Mechanical root canal preparation with NiTi rotary instruments: Rationale, performance and safety.
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ABSTRACT: The growing use of NiTi rotary instruments in dental practice demands a good understanding of their concept of alloy and design in relation to improved properties and inherent limitations. Nickel titanium's super elasticity allows more centered canal preparations with less transportation and a decreased incidence of canal aberrations. Furthermore, the production of files with increased taper became possible. This is of special importance because of concerns on the achievement of adequate irrigation and close adaptation of the filling material during endodontic treatment. Unique shaft and tip designs should permit the use of a rotary handpiece allowing different tactile awareness. On the other hand, special attention is paid to maximize cutting efficiency and cutting control throughout instrumentation. NiTi rotary instruments are generally used in a crown-down approach and a continuous reaming motion. Consequently, rounder root canal preparations, with less straightening and a smaller amount of apical extrusion is achievable. In spite of their increased flexibility, separation is still a concern with NiTi files. The phenomenon of repeated cyclic metal fatigue and the variable of torsional loading are two important factors in instrument fracture. However, with awareness of the appropriate manipulation and special attention to the equipment used, NiTi systems are safe with a minimal incidence of instrument failure. (*Am J Dent* 2001;14:324-333).

CLINICAL SIGNIFICANCE: Following guidelines based on different inherent properties, NiTi rotary systems may achieve final root canal preparations with superior qualities in a safe, simpler and more predictable fashion compared with most traditional methods.

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Introduction

Recent advances in the field of endodontics have led to the use of nickel titanium (NiTi) rotary instruments in dental practice. During the last few years the number of users has increased significantly and many new systems are on the market (Table 1). The idea behind these fairly new developments is the belief that they could improve the efficacy of root canal preparation. Together with the growing interest in thermoplastic obturation techniques, the use of especially greater taper NiTi rotary files has given way to "modern" methods, which should eliminate some of the shortcomings of traditional endodontics.

The choice of instruments and systems are a reflection of the different thoughts regarding taper of instrument and taper of the prepared canal. Regarding modern concepts, the final canal shape has to allow adequate irrigation and close adaptation of the filling material during obturation. However, innovation rarely comes without its own set of challenges. To understand the properties and inherent limitations of these new instrumentation techniques, it is helpful to examine the literature about this topic over the last few years.

Nickel titanium's super elasticity

Inherent in the material used, stainless steel files have a high stiffness that increases with increasing instrument size and causes high lateral forces in curved canals.[1] These restoring forces attempt to return the instrument to its original shape and act on the canal wall during preparation, influencing the amount of dentin removed. The forces are particularly influential at the junction of the instrument tip and its cutting edges. This instrument's rigidity is responsible for straightening and its consequences in the apical, middle and coronal thirds.[2-4] The resulting transportation and canal aberrations (including ledges, zippings and perforations) leave a significant portion of the canal wall un-instrumented, along with the creation of an irregular cross-sectional shape that is harder to obturate.[5-20]

Table 1. Overview of different existing NiTi rotary systems.

GT Rotary files[a]
Hero 642[b]
K3[c]
Lightspeed[d]
McXIM[e]/NT files[e]
Mity Roto[f] 360°
Naviflex[g]
ProFile[a]
ProTaper[a]
Quantec[h]

The answer to canal distortion was the introduction of a series of reamers and files made from nickel titanium (NiTi) rather than stainless steel. The unique property of super elasticity may allow NiTi files to be placed in curved canals with less lateral force exerted. Conceptually, the files are all made from nitinol, an equiatomic NiTi alloy with a very low elastic modulus. The size #15 nitinol hand files have been shown to have two to three times more elastic flexibility in bending and torsion, as well as superior resistance to torsional fracture (wider range of elastic deformation), when compared with size #15 stainless steel files manufactured by the same process.[21-24]

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 recovers to an austenitic phase and its original shape. This phenomenon is called a stress-induced thermoelastic transformation.

Research on the balanced force motion has stated that less force on the canal wall will ultimately decrease canal move-ment during preparation.[16,17,25,26] With reduced forces devel-oped by engine-driven NiTi instruments, it has been reported that significantly less transportation is caused compared with hand instrumentation.[27-29] The magnitude of absolute trans-portation caused by NiTi rotary instruments is very small with a similar direction at the end-point of preparation to that found with stainless steel hand instruments. However, at the curve, transportation is towards the inner or outer aspect. It is not clear why this outer pattern occurs and what aspect of the instrument is involved. In general, canals with greater curva-ture, described by angle and radius, are wider after preparation with the main differences being a greater degree of tissue removal from the outer aspect of the curve. The presence of multiple canal curvatures (either in one plane or multiple planes) did not significantly affect the removal of dentin and final canal shape in another study.[30]

In addition, NiTi rotary systems seem to create more centered canal preparations than stainless steel hand files.[26-28,31,32] Differences are more pronounced at a final preparation larger than size #30.[33,34] There are only small discrepancies among the various NiTi systems at different horizontal levels.[27,34,35]

The incidence of canal aberrations are more common when using conventional engine-driven devices than with stainless steel hand instruments.[36-39] However, with most of the recent NiTi rotary engine-driven systems, the degree of zipping and/or ledging is limited and relatively minor.[28,40-45] Nevertheless, some techniques produce a relatively high amount of ledges on the outer aspect of the curve. The majority of these aberrations occur in canals with short acute curves. Thompson & Dummer[42] found that instrumentation with Lightspeed created the smallest amount of distortions, a finding confirmed by others.[27,29,33,46]

On the other hand, it is important to realize that the elasticity of NiTi greatly reduces the degree of anti-curvature filing that can be accomplished with these instruments. Additionally, the prebending required for stainless steel files is impossible with NiTi instruments. Now and then, a size #10 or #15 precurved hand file will be necessary to reach working length during practice.

Greater taper concept

Because super elasticity diminishes the connection between cross-section and instrument stiffness, files with larger diameters became possible. Before the advent of NiTi instruments of greater tapers, all endodontic files and reamers were manufactured from stainless steel and had standard 0.02 tapers. This means that they would increase in diameter at a rate of 0.02 mm/mm from the tip of the instrument for a length of 16 mm.

Regarding existing theories, the irrigation that a 0.02 tapered space provides may be insufficient for maximum dissolution of organic debris by sodium hypochlorite. This can alter the treatment outcome because the cleaning of all spaces, including prolongations and fins, is a very important phase during endodontic therapy.[47-50] The use of greater tapers (0.04, 0.06, 0.08, 0.10 and 0.12) should allow more apical placement of the irrigant. In that way, a thorough removal of pulp tissue, necrotic debris, bacteria and dentin filings can be achieved by the combined cleaning effect of physical instrumentation and chemical irrigation.[51]

Another advantage is that a more conical preparation of the root canals permits the placement of a master gutta percha point of greater taper (non-standardized). Musikant *et al.*[52] concluded that the greater the taper, the more resistant the gutta percha cones are to apical displacement by condensing forces. This superior resistance reduces the incidence of overfills and should provide an intimate adaptation of the thermoplastic gutta percha against the canal walls.

An additional benefit of the taper variations is the maximized cutting efficiency of the files. By changing tapers either larger or smaller in the sequence of canal preparation, the cutting efficiency is improved over constant tapers by increasing the force per unit area of the file against the canal wall.

ProTaper,[a] a NiTi file design that combines multiple, progressive tapers within the shaft was recently introduced. Studies are required to investigate the biomechanical aspects of root canal preparation using this design.

Finally, it is important to consider that the preparation to a greater taper demands the removal of more dentin. Excessive deduction of hard tissues weakens the tooth structure and makes the roots more prone to fracture.

Shaft and tip design

Besides 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 (Table 2).

The shaft design (does not conform to ISO/FDI No.3630/1) of NiTi instruments is adapted 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.[53] 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

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Table 2. Overview of shaft and tip design

System	Taper (mm/mm)	Shaft	Radial land	Tip (mm)
GT Rotary files	0.04	U-file design	Yes	Modified (20 – 35)
	0.06 - 0.12	U-file design	Yes	Modified (20)
	0.12 (Accessory)	U-file design	Yes	Modified (35, 50 and 70)
Hero 642	0.02	Slightly positive rake angle / helical	No	Modified (20 - 45)
	0.04 and 0.06	Slightly positive rake angle / helical	No	Modified (20 - 30)
K3	0.04 and 0.06	Positive rake angle Asymmetric Variable core diameter	Yes (relieved)	Modified (15 – 60)
Lightspeed	Non-tapered shaft	Smooth, small diameter shaft Short cutting head (1-2 mm) U-file design	Yes	Modified (20 – 100) (includes half-sizes)
McXIM series	0.03 to 0.055	U-file design (0.03 / 0.045 / 0.055)	Yes	Modified (25)
		H-type design (0.04 / 0.05)	Yes	Modified (25)
NT files	0.02	H-type	Yes	Modified (15 – 35)
		Dissimilar helical design	No	Modified (37.5 – 60)
Mity Roto 360°	0.02	U-file design	Yes	Modified
Naviflex	0.02	U-file design	Yes	Modified
ProFile Series 29	0.04	U-file design	Yes	Modified (15 - 90)
	0.06	U-file design	Yes	Modified (15 – 40)
	0.05 – 0.08 (Orifice Shapers)	U-file design	Yes	Modified (20 – 80)
ProTaper	Progressive	Triangular	No	Modified
Quantec	0.02	Slightly positive rake angle / helical	relieved	SC (safe) / LX (non) (15 – 60)
	0.03 – 0.06	Slightly positive rake angle / helical	relieved	SC (safe) / LX (non) (25)
	0.08 - 0.12 (Flare)	Slightly positive rake angle / helical	relieved	LX (non) (25)

H-type file consists of a single L-shaped groove (Hedström type) produced in the same way.

In accordance with the shaft design, the existing rake angle can be verified. The rake angle may be seen as the direction of the cutting edge if visualized as a surface. In general, most traditional endodontic instruments have a slightly negative rake angle. On the contrary, most NiTi files have a neutral or slightly positive angle for maximum effectiveness.

One of the latest trends in NiTi rotary shaft design is the introduction of a radial land relief in combination with a positive rake angle (K3 from Kerr Europe). This asymmetrical, more aggressive file design should allow better debris removal, and a cutting rather than a planing action. Further research is necessary to investigate the biomechanical aspects of root canal preparation using this technique.

Regarding the instrument tip, one could summarize that practically all contemporary files have an acceptable non-aggressive tip design and there should be little concern over tip geometry in the selection of files (ANSI/ISO guidelines). From a historical perspective, Weine *et al.*[37] observed that the instrument tip had an important effect on the cutting control during root canal preparation. More specific, if stainless steel files with active tips were used, the inherent stiffness enhanced the machining of dentin on the concave side of the curvature, resulting in some straightening and ledging.[54-56] On the other hand, active cutting tips may be helpful when penetrating canals smaller than the file.

Recent NiTi rotary files have rounded and non-cutting tips that ride on the canal wall rather than gouging into it. Unlike a pilot tip, the instrument shaft retains its active cutting blades. Only the angle at D1 (transition angle) has been modified by rounding it.[16,17,57] Some systems use off-center tips that would facilitate negotiating around curvatures and ledges. Nevertheless, no rotary instrument should go where a hand instrument has not been placed before.

Quantec instruments seemed to have relatively sharp tips that appeared likely to predispose to transportation and the creation of defects along the outer aspect of severely curved canals.[45,46,58] The original design with the 90° tip was modified in order to produce a less aggressive second system.

Concerning tip size, most manufacturers make use of real increments (in 0.05 mm), equal to the standard guidelines used for the production of stainless steel instruments. However, the Lightspeed series makes use of additional "half" sizes and another company (Dentsply Endodontics[a]) has introduced the concept of dimensional increments in percent (29%) of diameter instead of real increments. Nevertheless, the possible advantage of this approach has not been demonstrated yet.[59-61]

In addition, Lightspeed instruments have been modified so that they hold only a short cutting zone apically, the so-called "apical action design".[62] This specialized design does not cut over most of the canal length because of a smooth, small-diameter shaft that also reduces their cross-sectional area. The first apical action design instruments (Canal Master and Canal Master ″U″)[g] prepared the apical portion with less transportation and less dentin removal.[18,27,63,64] Nevertheless, they had other problems such as instrument separation, need for special training and an increase in working time.[65-67] Lightspeed is an engine-driven version of the NiTi Canal Master ″U″ design that was modified to take advantage of the new NiTi alloy.

Quality control of most instruments seems to be very good. They appear as they are supposed to.[68] On the other hand, most of the new NiTi endodontic instruments cannot be evaluated

Table 3. Recommended speed and preparation approach.

System	Speed (rpm)	Flaring technique
GT Rotary files	150 - 350	Crown-down (no pecking motion)
Hero 642	350 - 800	Crown-down (anatomy related)
K3	300	Crown-down Modified double flare
Lightspeed	750 - 2000	Step-back Preflaring
McXIM series NT files	340	Crown-down
Mity Roto 360°	200 - 400	Crown-down
Naviflex	280	Crown-down
ProFile Series 29	150 - 350	Crown-down Modified double flare
ProTaper	250 - 350	Crown-down
Quantec	300 - 350	Crown-down Modified double flare

using the standards proposed by the ANSI/ADA Specification No.28 for files and reamers.[69,70] For Lightspeed, observation and video analysis showed that the system is not an instrument of any one determined shape that changes only in diameter, but rather a series of instruments that show gradual shifts in both size and shape as the instrument size increases.[69]

Crown-down *versus* step-back

In general, most NiTi devices advocate preflaring of the upper portion of the root canal prior to further preparation. Coronal widening with Peeso[i] and Gates Glidden[i] reamers provide straight line access and allow more control during the preparation of the middle and apical third.[9,71,72] As a result, groups that use orifice openers or Gates Glidden drills have more transportation coronally, representing an anti-curvature relocation of the canal.[73] On the other hand, less preflaring can result in a more conservative coronal preparation, leaving more of the cervical dentin intact and helping maintain structural integrity.[74] The delicate and final preparation will be performed with a coronal-apical (crown-down) or apical-coronal (step-back) approach, depending on the system used (Table 3).

The three-dimensional canal form after preparation has different characteristics according to instrument taper, shaft design and concept of preparation. Files with a standard 0.02 taper (*e.g.* Mity Roto and Naviflex) seem to create poor taper and/or flow characteristics. Lightspeed instruments tend to produce a round parallel preparation because of their non-cutting shaft with constant diameter. As a result of the small taper design, flare can only be achieved using a step-back technique. Achieving a good tapered three-dimensional form with these instruments implies that either the step-back sequence should be modified or another file with increased taper should be used to refine the canal walls before obturation. On the other hand, the desired taper is mainly dictated by the need to clean the canal and the chosen obturation technique. Using standardized gutta percha points and a lateral condensation technique, a more conservative taper can be advisable. Nevertheless, the additional use of orifice openers and 0.06 tapers in the ProFile series facilitates spreader placement after canal preparation.[73] This improved deep shaping could compensate the less close fit of the 0.02 tapered master point and improve the lateral obturation with additional cones.

Continuous reaming motion

The use of automated handpiece systems for canal preparation is accelerating with the introduction of NiTi engine-driven files. Although some variations exist, NiTi files are generally used in a very low-speed torque-control handpiece system and a full 360° file rotation. This continuous rotating movement has its influence on the canal preparation. Indeed, the strength of the restoring forces is directly related to the metal composition, the design and the instrument's angle of deflection, and also to the motion of action.

When an instrument is at rest, no cutting action is exerted on the canal walls. The only force is that from the instrument's rigidity or memory (curved canals). But when, for example, a pulling (filing) motion is initiated, the force increases against the walls. Accordingly, the greatest amount of cutting occurs at the inner curve and apex because of the action of a lever arm and fulcrum. By pulling, the operator loses control and cannot direct the cutting forces evenly along the entire canal. In contrast, when using NiTi rotary instruments, a reaming motion replaces the filing movement. As a result, less straightening will be accomplished. It takes more energy to pull an instrument than to turn it because reaming or rotating reduces these forces and results in less canal transportation and better centering. Both feed and speed are critical for engine-driven reamers.—

NiTi systems have a speed range for optimal performance, provided by the manufacturer. For Lightspeed it was demonstrated that the improved centering properties are not influenced by the chosen rotating speed (750, 1300, or 2000 rpm).[40] Nevertheless, increased rotational speeds seem to in-

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crease shaft stiffness. For that reason, slower speeds may be required to instrument small curved canals. Another result of this study was that the amount of dentin removed by Lightspeed instruments did not differ at various rotation speeds (750, 1300, or 2000rpm).[40]

Additionally, Vessey[75] found that more rounded preparations are produced when using a reaming action instead of a filing movement.[10,76] In the coronal two-thirds of wide or irregular shaped canals, these round preparations are sometimes produced only in the center or at one side leaving the remaining walls un-instrumented.[7,77] In the apical third, however, the root canal is adequately prepared by a reaming technique.[77] Furthermore, apical action design instruments seem to obtain a high amount of round preparations.[78] The best results were related to both the reaming action and the special design.[18,62-64] Within that group of instruments, Lightspeed has the largest number of round canals at all levels.[78] In general, overall canal planing may be dictated more by anatomy than by the difference in instrumentation method.[79] Haga[80] and Walton[7] concluded that all root canal systems have a limit as to the area of the canal that can be planed.

As a final point, hand or engine-driven instrumentation that uses rotation seems to reduce apical extrusion when compared with a filing technique.[20,81] Besides that, coronal flaring also seems to play an important role.[82] Less debris extruded has strong implications for a decreased incidence of postoperative inflammation and pain.

Cutting efficiency

Before discussing the cutting efficiency of NiTi rotary systems, it is important to realize that there are no clear standards for the cutting or machining effectiveness of endodontic files. These properties are also difficult to investigate because of the dynamic nature of the interaction between dentin and the cutting blades.

Due to the super elasticity, one could suppose that NiTi instruments are less efficient since little force is applied to the dentin as the file is deflected or bent away from the surface. However, studies demonstrated that NiTi instruments are as effective or better than comparable stainless steel instruments in machining dentin.[79]

A next important aspect to consider is the alloy hardness. Surface hardness of the NiTi alloy is lower than the hardness of conventional stainless steel. To improve nitinol instruments, the implantation of boron or nitrogen seems to have potential, without affecting the super elastic bulk-mechanical properties.[83-84]

Also demonstrated is the negative effect of sterilization. Repeated cycles under autoclave would decrease the cutting efficiency by altering the superficial structure of NiTi files.[85] The underlying explanation is that sterilized instruments show in-depth distributions of chemical compositions that are changed due to greater amounts of titanium oxide on the surface. In contrast, the presence of sodium hypochlorite would not cause any difference in cutting efficiency.[86] This is important because the use of an adequate amount of irrigant is crucial during the instrumentation process.

As discussed before, the rake angle of the cutting blade plays a central role. Nearly all NiTi files have a neutral or slightly positive angle for maximum effectiveness. However, if the rake angle is rather positive, the instrument may dig itself too deep into the dentin. In addition, a radial land file design with just a narrow flat area will generate a more aggressive side cutting ability relative to a wider strip.

A final factor that determines the cutting ability is the shape of the groove. A deep groove allows more debris transportation during action. In this way, cleaning effectiveness is closely related to cutting efficiency. The removal of cut dentin chips is important to reduce clogging of the cutting blades and eventually the canal itself. During the action of continuous rotation, macroscopic debris is taken out by the rotating grooves. Simultaneously, the radial lands push microscopic debris deep inside the dentin tubules.[87]

Most studies indicate that NiTi rotating systems are as good as or better than stainless steel hand instrumentation in removing superficial debris.[88-90] However, NiTi rotary files seem to produce a thicker smear layer particularly in the apical third, as demonstrated by some SEM evaluations.[91] Comparing systems, another study report points out that Hero achieved the best results for debris removal (80%), followed by Quantec (76%), Lightspeed (68%) and ProFile (50%). The results for smear layer were similar: Hero (53%), followed by Quantec (41%), Lightspeed (31%) and ProFile (18%).[46]

Instrument fracture

Despite their increased flexibility, separation is still a concern with NiTi instruments. Fracture can occur without any visible signs of previous permanent deformation, apparently within the elastic limit of the instrument.[68,92-94] Visible inspection, therefore, is not a reliable method for evaluating the used NiTi instruments. Another problem 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.[22,95,96] When instruments are placed in curved canals, they deform and stress occurs within the instrument. The half of the instrument shaft on the outside of the curve is in tension and the half on the inside is in compression. Consequently, each rotation causes the instrument to undergo one complete tension-compression cycle. Obviously, stress levels are the greatest in the area of curvature.[97] 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.[97] Considering cycle fatigue as a contributor to instrument failure, larger instruments should not be considered safer or stronger in clinical practice.[96,98]

Torsional loading during 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 findings also depend on the shape of the individual canals.[99,100] In another study,[101] the same author demonstrated that the areas of contact with dentin are positioned at or near 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, thus resulting in higher stress.[96] Interestingly, broken Lightspeed instruments have the benefit of an easy removal or bypass because of their design.[102]

Due to its wide range of elastic deformation, NiTi alloy may be strained 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.[23] 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 prone 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.[96,103] Moreover, machined files exhibit less ductility than twisted files prior to fracture and may be more susceptible to torsional failure clinically.[104] In this regard, the ability of the operator seems to be an important clinical factor of instrument failure[105] and early radicular access (flaring) reduces the chance of instrument failure caused by locking the file in dentin.[106]

Considering 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.[107] This is understandable considering the mechanisms for failure.[104] During clockwise torsion, the cutting spirals unravel. After a while, the outer portion of these spirals begins to experience longitudinal compression as the twist direction starts to reverse. After the spirals have reversed direction, tension will be created since the winding will be tightened and lastly 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.[96] 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.[96,108]

Dry heat sterilization does not influence the number of rotations to breakage of the file.[98,109] Comparably, heat treatment as a result of autoclave sterilization does not seem to extend the useful life.[110] In contrast, Serene *et al.*[22] 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 close 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.[68,111] NiTi files also wear noticeably, but they are much more resistant. The properties of the metal apparently reduce pressure and force on the flute edges and instrument body.[68] 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.[68]

Requirements for use

NiTi’s advantages removed several of the limitations of stainless steel, but also brought its own set of challenges. To achieve the best results, clear standards for use are essential.

The minimal requirement for NiTi rotary instrumentation is a high quality electric motor whereby a feedback circuitry compensates for torque to maintain a constant speed, and a suitable speed reducing handpiece. The speed range (rpm) depends on the selected system. One should always use the recommended speed and keep the instrument on the move using in and out “pecking” movements. In contrast, for the GT Rotary system a smooth steady pressure for about four seconds is advised. However, all types must be used with a light touch (the same pressure as applied to writing with a lead pencil) and minimal apical pressure (“advance and withdraw” motion when resistance is felt) to avoid instrument breakage. It is strongly advisable to establish a “glide path” with small stainless steel hand files prior to placement of the rotary instrument. Furthermore, one may not rotate the file for more that 10 s in the canal and during this period of time, the instrument may not stop rotating.

As mentioned, NiTi is very vulnerable to fracture, even when the distortion is temporary. The unpredictable point of fracture means that one has to be prepared to discard the files after only two to three uses even though they appear to be sound.[112]

When rotary instruments are used it is very important to learn the proper technique. The use of rotary instruments calls for a different tactile awareness from that of using hand files, because there seems to be less feedback from the instrument to the operator, particularly regarding direction of canal curvature.[113] For Lightspeed, the tactile sensitivity of the instruments differs at various rpm. At 750 rpm, many canal irregularities could be felt through the instrument feedback, but a rotation speed of 2000 rpm resulted in almost total loss of any sensation.[40] Today, several manufacturers have developed and marketed a rotary handpiece that reverses direction when it

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senses too much torque placed upon the engaged instrument. Auto reversing may reduce the incidence of fracture, but does not offer complete protection against fracturing instruments, since the file has to bind before it increases the torque level. The accuracy of the introduced step-motor technology may however minimize this problem. In addition, the possibility of accidental debris extrusion during rotation in reversed mode has to be further investigated.

The gain in length found in some studies could be a reflection of the effective removal of debris from the canal and the maintenance of canal curvature, or an inherent problem with length control.[114-118] The Tri Auto ZX[i] is a cordless endodontic handpiece with build-in apex locator and automatic apical reverse. Even with this device, the constriction is frequently enlarged.[119-120]

The use of an irrigating medium while cleaning and shaping the root canal system is an accepted practice. Irrigation plays an important role in lubricating the canal and in facilitating chip and debris removal. When a chelating agent is used, the dentinal walls become softened, making preparation easier. Some irrigants also serve the very important purpose of canal disinfection. Effective root canal irrigation cleans the grooves from debris to keep the optimal cutting efficiency. Dry condition may contribute to the fracture of instruments because a reduced efficiency will advocate excessive vertical forces by the operator.[87,90] The use of an irrigant has no side effects on the files, since the mechanical properties of NiTi are not altered in the presence of sodium hypochlorite.[121,122] Therefore, copious irrigation after each use of a rotary instrument is desirable. Additionally, it is important to remove debris from the flutes in the cutting part after each canal preparation. Simple sterilization would not be sufficient.[123]

Discussion

In the endodontic literature, techniques for cleaning and shaping of root canals differ and the best procedure for all conditions has not been established. [3,25,49,124-128] On the other hand, the introduction of new file designs and materials has increased dramatically during the past few years.

At its best, recent NiTi rotary systems solve most of the deficiencies of traditional stainless steel instruments. Undoubtedly, NiTi rotary instruments, if used properly, can achieve a final root canal preparation that conforms to the general shape and direction of the original canal.

Far before the invention of recent techniques, Schilder[129] pointed out that the most appropriate canal shape for filling with gutta percha and sealer is a continuous tapering funnel shape with smallest diameter at the end-point, whereas special attention should be paid to the apical constriction. Current hardware innovation seems to give the average practitioner the ability to achieve these superior results in a simpler and more predictable fashion compared to most traditional methods.

Comparably, using stainless steel hand files in small, curved canals, a size #30 preparation reflects what some clinicians regard as an instrumentation endpoint. Kerekes & Tronstad[130] reported that preparation to a #25 or #30 inadequately cleans the apical portion of small, curved molar root canals.[131] Using NiTi instruments, the size #40 preparation has become common in these canals since the super elasticity diminishes the connection between cross-section and instrument stiffness. The instrumentation of the apical matrix to a larger size incorporates more anatomical irregularities and provides more irrigant exchange in the apical third.[132-133]

An important issue to talk about is the evidence that the preparation time is different when using NiTi rotary systems.[73,114-118] NiTi systems are faster than hand instrumentation and the fatigue is reduced.[20,27,29,33,34] Differences between various rotary systems are more likely the result of variations in preparation technique than any differences between instrument performances. In addition, the frequency of irrigation can also influence preparation time. Using the engine-driven Lightspeed,[78,115] Mity Roto 360°, or Naviflex,[117] there is sufficient evidence to support the conclusion that the degree of difficulty of canal anatomy may not be a major time factor. Conversely, systems used by moving up and down the numerical sequence in a crown-down manner to flare the canal until the smaller files reach working length, have the widest percent variation in time. The anatomy of some canals requires moving up and down the sequence several times while in other canals working length is reached very quickly. Occasionally, NiTi rotary systems speed up the treatment very much so that the effective time for the irrigant is strongly reduced. If unnoticed, this fact may undermine the extent of chemical cleaning.

The use of NiTi rotary instruments during endodontic retreatment also shows potential. The continuous reaming at higher rpm facilitates the gutta percha removal. Further research will verify whether the additional use of a solvent (*e.g.* chloroform) is advisable.

Nevertheless, the fact that these modern techniques demand great skill and have become the source of some new problems, has made the acceptance of these new methods less than universal. Regarding the literature on NiTi rotary instruments, it is obvious that additional research is needed to further investigate different systems. New research tools like X-ray microfocus computed tomography (XMCT) could offer great potential for a more accurate evaluation of these endodontic procedures, supported by a unique combination of non-destructiveness, ease of visualization in the three dimensions and acceptable clinical validity.[77,134] Additionally, further work is needed to analyze the relationship between the vertical forces and torque developed during mechanical preparation and the incidence of instrument failure. Furthermore, there is a clear need for the development of a test protocol for the cyclic fatigue of NiTi engine-driven rotary instruments.

In conclusion, besides its biocompatibility and excellent corrosion resistance, NiTi is an expensive alloy that is difficult to manufacture and mill. Given the high price per instrument, the incorporation of NiTi as used in modern endodontics has increased the procedure costs dramatically. Therefore, patients should become informed and the highest possible level of care should be provided.

a. Dentsply Endodontics, Tulsa, OK, USA/Dentsply Maillefer, Ballaigues, Switzerland.
b. Prodonta S.A. - Micro-Mega export, Geneva, Switzerland.
c. Kerr Europe, Herts, UK.
d. Lightspeed Technology Inc., San Antonio, TX, USA.
e. NT Co., Chattanooga, TN, USA.
f. JS Dental Manufacturing Inc., Ridgefield, CT, USA.
g. Brasseler USA, Savannah, GA, USA.

h. Analytic Endodontics, Glendora, CA, USA / Tycom, Irvine, CA, USA.
i. Union Broach, Philadelphia, PA, USA.
j. J. Morita Co., Kyoto, Japan.

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References

1. Craig RG, McIlwain ED, Peyton FA. Bending and torsion properties of endodontic instruments. *Oral Surg Oral Med Oral Pathol* 1968; 25: 239-254.
2. Park H, Yoon S. A study on the stress of files and canal transportation in a curved canal. *J Endod* 1998; 24: 293.
3. Abou-Rass M, Frank AL, Glick DH. The anticurvature filing method to prepare the curved root canal. *J Am Dent Assoc* 1980; 101: 792-794.
4. Alodeh MHA, Doller R, Dummer PMH. Shaping of simulated root canals in resin blocks using the step-back technique with K-files manipulated in a simple in/out motion. *Int Endod J* 1989; 22: 107-117.
5. Weine FS, Kelly RF, Lio PS. The effect of preparation procedures on original canal shape and apical foramen shape. *J Endod* 1975; 1: 255-262.
6. Mizrahi SJ, Tucker JW, Seltzer S. A scanning electron microscopy study of the efficacy of various endodontic instruments. *J Endod* 1975; 1: 334-337.
7. Walton RE. Histologic evaluation of different methods of enlarging the pulp canal space. *J Endod* 1976; 2: 304-311.
8. Eldeeb ME, Boraas JC. The effect of different files on the preparation shape of severely curved canals. *Int Endod J* 1985; 18: 1-7.
9. Lim KC, Webber J. The effect of root canal preparation on the shape of the curved root canal. *Int Endod J* 1985; 18: 233-239.
10. Calhoun G, Montgomery S. The effect of four instrumentation techniques on root canal shape. *J Endod* 1988; 14: 273-277.
11. Cimis GM, Boyer TJ, Pelleu GB. Effect of three file types on the apical preparations of moderately curved canals. *J Endod* 1988; 14: 441-444.
12. Alodeh MHA, Dummer PMH. A comparison of the ability of K-files and Hedström files to shape simulated root canals in resin blocks. *Int Endod J* 1989; 22: 226-235.
13. Sepic A, Pantedra E, Neaverth E, *et al*. A comparison of Flex-R files and K-type files for enlargement of severely curved molar root canals. *J Endod* 1989; 15: 240-245.
14. Ciucchi B, Cergneux M, Holtz J. Comparison of curved canal shape using filing and rotational instrumentation techniques. *Int Endod J* 1990; 23: 139-147.
15. Briseño BM, Sonnabend E. The influence of different root canal instruments on root canal preparation; An *in-vitro* study. *Int Endod J* 1991; 23: 15-23.
16. Al-Omari MAO, Dummer PMH, Newcombe RG, *et al.* Comparison of six files to prepare simulated root canals. Part 1. *Int Endod J* 1992a; 25: 57-66.
17. Al-Omari MAO, Dummer PMH, Newcombe RG, *et al.* Comparison of six files to prepare simulated root canals. Part 2. *Int Endod J* 1992b; 25: 67-81.
18. Roig-Cayón M, Brau-Aguade E, Canalda-Sahli C, *et al.* A comparison of molar root canal preparations using Flexofile, Canal Master U and Heliapical instruments. *J Endod* 1994; 20: 495-499.
19. Schäfer E, Tepel J, Hoppe W. Properties of endodontic hand instruments used in rotary motion. Part 2. Instrumentation of curved canals. *J Endod* 1995; 21: 493-497.
20. Luiten DJ, Morgan LA, Baumgartner JC, *et al.* A comparison of four instrumentation techniques on apical canal transportation. *J Endod* 1995; 21: 26-32.
21. Walia H, Brantley WA, Gernstein H. An initial investigation of the bending and tortional properties of nitinol root canal files. *J Endod* 1988; 14: 346-351.
22. Serene TP, Adams JD, Saxena A. *Nickel-titanium instruments - applications in endodontics*. St. Louis: Ishiyaku Euro-America, Inc., 1994.
23. Tepel J, Schafer E, Hoppe W. Properties of endodontic hand instruments used in rotary motion. Part 3. Resistance to bending and fracture. *J Endod* 1997; 23: 141-145.
24. Schäfer E. Root canal instruments for manual use: A review. *Endod Dent Traumatol* 1997; 13: 51-64.
25. Roane JB, Sabala CL, Ducanson MG. The “balanced force” concept for instrumentation of curved canals. *J Endod* 1985; 11: 203-211.
26. Ehrlich D, Boyer TJ, Hicks L, *et al.* Effects of sonic instrumentation on the apical preparation of curved canals. *J Endod* 1989; 15: 200-203.
27. Glosson CR, Haller RH, Dove SB, *et al.* A comparison of root canal preparation using NiTi hand, NiTi engine-driven, and K-Flex endodontic instruments. *J Endod* 1995; 21: 146-151.
28. Tharuni SD, Parameswaran A, Sukumaran VG. A comparison of canal preparation using the K-File and Lightspeed in resin blocks. *J Endod* 1996; 22: 474-476.
29. Knowles KI, Ibarrola JL, Christiansen RK. Assessing apical deformation and transportation following the use of LightSpeed root-canal instruments. *Int Endod J* 1996; 29: 113-117.
30. Patel S, Ng YL, Gilthorpe M, *et al*. The effect of multiple canal curvatures on the preparation of root canal systems using rotary nickel-titanium instruments. *The 9th Biennial Congress of the ESE* 1999 (Abstr A7).
31. McSpadden JT. *Rationales for rotary nickel-titanium instruments*. Chattanooga, TN: NT Co, 1994.
32. Portenier I, Lutz F, Barbakow F. Preparation of the apical part of the root canal by the Lightspeed and step-back techniques. *Int Endod J* 1998; 31: 103-111.
33. Esposito PT, Cunningham CJ. A comparison of canal preparation with nickel-titanium and stainless steel instruments. *J Endod* 1995; 21: 173-176.
34. Short JA, Morgan LA, Baumgartner JC. A comparison of canal centring ability of four instrumentation techniques. *J Endod* 1997; 23: 503-507.
35. Colombo M, Gagliani M, Rossetti S. Shaping ability of two engine-driven Nickel-Titanium instruments in extracted molar roots. *The 9th Biennial Congress of the ESE* 1999 (Abstr A9).
36. O’Connell D, Brayton S. Evaluation of root canal preparations with two automatic endodontic handpieces. *Oral Surg Oral Med Oral Pathol* 1975; 39: 298-303.
37. Weine FS, Kelly RF, Bray KE. Effect of preparation with endodontic handpieces on original canal shape. *J Endod* 1976; 2: 298-303.
38. Campos JL, del Rio CE. Comparison of mechanical and standard hand instrumentation techniques in curved root canals. *J Endod* 1990; 16: 230-234.
39. Hülsmann M, Stryga F. Comparison of root canal preparation using different devices and hand instrumentation. *J Endod* 1993; 19: 141-145.
40. Poulsen WB, Dove SB, del Rio CE. Effect of Nickel-titanium engine-driven instrument rotational speed on root canal morphology. *J Endod* 1995; 21: 609-612.
41. Thompson SA, Dummer PMH. Shaping ability of ProFile .04 Taper Series 29 rotary nickel-titanium instruments in simulated root canals. Part 2. *Int Endod J* 1997b; 30: 8-15.
42. Thompson SA, Dummer PMH. Shaping ability of Lightspeed rotary nickel-titanium instruments in simulated root canals. Part 2. *Int Endod J* 1997d; 23: 742-747.
43. Thompson SA, Dummer PMH. Shaping ability of NT Engine and McXim rotary nickel-titanium instruments in simulated root canals. Part 2. *Int Endod J* 1997f; 30: 270-278.
44. Thompson SA, Dummer PMH. Shaping ability of Mity Roto 360 degrees and Naviflex rotary nickel-titanium instruments in simulated root canals. Part 2. *Int Endod J* 1998b; 24: 135-142.
45. Thompson SA, Dummer PMH. Shaping ability of Quantec Series 2000 rotary nickel-titanium instruments in simulated root canals. Part 2. *Int Endod J* 1998d; 31: 268-274.
46. Hülsmann M, Versümer J, Schade M. A comparative study of Lightspeed, ProFile 0.04, Quantec and Hero 642. *The 9th Biennial Congress of the ESE* 1999 (Abstr F1).
47. Ingle JI. A standardized endodontic technique using newly designed instruments and filling materials. *Oral Surg Oral Med Oral Pathol* 1961; 14: 83-91.
48. Schilder H. Cleaning and shaping the root canal. *Dent Clin North Am* 1974; 18: 269-296.
49. Weine FS. *Endodic therapy*, 3rd ed. St. Louis: CV Mosby, 1982; 256-340.
50. Cohen S, Burns RC. *Pathways of the pulp*, 3rd ed. St. Louis: CV Mosby, 1984; 181-201.
51. Rubin LM, Skobe Z, Krakow AA, *et al*. The effect of instrumentation and flushing of freshly extracted teeth in endodontic therapy: A scanning electron microscope study. *J Endod* 1979; 5: 328-335.
52. Musikant BL, Cohen BI, Deutsch AS. Simplified obturation of tapered canal preparations. *Compend Contin Educ Dent* 1998; 19: 1152-1155.
53. Serene TP, Adams JD, Saxena A. *Nickel titanium instruments- Applications in endodontics.* St. Louis, MO: Ishiyaku Euro-America Inc., 1995.
54. Villalobos R, Moser JB, Heuer MA. A method to determine the cutting efficiency of root canal instruments in rotary motion. *J Endod* 1980; 6: 667-672.
55. Felt RA, Moser JB, Heuer MA. Flute design of endodontic instruments: Its influence on cutting efficiency. *J Endod* 1982; 8: 253-259.

56. Miserendino LJ, Moser JB, Heuer MA, *et al*. Cutting efficiency of endodontic instruments. Part 1. A quantitative comparison of the tip and fluted regions. *J Endod* 1985; 11: 435-441.
57. Powell SE, Simon JH, Maxe BB. A comparison of the effect of modified and nonmodified instrument tips on apical canal configuration. *J Endod* 1986; 12: 293-300.
58. Griffiths I, Bryant ST, Dummer PMH. A study of simulated canal shapes produced by Quantec LX instruments at predetermined stages. *The 9th Biennial Congress of the ESE* 1999 (Abstr F2).
59. Bryant ST, Thompson SA, Al-Omari MAO, *et al*. Shaping ability of ProFile rotary nickel-titanium instruments with ISO sized tips in simulated root canals. Part 1. *Int Endod J* 1998a; 31: 275-281.
60. Bryant ST, Thompson SA, Al-Omari MAO, *et al*. Shaping ability of ProFile rotary nickel-titanium instruments with ISO sized tips in simulated root canals. Part 2. *Int Endod J* 1998b; 31: 282-289.
61. Bryant ST, Dummer PMH, Pitoni C, *et al*. Shaping ability of .04 and .06 taper ProFile rotary nickel-titanium instruments in simulated root canals. *Int Endod J* 1999; 32: 155-164.
62. Wildley WL, Senia ES. A new root canal instrument and instrumentation technique: A preliminary report. *Oral Surg Oral Med Oral Pathol* 1989; 67: 198-207.
63. Gilles JA, del Rio CE. A comparison of the Canal Master endodontic instrument and K-type files for enlargement of curved root canals. *J Endod* 1990; 16: 561-565.
64. Leseberg DA, Montgomery S. The effects of Canal Master, Flex-R, and K-flex instruments on root canal configuration. *J Endod* 1991; 17: 59-65.
65. Zuolo ML, Walton RE, Murgel CA. Canal Master files: Scanning electron microscopic evaluation of new instruments and their wear with clinical usage. *J Endod* 1992; 18: 336-339.
66. Massa GR, Nicholls JL, Harrington GW. Torsional properties of the Canal Master instrument. *J Endodon* 1992; 18: 222-227.
67. Mounce RE, Nakamuta H, Lovejoy C. Canal Master instrumentation: An *in vitro* study of separation frequency. *J Endod* 1993; 19: 1-3.
68. Zuolo ML, Walton RE. Instrument deterioration with usage: Nickel-titanium *versus* stainless steel. *Quintessence Int* 1997; 28: 397-402.
69. Marsicovetere ES, Burgess JO, Clement DJ, *et al.* Torsional tesing of the Lightspeed nickel-titanium instrument system. *J Endod* 1996; 22: 681-684.
70. Schrader C, Sener B, Barbakow F. Evaluating the sizes of Lightspeed instruments. *Int Endod J* 1998; 31: 295-300.
71. Abou-Rass M, Jastrab RJ. The use of rotary instruments as auxiliary aids to root canal preparation of molars. *J Endod* 1982; 8: 78-82.
72. Leeb J. Canal orifice enlargement as related to biomechanical preparation. *J Endod* 1983; 9: 463-470.
73. Kavanagh D, Lumley PJ. An *in vitro* evaluation of canal preparation using .04 and .06 taper instruments. *Endod Dent Traumatol* 1998; 14: 16-20.
74. Isom TL, Marshall JG, Baumgartner JC. Evaluation of root thickness in curved canals after flaring. *J Endod* 1995; 21: 368-371.
75. Vessey RA. The effect of filing *versus* reaming on the shape of the prepared root canal. *Oral Surg Oral Med oral Pathol* 1969; 27: 543-547.
76. Jungmann CL, Uchin RA, Bucher JF. Effect of instrumentation on the shape of the root canal. *J Endod* 1975; 1: 66-69.
77. Gambill JM, Alder M, del Rio CE. Comparison of nickel-titanium and stainless steel hand-file instrumentation using computed tomography. *J Endod* 1996; 22: 369-375.
78. Roig-Cayón M, Basilio-Monné J, Abós-Herrándiz R, *et al.* A comparison of molar root canal preparations using six instruments and instrumentation techniques. *J Endod* 1997; 23: 383-386.
79. Tucker DM, Wenckus CS, Bentkover SK. Canal wall planning by engine-driven Nickel-titanium instruments, compared with stainless steel hand instrumentation. *J Endod* 1997; 23: 170-173.
80. Haga CS. Microscopic measurements of root canal preparations following instrumentation. *J Br Endod Soc* 1968; 2: 41-46.
81. Reddy SA, Hicks ML. Apical extrusion of debris using two hand and two rotary instrumentation techniques. *J Endod* 1998; 24: 180-183.
82. Beeson TJ, Hartwell GR, Thornton JD, *et al*. Comparison of debris extruded apically in straight canals: Conventional filing *versus* ProFile .04 taper series 29. *J Endod* 1998; 24: 18-22.
83. Lee DH, Park B, Saxena A, *et al*. Enhanced surface hardness by boron implantation in Nitinol alloy. *J Endod* 1996; 22: 543-549.
84. Rapisarda E, Tripi TR, Bonaccorso A. Enhanced surface hardness by ion implantation and thermal nitridation in Nitinol alloy. *The 9th Biennial Congress of the ESE* 1999b, (Abstr A13).
85. Rapisarda E, Bonaccorso A, Tripi TR, *et al*. Effect of sterilization on the cutting efficiency of rotary nickel-titanium endodontic files. *Oral Surg Oral Med Oral Pathol* 1999a; 88: 343-347.
86. Haikel Y, Serfaty R, Wilson P, *et al*. Cutting efficiency of nickel-titanium endodontic instruments and the effect of sodium hypochlorite treatment. *J Endod* 1998b; 24: 736-739.
87. Pellini A, Cantatore G. The production of endodontic smear layer as a possible cause of Nickel-titanium instrument separation. *The 9th Biennial Congress of the ESE* 1999 (Abstr 9).
88. Dalton BC, Orstavik D, Phillips C, *et al*. Bacterial reduction with the nickel-titanium rotary instrumentation. *J Endod* 1998; 24: 763-767.
89. Bechelli C, Orlandini SZ, Colafranceschi M. Scanning electron microscope study on the efficacy of root canal wall debridement of hand *versus* Lightspeed instrumentation. *Int Endod J* 1999; 32: 484-493.
90. Bertrand MF, Pizzardini P, Muller M, *et al*. The removal of the smear layer using the Quantec system. A study using the scanning electron microscope. *Int Endod J* 1999; 32: 217-224.
91. Laszkiewicz JM, Gambarini G. Canal debridement with GT rotary files: SEM study. *The 9th Biennial Congress of the ESE* 1999 (Abstr A10).
92. Dieter GE. *Mechanical metallurgy*, 3rd ed. New York: McGraw-Hill, 1986; 119,138, 185-188, 382-387, 394.
93. Cohen S, Burns RC. *Pathways of the pulp*, 6th ed. St. Louis: CV Mosby, 1994; 206.
94. Zuolo ML, Walton RE. Instrument deterioration with usage: Nickel-titanium *versus* stainless steel. *Quintessence Int* 1995; 28: 397-402.
95. Sotokawa T. An analysis of clinical breakage of root canal instruments. *J Endod* 1988;14: 75-82.
96. Pruett JP, Clement DJ, Carnes DL. Cyclic fatigue testing of nickel-titanium endodontic instruments. *J Endod* 1997; 23: 77-85.
97. Crandall SH, Dahl NC, Lardner TJ. *An introduction to the mechanics of solids*, 2nd ed. New York: McGraw-Hill, 1972; 416-477.
98. Yared GM, Bou Dagher FE, Machtou P. Cycle fatigue of Profile rotary instruments after simulated clinical use. *Int Endod J* 1999; 32: 115-119.
99. Blum JY, Machtou P, Micallef JP. Analysis of forces developed during preparations: Balanced force concept. *Int Endod J* 1998; 30: 386-396.
100. Blum JY, Cohen A, Machtou P, *et al*. Analysis of forces developed during mechanical preparation of extracted teeth using ProFile NiTi rotary instruments. *Int Endod J* 1999b; 32: 24-31.
101. Blum JY, Machtou P, Micallef JP. Location of contact areas on rotary ProFile instruments in relationship to the forces developed during mechanical preparation on extracted teeth. *Int Endod J* 1999a; 32: 108-114.
102. Salomon MR, Soler-Bientz R, de la Garza-González R, *et al.* Incidence of Lightspeed separation and the potential for bypassing. *J Endod* 1997;23:586-587.
103. Camps J, Wilhelm JP. Torsional stiffness properties of Canal Master U stainless steel and Nitinol instruments. *J Endod* 1994; 20:395-398.
104. Seto B, Nicholls Jl, Harrington GW. Torsional properties of twisted and machined endodontic files. *J Endod* 1990; 16: 355-360.
105. Mandel E, Abid-Yazdi M, Benhamou LM, *et al*. Rotary NiTi profile systems for preparing curved canals in resin blocks: Influence of operator on instrument breakage. *Int Endod J* 1999; 32: 436-443.
106. Swindle RB, Neaverth EJ, Pantera EA, *et al*. Effect of coronal-radicular flaring on apical transportation. *J Endod* 1991; 17: 147-149.
107. Rowan MB, Nicholls JI, Steiner J. Torsional properties of stainless steel and nickel-titanium endodontic files. *J Endod* 1996; 22: 341-345.
108. Dederich DN, Zakariasen KL. The effects of cyclical axial motion on rotary endodontic instrument fatigue. *Oral Surg Oral Med Oral Pathol* 1986; 61: 192-196.
109. Silvaggio J, Hicks ML. Effect of heat sterilization on the torsional properties of rotary nickel-titanium endodontic files. *J Endod* 1997; 23: 731-734.
110. Mize SB, Clement DJ, Pruett JP, *et al*. Effect of sterilization on cyclic fatigue of rotary nickel-titanium endodontic instruments. *J Endod* 1998; 24: 843-847.
111. Kazemi RB, Stenman E, Spangberg LSW. The endodontic file is a disposable instrument. *J Endod* 1995; 21: 451-455.
112. Wolcott J, Himel VT. Torsional properties of nickel-titanium *versus* stainless steel endodontic files. *J Endod* 1997; 23:217-220.
113 Cohen S, Burns RC. *Pathways of the Pulp*, 7th ed. St. Louis: CV Mosby, 1998.
114. Thompson SA, Dummer PMH. Shaping ability of ProFile .04 Taper Series 29 rotary nickel-titanium instruments in simulated root canals. Part 1. *Int Endod J* 1997a; 30: 1-7.
115. Thompson SA, Dummer PMH. Shaping ability of Lightspeed rotary nickel-titanium instruments in simulated root canals. Part 1. *Int Endod J* 1997c; 23: 698-702.
116. Thompson SA, Dummer PMH. Shaping ability of NT Engine and McXim rotary nickel-titanium instruments in simulated root canals. Part 1. *Int Endod J* 1997e; 30: 262-269.

117. Thompson SA, Dummer PMH. Shaping ability of Mity Roto 360° and Naviflex rotary nickel-titanium instruments in simulated root canals. Part 1. *Int Endod J* 1998a; 24: 128-134.
118. Thompson SA, Dummer PMH. Shaping ability of Quantec Series 2000 rotary nickel-titanium instruments in simulated root canals. Part 1. *Int Endod J* 1998c; 31: 259-267.
119. Kobayashi C, Yoshioka T, Suda H. A new engine-driven canal preparation system with electronic canal measuring capability. *J Endod* 1997; 23: 751-754.
120. Campbell D, Friedman S, Nguyen HQ, *et al*. Apical extent of rotary canal instrumentation with an apex-locating handpiece *in vitro*. *Oral Surg Oral Med Oral Pathol* 1998; 85: 319-324.
121. Haikel Y, Serfaty R, Wilson P, *et al*. Mechanical properties of nickel-titanium endodontic instruments and the effect of sodium hypochlorite treatment. *J Endod* 1998a; 24: 731-735.
122. Busslinger A, Sener B, Barbakow F. Effects of sodium hypochlorite on nickel-titanium Lightspeed instruments. *Int Endod J* 1998; 31: 290-294.
123. Marending M, Lutz F, Barbakow F. Scanning electron microscope appearances of Lightspeed instruments used clinically: A pilot study. *Int Endod J* 1998; 31: 57-62.
124. Mullaney TP. Instrumentation of finely curved canals. *Dent Clin North Am* 1979; 23: 575-592.
125. Goerig AC, Michelich RJ, Schultz HH. Instrumentation of root canals in molars using the step-down technique. *J Endod* 1982; 8: 550-554.
126. Morgan LF, Montgomery S. An evaluation of the crown-down pressureless technique. *J Endod* 1984; 10: 491-498.
127. Fava RG. The double-flared technique: An alternative for biomechanical preparation. *J Endod* 1983; 9: 76-80.
128. Marshall FJ, Pappin J. A crown-down pressureless preparation root canal enlargement technique. *Technique manual*, 1988. Portland: University of Oregon Health Sciences University.
129. Schilder H, Yee F. Canal debridement and disinfection. *Pathways of the pulp*, 3rd ed. St. Louis: CV Mosby, 1984, 175-204.
130. Kerekes K, Tronstad L. Morphometric observations on root canals of human teeth. J *Endod* 1977; 3: 114-118.
131. Miyashita M, Kasahara E, Yasuda E, *et al*. Root canal system of the mandibular incisor. *J Endod* 1997; 23: 479-484.
132. Weine SW. *Endodontic therapy*, 4th ed. St. Louis: CV Mosby, 1989, 303.
133. Wu MK, Wesselink PR. Efficacy of three techniques in cleaning the apical portion of curved root canals. *Oral Surg Oral Med Oral Pathol* 1995; 79: 492-496.
134. Bergmans L, Van Cleynenbreugel J, Wevers M, *et al*. A methodology for quantitative evaluation of root canal instrumentation using microcomputed tomography. *Int Endod J* 2001 *(In press)*.