower for the NiTi instruments (36). The phase changes along with the stress-induced transformation can be slow thermoelastic or burst type of martensite. During the crystal changes, the instrument is very liable to fracture. This is of special concern when used for rotary instruments. Upon rotation, abruptly changed stress levels cause movement of dislocation defects and breaks anatomic bonds within the matrix, leading to crack initiation and propagation (30, 37). Moreover, machined files exhibit less ductility than twisted files prior to fracture and may be more susceptible to torsional failure clinically (38). In this regard, the ability of the operator seems to be an important clinical factor of instrument failure (39) and early radicular access (flaring) reduces the chance of instrument failure caused by locking the file in dentin (40).

Taking in consideration separation caused by rotation, the direction of use must be addressed. Both the stainless steel and NiTi files demonstrated greater rotation to failure in the clockwise direction than in the counter-clockwise direction for the same file size (9). This is understandable considering the mechanisms for failure (38). While in a clockwise torsion, the cutting spirals unravel. After a while, the outer portion of these spirals starts to experience longitudinal compression as the twist direction begins to reverse. After the spirals have reversed direction, tension will be created since the winding will be tightened and at last fracture will occur.

It is important to recognize that, if separation does not occur because of static torsional overload, the instrument will have a mean number of cycles to failure that is determined by specific parameters of canal radius, canal angle and instrument diameter (30). A higher rpm will consume the useful life much faster than a lower rpm. The separation of unbound instruments in the area of the most severe canal curvature should always be considered a result of cycle fatigue with any system. In some severe angles, discarding an instrument after a single use may be the safest advice.

Handpiece systems have been designed to maintain the material in its martensitic phase (constant stresses through controlled speed and torque on rotation). Clinically, axial motion (in and out "pecking" movements) during instrumentation would be expected to significantly extend the instrument's life (30, 41).

Dry heat sterilization does not influence the number of rotations to breakage of the file (32, 42). Comparably, heat treatment as a result of autoclave sterilization does not seem to extend the useful life (43). In contrast, Serene et al.(28) noted an effect on prolonging the clinical life expectancy, according to the theoretical possibility to remove any deformation in a NiTi instrument as a result of use, by heating the file to a temperature above 125°C.

Besides instrument failure by separation, resistance to wear of NiTi rotary files needs more attention. First of all, there are no clear requirements regarding resistance to wear. Stainless steel files wear significantly when used on dentin and will lose their original effectiveness (24,44). NiTi files also wear noticeably, but they are significantly more resistant. The properties of the metal apparently reduce pressure and force on the flute edges and instrument body (24) The more rapid wear of rotary NiTi instruments compared with NiTi hand instruments could be attributed to the use of a high-torque handpiece. Longer usage times result in an increased deterioration, but with marked differences in rate, depending on other characteristics such as design (24).

Strategies To Reduce Risk Of Fracture And New Technologies

Despite the undeniable advantages of Ni-Ti alloys, the rotary instrumentation still meets some resistances mostly linked to the increased risk of intraoperative fracture, and to the relative rigidity of the instruments (that can lead to aberrations of the root canal).

As stated before, many attempts to improve the features of the instruments and bypass these drawbacksas has been made over the years.

The most important innovations concerned the design variations as in the case of instruments with progressive taper, the introduction of the reciprocating motion to decrease the impact of cyclic fatigue and, finally, the use of a single instrument for the whole treatment of a root canal. However, only recently there is some interest by the manufacturers to use new alloys and manufacturing processes different from the common turning employed so far.

These processes are intended to not weaken the instruments during the manufacturing phase, and make use of special heat treatments on the alloy and innovative production methods able to preserve and increase the mechanical properties of the instruments themselves.

In particular heat treatments have been proposed to enhance flexibility and resistance of files, as in the M-Wire™ technology.

In general, even though these innovations show encouraging results, they make the production process more complex and with more difficulty in standardization: in particular, is not simple to obtain alloys with constant mechanical properties, since their remarkable sensitivity (with consequent variability) to these treatments.

Recently the Sybron Endo (Orange, USA) has developed an original manufacturing process for rotary Ni-Ti torsion, up to now considered impossible, since the Ni-Ti alloy, super-elastic, tends to return to its original shape if subjected to torsion.

The manufacturing process mentioned above for twisting is instead possible, since the use of innovative and patented heat treatments (cycles of cooling and heating) and finishing processes, which allow a control of the phases and of the characteristics of the alloy, used both for the production both to improve the final properties of the alloy.

The differences with the conventional production processes for turning or notch (grinding) are various, since they inevitably involve a major damage to the internal and external structure of the instruments, with the formation of defects and micro-cracks.

These aspects represent factors contributing to weakening the mechanical strength of the instruments also for stresses lower than the breaking load (loci minoris resistentiae). This also explains the possibility of "unexpected and sudden" fractures during clinical use.

These surface defects can be minimized in part also by performing sophisticated finishing treatments, like the electro-polishing, which affect, however, only the outer surface of the instrument and , therefore, do not solve the problem entirely, with the further disadvantage of reducing the effectiveness of the cut. In fact in the literature we find conflicting opinions about their use. While some authors argue an increased resistance to cyclic fatigue (45), others do not notice significant improvements in these terms (46-48) and others, instead, demonstrated a reduction in cutting capacity because this process softens the sharp edges of the instrument (49): this requires the clinician the application of a greater pressure, by increasing, in undesirable manner, the torque of the rotary instrument during the working phase.

Variable Taper Instruments

Optimal root canal shaping is difficult to practice and teach with traditional instruments. Instrument sequences are complex, with up to 18 instruments and 63 procedural stages, providing almost limitless scope for faulty results and iatrogenic error.

Once a root canal has been negotiated to its terminus and its length determined, the only thing withholding the thoroughly cleaning and filling it is the need for ideal shape. Without adequate shape, the irrigation devices available at this time cannot adequately clean complex root canals to their full apical and lateral extents (50). Likewise, our obturation results, regardless of the filling technique used, are almost wholly dependent upon the shape into which the filling materials are placed (51).

Alas, however, shaping root canals has been the most dangerous, difficult, and time-consuming aspect of conventional endodontic treatment; the frequent occurrence of inadequate or iatrogenic shapes in root canals treated over the past 20 years provides us with significant evidence. Coronal enlargement has often been excessive, resulting in short-term loss of teeth when strip perforations occurred. Nearly any iatrogenic result in the apical third of a root can be

repaired predictably, surgically or nonsurgically. This is not so in the cervical third of roots.
The most common, but less noticed, failures are long-term losses due to vertical fracture when roots are not perforated but unduly weakened.

Apart from coronal leakage, root fractures are the competent endodontist's greatest menace to long-term clinical success. Shapes achieved by the use of relatively nontapered coronal enlargement tools, such as Gates Glidden, are even in the most favorable circumstances, irregular. Whilst experienced clinicians can learn how to use these cutting instruments safely, neophytes are destined for distressing learning experiences. A less ruinous but frequent outcome is the inadequate cleaning and filling that routinely results from ineffective shaping in the apical half of the canal.

An unsatisfactory shape in the middle third of canals is a setup for poor cleaning, as irrigating solutions cannot be introduced to the full apical and lateral extents of root canal systems. Obturation results are also demeaned, especially in the apical third. Apically, the classic error is to over-enlarge the terminal diameter of the canal. Taking successively larger files to the same length in a root canal is a setup for apical lacerations, even when using the Balanced Force technique (52). If the working length is too short (1–2 mm), the canal is often ledged, causing poor apical cleaning and a short fill. If the working length is even slightly in error beyond the terminus, all working length has been lost.

Advantages of tapered preparations

Research and clinical experience have demonstrated many advantages of tapered root canal preparations over the commonly taught 'apical stop preparation.' These advantages include improved cleansing ability (53), dramatically enhanced apical control of instruments (51), less dependence on exact length determination, more dependable apical resistance form, greater confidence of cone fit (54), and that these tapered preparation shapes are optimal for virtually all filling techniques (55).

A conclusive strong argument for these tapered root canal shapes is that they are very similar to the morphology of root canals when they are first formed.

Problems with tapered preparations

Alas, carving tapered root canal preparations with ISO-tapered instruments, regardless of whether they are used in a serial

step-back or a serial crown-down procedure, presents several significant challenges to clinicians. Amongst these difficulties is the need for 15–18 instruments that are used in 47–63 procedural steps, if you want consistently ideal outcomes. Just as difficult is the fact that each successively larger instrument must fit further back from terminal length by fairly exact 0.5–0.25 mm increments.
Furthermore, because of this indirect method of creating a tapered shape with relatively nontapered instruments, there is no precise way of knowing which cone to fit after shaping is completed.

Also associated to this technique is the same problem seen with the apical stop preparation, the nightmare of uncontrolled coronal enlargement with Gates Glidden burs.

The variably tapered file concept and its advantages

The power of the variably tapered file concept is in its total control of the root canal shape, from orifice to terminus. For the first time in endodontics since the single-cone era, dentists can predictably create a predefined specific shape throughout the full length of a root canal. This provides many advantages some of them obvious, some not as much.

- Perfectly adequate coronal enlargement

The first advantage is safety, because we can now determine exactly how much coronal enlargement we want. As it turns out, we only need a certain amount of shape in a root canal, not endless shape. Creating just enough shape – skirting the fine line – is very difficult to do with serial step-back shaping and Gates Glidden burs. With these techniques, most of us prepared canals to slightly larger diameters than was required.

- Confirmed full deep shape

An underrated, but frequent problem is the under-shaping of canal preparations near the junction of the middle and apical thirds. Whilst the most common shaping error is to over-shape coronally and under-shape the canal beyond mid-root, the opposite result is needed; more conservative coronal enlargement and fuller deep shape. 'Anaemic' deep shape significantly limits irrigation efficacy in the apical third and causes conefit prematurities, a setup for overextended filling material.

- Predictable apical resistance form

A more subtle safety feature of this concept is expressed in the apical regions of the preparation. With relatively untapered files (conventional files with 0.02 mm mm^{-1} tapers), there is a great chance of apical iatrogenesis if the working length is even fractionally incorrect. If 12 file sizes are stepped back from an erroneously long working length, then perhaps six of the files have blundered through the apical constriction, destroying any apical resistance form that may have been present preoperatively. Conversely, if a file of greater taper is mistakenly taken 1 or even 2 mm beyond the root canal terminus , there is still linear, tapered resistance form present because even the most tapered file size has a 0.2 mm tip diameter.

- Standardized predefined tapers

Safety aside, the most striking advantage of these files is that they enable clinicians to control the canal shape from orifice to terminus. This is very effective because it ensures that the preparation has adequate deep shape, an accomplishment that will guarantee ideal cone-fitting and apically controlled obturation.

- Enhanced cleaning efficacy

The difficult task of thoroughly cleaning complex root canal spaces continues to yield to studies of different irrigation techniques and devices. We know that apical irrigant exchange occurs when the inactivated irrigant is displaced by patency files, so it follows that irrigating cannulas with tapers matching the shaping files could more effectively freshen solutions in that tiny, complex, apical region.

- Enhanced obturation efficacy

In considering 3D obturation of root canal systems, it is certain that warm gutta percha techniques can gain advantage in predefined canal shapes. Predefined canal shapes allow for a simple but accurate size selection of gutta percha points, paper points, obturation carriers, and Continuous Wave electric heat pluggers, which will work optimally in the preparation.

A revolution was introduced on the market with the launch of ProTaper® system in 2001 which are, also now, the most used endodontic instrument system in the world.
Their history began in 1995 as a project to built a set of Ni-Ti instruments easy to use and safe for respecting root canal anatomy.
Doctors Pierre Machtou, John West and Cliff Ruddle with a team of Maillefer engineers developed the idea of a new family of instruments which respected all the Shilder’s shaping principles.

The introduction both of Ni-Ti alloys and the concept of variable taper helped in simplifying procedures. On the other hand is well known that an increasing taper means also more metallic mass and a consequent augmented instrument's stiffness.

An increased stiffness could lead to an alteration of the original root canal anatomy.
A unique feature of ProTaper instruments is each one has changing percentage tapers over the length of its cutting blades. ProTaper instruments also have convex, triangular cross-sections, a changing helical angle and pitch over their cutting blades and a non-cutting, modified guiding tip.

The Protaper® System

The ProTaper system is comprised of three Shaping and three Finishing instruments.
Shaping instrument no. 1 (S1) and Shaping instrument no. 2 (S2), have respectively purple and white identification rings on their handles. The S1 and S2 instruments have D0 diameters of 0.17 and 0.20mm, respectively, and their D14 maximal flute diameters approach 1.20 mm. The Auxiliary Shaping

instrument (Sx) has no identification ring on its gold-colored handle and a shorter overall length of 19 mm. The Sx has a D0 diameter of 0.19mm and a D14 diameter approaching 1.20 mm. The shaping instruments have progressively larger percentage tapers over the length of their cutting blades allowing each instrument to engage, cut and prepare a specific area of the canal and perform its own ‘crown-down’ preparation. Because Sx has a much quicker rate of taper between D1 and D9 as compared with the other ProTaper Shaping files, it is mainly used to optimally shape canals in coronally broken down or shorter teeth.

Three finishing instruments named F1, F2 and F3 have yellow, red and blue identification rings on their handles corresponding to D0 diameters and apical tapers of 20/07, 25/08 and 30/09, respectively. From D4 to D14 each instrument has a decreasing percentage taper.

Protaper Features & Benefits

- Multiple Tapers

A distinctive feature of the Shaping files is their progressively tapered design which clinically helpes to significantly improve flexibility, cutting efficiency and typically reduces the number of recapitulations needed to achieve length, especially in tight or more curved canals. As an example, the SX file exhibits nine increasingly larger tapers ranging from 3.5% to 19% between D1 and D9, and a fixed 2% taper between D10 and D14. The S1 file exhibits twelve increasingly larger tapers ranging from 2% to 11% between D1 and D14. The S2 file exhibits nine increasingly larger tapers ranging from 4% to 11.5% between D1 and D14. This design feature allows each Shaping file to perform its own "crown down" work. One of the advantages of a progressively tapered Shaping file is that each instrument engages a smaller zone of dentin, which reduces torsional loads, file fatigue and the potential for breakage.

- Convex Triangular Cross-Section

Another unique feature of the ProTaper instruments relates to their convex triangular cross-section. This feature reduces the contact area between the blade of the file and dentin, and serves to increase the cutting action and improve safety by decreasing the torsional load. As is true with any instrument, increasing its D0 diameter and percentage taper correspondingly increases its stiffness. To improve flexibility, Finisher No. 3 has a reduced core, as compared to the other instruments in the series.

- Helical Angle & Pitch

ProTaper files have a continuously changing helical angle and pitch over their 14 mm of cutting blades. Balancing the pitch and helical angles of an instrument optimizes its cutting action, effectively allows its blades to auger debris out of the canal, and importantly prevents the instruments from inadvertently screwing into the canal.

- Variable Tip Diameters

The three Shaping files have variable D0 diameters to permit clinicians to safely and efficiently follow the canal while allowing each instruments' more coronal cutting blades to pre-enlarge specific zones of the canal. Shaper No. 1 has a diameter of 0.17 mm at D0. Shaper X has a diameter of 0.19 mm at D0 and Shaper No. 2 has a D0 diameter of 0.20 mm. The finishing files have variable D0 diameters of 0.20, 0.25 and 0.30 mm to address the obvious variations in cross-sectional diameters that canals exhibit in their apical one-thirds. Generally, only one finishing file is necessary to optimally finish the apical one-third of an anatomically difficult or significantly curved canal.

- **Modified Guiding Tip**

Another specific feature of the ProTaper files is each instrument has a modified guiding tip. This design feature allows each instrument to better follow the canal and enhances its ability to find its way through soft tissue and loose debris without damaging the root canal walls.

- **Short Handles**

ProTaper files have short, 12.5 mm handles as compared to the more standard file handle length of 15 mm. This feature serves to give a better access into the posterior regions of the mouth, especially when there is a narrow interocclusal space.

The Evolution: Protaper Universal®

Although the high-quality performance guaranteed by the first series of rotary instruments, the market had made a wishlist for a possible new generation of instruments. First, it was necessary to obtain a diameter of the tip for greater apexes and for the cases where the clinician wanted to shape up to a diameter equal to that of instruments ISO # 40 or # 50 in an attempt to further ensure the maximum cleansing of the apical foramen. Secondly, there was the need of instruments for teeth with

greater axial length, as the canines.
Third, some clinicians felt that the F3, while being more flexible than other instruments of comparable size, it was still too hard. Finally, some authors began to highlight the aggressiveness of ProTaper®. At Maillefer Instruments of Ballaigues, a group led by endodontists Clifford Ruddle, Pierre Machtou and West, in collaboration with the Swiss engineers company, met for a second time for support these new needs.

So, despite the ProTaper® instruments has enjoyed a series of successes crowned with five years of explosive growth on the international market in 2005 has been further refined and proposed on the market as a new generation of instrumens with variable taper, renamed ProTaper® Universal. The new ProTaper® Universal files presented a redesign. The multiple taper on the stem and the convex triangular cross-section have been preserved, the angle of transition between the tip of the file and the first cutting blade has been removed, the space for the collection of debris has been increased as well as to facilitate unloading from tip to base.

Additionally an industrial electro-polishing treatment was introduced to made the alloy more resistant to fracture. Two new Finishing files (F4 and F5) designed for large apices

(ISO sizes # 40 and # 50) were introduced. New features are also present in the Finishing files of ProTaper® Universal: more rounded tip, which facilitates the centering of the preparation compared to the original root canal, and a reduced section, with increase in the number of grooves, which increases the flexibility. The design of the larger Finishing files , F3, F4 and F5, was modified to further increase the flexibility.

Changes Compared To The Previous Generation.

- SX: The shaper SX, despite demands for further increase geometries, has remained unchanged, except for the replacement of the "partially active" tip with a rounded toe safe-tip.
  It offers an unchanged clinical experience, but safer, since a further increase in size would have entailed the risk of inadvertently affect the internal wall of the root canal and thus injure the delicate area of the bifurcation.
- S1 (PURPLE): The S1 has remained unchanged, apart from the added of a safe tip.
- S2 (WHITE): The change of S2, though small, is essential conceptual and practical because now, clinically, there is a clear distinction between "shapers" and "finishers". A slight increase of geometries of S2 promotes more aggressive action on the canal walls, easing the work of

the F1 that will benefit from a reduction in the volume of dentin to be cut and therefore gain in terms of security. Moreover, thanks to the changes introduced, brushing with ProTaper® Universal S2 will reduce the number of steps required by the progressive passive finisher F1. Now F1 is really a finisher, in the sense that "connects the dots" giving the idea of a shape without interruption.

- F1 (YELLOW): No major changes made, except for the addition of the safe tip that allows a easier and less aggressive sliding up to the working length.
- The transition from the "shapers" to "finishers", as already seen, is more harmonic and appears, in most cases, free of imperfections: with the change to the S2 ProTaper® Universal, the workload of the F1 is perfectly distributed between S2 and F2.
- F2 (RED): No change, except for the change from a "pilot modified" tip to a "safe rounded" tip.
- F3 (BLUE): F3 (Finisher No. 3) has been one of those files that clinicians either loved or hated. In the past, this was the instrument that motivated some dentists to "hybridize." Hybridization of files has always been a dilemma. It also required increased instrument inventory. Dentists discovered that F3 success, as it was intended

and designed, required extreme manual restraint. If the ProTaper F3 is "followed" in the same fashion as the F1 and F2, it could, in uneducated hands, follow further than desired. It was clear to the Ballaigues team that we wanted to "slow down F3 ever so slightly" in order to preserve the experience of doing the same thing with each of the Finishers. The bottom line was the F3's "work" had already been done. F1 and F2 had literally paved the way. All F3 ever had to do was act like a true Finisher and, once again, "connect the dots." What it boiled down to was that F3 was actually "over-qualified.". By changing the cross-sectional blades and other slight modifications, the engineers were able to give F3 a whole new feeling of increased safety and flexibility. As with all the new ProTaper Universal rotary and manual files, the file tip was changed from the "modified guiding tip" to the "rounded safe tip."

New Finishing Files: F4 And F5

F4 and F5 (Finisher Nos. 4 and 5) did not originally fit into the ProTaper philosophy of "less is more." ProTaper was not intended to be the instrument system for all seasons, but rather for one specific season, and that was to predictably, safely, simply, and efficiently carve a natural preparation shape in a canal that needed to be shaped, ie, where restrictive dentin was present. It did not matter if the canal was long or curved. If the walls are smooth, ProTaper can always follow to the terminus when the DFUs are observed. And we already had countless products that were attempting to provide a solution for every possible circumstance. Complexity and confusion was what the ProTaper philosophy was avoiding. To add instruments was clearly not part of the "thinking process." The F4 is an ISO 040 tip size, a 6% apical third taper, and then a progressively decreasing taper in the body, which produces excellent flexibility. F5 is an ISO 050 tip size, a 5% apical third taper, and then a progressively decreasing taper in the body, which, similar to the F4, provides the clinician with superior file flexibility. As with the entire ProTaper family, F4 and F5 are produced with a "rounded safe tip".

The F4 and F5 Finishers do what they are designed to do: increase the apical preparation size, or shape a canal that presents with an apical constriction of more than size 30. They are surprisingly flexible and have matching F4 and F5 ProTaper gutta-percha cones and matching F4 and F5 ProTaper obturators (Figure 11). This clinician finishes with F1 approximately 20% of the canals, F2 approximately 70% of the canals, and F3 approximately 10% of the canals. It is infrequent that the apices in clinical practice have been greater than a size No. 30, but when that patient presents, hybridization can now be avoided, and the same highly effective ProTaper efficiency can be enjoyed.

New 31-Mm S1 To F5 Lengths

Occasionally, a patient presents with root canal lengths greater than 25 mm. Longer ProTaper files were clearly needed to maintain ProTaper efficiency in longer canals and to minimize the inventory hybridization. The Ballaigues team found a need and filled it.

No change was made except increased shaft length for longer teeth with longer canals. The same ProTaper "preparation blades" have been preserved.

Protaper Universal® Sequence Of Use

The crown down technique is the technique of choice for rotary instruments. This technique initiates in the coronal area and progresses in an apical direction. The progression of instrumentation and examination continues until you take an appropriate finishing file to working length.

The basic ProTaper Universal System sequence will be the same, regardless of the canal size.

- Create straight-line access to canal orifice.
- In the presence of a viscous chelator, passively scout the coronal 2/3 with 10 and 15 hand files. Gently work these instruments until a smooth, reproducible glide path is confirmed.
- In the presence of NaOCl, “float” the S1 into the canal and passively “follow” the glide path. Before light resistance is encountered, laterally “brush” and cut dentin on the outstroke to improve straight line access and apical progression. Always brush away from the furcation.
- Continue shaping with the S1 as described until the depth of the 15 hand file is reached.
- Use the S2, exactly as described for the S1, until the depth of the 15 hand file is reached.
- In the presence of NaOCl or a viscous chelator, scout the apical 1/3 with 10 and 15 hand files and

gently work them until they are loose at length.

- Establish working length, confirm patency and verify the presence of a smooth, reproducible glide path in the apical 1/3.
Use the S1, as described, until working length is reached.
- Use the S2, as described, until working length is reached.
- Reconfirm working length, especially in more curved canals.
- Use the F1 in a non-brushing action until working length is reached.
- Gauge the foramen with a 20 hand file. If this instrument is snug at length, the canal is shaped and ready to obturate.
- If the 20 hand file is loose at length, proceed to the F2 and, when necessary, the F3, F4 and F5 gauging after each finishing file with corresponding hand file.

The Reciprocating Motion

If on one hand with the advances in the design of the instrument it was possible to reduce their rigidity, improving clinical performance, on the other hand, the NiTi instruments' tendency to fracture, remained a possible event.

Referring to the concepts expressed above, an important reflection arises: the risk of fracture by cyclic fatigue can be reduced by varying the type of movement that is impressed to the instruments passing, from their usual rotation in continuous movement at a uniform speed and clockwise, to a movement of alternating rotation: that is more and more clear if the angle of rotation is reduced, by not performing a full turn (360 °).

Reciprocating movement means a counterclockwise an clockwise motion that the instrument performs regularly, cyclically; it corresponds to an alternating and asymmetrical movement: a rotation by a certain angle in one direction makes the instrument advance, engages it into the dentin and cut it; immediately after, a counter-rotation with smallest angle in the opposite direction disengages it, reducing the accumulation of stress and the possibility of a block (taper lock), frequently seen in continuous motion.

This idea, on the basis of the newest mono-instrument systems, is not entirely new and has its roots in the past. Inspired by the principle of "Balanced Force" by Roane who, already in 1984, showed that an instrument, if rotated counterclockwise, is much stronger than the same tool rotated clockwise (56).

The following year, in 1985, he published the famous article "The balanced force concept for instrumentation of curved canals" showing that if a tool is rotated counter clockwise and simultaneously pushed firmly apical remains perfectly centred in the root canal and its cut is centrifugal respect to its axis.45. In 2008, Dr. Yared described a unusual approach to NiTi instrumentation, which utilizes a reciprocating movement of unequal CW and CCW cutting angles versus purely rotating movement of NiTi files in order to prevail the complication of torsional fracture (57). The reciprocating movement aims to minimize this risk by engaging the file in a cutting motion, and then immediately disengaging it in a non-cutting motion. The cutting/engaging motion is designed to be below the elastic limit of the file, so that torsional fatigue is reduced or avoided all together. Since the elastic limit of the file is theoretically never met, this may lead to less or no instrument fracture. The NiTi reciprocating concept is based on the balanced force hand filing technique, which was employed using flexible hand files in a specific CW and CCW sequence in order to prepare curved canals (52). This technique was shown to be beneficial at negotiating even the most severely curved canals with large hand files in order to accomplish apical preparations while maintaining the original canal shape (58).

Dr. Yared also advocates the single use of NiTi instruments due to the growing interest related to cross-contamination associated with the inability to effectively remove prions from endodontic instruments through routine sterilization procedures (57). Consequently, he described a technique utilizing a single F2 ProTaper instrument that was able to complete canal preparation objectives with a combination of CW and CCW reciprocating movement. This novel canal preparation technique was applauded for two reasons: first, the reciprocating movement was safer due to the avoidance of torsional fatigue; and second, the ability to complete canal preparations with a single file allowed for a more cost effective way to practice single use file protocols thereby eliminating the risks associated with prion cross-contamination.

Advantages of Reciprocation Instrumentation

The key advantages of reciprocating motion is that it reduces the effects of torsional fatigue on the instrument, which thereby increases the cyclic fatigue life of the instrument when compared to instruments used in rotational motion (59). This ultimately

leads to a safer endodontic instrumentation because file fracture is avoided or the time required before the instrument fractures is prolonged. Many recent articles have substantiated that instruments used in reciprocating motion have a higher cyclic fatigue resistance when compared to instruments used in continuous rotary motion (60-63). Specifically, in a study by Pedulla et al., 4 different NiTi rotary instruments were compared for cyclic fatigue life using the commercially available WaveOne and Reciproc motors versus continuous rotational movement motor. This study showed that all instruments unanimously resulted in a significantly higher cyclic fatigue resistance when run in either of the two reciprocating motors (62). For this reason, reciprocating motion may be an appealing alternative to traditional rotary motion in an effort to reduce undesired instrument failures.

Disadvantages of Reciprocation Instrumentation

One of the many reported advantages of NiTi rotary instrumentation over SS hand file instrumentation is that the action of the rotary motion augers debris up and out of the canal space minimizing the amount of debris that is extruded into the apical tissues (64, 65). Extrusion of debris, which may include dentin chips, necrotic pulp tissues, microorganisms, and intracanal irrigants, may cause increased inflammation, post- operative pain, and a delay in healing of the apical tissues after endodontic therapy (66). Given that instruments used in reciprocal motion move in a back and forth manner, debate exists as to whether or not this motion may cause an increase in the amount of debris extrusion during instrumentation procedures, which may translate into inflammation and pain clinically. Burklein and Schafer demonstrated in an article that there was a significant increase in the amount of apically extruded debris with reciprocating file systems WaveOne and Reciproc when compared to two similar rotary instrument systems (67). On the other hand, a different study compared ProTaper F2 instrumentation in rotary motion and reciprocation motion and found no significant difference in the amount of apically extruded debris between the two instrumentation motions (68).

Another ongoing argument in the reciprocation literature involves the alleged induction of dentin damage or cracks in dentin resulting from reciprocating instrumentation techniques. An article by Burklein et al. in 2013 initiated this debate when they reported that reciprocating file systems generated more cracks in dentin, especially in the apical region of the tooth, when compared to continuous rotary file systems (69). This finding raised concern because dentin cracks may lead to larger fractures in the root dentin, or vertical root fracture, which dooms the prognosis of the tooth. Lately, two articles have been released which prove to be wrong the initial claims by Burklein et al. De-Deus et al. studied crack propagation using micro-CT imaging, a nondestructive technique, in extracted teeth, and found no differences between reciprocating file systems and rotary file systems (70). Another study aimed at addressing the topic of crack propagation used an *in situ* cadaver model in order to determine whether or not these cracks may occur when a tooth in present in a jaw with a periodontal ligament. The results of this study found that microcracks were present in all groups and that there was no correlation with respect to the type of instrumentation, reciprocation or hand filing, and the presence of cracks (71).

Single File Techniques

Endodontics has undergone, in recent years, significant and profound changes, in conjunction with the development of new techniques and with the production of innovative materials and new technologies.
Its development has been so rapid that often we did not have time to become familiar with an instrument or a technique that we have to have to start over.
Some may ask: "Why should I change now? I am so well with these instruments."
The answer is simple. In Endodontics change means technology and all translates into a simplification of procedures, in a reduction of the working times and an increase in the success of the treatment in the long term.

Over the past fifteen years there have been more changes than in the entire history of endodontics.
In the past, the ability of an endodontist was closely linked to the knowledge of the root anatomy, experience and his sense of touch; the inability to have means of magnifying suitable to such small spaces made difficult to perceive both the roof and the floor of the pulp chamber; root canals were often reduced to mere "black holes" and many results were obtained by chance.

The introduction of the operating microscope and the consequent possibility to see inside the root canals allowed, to those who practice endodontics, to deal with the morphology and the complexity of the root canal system 187-189, already highlighted in the tables of W. Hess (72). Practitioners have also been able to benefit, in shaping of the root canals, the innovative rotary NiTi instruments that have resulted in reproducible preparations respectful of root canal anatomy. The introduction of the NTR instruments allowed, the operators, to switch from using manual instrumentation, which required at least 30-40 minutes per canal, the possibility of making perfect shapes in a few time regardless of the operator skills.

Recent advances endodontic, in terms of canal preparation, focused on the concept of "less is more", which in clinical practice results in a drastic reduction in the number of instruments needed for treatment (73), and in parallel at a reduction of potential errors.

The dream of a canal preparation obtained with a single instrument, pursued by endodontists over fifty years, is slowly taking shape, opening the door to more and more encouraging prospects and results.

By far, the greatest number of commercially available files utilized to shape root canals are manufactured from nickel-titanium (Ni-Ti) and are mechanically driven in continuous rotation. On the other hand, reciprocation, defined as any repetitive back-and-forth motion, has been clinically utilized to drive stainless steel files since 1958. Initially, all reciprocating motors and related handpieces rotated files in large equal angles of 90° clockwise (CW) and counterclockwise (CCW) rotation. Over time, virtually all reciprocating systems in the marketplace began to utilize smaller, yet equal, angles of CW/CCW rotation.

In about 1998, Dr. Ben Johnson and Professor Pierre Machtou co-discovered the unmistakable advantages of reciprocating Ni-Ti files utilizing unequal bidirectional movements. Subsequently, in the late 1990s, Professor Machtou and his endodontic residents extensively analyzed this novel unequal reciprocating movement using the entire series of not-yet-to-market ProTaper files. Starting with the end in mind, Dr. Ghassan Yared, a former student of Professor Machtou, performed exhaustive work to identify the precise unequal CW/CCW angles that would enable a single reciprocating 25/08 ProTaper file to optimally shape virtually any canal. Although this specific reciprocation technique stimulated considerable interest, this file was never designed to be used in this manner. Yet, Dr. Yared's work rekindled interest to take this singlefile concept closer to its full potential.

Waveone

In 2008, a team of 8 international clinicians including Drs. Johnson, Kuttler, Machtou, Pertot, Webber, West, Yared, and Ruddle, in collaboration with DENTSPLY International, began the serious work of developing both a new reciprocating file and motor for shaping canals. In 2011, both WaveOne (DENTSPLY Tulsa Dental Specialties and DENTSPLY Maillefer) and Reciproc (VDW) were internationally launched as single-file shaping techniques.

In most instances, the WaveOne concept provides a single-file shaping technique, regardless of the length, diameter, or curvature of any given canal. In fact, it has been shown that a single-file reciprocating shaping technique utilizing unequal CW/CCW angles is more than 4 times safer and almost 3 times faster than using multiple rotary files to achieve the same final shape.

Pundits should not concern themselves with whether one file or multiple files are utilized to prepare canals, whether the movement is continuous rotation versus reciprocation, or if the files are manufactured from stainless steel or Ni-Ti, as long as the final shape fulfills the mechanical and biological objectives for shaping canals.

Design

Strategically, only one file is generally utilized to fully shape virtually any given canal. However, there are 3 WaveOne files available to effectively address a wide range of endodontic anatomy commonly encountered in everyday practice. The 3 WaveOne instruments are termed small (yellow 21/06), primary (red 25/08), and large (black 40/08). The small 21/06 file has a fixed taper of 6% over its active portion. The primary 25/08 and the large 40/08 WaveOne files have fixed tapers of 8% from D1 to D3, whereas from D4 to D16, they have a unique progressively decreasing percentage tapered design. This design serves to improve flexibility and conserve remaining dentin in the coronal two thirds of the finished preparation. Another unique design feature of the WaveOne files is they have a reverse helix and 2 distinct cross-sections along the length of their active portions. From D1 to D8, the WaveOne files have a modified convex triangular cross section, whereas from D9 to D16, these files have a convex triangular cross section. The design of the 2 WaveOne cross sections is further enhanced by a changing pitch and helical angle along their active portions. The WaveOne files have noncutting modified guiding tips, which enable these files to safely progress through virtually any secured canal. Together, these design features enhance safety and efficiency when shaping canals that have a confirmed, smooth, and reproducible glide path.

Advanced Nickel-Titanium Alloy

Technological improvements in Ni-Ti metallurgy have generated a new supermetal, commercially termed M-wire. Engineers can identify the desired phase-transition point between martensite and austenite and produce a more clinically optimal metal than traditional Ni-Ti itself. Studies have shown that M-wire technology significantly improves the resistance to cyclic fatigue by almost 400% compared to commercially available 25/04 Ni-Ti files. The good news is that reducing cyclic fatigue serves to clinically decrease the potential for broken instruments.

Reciprocating Motion

The e3 motor (DENTSPLY Tulsa Dental Specialties) is specially engineered and programmed to drive the new WaveOne reciprocating files. This motor produces a feature-specific, unequal bidirectional file movement. Because of the reverse helix design, the CCW engaging angle is 5 times the CW disengaging angle. Additionally, it should be noted, this motor can drive any market version file system in full CW rotation at the desired speed and torque.

There are 3 critical distinctions with this novel, unequal bidirectional movement. One, compared to continuous rotation, there is a significant improvement in safety, as the CCW engaging angle has been designed to be smaller than the elastic metallurgical limit of the file. Two, opposed to all other reciprocating systems that utilize equal bidirectional angles, the WaveOne system utilizes an engaging angle that is 5 times the disengaging angle. Fortuitously, after 3 engaging/disengaging cutting cycles, the WaveOne file will have rotated 360°, or turned one CCW circle. This unique reciprocating movement enables the file to more readily advance toward the desired working length. Three, compared to an equal bidirectional movement, an unequal bidirectional movement strategically enhances augering debris out of the canal. Auguring debris in a coronal direction promotes the biological objectives for preparing canals, 3-D disinfection, and filling root canal systems.

Single-File/Single-Use Concept

The WaveOne technique is both a single-file and single-use concept. As stated, it is a single-file concept given that one single file is able to transition a secured canal to a well-shaped canal, in most instances. Further, appreciate that a single WaveOne file is frequently used to prepare multiple canals in a single furcated tooth, performing a significant amount of work. The WaveOne concept must be considered a single-use concept due to the obvious stress and wear on the active portion of the file. This is in line with the growing concern in the dental community, especially in institutional settings, that all endodontic files be considered single-use. The rationale behind this legitimate concern is the documentable potential for cross-contamination between and among patients, regardless of the sterilization protocol utilized.

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Shaping Ability of WaveOne Primary Reciprocating Files and ProTaper System Used in Continuous and Reciprocating Motion

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Introduction

A continuously tapered funnel shape with a diameter decreasing from the orifice to the apex has been recognized as fundamental for the adequate cleaning and obturation of the root canal system (1). The introduction of rotary endodontic nickel-titanium (NiTi) instruments has led to significant progress in treatment by reducing the time required for root canal preparation (2, 3) and maintaining the original canal shape (4–6). The superelasticity of the NiTi alloy has made it possible to reduce the incidence of canal aberrations such as zips, ledges, or perforations, especially in narrow and curved canals (7, 8).

Despite these advantages, the high degree of canal curvature and small canal cross-section increase the risk of NiTi instrument failure caused by flexural and torsional stresses (9–11). Recently, to overcome the breakage of endodontic instruments caused by flexural fatigue, a reciprocating movement using 1 single NiTi file has been suggested (12).

Yared (13) was the first to propose the use of only 1 NiTi rotary instrument, the ProTaper F2 (Dentsply Maillefer, Ballaigues, Switzerland), in clockwise and counterclockwise movements to shape root canals.

Currently, 2 new systems of instruments, WaveOne (Dentsply Maillefer) and Reciproc (VDW, Munich, Germany), have been introduced for root canal preparation using only 1 monouse rotary NiTi file. The 2 file systems, used in reciprocating motions, are manufactured with a novel variant NiTi alloy called M-Wire (Dentsply Tulsa Dental Specialties, Tulsa, OK); it is made via an innovative process for heat treating NiTi that aims at optimizing the mechanical properties of endodontic instruments. Even though the M-Wire alloy was introduced to improve the mechanical and physical properties of endodontic instruments, the design of the instrument may also influence torsional resis- tance and cycling flexural fatigue (14–16). As opposed to the F2 ProTaper single-file technique, in the WaveOne instrumentation technique, the file is designed to cut during counterclockwise motions so that the WaveOne reaches the apex of the canal by recip- rocating movements in opposite directions (ie, counterclockwise [cutting direction] and clockwise [release of the instrument]). Because the counterclockwise cutting angle is greater than the angle of reverse direction, the reverse movement could improve the progression of the instrument toward the apex (17) with respect to continuous motion.

As part of the new single-file system, WaveOne files are available in 3 sizes: small files for root canals with an initial apical diameter less than an ISO standard size #10 K- file, primary files for root canals with an initial apical diameter equal to that of an ISO standard size #10 K-file, and large files for root canals with an initial apical diameter greater than that of an ISO standard size #20 K-file. The manufacturer maintains that using these disposable instruments reduces the incidence of fatigue fracture, is more cost-effective, and reduces possible cross-contamination.

To date, reciprocating motions have been tried only in association with the single-file technique (ie, WaveOne and Reciproc) and not with instruments commonly used in a full sequence. The literature reports that alternating movements associated with the full sequence of ProTaper files improve the life span of the instruments and maintains the original canal shape (17, 18).

The purpose of this study was to evaluate the shaping effect of the WaveOne files and the traditional full sequence of the

ProTaper Universal NiTi rotary file system in continuous and reciprocating movements using S-shaped resin blocks as simulated root canals. The null hypothesis was that the 3 preparation techniques would have similar shaping effects.

Materials and Methods

Seventy-five ISO 15, 0.02 taper, S-shaped root canals in clear resin blocks (Endo Training Blocks, Dentsply Maillefer) were used. Each simulated canal had a 20 apical curvature (3.5-mm radius), a 30 cor- onal curvature (5-mm radius), and a 16-mm canal length.

Four landmarks were marked on the surface of each specimen, and the simulated canals were colored with ink injected with a syringe. A round support with a rectangular slot the size of the specimen was positioned under a stereomicroscope connected to a digital camera (Nikon D70; Nikon, Tokyo, Japan); each specimen was inserted into the slot and photographed at 10 magnification. The digital images were saved as TIFF format files. Patency was confirmed for each spec- imen using an ISO standard size #10 K-file just beyond the working length.

Specimens were randomly assigned to 3 different groups (n = 25). In group 1, the simulated canals were shaped with WaveOne Primary reciprocating files (Dentsply Maillefer) in a pecking motion until reaching the full working length; the reciprocating motor (WaveOne Endo Motor, Dentsply Maillefer) with a 6:1 reduction handpiece was assembled as recommended by the manufacturer. In group 2, the simulated canals were shaped using ProTaper Universal NiTi files in the following sequence: S1, S2, F1, and F2 until each instrument reached the working length. ProTaper NiTi instruments were driven in a conventional movement with an endodontic motor (WaveOne Endo Motor) with a 16:1 contra angle set up as suggested by the manu- facturer. Group 3 followed the same sequence as group 2, but the prep- aration of all specimens was performed in clockwise and counterclockwise motions; the settings of the ATR Tecnika Vision motor (ATR Pistoia, Italy) were four tenths of a clockwise circle and two tenths of a counterclockwise circle, with a 500-rpm rotational speed with maximum torque. Glyde (Dentsply Maillefer) was used as the lubricating agent in each group.

Assessment of Canal Preparation

After instrumentation, all specimens were repositioned in the same slot and photographed as described previously. The images saved as TIFF format files before and after the instrumentation were superimposed using imaging software (Adobe Photoshop; Adobe System, San Jose, CA), and the 4 landmarks were used as reference points.

The shaping effect of the 3 systems, the WaveOne Primary files and the full sequence of the ProTaper Universal NiTi files with continuous and reciprocating motions, was analyzed using 2 different methods. As previously described by Berutti et al (19), LabView software (2009 version; National Instruments, Austin, TX) was used to evaluate the following parameters: the mean axis of simulated canals before and after instrumentation and the curvature-radius ratio of the best-fitting circumferences of known radii of the coronal and apical curvatures of each canal in the 3 groups.

The same software (LabView software) was used to measure the distance from the center of the original canal to the left and right proximal sides of the canal surface before and after instrumentation. Measurements were taken on the superimposed images at 7 consecutive points positioned perpendicularly to the long axis of resin blocks with 1-mm incremental measurement points. The first 4 measurement points (from 0–4 mm from the apex) represented the apical curvature, whereas the coronal curvature was measured from 3–7 mm from the apex. As previously described by Burroughus et al (20), there was a curvature overlap at levels 3 and 4 because of the straightness of the simulated canals.

Data Analysis

The results obtained with the WaveOne Primary files and the full sequence of the ProTaper Universal NiTi files with continuous and reciprocating motions were analyzed using 2 different methods. The best-fitting apical and coronal circumferences before and after instrumentation were used to evaluate the shaping effect of the 3 systems, and the differences among groups was assessed using 1-way analysis of vari- ance followed by a Tukey-Kramer multiple comparison post hoc test. Differences were considered statistically significant when $P < .0001$.

Further statistical analysis was performed using a mixed-effects linear model (PROC MIXED, SAS 9.1; SAS Institute, Cary, NC) with a compound symmetry covariance structure fit using the independent variables of level, side and group.

The same type of analysis was performed for each side considering group and level as independent variables, and for each level considering group and side as independent variables. In addition, an analysis for each side and level with group as an independent variable was performed.

The centering ability was evaluated using an intragroup compari- son between the left and the right sides and at each level (t-test).

Results

The apical circumference of the simulated canals shaped with ProTaper Universal instruments in reciprocating motions showed significant differences with respect to the other 2 groups, Wave One and ProTaper Universal in continuous motion ($P < .05$). The samples in group 3 maintained a radius of curvature that was more similar to the radius of the original simulated canals (Table 1). There were no differences in the coronal curvatures among the 3 experimental groups ($P > .05$). After adjusting for the level and canal sides, the total amount of resin removed at both sides of the simulated canals was not significantly different in the 3 groups (Fig. 1).

In the overall analysis, considering group and level as independent variables, at 0, 2, 3, and 4 mm from the apex, significantly greater amounts of resin were removed in group 2 versus groups 1 and 3; furthermore, group 1 showed a significantly greater amount of resin removed than group 3 except for level 4. At 1, 5, 6, and 7 mm from the apex, group 2 had a significantly greater amount of resin removal than groups

1 and 3 (Fig. 2).

Considering the intragroup analysis to evaluate the centering ability, in groups 1 and group 2, there were statistically significant differences in the amount of resin removed at the same level between the right and left sides. In group 3, there were statistically significant differ- ences between the right and left sides except at levels 0 and 4.

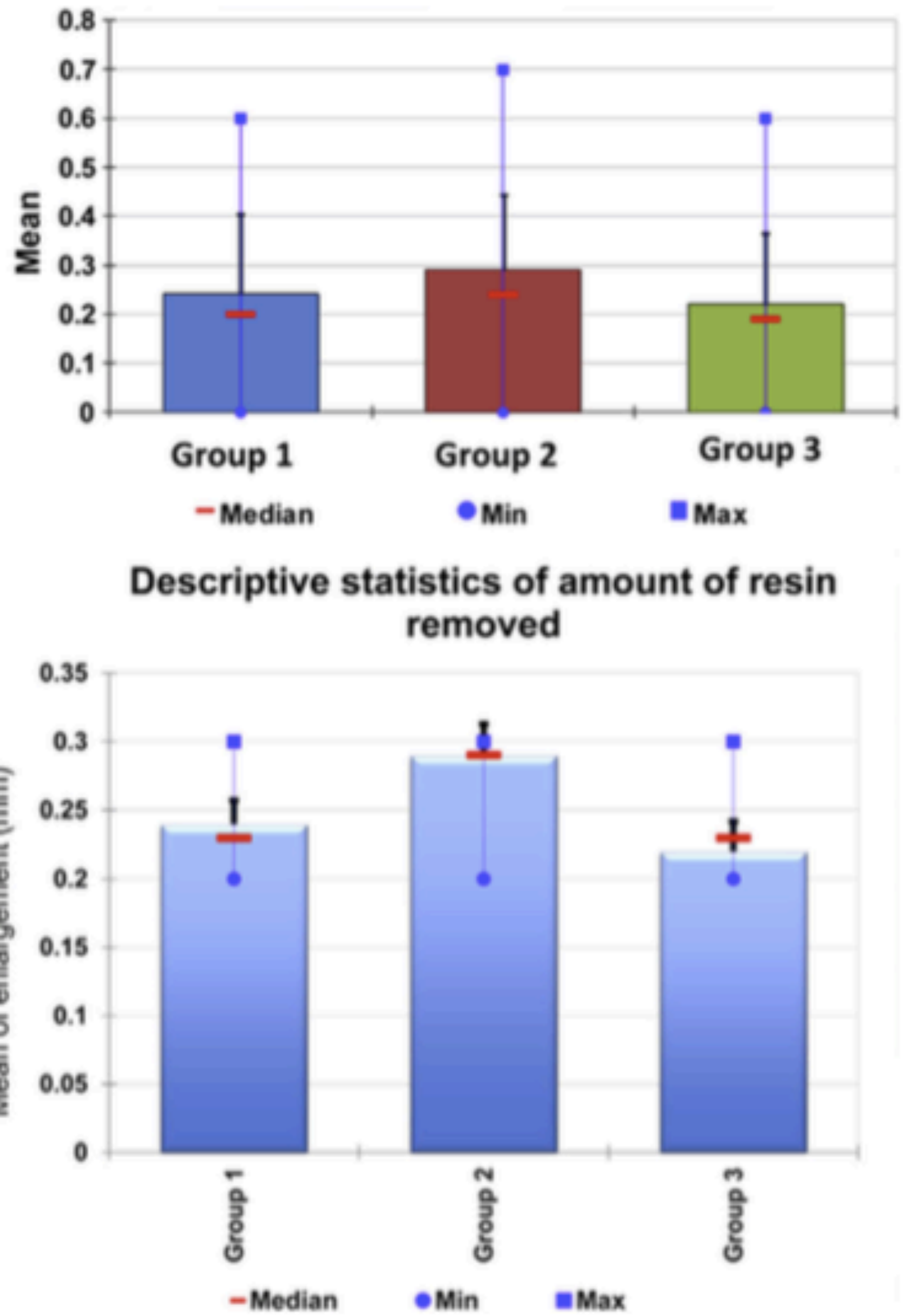
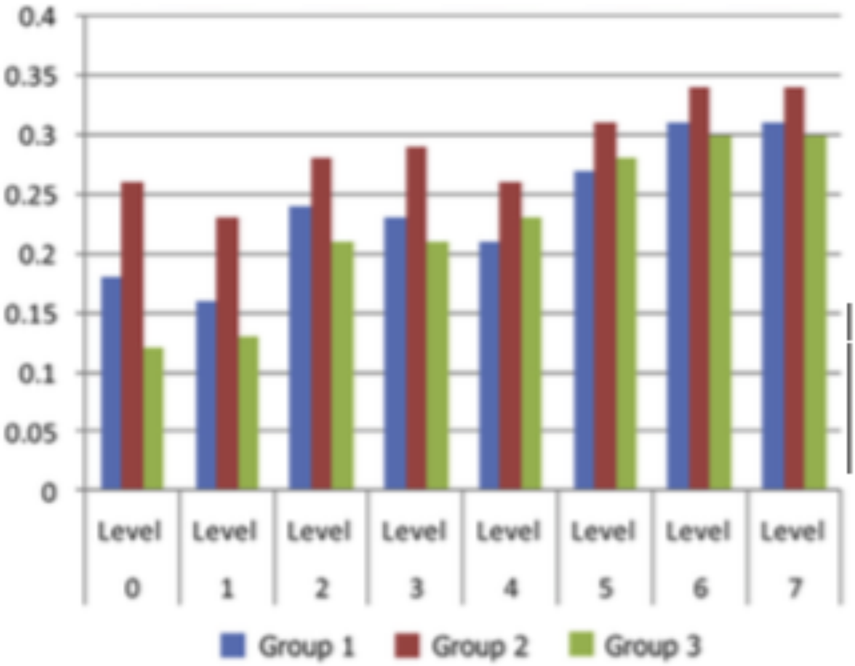


Figure 1. Overall descriptive statistics: the total amount of resin removed at both sides in the 3 groups.



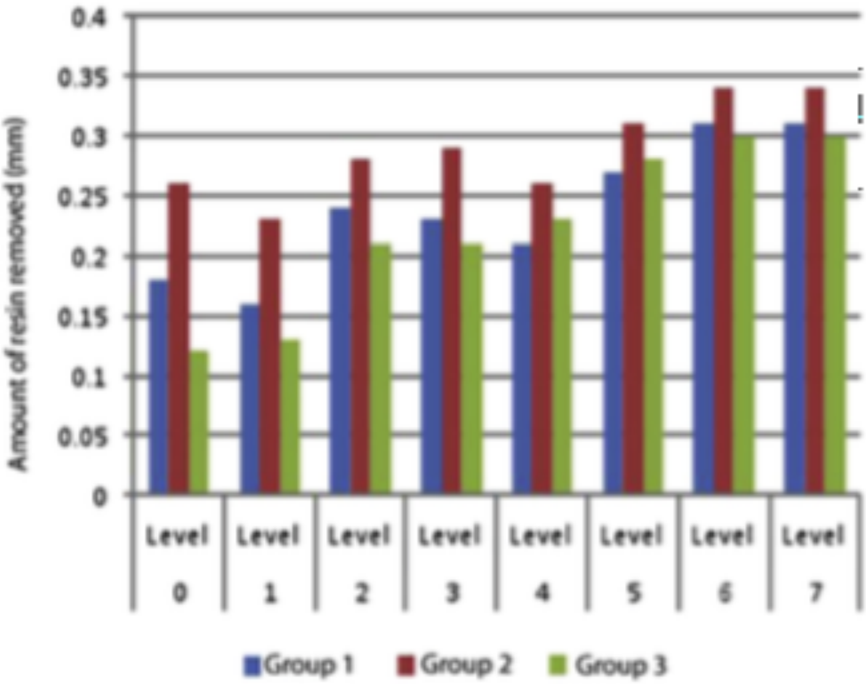


Figure 2. Descriptive statistics by level and group.

TABLE 1. Differences in the Apical Curvature Means between Groups and Relative Confidence Intervals (CIs)

Group	Means difference (CI low–CI upper)
Group 1 vs group 2	100,69 (−165,85 to 367,24)
Group 1 vs group 3	460,45 (158,41–762,48)
Group 2 vs group 3	359,756 (48,74–670,76)

Discussion

In the present study, simulated canals in resin blocks were used to make a direct comparison of the shapes obtained with different movements and instruments. Previous studies suggest that the analysis of pre- and postinstrumentation root canal outlines guarantees a high degree of reproducibility and standardization of the experimental design (21, 22). In this study, 2 different instruments, WaveOne Primary files and ProTaper Universal NiTi files, and 2 different movements, continuous and reciprocating, were compared in terms of shaping effects.

In the single-file technique, the instrument reaches the working length in a pecking and reciprocating motion; this type of movement is similar to the concept of balanced force proposed by Roane et al (23). The reciprocating movement seemed to positively affect the instrument's life span when full sequences of the ProTaper Universal NiTi files and F2 ProTaper single-file technique were compared with the ProTaper full-sequence technique and the F2 single-file technique, both in continuous movement (12, 17). The reciprocating movement promotes the safe use of file instruments because when the instruments engage dentin during the counterclockwise movement, the subsequent clockwise movement disengages the instruments, reducing torsional stress and consequently the incidence of instrument fracture because of taper lock (13, 23).

When analyzing the quality of root canal preparation achieved with instruments and techniques, shaping ability is 1 of the most interesting parameters evaluated. Although results vary from study to study, reciprocating motion could contribute to improving the shaping ability of endodontic instruments. A recent study on root canals of extracted human mandibular molars showed that in terms of root canal curvature, F2 ProTaper in reciprocating motion is as efficient as the conventional ProTaper full-sequence technique in contin- uous motion (24). In cases of specific NiTi files designed for the single-file technique, such as WaveOne and Reciproc, the results were conflicting when compared with the conventional full sequence of ProTaper NiTi instruments. Berutti et al (25) reported that WaveOne had a better centering ability with respect to the full sequence of ProTaper

NiTiinstruments,whereas Burklein et al (26) did not observe any significant difference between the use of the full NiTi file sequence technique and the single-file technique.

The advantages of reciprocating motion using an appropriate endodontic motor could be applied to the NiTi file system, which is generally used in a full sequence. Franco et al (27) showed that Flex Master NiTi instruments, designed for use with continuous rotary movement, shaped the simulated canal in a more uniform manner, centering the original canal, when used in an alternating rotary motion compared with the same instruments used in a continuous rotary movement. A possible explanation of the better performance of reciprocating movement could be the greater contact area between the instruments and the canal walls, which permits equal canal enlargement on the inner and outer aspects of the curvature. The results of the present study only partially concur with this concept; even if reciprocating movements in association with the Pro-Taper full-sequence rotary technique showed a different amount of resin removed at the right and left sides of S-shaped simulated root canals, at levels 0 and 4, there were no differences between the left and right sides in maintaining the original canal central axis. Moreover, at every level from the apex, the full sequence of the ProTaper Universal NiTi files in continuous motion (group 2) removed a significantly greater amount of resin compared with the other 2 groups.

When centering ability was evaluated with the best-fitting circumference, better results were obtained in group 3 with no statistically significant changes in the radius of apical curvature before and after shaping the simulated canals. In both groups 1 and 2, the radius of the coronal and apical curvature changed significantly before and after instrumentation, resulting in a straightening of the canal. Similar results were obtained in previous studies (28, 29).

The WaveOne single-file system was designed specifically for recip- rocating motions only; the technique is not free from procedural errors. In an in vitro study, Berutti et al (30) showed that the use of WaveOne was associated with a significant reduction of canal length, especially in curved canals, mainly because it straightens the root canal curvature. The performance of WaveOne seems to be affected by the absence of a previous glide path; when WaveOne was used as the sole file, the consequent alteration of the original canal curvatures could lead to unsuccessful root canal therapy (30). In the present study, the better performance of the full sequence of the ProTaper Universal NiTi files in reciprocating motions using both methods to evaluate the shaping effect could be explained by the fact that this technique offered the advantage of reaching the working length with a more gradual and centered enlargement progressing from small to big tapers without forcing the rotary file apically, which is similar to the results reported by Berutti et al (30) with WaveOne in combination with path files. Even though resin blocks are useful in standardized experimental conditions, they may not represent the anatomic variability of the root canal system. Similar studies in extracted teeth evaluating outcomes using cone- beam computed tomographic imaging might significantly advance knowledge on this issue.

Within the limits of this study, better results were obtained using the full sequence of the ProTaper Universal NiTi files with reciprocating motions. ProTaper Universal NiTi files with continuous motion removed the largest total amount of resin-shaping simulated S-shape canals.

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Chapter 3: Root Canal Irrigation

Sterilization of root canals, that is the complete eradication of the bacteria and their substrate has always been the main goal of endodontic therapy. Bacteria have been implicated as major aetiological agents of pulp and periapical disease. The species involved in infection of these tissues draw from a potentially large pool of up to 700 different microorganisms that is estimated to exist in the oral cavity (1). However, selective pressures exerted by the root canal systems and periapical tissues limit the local flora to a selective and special assortment (2). Although individual bacteria can be recovered from an infected root canal system, bacteria in the root canal system exist as a biofilm. A biofilm is a group of microorganisms in which cells stick to each other and often these cells adhere to a surface. These adherent cells are frequently embedded within a self-produced matrix of extracellular polymeric substance (EPS). These communities exhibit a wide range of physical, metabolic and molecular interactions. These interactions are important for the attachment, growth and survival of species that enable the biofilm to develop and persist in what often appear to be hostile environments such as the oral cavity. This community life-style provides potential benefits to the resident microorganisms, including a broader habitat range for growth, increased metabolic diversity and efficiency, and enhanced resistance to environmental stress, antimicrobial agents and host defenses (3).

For a long time root canal therapy it was essentially a drug: the canals were cleaned in summary and preparation was made solely on the basis of the location of an intracanal medication.

Only in the 70s the belief that bacteria could be removed as well as killed by drugs has allowed the introduction of the concept of "sterilization mechanics" typical of modern endodontics.

In its publication Shilder supports for the first time that the two procedures, cleaning and shaping, are closely related and are carried out simultaneously: while the canal is shaped, automatically the content is also removed.

At this stage of the endodontic therapy it is therefore necessary to be clear about the role and the importance of not only the root canal instruments, but also of irrigating solutions.

The operator must know the objectives of irrigation, knowing how to choose the type of solution and the irrigation method and must also know what influence may have the technique of root canal preparation on the action of irrigants.

Irrigation objectives

- Remove both vital and necrotic pulp tissue through a solvent action
- Remove bacteria and their products through a bactericide action
- Remove debris and the smear layer produced with the instrumentation through a chelating and hydrodynamic action
- Facilitate the penetration and the action of the instruments through a lubricating action

The mechanisms of action, which must regulate the phase of irrigation, are therefore two: both physical and the chemical. The first is necessary to remove the debris that are accumulated during the instrumentation and to facilitate the penetration and action of the instruments; This mechanism uses the hydrodynamic action of the irrigant and is essentially linked to the volume of the solution and aspiration. The second mechanism is necessary to eliminate the bacteria and the organic and inorganic components and is essentially linked to the nature of the irrigant solution.

Choice Of The Irrigant Solution

Today we have many types of irrigants, but surely the most widely used and effective are essentially sodium hypochlorite and chelating agents.

Sodium Hypochlorite

The most widely used in endodontic root canal irrigant is sodium hypochlorite. Its popularity as a flushing agent stems from its widespread use, its low cost as well as its proven antiseptic.

Its use as a disinfectant dates back to 1915 and as a root canal irrigant to 1920 (4). Sodium hypochlorite is produced by the passage of chlorine gas into a solution of sodium hydroxide (NaOH) according to the following reaction: $CL2 + 2NaOH \rightarrow NaOCl + NaCl + H2O$.

On contact with water the sodium hypochlorite dissociates into sodium hydroxide (NaOH) and hypochlorous acid (HOCl) or "active chlorine". The disinfecting action is attributable hypochlorous acid which is the active part of the various solutions on the market (5) this, thanks to the molecular structure very small and comparable to that of water, is in fact able to pass with ease the membrane bacterial cell and to exert its lytic action (5).

For acidic pH values the solutions will be more rich in hypochlorous acid and therefore more antiseptic, with values of the basic pH disinfectant activity would be rather lower. The pH is preferred for the solutions of sodium hypochlorite will be around 5 so as to allow greater release of hypochlorous acid. Hypochlorite solutions are unstable when exposed to light and can, with the exception of keratinized epithelia, damaging all living tissues (4). Given the variability of active chlorine concentration in commercial solutions (bleach), which otherwise contain additional compounds aimed at optimizing the properties brighteners, fragrances ect., It would always be advisable to make use of solutions of sodium hypochlorite prepared solely for endodontic. In any case, the same must be kept at the right temperature (about 4 ° C), protected from light and contamination.

Solvent action on the organic tissues

The solvent action of the hypochlorite was demonstrated by Grossman and Neimann (6,7) at the level of the dental pulp and then by Rosenfeld on the predentin (8).

The lytic action would seem to work on necrotic tissue and fragments. Some authors are in agreement that the blood circulation of the vital tissue is responsible for removal and neutralization of chlorine ions (9). Furthermore the effectiveness of the irrigant, even in the presence of necrotic tissue, appears to be minor if this is fixed with medicaments such as formaldehyde or paraclorophenol.

The lytic capacity of necrotic tissue, already confirmed in 1970 by Grey (10), is conditioned by parameters such as the concentration and the temperature of use of the solutions. With the increase of the concentration increases the ability of dissolution of necrotic tissue. In 1978, Hand (11) has shown that solutions of sodium hypochlorite at 5.25% possessed a protolithic power three times higher than in solutions of 2.5% NaOCl. However it is true that more concentrated solutions of NaOCl improve and increase the capacity of dissolution of organic tissue, it is true that it is not possible to further increase the concentration of the irrigant because it would raise its toxicity. A concentration of between 2.5% and 5.25% would seem to be the best compromise between protolithic power and toxicity. However it is possible, by increasing the temperature of clinical use, increase the dissolutive capacity of the solutions of NaOCl, without necessarily increasing the concentration. Tea et Al. (12 Tea 1979) in a study of 1979, showed how the rise in temperature of the hypochlorite to 35.5

° C, allowed to obtain a capacity of dissolution of the connective tissue of the rat.

Berutti et al. (13) have shown how it is possible to obtain canal surfaces well cleansed and free of smear layer using solutions of sodium hypochlorite heated to 50 ° C, alternating with solutions of EDTA. According Sirtes (14) temperature selection for clinical use hypochlorite, seems to be even more relevant in the choice of the concentration of use of the solution. With their study, the authors have in fact demonstrated as 1% solutions of sodium hypochlorite heated to 45 ° have detected protolithic capacity similar to those obtained with solutions at 5.25%, heated to 20 °.

The increase in temperature of the hypochlorite, however, due to a change in the title of the solution, resulting in a decrease in the percentage of available chlorine and liberation of vapors of chlorine, so when hypochlorite is heated, it should be used within a short time.

The action of hypochlorite digestion seems to be explained in the first 2 minutes to about 75%, to be concluded within 5 minutes. The histolytic action of hypochlorite is expressed in greater way on the necrotic pulp, the organic debris and predentin, while it is slightly lower on the vital pulp and minimum mineralized dentin. Already Gordon in 1981 (15) had shown that, by exposing for 10 minutes, different amounts of pulp tissue to a solutions of hypochlorite, it was dissolved a varying percentage from 6% (50mg pulp / ml NaOCl) to 73% (10mg pulp / ml NaOCl) and as this percentage was negatively influenced by the presence of pulp tissue.

Antibacterial action

The Sodium Hypochlorite is a powerful bactericide and is able to quickly kill vegetative bacteria, spores, fungi, protozoa and viruses (including HIV, rotavirus, viruses HSV-1 and HSV-2 and hepatitis and B) (16, 17). Its action is manifested when coming in contact with the water, free hypochlorous acid and sodium hydroxide. In turn, the hypochlorous acid free hydrochloric acid and oxygen. The chlorine which is liberated performs its bactericidal action entering in combination with main constituents protoplasmatic and in particular with sulfhydryl groups of bacterial essential enzymes (16). The antibacterial action is conditioned by the concentration of the solution, the pH as well as by the resistance of pathogens (16, 18).

Other factors which can influence the antiseptic hypochlorite, are represented by the flow, the amount of the irrigant in addition to the time spent inside the canal system. There is no full agreement on what might be the ideal concentration of hypochlorite for use in endodontics.

In a study conducted by Bystrom (19) it was possible to obtain, using hypochlorite solutions at 5%, a sterilization of 50% of infected canals against 20% obtained with only physiological solution; Hand (11) has shown the destruction of streptococci with hypochlorite solutions at 5% even in the presence of albumin and blood; Shih (20) tested the efficacy of various dilutions of hypochlorite on Streptococcus Faecalis and on Staphylococcus Aureus confirming the superiority of the solutions to 5%; similar results have been reported by Ellerbruch (21) and Spangberg (22) and Foley (23), with 100% of positive values on Bacteroides melaninogenicus. Senia (24) obtained the sterilization of gutta-percha cones dipping them for one minute in sodium hypochlorite at 5.25%. According Spangberg et al. (22) concentrations of 5.25% would be excessive given the bacterial species responsible for infections pulpo-periapical while, according Tea et al (25) and Yesilsoy et al.(26) the solutions at 5.25% would not be more toxic than those at lower concentrations and compared to chlorhexidine gluconate (26). There are many disputes on antimicrobial efficacy of different concentrations of hypochlorite. In some studies it has not been found any difference between antimicrobial concentrations of between 0.5% and 5%, while results of other researches show that there is loss of efficacy with dilution. Siqueira et al. have assessed in vitro the action of three different concentrations of hypochlorite (1%; 2.5% and 5%) in the extracted teeth and infected with Enterococcus Faecalis demonstrating greater efficacy for concentrations of 5.25% and thus confirming the relationship between concentration and antiseptic activity (27). The same authors have demonstrated how it was possible to achieve good results with lower concentrations provided that were used in greater quantities and with an exposure time sufficient to eliminate even the most resistant bacteria such as Enterococcus Faecalis. This antibacterial efficacy has been demonstrated in several studies also for concentrations below 5.25%. The antibacterial action is however drastically lower if the hypochlorite solution is used in a concentration of less than 1%. (27, 28, 29). The concentration at which the sodium hypochlorite seems to show the best antibacterial ability is the concentration of 5.25%.

Chelating agents

The introduction of solutions of chelating and in particular of Ethylene diamine tetra-acetic acid (EDTA) in endodontics dates back to 1957. The EDTA has the ability to bind to the Ca^{++} ions of hydroxyapatite crystals and form soluble salts and thus produces a demineralization. This action, in endodontics, is used to soften the dentin, to facilitate the removal of calcifications and to remove the smear layer, ie the layer of debris produced by the action of the instruments on dentin and spreaded on the canal walls.

Currently there is a tendency to consider the presence of smear layer as an obstacle to the success of endodontic treatment because:

- It can give shelter to bacteria forming an outbreak of chronic irritation. The smear layer is in fact a very good breeding ground for various types of bacteria (Actynomices viscosus, Corynebacterium, Streptococcus Sanguis)
- It can reduce the cleansing efficacy of the irrigants in the dentinal tubules or the contact and diffusion of medicinal substances such as calcium hydroxide
- It is interposed between the filling material and the dentinal wall creating areas where bacteria can breed and foster their penetration.

The hypochlorite, alone, is not able to eliminate the smear layer and for this reason is always suitable using it in association with EDTA which, in turn, however, is not able to act on the organic components.

The action of EDTA demineralizing varies as a function of pH (is most effective at a pH of 5-6), of the time and its concentration (the optimum is 17%)

Chlorhexidine

Chlorhexidine (CHX) is a broad spectrum antimicrobial agent which acts on both gram positive and gram negative bacteria. This cationic molecule causes cell lysis by attacking the bacteria's negatively charged cell membrane. Although it has been used as an endodontic irrigation solution due to its antibacterial property, it was not shown to have any advantage when compared with NaOCl (30). In contrast, Oncag et al. (31) and Vianna et al. (32) found CHX was superior to NaOCl in killing E. faecalis and S. aureus. Lin et al. (33) reported that CHX was a better antimicrobial than Ca(OH)2, while a combination of both showed stronger activity against microorganisms than used alone (34). Variations in its efficacy can be partly explained by differences in experiment methods.

Passive And Active Irrigation

Recent works show that, optimization of dynamic flow of irrigating solutions, substantially enhance the quality of root canal cleaning. It is believed that an improvement in the dynamics of irrigation can make even possible a reduction of the time of action of sodium hypochlorite without any loss of effectiveness. There is not, today, a technical default to optimize irrigation but, certainly, it is clear that the decision to activate the irrigating solution, is to be preferred to a technique that provides a passive use of them.

It can be defined as a passive a technique of irrigation which provide the introduction of the irrigant into the canal without promoting in any way the penetration into the deeper portions. The penetration of the irrigant is affected by many variables:

- the size and length of the needle used (35);
- the size of the root canal in terms of taper (36) and apical enlargement (37);
- the irrigant flow (38).

It is recommended, therefore, the choice of fine, long and flexible needles, which will deliver the irrigant in the apical area. The smaller the diameter of the needles used for the irrigation, the higher is the pressure necessary to allow the discharge of the liquid in the canal. This can generate, especially with point needles with front exit, an increased risk of intraoperative accidents. Nickel-titanium needles , exploiting the alloy flexibility are able to follow root canal curvatures and are a valid choice .

The permeability of the irrigating solutions is also influenced by the anatomical complexity of the root canal, in addition to the techniques used for shaping the root canal. (39). The frequent renewal of the irrigating solutions during the whole shaping step seems essential to always have "active quotas" of irrigant solution in contact with the bacterial species and with the smear layer present within the root canal.

Dynamic irrigation

In a dynamic mode of endodontic irrigation irrigant solution is pushed, by a mechanical agitation created with an instrument or any other active agent within the root canal , in any direction thanks to a higher pressure that is exerted on the liquid and which allows and facilitates a progression even in very small ducts as the side canals. Irrigation would cause a structural change inendodontic biofilm (40) that facilitates its elimination improving the quality of root canal disinfection. There are different systems to enable irrigating solutions through a manual action or technologically assisted:

- manual files;
- gutta percha points;
- mechanical instruments (metal or plastic)
- microbrushes;
- ultrasonic inserts;
- sonic inserts;

In a study conducted by Machtou, it was possible to assess, with the aid of a contrast medium with physical properties similar to sodium hypochlorite, as in the most apical portion of the canal, where the needle doesn't arrive, the penetration of the irrigant only takes place after the introduction of an instrument to the working length (41).

An activation of irrigating solutions can also be obtained in the pre-filling phase. Use master gutta-percha cones, moving them up and down within the root canal filled with hypochlorite or EDTA, may be a valuable expedient to activate irrigating solutions.

A mode of activation of irrigating solutions widely used take advantage of ultrasonic devices. The passive ultrasonic irrigation (PUI), defined for the first time by Weller, does not adequately describe a process that is actually active (42). In fact the term "passive" has been chosen to signal an "non-cut" action by the oscillating part of the instrument . However, the ultrasonic oscillation of a file or a file activated indirectly from a ultrasonic source , in the presence of an irrigant solution, generates a transverse oscillation direction determining the presence of points of slight or zero displacement (nodes), and points maximum displacement (antinodes). The maximum displacement occurs at the tip of the instrument which remains for this reason the point most susceptible to fracture (43).

This mechanical action produces two important physical effects: the cavitation and the so-called "acoustic streaming". The phenomenon of cavitation is determined when an oscillating file, immersed in a fluid, produces in it positive pressures followed by negative pressures. Cavitation involves the formation of gas microbubbles with size, speed and random orientation that, imploding against the surfaces of root canal, have considerable disruptive action on all materials, in particular those equipped with the crystal structure (44). The oscillation releases energy that is converted into heat and hydrodynamic fields which can disrupt biological tissues and inorganic materials.

These microflows express their maximum power in the final stretch of the endodontic instrument causing bacterial destruction and an enzymatic inactivation of bacterial DNA. The acoustic streaming creates small circular motions in the fluid around the file. Since these movements are more present in the proximity of the instrument tip than the coronal portion, the liquid flow in a coronoapical direction. The phenomenon of acoustic streaming has great importance because it increases the effect of irrigating through the hydrodynamic shear effect. Ultrasound, used in the absence of suitable irrigants, weakly reduce the presence of bacteria in the root canal, but when they are used in the presence of an irrigant with a bactericidal action (for example, NaOCl) produce a relevant synergistic effect. The synergistic effect is both in relation to the effects produced by the cavitation and, above all, from those determined by the acoustic streaming. Several studies have been conducted to test the effectiveness of the synergy between ultrasound and antiseptic solutions: the results show that ultrasound, coupled to these irrigants, allow to obtain sterile samples at a significantly higher percentage compared to the use of only irrigants. The synergistic effect between ultrasonic and bactericidal irrigants also translates into a reduction of the time needed to get the full disinfection of the root canal.

The ultrasonic activity intensifies the cleaning action produced by irrigants, especially in the apical third and those parts of the endodontic space not achievable by intruments. However, to achieve an optimum cleaning the file should vibrate without coming into contact with the canal walls.

Consequently, it is indicated the use of files of small size with non active coils and tip , that do not engage in the root canal.

Positive and negative pressure irrigation

Traditionally, the placement of the irrigant with an end-port or side-port needle into the apical canal and expressing solution out of the needle to be suctioned coronally. This creates a positive pressure system, with force created at the end of the needle, which may lead to solution being forced into the periapical tissue. Positive pressure irrigation has its risks, as some irrigation solutions, such as NaOCl, have the potential to cause tissue injury that may be extensive when encountering the periapical tissue and its communication with tissue spaces . These NaOCl accidents can lead to permanent physical injury or disability, with facial deformation and neurological complications (45, 46).

Chow was able to show as early as 1983 that positive pressure irrigation has little or no effect apical to the needle's orifice(47) This is highlighted in his paradigm on endodontic irrigation, For the solution to be mechanically effective in removing all the particles, it has to:

(a) reach the apex,

(b) create a current force

(c) carry the particles away.

The inability to eliminate intraradicular microrganisms from the canal system, especially in the apical portion of the root, increases the risk of clinical failure (48).

A negative pressure irrigation system however does not create positive pressure at the needle's tip, so potential accidents are essentially eliminated. In a negative pressure irrigation system, the irrigation solution is expressed coronally, and suction at the tip of the irrigation needle at the apex creates a current flow down the canal towards the apex and drawn up the needle. True apical negative pressure only occurs when the needle (cannula) is utilised to aspirate irrigants from the apical constriction of the root canal. The apical suction pulls irrigation solution down the canal walls towards the apex, creating a rapid, turbulent current force towards the terminus of the needle.

Haas and Edson found that "The teeth irrigated with negative apical pressure had no apical leakage. While the teeth irrigated with positive pressure leaked an average of 2.41ml out of 3ml" (49) Fukumoto found that when using negative pressure there was less extrusion of irrigant than when using needle irrigation (positive pressure) when both were placed 2 mm from working length (50)

What other sequelae can occur with minute amounts of NaOCl leaking from the apex during the irrigation process? Gondim et al. in a study of post-operative pain comparing positive and negative pressure irrigation systems report, "The outcome of this investigation indicates that the use of a negative pressure irrigation device can result in a significant reduction in postoperative pain levels in comparison to conventional needle irrigation"(51). So although we may not see NaOCl accidents frequently, it is possible to see the effects of positive pressure irriga- tion allowing some minute extrusion apically in our normal, day-to-day endodontic treatment. They further state that "the use of the EndoVac system did not result in apical extrusion of irrigant, hence chemical irritation of the periapical tissues leading to postoperative pain may not be likely." They conclude that "It is safe to use a negative pressure irrigation protocol for antimicrobial debridement up to the full working length" (51).

EndoVac endodontic irrigation system

Designed by Dr. G. John Schoeffel after almost a decade of research, the EndoVac irrigation system (Discus Dental, Culver

City, California) was developed as a means to irrigate and remove debris to the apical constric- ture without forcing solution out the apex into the periapical tissue. The system utilizes apical negative pres- sure through the of ce's high volume evacuation system, permitting thor- ough irrigation with high volumes of irrigation solution.

The EndoVac system consists of a Hi-Vac adapter assembly that connects to the high volume evacuation hose in the dental operatory at one end and has a "T" connector at the other end. The "T" connector permits a Master Delivery irrigation-suction tip with a disposable syringe lled with irrigation solution and either a MacroCannula or MicroCannula to be attached and used simultaneously during treatment. The plastic MacroCannula is placed on a titanium handpiece, which is attached to tubing that connects to the "T" connector. This is used for coarse debris removal. The MicroCannula is a metal suction tip available in either 25 or 31 mm lengths with 12 micro holes in the terminal 0.7 mm of the tip, permitting removal of particles that are 100 microns or smaller to the apical constricture. This tip ts into a metal finger piece and is connected to the "T" connector via tubing. The turbulent current forces developed by the MicroCannula rapidly flow to the micro holes at the terminus, which can be placed as close as 0.2 mm from the full working length. The vacuum formed at the tip of the MicroCannula is able to achieve each of Chow's objectives in his irrigation paradigm.

The system comes packed in a single-use package that contains a Master Delivery Tip, a MacroCannula, a MicroCannula and tubing assembly .

Nielsen and Baumgartner found that the volume of irrigant delivered with the EndoVac system was signicantly more than the volume deliv- ered with needle irrigation over the same amount of time (52). Further, they reported significantly better debridement 1 mm from working length for the EndoVac system compared with needle irrigation.

Since one of the laws of physics states "only one object can occupy a space at a time," if the tissue remnants can be removed from the lateral canals, apical deltas and fins within the canal system, these areas can be filled with obturation material, providing a better seal and inhibiting bacterial migration throughout the canal system. The EndoVac irrigation system, as Nielsen and Baumgartner demonstrated, is able to better clean at the apex where other irrigation methods and systems have not been able to do as thorough a job.

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Comparison of four different final irrigation systems for irrigant delivery to the working length in extracted teeth: An ex vivo study.

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Introduction

The chemical-mechanical disinfection of the root canal system remains on of the most important step to achieving a successful endodontic treatment (1,2). Notwithstanding innovations in mechanical instrumentation techniques adequate irrigation is essential in order to dissolve pulp tissue, remove dentin debris and decrease the microbial load within the root canal system (3,4). This is true especially in the presence of narrow curved canals or morphological irregularities, such as ramification and apical deltas, that could harbor microbes and debris (3,5). Different devices for irrigation may improve the penetration of irrigant into the irregularities of the canals or into all areas which cannot be reached by mechanical instrumentations. The phenomenon of vapor lock might be additionally considered when the efficacy of endodontic irrigant technique has been tested. Considering the root canal system as a closed- ended gas channel that is produced by the reaction of sodium hypochlorite (NaOCl) with organic tissues, it may be possible to cause entrapment and obstruct the penetration of irrigant solutions (6, 7).

The two irrigation techniques, regardless of the quality of irrigation products and its antibacterial properties, include irrigant delivery and irrigant activation. Conventional needle irrigation is the most widely used delivery technique. Irrigant activation techniques range from the movement of gutta-percha cones up and down into the root canal to sonic and ultrasonic activation techniques and laser devices (8-10). All these systems have been proposed to improve the safe hydrodynamic action of irrigant flow into the apical third of the root canal, thereby reducing the formation of apical bubbles that might pose as an obstacle to the exchange of irrigants and their respective debridement efficacies (11,12). Endo Vac (Discus Dental, Curver, CA) is a negative pressure irrigation system and it has been designed to safely deliver irrigant solution in the apical portion of the canal. The EndoVac system consists of one micro-cannula and one macro-cannula that are connected to a vacuum line; the irrigant is delivered into the pulp chamber by the macro-cannula which is a master delivery/suction tip. The literature reports excellent results in terms of depth penetration of irrigants when the ultrasonic activation technique and negative pressure irrigation systems have been used in extracted root canals (13-15). The purpose of this *ex vivo* study was to compare four irrigation systems: conventional endodontic irrigation syringe and needle, irrigant activation with gutt-percha cone, passive ultrasonic irrigant activation, and apical negative pressure irrigation system (ANP) using the Endo Vac system to deliver a solution of contrast medium Iomeprol (Iomeron, Bracco Spa, Patheon, Italy) and

NaOCl 5.25% into the apical portion of the root canal in cleaned extracted teeth. The null hypothesis was that there is no difference among the tested irrigation systems.

Material and methods

Eighty extracted human single-rooted teeth (maxillary central and lateral incisor with similar canal curvature and morphology) were used in this study. The root surface of each specimen was derided (decontaminated) in a 5.25% of sodium hypochlorite solution and then stored in a saline solution until preparation. Pre-procedure X-ray were been taken from both buccolingual and mesiodistal angles to ascertain the presence of a single straight canal; teeth with root canal curvatures greater than 20° or calcified root canals were excluded. All the procedures were performed by the same operator. In order to standardizing the working length (WL) to around 16 mm, the specimens were decoronated using a high-speed, water-cooled diamond disc.

Apical patency and the exact working length were established under microscope (Global surgical corporation) at 8X magnification with the tip of the instrument visible in the apical foramen. The first digital X-ray was taken at this time using the Visualix Digital Imaging System (Gendex, Des Plaines, IL). All the roots were embedded in polyvinyl siloxane impression material (Dentsply Caulk, Milford, DE) and blocked into Pro-Train (Simit Dental, Mantova, Italy) to simulate clinical condition. The apices and the root canals were temporary sealed with gutta-percha cone to prevent the impression material from entering the canal.

All teeth were prepared to an apical size 30 K-file (Dentsply Maillefer, Ballaigues, Switzerland) at the working length by using the following instrument sequence: 10, 15, 20, 25, 30 K-file and ProTaper S1-S2-F1-F2-F3. Irrigation was done with 1 ml of 5.25% NaOCl, after each instrumentation, delivered with a 30-gauge side-vented needle (Perio/Endo irrigation needle; KerrHawe SA, Switzerland) passively introduced up to 2 mm from the working length. A 10 K-file was used to ensure apical patency.

The canals were randomly assigned into 4 different groups based on the final irrigation procedure performed with 2 ml of radiopaque irrigant (RI) solution of NaOCl 5.25% and contrast medium (RI) at a proportion of 73:27 in order to have an irrigating solution with a viscosity similar to that of NaOCl 2% to 5% (10).

Group 1 Conventional endodontic syringe/needle irrigation: two milliliters of RI solution was delivered in 30 s using a 5-mL syringe with a 30-gauge needle (Perio/Endo irrigation needle; KerrHawe SA, Switzerland) placed 2 mm from WL.

Group 2 Gutta-percha cone: the process was the same as for group 1 but the RI solution was activated by moving a ProTaper Universal gutta-percha point F3 (Dentsply Caulk, Milford, DE) up and down from WL – 5 mm to WL for 30 s (3 strokes/sec^{-1}).

Group 3 Passive ultrasonic activation: the process was the same as that for group 1 but the RI solution was activated by a ESI File (EMS, Nyon, Switzerland) for 30 s. The non-cutting NiTi ESI instrument was passively inserted to 1 mm from the WL and driven by an ultrasonic device (Piezon ® Master 600, EMS, Nyon , Switzerland) at low power setting of 4.

Group 4 Negative pressure irrigation system: a total amount of 5 ml of RI with a flow rate of 0.1 ml/sec^{-1} aws delivered in the coronal third of the root by using the Master Delivery Tip from Endovac System. Following this, the microcannula (32/0.00) was placed under negative pressure at working length for 30 s.

Digital X-ray image were taken for each tooth with the irrigant solution inside the canal using parallel technique at the same angle and exposition as the WL image. A blinded calibrated observer measured the distance in mm. between WL and maximum irrigant penetration using image editing software Vixwin Platinum 1.3 Gendex Dental Systems (Gendex, Des Plaines, IL),

Statistical analysis

Mean, standard deviation and maximum/minimum values were calculated for each group. Analysis of variance test was performed to determine statistically significant differences among the groups ($p<0.05$). A t-Test post hoc comparison was also done.

Results

The longest distances between WL and maximum irrigant penetration were observed in the group 4, with a mean distance of 1.51±1.17 mm, followed by the group 1 with a mean distance of 1.19±0.99 mm; the shortest distances were observed in the group 2 with a mean distance of 0.59±0.57 mm (Fig. 1). The analysis of variance test showed statistically significant differences between the groups ($P < 0.05$). The post hoc t-Test with Bonferroni adjustment showed significant differences between the group 2 and the group 4 ($P < 0.05$). No significant difference was observed in other comparisons between groups (Table 1).

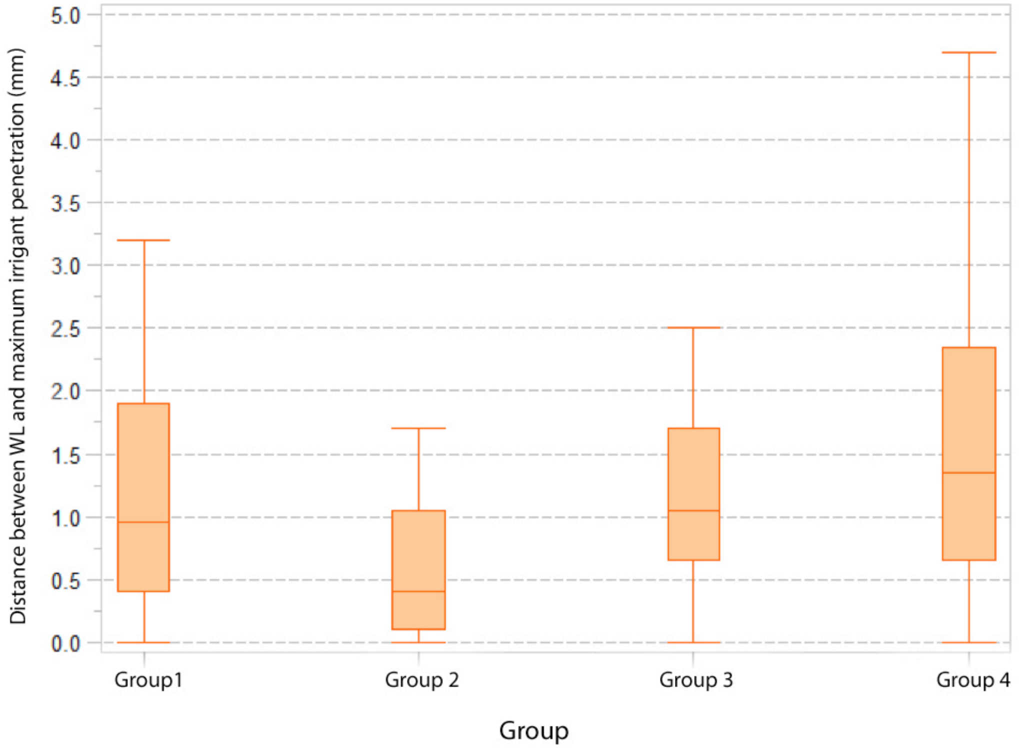

Figure 1 Box plots showing the median, the maximun and the minimun (in mm.) depth of final irrigant penetration.

Group	**Group**	**StdErr**	**tValue**	**Probt**	**Adjp**
Group 1	Group 2	0.2859	2.10	0.0392	0.2350
Group 1	Group 3	0.2859	0.05	0.9583	1.0000
Group 1	Group 4	0.2859	1.12	0.2665	1.0000
Group 2	Group 3	0.2859	2.05	0.0442	0.2651
Group 2	Group 4	0.2859	3.22	0.0019	0.0114
Group 3	Group 4	0.2859	1.17	0.2449	1.0000

Table. 1 Multiple t-test comparison with Bonferroni adjustment between groups

Discussion

The purpose of this study was to compare the penetration depth of final irrigant solution using four different irrigation devices. The irrigant is more effective when the needle is placed closer to the apex, and when a smaller gauge needle is used (16,17). Substantially straight root canals with similar anatomic features and closed-end canals were used in this study to standardize the specimens and to best reproduce the clinical situation. In contrast to the studies by Castelo-Baz et al and de Gregorio et al (3, 7, 13) a solution of radiographic contrast media and 5.25% of NaOCl was used to obtain a radiopaque irrigant solution. This radiographic contrast medium is widely used in medicine (18, 19), it was mixed with 5.25% of NaOCl to yield a solution with density and surface tension similar to that of NaOCl 2% to 5% (20). In previous *ex vivo* studies, contrast medium solution has been used in extracted human teeth to map the penetration of irrigant solution in the apical portion of the root canal (21,22), and olso to assess the efficacy of laser-drive irrigation in removing the air lock (10). Until now, there have only been *in vivo* studies regarding detection of irrigant penetration into the apical third of the root canals using a radiopaque irrigating solution (14,20) containing NaOCl and Chinese ink. In the present *ex vivo* study a radiopaque solution was used in extracted human teeth to simplify the preparation of the specimens and maintain the previously proposed method of cleaning the tooth and staining it with an irrigating contrast solution (3,7,13,18).

Effective irrigant delivery and agitation up to the apical portion of the root canals are important in achieving a complete debridement of the system (2, 4, 23). Several studies have reported improved cleaning properties of irrigants when mechanical (by means of ultrasonic device) and or manual agitation of irrigant solution were performed (13,14,19). When negative pressure irrigation (EndoVac) device was compared to the passive ultrasonic irrigation (PUI) system Munoz et al. observed significantly shorter distances of irrigant solution from the WL in the PUI group than in EndoVac group; while Spoorthy et al reported a significantly better depth penetration of the irrigant solution in the EndoVac group than in the PUI group. Spoorthy et al (18) reported a significantly better depth penetration of the irrigant solution in the Endo-Vac group than in the PUI group. In our study the results are similar to those of Munoz's (14), even though better penetration depth was observed in the gutta-percha cone group; the EndoVac group was significantly worse than the gutta-percha group. The present study's findings can be attributed to the taper and apical size of the specimens; all the root canals were shaped with a ProTaper F3 (apical size 30, taper 9%) at WL. As suggested in a previous study (24) an apical size of 40 may make it possible to WL with the EndoVac micro-cannula that has a tip of 0.32 mm in diameter (25, 26). In the study by Munoz's, EndoVac did not show superior performance when compared to the ultrasonic system; this may be due to the apical size of the root canals 35/0.04. In the present study the apical diameter of the remaining experimental devices (30 G needle, F3 gutta-percha point and the ESI File) was 0.30 mm and the differences between group 1, 2 and 3 were not statistically significant. These findings may suggest that the apical size of root canals and the apical size of the devices used for final irrigation may significantly influence the depth penetration of the irrigant. As reported in an *in vivo* study, when the root canal is prepared to an apical size of 40/0.06 and apical patency is maintained, significant better irrigant penetration can be achieved (20).

In conclusion, within the limitations of this study, the activation of final irrigant solution with a gutta-percha cone is more effectively than the EndoVac negative pressure system.

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Summary

The field of endodontics is undergoing a continual evolution in terms of materials and techniques, as well as growth in the number of patients who can benefit from endodontic treatment.

The most important objective of root canal therapy is to minimize the number of microorganisms and pathologic debris in root canal systems to prevent or treat apical periodontitis, but despite the technologies is still difficult to reach it.

One of the most important innovations in Endodontics has been the utilization of the nickel-titanium (NiTi) rotary shaping files.

The first NiTi rotary instrument came to market in about 1992. Dr. John McSpadden's company distributed this 0.02 tapered file utilizing Dr. Ben Johnson's idea of creating a rotary file with three radial lands and a taper similar to the carriers used with the Thermafil obturators.

There are many advantages for utilizing NiTi rotary instruments for shaping root canals. Traditionally, canal preparations have been performed using a series of stainless steel files, oftentimes in conjunction with gates glidden drills or reamers. During use, the potential for blocks, ledges, external

transportations, and/or strip or apical perforations is always present. Advantageously, NiTi rotary shaping files have nearly eliminated these iatrogenic events. Other important advantages of shaping canals with NiTi files are improved efficiency, the opportunity to schedule more "one visit" endodontic procedures, and improved profitability. Additional advantages of using NiTi files are fewer post-operative flare-ups, the ability to open canals more easily and with less effort, and the creation of more consistent and uniform canal shapes.

There are several new lines of files that have become available, all of which are quite different in design and performance. Over several years, as we have used NiTi files, taught rotary preparations, and invited clinical feedback, we have learned that dentists are looking for four features. The features are improved efficiency, better flexibility, greater safety, and importantly, simplicity. Surveys from the international opinion leaders have rated the ProTaper files as coming closest to fulfilling these desirable and sought after features. Synergistically, more creative and sophisticated instrument designs, in conjunction with advanced machining techniques, have taken NiTi rotary files to the next level and have dramatically benefited clinical performance.

A complementary research field, tightly connected with the root canal shaping is irrigation.

The chemo-mechanical disinfection of the root canal system remain on of the most important step to achieve an endodontic success. Although the innovations of mechanical instrumentation techniques, an adequate irrigation is essential to dissolve pulp tissue, remove dentin debris and decrease the microbial load within the root canal system.

Different device for irrigation could improve the penetration of irrigant into the irregularities of the canals or in all areas don't reach by mechanical instrumentations. Phenomenon of vapor lock could be additionally considered when the efficacy of endodontic irrigant technique have been tested.

Different irrigation techniques, irrespective of the quality of irrigation products and its antibacterial properties, could be recognize: manual and machine assisted irrigation techniques.

An in vitro study to compare four irrigation systems: conventional endodontic irrigation syringe and needle, Manual Dynamic Activation, Passive Ultrasonic Irrigation and Negative Pressure irrigation by EndoVac system on solution of contrast medium and NaOCl 5.25% delivery into the apical portion of the root canal in cleared extracted teeth was assessed.

The purpose of the PhD thesis is to give an overview on the state of the art in the shaping and cleaning the root canal system and consider the technological innovations that can lead to an improvement in the disinfection of the endodontic system.

During the PhD program the research at the Endodontic department was also focused on bioactive materials and especially on Mineral trioxide Aggregate and its use in different clinical situation.

MTA has shown potential as an endodontic material in several in vitro and in vivo studies. It was first recommended as a material for repair of root perforations. It was then widely used as a root-end filling material and for vital pulp therapy, including direct pulp capping and pulpotomy of immature teeth with vital pulps (apexogenesis). In addition, because of its sealing ability, it was also suggested as an apical barrier in the treatment of teeth with opened apices and necrotic pulps.

Several patients with necrotic teeth and open apices treated ate the department of Endodontics during the last 10 years has been monitored and data about clinical and radiographic outcome were collected.

A manuscript intitoled "Mineral Trioxide Aggregate as Apical Plug in Teeth with Necrotic Pulp and Immature Apices: A 10-

year Case Series” was accepted and published on the Journal of Endodontics (J Endod. 2014 Aug;40(8):1250-4).