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NITI TECHNOLOGY HAS REVOLUTIONISED ENDODONTIC THERAPY WITH NEWER THERMOMECHANICALLY TREATED NITI ALLOYS: A LITERATURE REVIEW

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ABSTRACT

Over the past two decades, the nickel–titanium (NiTi) rotary instruments have highly improved the quality of the cleaning and shaping of the root canals. The superelasticity and shape memory of these instruments reduce the possibility of the canal transportation along with saving the time for both the patients and the clinicians. Several commercial types of these instruments, produced by different manufacturers, have currently become available by modifying the characteristics of the wonder NiTi alloy and also the cross-sectional shapes, cutting edges, tapering and numbers and distances of the flutes of the instruments. Up to this date, five generations for NiTi rotary instruments have been described according to the time of introduction, properties, and method of application.

KEYWORDS: NiTi alloy technology, Thermomechanically treated NiTi alloys, rotary file systems.

INTRODUCTION

Root canal instrumentation is accomplished by the use of endodontic instruments and irrigating solutions under aseptic working conditions. Root canal instrumentation may be carried out using hand-held or engine-driven (rotary) instruments. It was in late 1988 that Walia *et al.*[1] introduced the magic properties of a corrosion resistant alloy to the manufacturers for making the nickel–titanium (NiTi) rotary instruments. Stainless steel instruments inherent stiffness that increases as the size of the instruments increases. Nickel-Titanium (NiTi) endodontic instruments were found to be more flexible with an increased torsional fracture resistance when compared to stainless steel instruments. Though, fracture of rotary NiTi instruments remained an inadvertent incident during clinical use[2]. Beside variations in the design of NiTi instruments, NiTi rotary instruments have undergone revolutionary changes as manufacturers introduced several proprietary manufacturing procedures including thermal, mechanical and surface treatment to improve the mechanical properties of NiTi alloys, in order to produce instruments with enhanced resistance to fracture and increased flexibility. while preparing curved root canals using simple hand instruments, some degrees of canal transportation may happen which may also end to ledge formation and zipping perforation, and canal transportation if proper precurving the higher sizes of the instruments and also the recapitulation and copious irrigation of the curved canals is overlooked by the clinician. Precurving the stainless-steel hand instruments inhibits them to have rotational motions inside the curved root canals, meanwhile the elasticity and flexibility of the NiTi rotary files eliminate the iatrogenic errors and Endo mishaps which may happen following improper use of the stainless-steel hand Endo files in curved root canals.

This article presents an over view on the mechanical properties, fracture of NiTi endodontic instruments, five generations of NiTi rotary instruments since their inception and evolution of NiTi alloy treatment.

Metallurgy and Mechanical properties of nickel-titanium

NiTi alloy used in endodontic instruments contain approximately 56 wt% nickel and 44 wt% titanium resulting in a nearly one-to-one atomic ratio (equiatomic). This equiatomic NiTi alloy can exist in two different temperature-dependent crystal structures named austenite (high-temperature or parent phase, with a body centered cubic crystal structure) and martensite phase (low-temperature phase, with a monoclinic crystal structure) and possesses typical characteristics which are superelasticity (SE) and shape memory effect (SME).[3]

These properties occur as a result of the austenite to martensite transition (martensitic transformation), which can be induced by stress or temperature (Fig. 1). Under certain conditions rhombohedrally distorted phase (R-phase) may appear prior to the transformation to martensite. This R-phase transformation is established as a martensitic transformation itself that competes with the subsequent martensitic transformation. The stress occurring during this cubic (austenite) to rhombohedrally (R-phase) respectively monoclinic (martensite) lattice transformation is released by twinning of the new phase structure (twinned R-phase or martensite). Martensite exhibits a lower elastic modulus (about 30-40 GPa) than austenite (about 80-90 GPa) and the elastic modulus of the R-phase is even lower than that of martensite.[4]

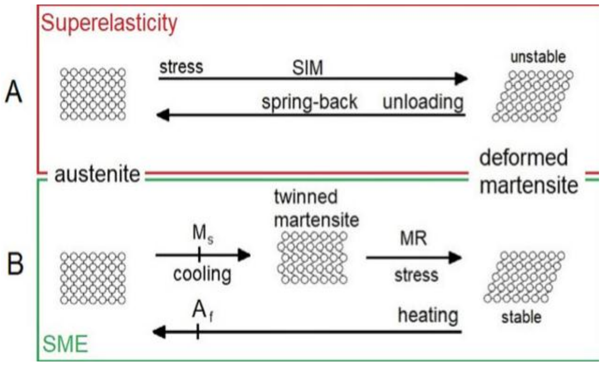

Figure 1: Martensitic transformations. (A) Superelasticity (SE) at ambient temperature above austenite finish temperature (Af). (B) Shape memory effect (SME). For the martensite reorientation (MR) less stress is required than for stress-induced martensite (SIM) transformation. (Ms = martensite start temperature).

The phase composition and consequently the mechanical properties of NiTi alloy are dependent on the ambient temperature and whether the alloy is cooled or heated to this temperature (Fig. 2). If the temperature is above austenite finish temperature (Af), the alloy is in austenitic state, i.e., it is stiff, hard, and possesses superior superelastic properties. If the temperature is below martensite finish temperature (Mf), the NiTi alloy is in martensitic state, i.e., it is soft, ductile, can easily be deformed, and possesses the shape memory effect. Because of the reorientation capacity of the twinned phase structure, martensite has a superior cyclic fatigue resistance compared to austenite.[3]

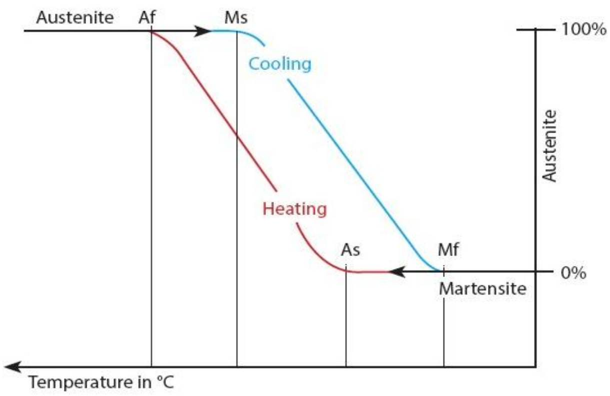

Figure 2: Temperature hysteresis diagram of NiTi alloy. (Ms) martensite start temperature, (Mf) martensite finish temperature, (As) austenite start temperature, (Af) austenite finish temperature.

Fracture of NiTi endodontic instruments

In spite of the advanced flexibility of NiTi alloy compared to stainless steel, fracture of NiTi endodontic instruments remains a problem in clinical practice. Fracture of rotary NiTi instruments occurs in different ways: due to torsional failure or due to cyclic fatigue. The total cyclic life of NiTi endodontic instruments can be divided into two stages: Starting with crack initiation in which microcracks form and start to grow preferentially along specific crystallographic planes or grain boundaries followed by crack propagation until final fracture. Cyclic fatigue resistance is usually measured by the time until fracture occurs or by the number of cycles to fracture (NCF). Fracture due to torsion occurs when the tip or another part of the instrument binds within the canal whilst the handpiece keeps turning resulting in the elastic limit of the NiTi endodontic instrument being exceeded.[5] It is important to mention that torsional stress occurs during every cutting action in the canal. Torsional tests of endodontic instruments are carried out by measuring the maximum torque and angle of rotation during fracture.

Numerous studies have examined the resistance to fracture of NiTi files. Beside variations in the experimental design, and testing model, many studies have not considered the intracanal temperature, even though a change in environmental temperature profoundly affects the mechanical properties of NiTi endodontic instruments. Recently it was shown, that increasing the environmental temperature from room to intracanal temperature significantly decreases cyclic fatigue resistance.[6] It is important to mention that in addition to the used alloy the mechanical properties of endodontic instruments are affected by the design and diameter of the instruments as well as the working motion (rotary or reciprocation). The maximum torque increases with greater instrument diameter, while flexibility decreases. Cyclic fatigue resistance decreases as the maximum tensile strain amplitude on the surface of the instruments increases, which occurs at the maximum bending point during shaping of a curved root canal. Because the tensile strain amplitude on the surface of an instrument increases with diameter, small instruments with little taper have increased cyclic fatigue resistance compared to large and greater tapered instruments.[7] Reciprocal motion revealed an enhanced cyclic fatigue resistance compared to rotary motion.[8]

DESIGN FEATURES OF EACH FILE GENERATION

Walia et al. used nitinol orthodontic wire to fabricate intracanal files, size 15.[1] These files had two to three times the elastic flexibility in bending and torsion, as well as superior resistance to torsional fracturing when compared to similar stainless-steel instruments. The first commercially available NiTi rotary files came to market by 1990's. Most NiTi rotary files have rounded non-cutting tips that serve as a guide in the canal.[3] Rather than identify the myriad of cross-sections available, files will be characterized as having either a passive or an active cutting action.

Instrument/Manufacturer (Year)	Application/Kinematics	Cross-section/Special Features	Diameter/Taper	Manufacturing/Treatment
Race/FKG (1999)	Shaping/Rotary centric	Triangular with alternating cutting edges along the instrument		Micromilling, Electropolishing
IRace (2011)			10–60	
BioRace (2012)			.02, .04, .06	
Series ISO 10 (2010)	Glide path/Rotary centric	Quadrangular	10 .02, .04, .06	
Scout Race (2014)	Glide path/Rotary centric	Quadrangular	10, 15, 20 .02	
BT Race (2014)	Shaping/Rotary centric	Triangular with alternating cutting edges along the instrument	BT1 – 10.06 BT2 – 35.00 BT3 – 35.04 BT4 – 40.04 BT5 – 40.04	
K3/Sybron Endo (2001)	Shaping/Rotary centric	Triple-fluted, Positive rake angle with asymmetric radial lands	15–60	Micromilling
K3XF (2011)			.04, .06	Micromilling, R-Phase
Mtwo/VDW (2003)	Shaping/Rotary centric	S-shaped with two active cutting edges	10–60 .04, .05, .06, .07	Micromilling
ProTaper Universal/Dentsply-Sirona (2006)	Shaping/Rotary centric	Convex triangular	Regressive taper 17–50	Micromilling
ProTaper Gold (2013)		Variable and progressive tapers along the instrument		Micromilling, post-manufacture heat treatment
ProTaper Next (2013)	Shaping/Rotary centric	Rectangular eccentric	Variable taper 17-50 .04, .06, .07	Micromilling, Pre-manufacture heat treatment: M-wire
Twisted File/Sybron Endo (2008)	Shaping/Rotary centric	Triangular	10–40 .04, .06, .08, .10, .12	Twisted under heat, R-Phase, Electropolished
Twisted File Adaptive (2013)	Shaping/Adaptive	Triangular	SM – *small* 25/.04, 25/.06, 35/.04 ML – *medium large* 25/.08, 30/.06, 50/.04	
EndoSequence/Brassler (2009)	Shaping/Rotary centric	Triangular, with alternating contact points along the instrument	15–60 .04 e .06	Micromilling, Electropolished
Profile Vortex/Dentsply Sirona (2009)	Shaping/Rotary centric	Convex triangular	15–50 .04, .06.	Micromilling, Pre-manufacture heat treatment: M-wire
Vortex Blue (2012)				Micromilling, pre and postmanufacture hea treatment:Blue
SAF/ReDent (2010)	Shaping/Vertical vibration	Hollow	1.5 mm 2.0 mm	Laser cutting
Hyflex CM/Coltene (2011)	Shaping/Rotary centric	Double fluted Hedström design with positive rake ange	15–40	Micromilling, Post-manufacture heat treatment: CM
Hyflex EDM (2016)			.04, .06, .08	Electrodischarge Machining, post-manufacture heat-treatment: CM-EDM
Reciproc/VDW (2011)	Shaping/Reciprocating	"S-shaped" Single File technique	Variable taper R25 (25/0.08) R40 (40/0.06) R50 (50/0.05)	Micromilling, pre-manufacture heat-treatment: M-wire
Reciproc Blue (2016)				Micromilling, pre and postmanufacture hea-treatment: Blue
R-Pilot (2017)	Glide oath/Reciprocating	S-shaped	Variable taper 12.5/0.04	Micromilling, pre and postmanufacture hea treatment: Blue
Pathfile/Dentsply-Sirona (2011)	Glide-path/Rotary centric	Quadrangular	13, 16, 19 .02	Micromilling
Typhoon/Clinician's Choice (2011)	Shaping/Rotary centric	Convex triangular	20 – 35 .04, .06	Micromilling, pre and postmanufacture hea treatment: CM
Wave One/Dentsply-Sirona (2011)	Shaping/Reciprocating	Modified convex triangular (apical) Convex triangular (coronal)	Variable taper Small (21/0.06) Primary (25/0.08) Large (40/0.08)	Micromilling, pre-manufacture heat-treatment: M-wire
Wave One Gold (2015)		Paralleogram	Variable taper Small (20/.07) Primary (25/.07) Medium (35/.06) Large (45/.05)	Micromilling, post-manufacture heat treatment
Wave One Glider (2017)	Glide path/Reciprocating		Variable taper 15/.02	
Proglider/Dentsply-Sirona (2014)	Glide-path/Rotary centric	Quadrangular	Variable Taper 16/.02	Micromilling, pre-manufacture heat-treatment: M-wire
ProDesign Logic/Easy (2014)	Shaping/Rotary centric	Triangular	25/50 .03, .05. 06	Micromilling, post-manufacture heat treatment: CM
ProDesign Logic Glide-Path/Easy (2014)	Glide-path/Rotary centric	Quadrangular	25-50 .01	
ProDesign R/Easy (2014)	Shaping/Reciprocating	Double Helix	Single File 25/.08	
TRUShape/Dentsply-Sirona (2015)	Shaping/Rotary eccentric	Triangular S-curve in the instrument's longitudinal axis	Variable regressive .06v. 20–40	Micomilling, Shape-setting, Heat-treatment
XP-endo Shaper/FKG Dentaire (2015)	Shaping/Rotary eccentric	Triangular Booster Tip	Single file 15 – 30 .01 - minimum .04	Micomilling, Shape-setting, Heat-treatment
Genius/Ultradent (2016)	Shaping/Rotary and reciprocating centric	S-shaped	25-50 .04	Micromilling, heat treatment
Sequence Rotary File/MK life (2017)	Shaping/Rotary Centric	Triangular	15 – 35 .04, .06	Micromilling, post-manufacture heat treatment
X1 Blue/MK life (2017)	Shaping/Reciprocating		Single file 20, 25, 40 .06	
Typhoon/Clinician's Choice (2011)	Shaping/Rotary tentric	Convex triangular	20 – 35 .04, .06	Micromilling, post-manufacture heat treatment: CM

* CM: Controlled-memory

Figure 3: Features of the main automated instrumentation systems in the current world panorama.

First-generation files

The first rotary 0.02 taper NiTi instrument was designed by Dr. John McSpadden and came to market in 1992. Although these instruments began to change how dentists viewed instrumentation, there were problems associated with file breakage. In 1994, Dr. Johnson introduced a line of files which became known as the ProFile 0.04 tapered series. Following soon after were the ProFile 0.06 tapers and the "Orifice Shapers." Their cross-sectional shapes were made by machining three equally spaced U-shaped grooves around the shaft of a tapered NiTi wire. For this "classical" design, an unground space remained next to each groove, providing the so-called "radial land" area. This flat area prevents the file from locking in the dentin, while cutting occurs through a passive planing action.

Dr. Johnson broke the paradigm of ISO 0.02 tapered files by making these more highly tapered files, and together with Dr. McSpadden, the two are generally regarded as the fathers of NiTi rotary files. Other rotary file lines came along soon afterwards, each with its purported advantages, such as the LightSpeed developed by Dr. Steve Senia and Dr. William Wildey, the Quantec developed by Dr. John McSpadden, and the Greater Taper files developed by Dr. Steve Buchanan. The design of the LightSpeed files (now also known as LS1) deserves special attention. LightSpeed was introduced as an instrument differing from all others because of its long, thin non-cutting shaft and short anterior cutting part. The same design principles apply to the recently developed LSX instrument that is manufactured not by milling but by stamping. The files are used for apical preparation and do not cut over most of the canal length because of the existence of a smooth small diameter shaft that also enhances the flexibility of the instrument.

Second-generation files

To appreciate the evolution of instruments, it is useful to know that all first-generation NiTi rotary files had passive cutting radial lands, fixed tapers over the length of their working parts, and required a considerable number of files to achieve preparation objectives. By the end of the 1990s, the next generation of NiTi rotary files came to market. The critical distinctions of this generation of instruments are that they have actively cutting edges without radial lands and fewer instruments are required to fully prepare a canal. The angle between the cutting blade and the longitudinal axis of the instrument is lower than in first-generation files, which greatly reduces the tendency for a screwing effect during use. This generation of NiTi files includes the ProTaper (Dentsply Tulsa) rotary files which, unlike all other passive or active NiTi cutting instruments, have multiple tapers of increasing and decreasing size on a single file. The ProTaper system is based on a unique concept and originally comprised just six instruments: three shaping files and three finishing files. The ProTaper Universal set is now complemented by two larger finishing files and a set designed for re-treatment procedures. The crosssection of finishing files F3, F4, and F5 is slightly relieved for increased flexibility.

The first-generation rotary systems had neutral or slightly negative rake angles. Several second-generation systems were designed with positive rake angles, which gave them greater cutting efficiency [e.g., K3 system (SybronEndo, Orange, CA) invented by Dr. McSpadden]. The most obvious difference between the Quantec and K3 models is the K3's unique cross-sectional design: a slightly positive rake angle for greater cutting efficiency, wide radial lands, and a peripheral blade relief for reduced friction. Unlike the Quantec, a two-flute file, the K3 features a third radial land to help prevent threading-in. In the lateral aspect, the K3 has a variable pitch and variable core diameter, which makes the file stronger close to its apical tip. To discourage taper lock and the resultant screw effect associated with both passive and active fixed tapered NiTi cutting instruments, EndoSequence (Brasseler, Savannah, GA, USA) and BioRaCe (FKG Dentaire, La Chaux-de-Fonds, Switzerland) provide files with alternating contact points.[9] Although this feature is intended to mitigate a taper lock, these files still have a fixed taper over their active portions. The BioRaCe instruments undergo a proprietary finishing treatment (electropolishing) after the traditional grinding process aimed at reducing the surface defects and improving the mechanical properties of the instruments.[10] It has been suggested that the surface condition of the NiTi instrument contributes to fatigue resistance because most fatigue failures nucleate from the surface, especially in the presence of high stress amplitude or surface defects. During this period, manufacturers began to focus on other methods to increase the resistance to file separation. Attempts to enhance the surface of NiTi instruments, resistance to cyclic fatigue, and cutting efficiency have resulted in a variety of strategies including ion implantation and electropolishing.[11]

Third-generation files

Improvements in NiTi metallurgy became the hallmark of what may be identified as the third generation of mechanical shaping files. Heat treatment (thermal processing) is one of the most fundamental approaches toward adjusting the transition temperatures of NiTi alloys[12] and affecting the fatigue resistance of NiTi endodontic files. Since 2007, several new thermomechanical processing and manufacturing technologies have been developed in order to optimize the microstructure of NiTi alloys. Recently, several new thermomechanically processed endodontic NiTi files such as the HyFlex CM (HyFlex; Coltene Whaledent, Cuyahoga Falls, OH), K3XF (SybronEndo, Orange, CA), ProFile GT Series X (GTX; Dentsply Tulsa Dental Specialties, Tulsa, OK), ProFile Vortex (Vortex) and Vortex Blue (Dentsply Tulsa), TYPHOON™ Infinite Flex NiTi (TYP CM; Clinician's Choice Dental Products, New Milford, CT), and Twisted Files (TFs; SybronEndo) have been introduced.

M-wire (SportsWire, Langley, OK) was introduced in 2007. It is produced by applying a series of heat treatments to NiTi wire blanks. M-wire instruments include Dentsply's ProFile GT Series X, ProFile Vortex, and Vortex Blue. The first commercially available endodontic rotary system using the new M-wire NiTi material was the GT Series X files. The design principles of GT files are mostly still present in the current incarnation of GTX instruments. The main differences are the use of M-wire for GTX, subtle changes in the longitudinal design, and a different approach to instrument usage, emphasizing the use of the no. 20/0.06 rotary. In 2009, the ProFile Vortex file was introduced by Dentsply Tulsa Dental. The major difference between the Vortex and the classical ProFile files lies in the non-landed cross-section of the Vortex files, whereas the tip sizes and tapers are similar in both files. Manufactured out of M-wire, the ProFile Vortex also has a varying helical angle to counteract the tendency of the non-landed files to thread into the root canal. Vortex Blue instruments, new NiTi rotary instruments made out of M-wire, show a unique "blue color" not seen in traditional superelastic (SE) NiTi instruments. The "blue-color" oxide surface layer of Vortex Blue files is a result of the proprietary manufacturing process (Fig. 1). The relatively hard titanium oxide surface layer on the Vortex Blue instrument may compensate for the loss of hardness compared with ProFile Vortex M-wire[13] by improving the cutting efficiency and wear resistance. CM Wire (DS Dental, Johnson City, TN) is a novel NiTi alloy with flexible properties that was introduced to endodontics in 2010.

CM NiTi files are manufactured using a special thermomechanical process that controls the memory of the material, making the files extremely flexible but without the shape memory of other NiTi files. Both the HyFlex and TYPHOON CM instruments are made out of CM Wire. They exhibit a lower percent by weight of nickel (52 Ni %wt) than the common 54.5–57 Ni %wt of the great majority of commercially available SE NiTi rotary instruments. HyFlex instruments have a triangular cross-sectional design. TYP CM files, introduced in 2011, feature a triangular cross-section and a 12-mm-long cutting flute. In 2008, SybronEndo presented the first fluted NiTi file manufactured by plastic deformation, a process similar to the twisting process that is used to produce the majority of stainless-steel K-files and reamers. According to the manufacturer, a thermal process allows twisting during a phase transformation into the so-called R-phase of NiTi. The instrument was first available with only no. 25 tip sizes in tapers 0.04 up to 0.12. However, instruments with tip sizes no. 30, 35, and 40 were recently added. The design of K3 instruments was recently updated by SybronEndo, and the system has been available under the name of K3XF since 2011. K3 and K3XF instruments are identical in shape and differ only in that K3XF instruments undergo post-machining heat treatment.[14] The manufacturer claims that K3XF has a third radial land and variable pitch, superior flexibility, and resistance to fatigue. Numerous micropores with various diameters can be seen on the surface of the instrument flute on K3XF instruments (Fig. 2). These small pores do not contribute to the failure, but serve as a local stress/strain discontinuity from which the crack nucleates.

Fourth-generation files

The greatest number of commercially available files that are utilized to shape root canals are manufactured out of NiTi and are mechanically driven in continuous rotation. However, 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. Currently, the M4 (SybronEndo), Endo-Eze AET (Ultradent), and Endo-Express (Essential Dental Systems) are examples of reciprocating systems that utilize small, equal 30° angles of CW/CCW rotation.

In 2008, Dr. Ghassan Yared identified the precise unequal CW/CCW angles that would enable a single reciprocating 25/0.08 ProTaper file to optimally shape virtually any canal (20). Although this specific reciprocation technique stimulated considerable interest, this ProTaper F2 file was never designed to be used in this manner. In 2011, both WaveOne (Dentsply Tulsa Dental Specialties and Dentsply Maillefer) and Reciproc (VDW) were launched as single-file shaping techniques. Both files are made out of M-wire. Innovation in reciprocation technology led to a fourth generation of instruments for shaping canals. Clinical experience and future studies will determine whether this generation of instruments and the related technology has fulfilled the promise of the long hoped-for single-file technique. WaveOne represents a convergence of the design features from the second and third generation of files, coupled with a reciprocating motor that drives any given file at unequal bidirectional angles. The CCW engaging angle is five times the CW disengaging angle and is designed to be less than the elastic limit of the file. Strategically, after three CCW and CW cutting cycles, the file will have rotated 360°, or one complete circle. This novel reciprocating movement allows a file to progress more readily, cut efficiently, and auger debris effectively out of the canal.[15]

The WaveOne technique is both a single-file and single-use concept. Strategically, only one file is generally utilized to fully shape virtually any given canal. However, there are three WaveOne files available to address a wide range of endodontic anatomy commonly encountered in practice. The three WaveOne instruments are termed Small (yellow 21/0.06), Primary (red 25/0.08), and Large (black 40/0.08). The Small 21/0.06

file has a fixed taper of 6% over its active portion. The Primary 25/0.08 and the Large 40/0.08 WaveOne files have fixed tapers of 8% from D1-D3, whereas from D4-D16, they have a unique progressively decreasing percentage tapered design. The design feature of the WaveOne files is that they have a reverse helix and two distinct cross-sections along the length of their active portions. From D1-D8, the WaveOne files have a modified convex triangular cross-section, whereas from D9-D16, these files have a convex triangular cross-section. The design of the two WaveOne cross-sections is further enhanced by a changing pitch and helical angle along their active portions. The WaveOne files have non-cutting modified guiding tips, which enable these files to safely progress through virtually any secured canal.[16]

Reciproc instruments have a short shaft of 11 mm, enabling better access to molars compared to many other instruments which have a shaft of 13 mm or longer. The design of the cross-section is S-shaped. The three Reciproc files have a regressive taper: R25 (25/0.08) for narrow canals; R40 (40/0.06) for medium canals, and R50 (50/0.05) for wide canals. The instruments are used at 10 cycles of reciprocation per second, the equivalent of approximately 300 rpm. The values of the CW and CCW rotations are different. When the instrument rotates in the cutting direction, it will advance in the canal and engage dentin. When it rotates in the opposite direction (smaller rotation), the instrument will immediately disengage. The end result, related to the degree of CW and CCW rotations, is an advancement of the instrument in the canal without the risk of a screwing effect.

The self-adjusting file (SAF; ReDent-Nova, Raanana, Israel) represents a new approach in file design and mode of operation.[17] The file is a hollow device, designed as a cylinder of thin-walled, delicate NiTi lattice with a lightly abrasive surface. Different from the traditional nickel–titanium (NiTi) rotary files, the SAF system uses a hollow reciprocating instrument that allows for simultaneous irrigation throughout the mechanical preparation. When inserted into the root canal, the manufacturer claims that the SAF is capable of adapting itself to the canal shape three-dimensionally.[18] The instrument is used in a transline (in-and-out) motion, and the abrasive surface of the lattice threads promotes a uniform removal of dentin.[17] An initial glide path is established with a #20 K-file to allow the insertion of the SAF file.[17]

Fifth-generation files

The fifth generation of shaping files has been designed such that the center of mass and/or the center of rotation are offset. In rotation, the files that have an offset design produce a mechanical wave of motion that travels along the active length of the file. Like the progressively percentage tapered design of any given ProTaper file, this offset design serves to further minimize the engagement between the file and dentin.[19] Commercial examples of file brands that offer variations of this technology are Revo-S, One Shape® (Micro-Mega®, Besançon, France), and ProTaper Next (PTN; Dentsply Tulsa Dental Specialties/ Dentsply Maillefer).

ProTaper Next is the successor to the ProTaper Universal system. There are five PTN files available, in different lengths, for shaping canals: X1 (17/0.04), X2 (25/0.06), X3 (30/0.07), X4 (40/0.06), and X5 (50/ 0.06). The tapers shown above indicate the taper of the tip region of each file and are not fixed over the active portion of any given PTN file. The PTN X1 and X2 files have both an increasing and decreasing percentage tapered design on a single file; whereas the PTN X3, X4, and X5 files have a fixed taper from D1-D3, then a decreasing percentage tapered design over the rest of their active portions. PTN files are the convergence of three significant design features, including various tapers on a single file, M-wire technology, and the fifth generation of continual improvement, the offset design. An offset design generates a traveling mechanical wave of motion along the active portion of a file. This swaggering effect serves to minimize the engagement between the file and dentin compared to the action of a fixed tapered file with a centered mass of rotation. Reduced engagement limits any undesirable taper lock, the screw effect, and the torque on any given file. An offset file design may also decrease the probability of laterally compacting the debris and blocking the root canal system anatomy.

The Revo-S NiTi instrument system includes three shaping instruments: the shaping and cleaning instrument (SC) number 1 (SC1) (#25/0.06), SC2 (#25/0.04), and the universal shaper (#25/0.06). The asymmetrical cross-section of the Revo-S facilitates penetration by a “snake-like” movement and is intended to reduce torsional stress on the instrument. The manufacturer claims that this sequence has a cutting, debris elimination, and cleaning cycle which optimizes the root canal cleaning by improving the upward removal of the generated dentin debris. The One Shape file from Micro-Mega (Besançon, France) is the only single-file NiTi instrument in continuous rotation for root canal preparations. The One Shape instrument presents a variable cross-section along the blade which has an optimal cutting action in three zones of the canal. The first zone presents a variable three-cutting-edge design; the second, prior to the transition, has a cross-section that progressively changes from three to two cutting edges; and the last (coronal) has two cutting edges.

Evolution of NiTi Alloy Treatments

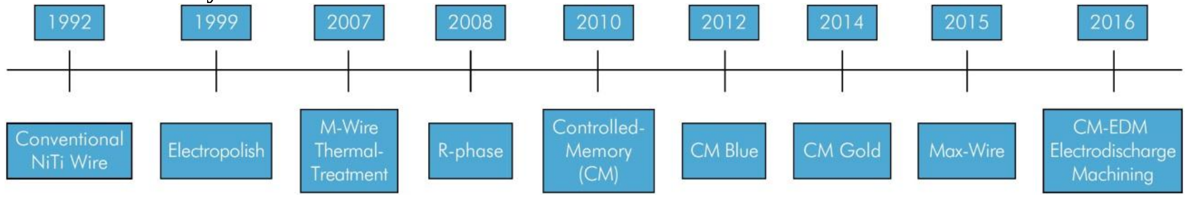

Figure 4: Evolution of NiTi Alloy Treatments.

Conventional NiTi alloy

Conventional NiTi endodontic instruments approximately contain 56 wt% nickel and 44 wt% titanium.[20] The austenite finish temperature is below body temperature. Hence, conventional NiTi endodontic instruments mainly consist of the austenite phase and possess superelastic properties. These instruments have to be grinded rather than twisted. The grinding process may lead to defects on the surface of the NiTi instruments, which are supposed to have negative effects concerning fracture resistance, cutting efficiency and resistance to corrosion.[20,21]

Electropolishing

Electropolishing (EP) is an established final surface finishing process for metal workpieces that allows for a controlled electrochemical removal of surface material leading to a smoother surface with increased gloss.[22] During manufacturing of NiTi endodontic instruments, EP is used to remove surface irregularities, cracks, and residual stress that are caused by the previous grinding process. This is supposed to improve fracture resistance, cutting efficiency, and resistance to corrosion. Several studies revealed that the presence of microcracks, surface debris, and milling grooves can be reduced by EP, although EP is not able to inhibit the development of microfractures.[23] Most studies indicated an advanced resistance to cyclic fatigue of electropolished versus non-electropolished instruments. EP significantly reduces the resistance to cyclic fatigue while increasing the angle of deflection at failure. Maximum torque at failure was not affected by EP.

M Wire

The starting material for the heat treatment of M-Wire is a Nitinol composition consisting of 55.8±1.5 wt% nickel (Ni), 44.2±1.5 wt% titanium (Ti), and trace elements less than 1 wt%.[24] The austenite finish temperature of M-Wire was found to be around 43-50°C, indicating that M-Wire is not completely composed of austenite under clinical conditions. M-Wire contains austenite phase with small amounts of martensite and R-phase at body temperature. M-Wire exhibits greater flexibility than conventionally processed NiTi wire. It is known, that the elastic moduli of martensite and R-phase are lower than that of austenite. Thus, improved flexibility of MWire could be attributed to the presence of these two phases. Additionally, Pereira et al.[25] found that the stress-strain curve of M-Wire shows that less stress is required to induce martensite transformation in M-Wire than in conventional NiTi. While maintaining comparable torsional properties M-Wire was found to be significantly more resistant to cyclic fatigue compared to conventional NiTi alloy.

R-Phase

In 2008, shortly after the introduction of M-Wire, SybronEndo (Orange, CA, USA) developed another manufacturing process to create a new rotary NiTi system named Twisted File (TF). The manufacturing procedure of TF includes 3 new methods: R-phase heat treatment, twisting of the metal wire and a special surface conditioning.[26] The twisting process is conducted by transforming a raw NiTi wire in austenitic state through a proprietary thermal process into R-phase. R-phase possesses a lower shear modulus and its transformation strain is less than one-tenth of that of the martensite transformation Consequently, less stress is required to cause a plastic deformation in R-phase allowing the twisting process.[27] After twisting, TF is converted back to austenite by additional thermal procedures to maintain its new shape. austenite finish temperature of R-phase instruments is around 18-25°C indicating that these instruments mainly contain superelastic austenite in the oral environment.

In several studies R-phase instruments revealed superior resistance to cyclic fatigue and superior flexibility compared to conventional NiTi without heat treatment. R-phase instruments allows a more centred canal preparation with less transportation than conventional NiTi rotary systems. R-phase instruments reveal similar cyclic fatigue resistance in comparison to those made of M-Wire. Concerning torsional fracture, the R-phase instruments have a greater angle of deflection at failure but a decreased maximum torque compared to M-Wire and conventional NiTi instruments.

Controlled Memory (CM) Wire

Controlled memory (CM) Wire which was introduced in 2010 is the first thermomechanically treated NiTi endodontic alloy that does not possess superelastic properties at neither room nor body temperature.[28] Because of a modified phase composition, CM Wire instruments can be deformed because of reorientation of the martensite variants.[3] Thus, in contrast to austenitic NiTi files, CM Wire instruments do not tend to fully straighten during the preparation of curved root canals. compared to Revo-S (Micro Méga, Besançon, France), ProTaper Next (Dentsply Sirona Endodontics, Ballaigues, Switzerland), and Reciproc (VDW, Munich, Germany) Hyflex CM have significantly less root canal straightening.

Austenite finish temperature of CM Wire instruments is above intracanal temperature (around 47-55°C). DSC analysis revealed that the austenite finish temperature of CM Wire instruments is above intracanal temperature (around 47-55°C)[3,29] found that unused Hyflex CM instruments exhibit Af temperatures around 32-37°C, while the Af temperature for used Hyflex CM instruments is about 54-61°C. However, XRD analysis of Hyflex CM and Typhoon CM (Clinician's Choice Dental Products, New Milford, CT, USA) revealed that both new and used CM Wire instruments are a mixture of austenite and martensite structure with small amounts of the R-phase at room temperature.

CM Wire instruments have greater flexibility than M-Wire and conventional NiTi instruments. The improved flexibility is mainly be attributed to the fact that the critical stress to induce martensite reorientation (twinned to deformed martensite) in martensitic instruments is much lower than the critical stress to induce SIM transformation (austenite to deformed martensite) in austenitic instruments (Fig. 1).[28] Despite increased flexibility, which is considered to affect cutting efficiency negatively, Hyflex CM instruments have an enhanced cutting efficiency in lateral action compared to electropolished and conventional NiTi instruments.
CM Wire instruments have a significantly enhanced cyclic fatigue resistance compared to Mwire and conventional NiTi instruments, which might be attributed to their martensitic state. CM Wire instruments exhibited a greater angle of deflection at failure than M-Wire and conventional NiTi, but the maximum torque was nearly equal.[30]

Gold and Blue heat-treated instruments
Dentsply Tulsa Dental (Tulsa, OK, USA) introduced ProFile Vortex Blue, which was the first endodontic instrument possessing a distinctive blue colour. There are now two Gold and two Blue heat-treated NiTi systems available. Two of them are used in a rotary (ProFile Vortex Blue; ProTaper Gold, Dentsply Sirona Endodontics) and two of them are used in a reciprocating motion (Reciproc Blue, VDW; WaveOne Gold, Dentsply Sirona Endodontics). These instruments also exhibit a controlled memory effect and can be deformed.[31] The main difference between CM Wire and the Gold respectively Blue heattreated instruments is that these files are ground before they go through a proprietary postmachining heat treatment.

For Vortex Blue instruments it is known that a visible titanium oxide layer is responsible for the distinctive blue colour that remains on the surface as a result of the post-machining heat treatment. The austenite finish temperature for Vortex Blue was found to be around body temperature (38.5°C), while the martensite start temperature is approximately 31°C. Blue heat-treated instruments exhibited less Vickers surface hardness than M-Wire instruments.[32] Considering the controlled memory behaviour of the Blue heat-treated file, it can be assumed that despite lower transformation temperatures these instruments contain a greater amount of stable martensite than M-Wire, leading to a softer and more ductile NiTi alloy.

For Gold heat-treated instruments a surface layer may also be responsible for the distinctive colour. DSC analysis of ProTaper Gold revealed approximately 50°C for austenite finish temperature[33], indicating that these instruments also mainly contain martensite or R-phase under clinical conditions. All Gold and Blue heat-treated files demonstrated enhanced flexibility and fatigue resistance compared to conventional NiTi and M-Wire instruments which might be attributed to their martensitic state. Only Hyflex EDM files have a significantly increased cyclic fatigue resistance compared to ProTaper Gold, WaveOne Gold, and Reciproc Blue. Kaval et al. (2016)[34] reported that ProTaper Gold had a significantly higher maximum torque than Hyflex EDM and ProTaper Universal (Dentsply Sirona Endodontics), whilst Hyflex EDM had an increased distortion angle. ProTaper Gold was found to be more effective in lateral cutting action than ProTaper Universal.

MaxWire
Recently, FKG Dentaire introduced another proprietary thermomechanically treated NiTi alloy named MaxWire (Martensite-Austenite-electropolish-fileX), which is the first endodontic NiTi alloy that combines both shape memory effect and superelasticity in clinical application. At the moment there are two instruments available that are made of MaxWire; the XP-endo Shaper and XP-endo Finisher (both FKG Dentaire). While these instruments are relatively straight in their M-phase (martensitic state) at room temperature, they change to a curved shape when exposed to intracanal temperature due to a phase transformation to A-phase (austenitic state). Thus, these instruments exhibit a shape memory effect when inserted into the root canal (M-phase to A-phase) and possess superelasticity during preparation. The curved shape is claimed to enable a preparation of complex root canal morphologies with the potential to adapt to canal irregularities.

The XP-endo Shaper revealed significantly increased cyclic fatigue resistance compared to Hyflex CM, Vortex Blue, and iRaCe,[35] but had less torsional resistance compared to Vortex. It is important to mention that the special low taper design (0.01) of the XP-endo Shaper instrument profoundly affects its cyclic and torsional resistance. It is well known, that a smaller diameter increases the cyclic fatigue and reduces the torsional resistance of NiTi rotary instruments.

Electrical discharge machining (Hyflex EDM)
Hyflex EDM is the first endodontic instrument that is manufactured via an electrical discharge machining

(EDM) process.[36] According to the manufacturer, this innovative machining process should harden the surface of the NiTi file, resulting in an improved fracture resistance and superior cutting efficiency. EDM is a well-known noncontact machining procedure that allows precise material removal via pulsed electrical discharge. For EDM both the machining tool (electrode) and the workpiece have to be electrically conductive. Embedded in a dielectric liquid, the machining tool is moved toward the workpiece until the gap is small enough so that the applied voltage is able to ionize the dielectric liquid.[37] The resulting spark vaporizes small particles from the workpiece, which resolidify in the dielectric liquid and are subsequently flushed away[37], EDM does not require direct contact with the workpiece, which eliminates the chance of mechanical stress as in the traditional grinding process.

Optical metallographic analysis of Hyflex EDM revealed a microstructure mainly composed of lenticular grains (assumed to be martensite) alternating with large flat grains (assumed to be austenite).[36] in contrast XRD analysis revealed that Hyflex EDM consists of martensite and substantial amounts of R-phase, while Hyflex CM was a mixture of martensite and austenite.

Hyflex EDM exhibits a significantly increased cyclic fatigue resistance compared to Hyflex CM, M-Wire, and conventional NiTi instruments.[8,36] The flexibility of Hyflex EDM was found to be similar to other CM Wire instruments.[29] Hyflex EDM has been reported to create a centred root canal preparation. In addition, Hyflex EDM instruments revealed a greater angle of rotation at fracture but a lower torque to fracture than M-Wire instruments. Despite reduced austenite phase, Hyflex EDM instruments exhibited a higher hardness than conventional manufactured CM Wire files, consequently proving the surface hardening effect of EDM.[29]

Alloy	Phase composition / properties	NiTi system
conventional NiTi alloy	**austenitic** - superelastic	Mtwo OneShape ProFile ProTaper Universal
electropolishing		RaCe, BioRaCe, iRace F360, F6 Skytaper
R-phase	**austenitic** - superelastic - twisted	Twisted File Twisted File Adaptive K3XF (not twisted)
M-Wire	**austenitic with small amounts of R-phase and martensite** - superelastic - two stage stress-induced transformation through an R-phase	ProFile Vortex ProFile GT Series X ProTaper Next Reciproc WaveOne
CM Wire	**martensitic with varying amounts of austenite and R-phase** - controlled memory effect - deformable, pseudoplastic - shape-memory effect	Hyflex CM THYPOON Infinite Flex NiTi Files V-Taper 2H Hyflex EDM
Gold heat-treated **Blue heat-treated**	- superior flexibility - enhanced cyclic fatigue resistance - greater angle of rotation at fracture - lower maximum torque	ProTaper Gold WaveOne Gold ProFile Vortex Blue Reciproc Blue
MaxWire	**martensitic** (20°C), **austenitic** (35°C) - shape-memory effect - superelastic	XP-endo Finisher XP-endo Shaper

Figure 5: Overview of NiTi alloy used for the manufacture of endodontic instruments.

CONCLUSION

New endodontic files for root canal instrumentation are continually added to the armamentarium, and older systems are updated. First-generation NiTi rotary files relied much on the superelasticity of the metal, while in instrument design the emphasis was on maximized safety (e.g., radial lands) rather than cutting effectiveness. Since then, the focus has shifted to new manufacturing processes (thermomechanical treatment and R-phase) and different unique features such as a variable cross-section along the length of the active portion of the file. Many variables and physical properties influence the clinical performance of NiTi rotaries. Ultimately, clinical experience, handling properties, safety, and case outcomes will decide the fate of a particular design. In the future, new instruments should fulfill the three sacred tenets for shaping canals: safety, effectiveness, and simplicity. Research will be needed to validate the performance and benefits of each new system.

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