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NICKEL–TITANIUM INSTRUMENTS: A CONCISE REVIEW ON EVOLUTION OF INSTRUMENTS AND INSTRUMENTATION IN ENDODONTICS

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ABSTRACT
The introduction of automated instrumentation in endodontics promised a major advance in progress for this specialty, with improvements in the quality and predictability of root canal treatment and a significant reduction in endodontic failures. In recent years, endodontic instruments have undergone a series of changes brought about by modifications in design, taper, surface treatments, and thermal treatments. In addition, new movements have also been incorporated to offer greater safety and efficiency, maximising the properties of the Nickel–Titanium (NiTi) alloy, mainly through eccentric rotary motion. An understanding of the mechanical properties of these new instruments and their effect on the clinical performance of preparation of root canal is essential to provide optimal clinical outcomes, especially in curved or flattened canals. The objective of this review is to present the characteristics of the NiTi alloys used in the major instrumentation systems available in the market, as well as the influence of the metallurgical and mechanical properties of these instruments and the movements that drive them, to enable more accurate and predictable planning of root canal preparation.

KEYWORDS: Nickel–Titanium, Superelasticity, Shape memory effect, R-phase, Thermal treatment.

INTRODUCTION
In the early 1960s, a nickel–titanium(NiTi) alloy was developed by William F. Buehler for the space programme at the Naval Ordnance Laboratory in Silver Springs, Maryland, USA. Nitinol- an acronym for the elements from which the material was composed; Ni for nickel, Ti for titanium and nol from the Naval Ordnance Laboratory. Nitinol- family of intermetallic alloys of nickel and titanium which have been found to have unique properties of shape memory and super-elasticity. (Figure 1)

Superelasticity (SE) or pseudoelasticity is defined as Complete recoverable elastic deformation up to 8% strain due to phase transformation between stable austenite and stress-induced martensite phase and Shape memory effect (SME) is defined as Ability of deformed NiTi to recover its original shape when heated due to phase transformation of stable deformed martensite to stable austenite phase.

The largely tension-free behaviour of this new file generation caused quite a sensation in the industry, as it had not been possible to simply bend NiTi files by hand. Clearer understanding of what NiTi systems with a 'controlled memory' effect can offer, it pays to take a more profound look at the physical and molecular relationships.

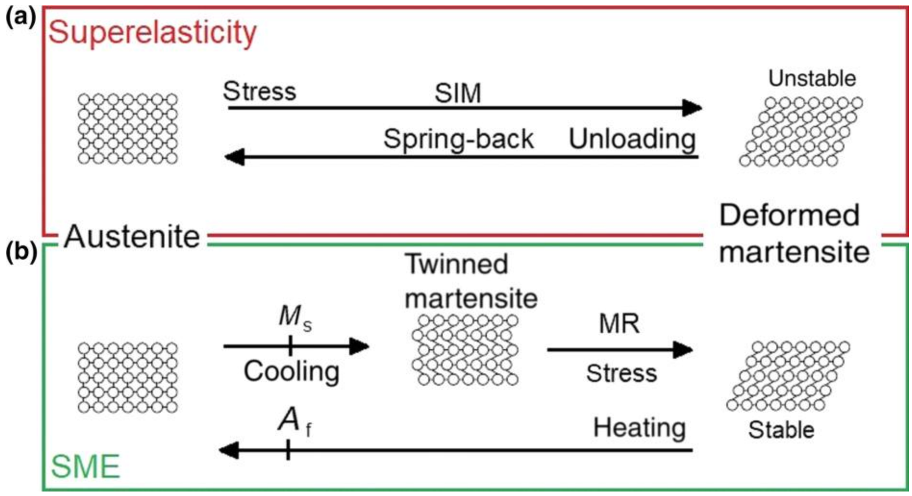

Figure 1: Martensitic transformations. (a) Superelasticity (SE) at ambient temperature above austenite finish temperature (*A*). (b) Shape memory effect (SME). For the martensite reorientation (MR), less stress is required than for stress-induced martensite (SIM) transformation. (Ms = martensite start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

NiTi alloy has three different, temperature-dependent, microstructure phases: Austenite, Martensite, and Rphase. Austenitic NiTi is strong and hard, while martensitic and R-phase NiTi are soft and ductile and can be easily deformed. The mechanical characteristics of NiTi alloy are influenced by the compositions of the three phases.[1] The conventional NiTi alloy is primarily in the austenite phase at room temperature. Thermomechanical treatments could maintain the alloy in the martensite phase, R-phase, or mixed form by altering the transformation temperature and consequently changing the characteristics of the alloy (Table 1).[2]

Table 1: Mechanical Properties of NiTi Alloy.

Sl. No.	Mechanical property	Austenitic NiTi	Martensite NiTi
1	Ultimate tensile strength (MPa)	800 – 1500	103 – 1100
2	Tensile yield strength (MPa)	100 – 800	50 – 300
3	Modulus of elasticity (GPa)	70 – 110	21 – 69
4	Elongation at failure (%)	1 – 20	up to 60

CLASSIFICATION OF NITI ALLOYS

In 1992 NiTi wires are classified into three groups depending on Transformation Temperature Range(TTR) (Table 2)

Table 2: Classification of NiTi alloys.

Group I	TTR between the room temperature and body temperature(Martenstic alloy)
Group II	TTR below the room temperature(Austenitic alloy)
Group III	TTR close to the body temperature, which by virtue of shape memory effect spring back to their original shape when activated by body temperature

METALLURGICAL PROPERTIES

NiTi alloy used in endodontic instruments contain approximately 56 wt% nickel and 44 wt% titanium resulting in equiatomic ratio.[3] This equiatomic NiTi alloy can exist in two different temperature-dependent crystal structures named Austenite (high-temperature or parent phase, with a cubic B2 crystal structure) and Martensite phase (low-temperature phase, with a monoclinic B19′ crystal structure) possesses typical characteristics which are superelasticity (SE) and shape memory effect (SME). These properties occur as a result of the austenite-to-martensite transition (martensitic transformation), which can be induced by stress or temperature.

The phase composition and mechanical properties of NiTi alloy are dependent on the ambient temperature and whether the alloy is cooled or heated to this temperature. If the temperature is above austenite finish temperature (*A*), the alloy is in austenitic state, that is, it is still, hard and possesses superior superelastic properties. If the temperature is below Martensite finish temperature (*M*), the NiTi alloy is in martensitic state, that means, it is soft, ductile, can easily be deformed and possesses the shape(Figure 2)

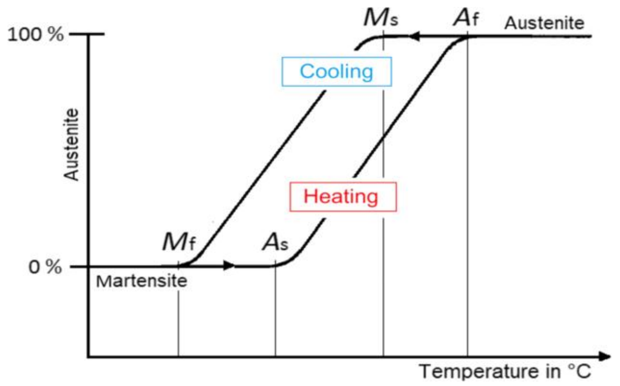

Figure 2: Temperature hysteresis diagram of NiTi alloy. (*M*) martensite start temperature, (*M*) martensite finish temperature, (*A*) austenite start temperature, (*A*) austenite finish temperature.

A modified phase composition due to changed transformation temperatures is the main difference between thermomechanically treated and conventional NiTi alloy. While conventional NiTi alloy contains austenite[3] thermomechanically treated NiTi alloy additionally contains varying amounts of R-phase and martensite under clinical conditions. These modifications are supposed to lead to more flexible endodontic instruments with an advanced resistance to fracture.

NITI ALLOY TREATMENTS

The mechanical properties and behaviour of the NiTi alloy vary according to its chemical composition and thermal/mechanical treatment during manufacturing. A timeline of these treatments is presented in Figure 3.

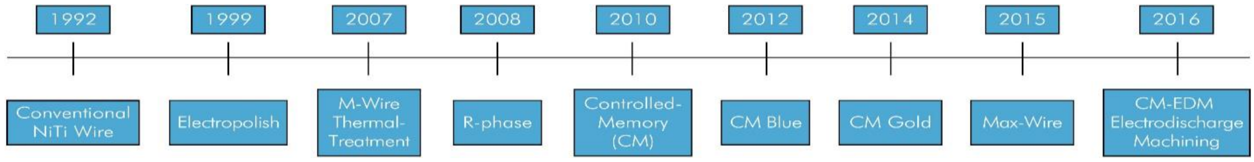

Figure 3: Evolution of NiTi Alloy Treatments.

1. Conventional NiTi alloy

Conventional NiTi endodontic instruments approximately contain 56 wt% nickel and 44 wt% Titanium.[3] The austenite finish temperature is below body temperature.[4] 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.

2. 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 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

3. M-Wire

To produce a more flexible NiTi alloy with enhanced cyclic fatigue resistance, Sportswire LLC (Langley, OK, USA) developed a proprietary thermomechanical manufacturing procedure in 2007. The newly developed NiTi alloy was named 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%. The austenite finish temperature of M-Wire was found to be around 43–50 °C and consequently well above *the temperature* of conventional NiTi and body temperature, which indicates M-Wire is not completely composed of austenite under clinical conditions. According to this, various metallurgical laboratory techniques (e.g. DSC, XRD, and SEM) revealed that M-Wire contains austenite phase with small amounts of Martensite and R-phase at body temperature.[4,5] Hence, M-Wire maintains a superelastic state.

4. R-phase (Twisted file)

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 three new methods: R-phase heat treatment, twisting of the metal wire and a special surface conditioning. 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. After twisting, TF is converted back to austenite by additional thermal procedures to maintain its new shape.

5. 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. Because of a modified phase composition, CM Wire instruments can be deformed because of reorientation of the Martensite variants.[6] Thus, in contrast to austenitic NiTi files, CM Wire instruments do not tend to fully straighten during the preparation of curved root canals (Figure 4). According to the manufacturer, this controlled memory effect is supposed to reduce the incidence of preparation errors. Coltène/Whaledent has introduced Hyflex EDM, which is another rotary NiTi system manufactured from CM Wire. Hyflex EDM is the first endodontic instrument that is manufactured via an electrical discharge machining (EDM) process.[7]

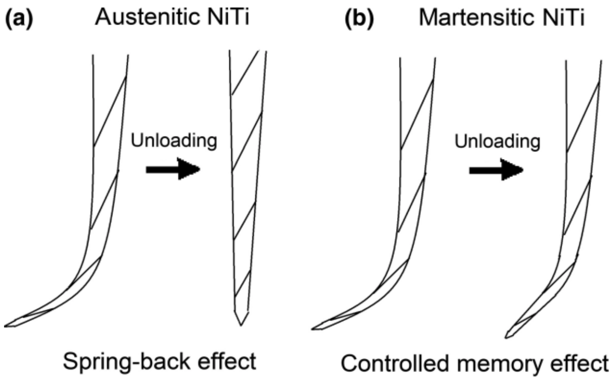

Figure 4 (a): Spring-back effect of austenitic NiTi alloys (b) controlled memory effect of martensitic NiTi alloys.

6. Gold and Blue heat-treated instruments

In 2011, 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; Wave One Gold, Dentsply Sirona Endodontics). These instruments also exhibit a controlled memory effect and can be deformed.

7. MaxWire

In 2015, 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). NiTi alloy used for the manufacture of endodontic instruments are summarised in Table 3.

Table 3: Overview of NiTi alloy used for the manufacture of endodontic instruments.

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:	Hyflex CM THYPOON Infinite Flex NiTi Files V-Taper 2H Hyflex EDM
Gold heat-treated Blue heat-treated	•controlled memory effect • deformable, pseudoplastic •shape memory effect • 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

Movements Used In Mechanical Root Canal Preparation

The introduction of NiTi instruments has made the process of mechanical root canal Preparation more predictable in the clinical setting, with a significant reduction in working time and less stress on the practitioner. Movements used in mechanical root preparation changed from time to time (Figure 5).

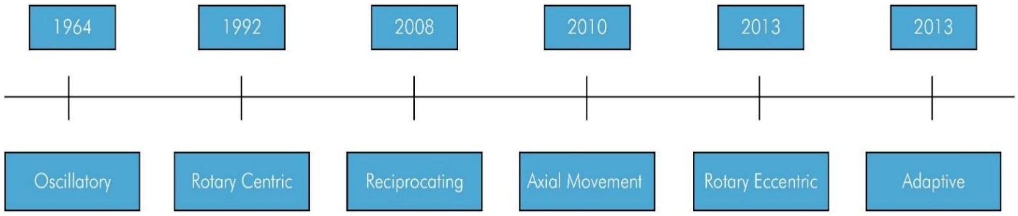

Figure 5: Timeline of movements used in mechanical root canal preparation.

1. Centric rotary motion

Introduced in the late 1980s, it is still employed by the majority of mechanical preparation systems on the market today. It is performed by electric motors and reduction gear contra-angle handpieces driving NiTi files in full rotation (360°) within the root canal. However, new mechanized techniques have been proposed in an attempt to minimize the risk of fracture of endodontic instruments.

2. Reciprocating movement

Reciprocating motion also uses electric motors and contra-angle handpieces that drive NiTi files, but in this case the angles of rotation are asymmetrical, in the counterclockwise and clockwise directions.[8] facilitating advancement of the instrument with little apical pressure. This landmark study represented an evolution in endodontic instrument kinematics, as the use of sequential files would no longer be necessary to achieve tapered shaping of the root canal system.

3. Combined movements (centric rotary + reciprocating)

Some systems have been designed to combine rotary and reciprocating movements, taking advantage of each one. Ultradent, Sybron Endo, Easy and J Morita have presented proposals of engines or instrument systems capable of working in the root canal with both kinematics. The Genius system (Ultradent, South Jordan, UT, USA), introduced in 2016, was developed for use in clockwise rotary and reciprocating (90° clockwise, 30° counterclockwise) motion. Canal preparation is first performed with reciprocating motion, which allows safer negotiation of the canal; then, the rotary action is used to finish the preparation, which work with greater efficiency in dentin removal from the canal and less extrusion of debris through apical foramen.

4. Eccentric rotary motion

Some systems, due to the characteristics of their instruments, rotate eccentrically or asymmetrically (i.e., the axis of rotation is off-center). These include the ProTaper Next system, with its asymmetrical rectangular cross-section, and XP-endo Shaper, which expands beyond the size of its core at temperatures equal to or greater than 35°C.

The TRUShape system (Dentsply Sirona) also performs asymmetric rotary motion, due to the variable taper of the instruments and modified crosssection with an eccentric center of mass, which makes only two points of the cross-section ever touch the dentin walls at any one time during canal preparation.[9,10] The instruments receive heat treatment after machining, and their long axis is S-shaped, with a triangular cross section and a variable taper.

5. Transaxial motion

With a design and kinematics completely different from those of existing systems, the Self-Adjusting File (SAF) instrument was developed by ReDent-Nova (Ra'anana, I srael) in 2010. This Instrument is a hollow file in the shape of a cylindrical meshwork, made from a thin NiTi structure with an abrasive surface that is able to adapt to the walls of the root canal. The file operates coupled to a silicone irrigation device (VATEA, ReDent-Nova), which provides a continuous flow of irrigation solution during instrumentation.

CURRENT INSTRUMENTS AND INSTRUMENTATION SYSTEMS

Current instrument and instrumentation systems with their application, cross section, taper and manufacturing/treatment are described in Table 4.

Table 4: Features of the main automated instrumentation systems in the current world panorama.

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	
ProDesign Logic Glide-Path/Easy (2014)	Glide-path/Rotary centric	Quadrangular	25-50 .01	Micromilling, post-manufacture heat treatment: CM
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

CONCLUSION

Thermomechanical treatment of NiTi alloy allows a change in the phase composition leading to the appearance of Martensite or R-phase under clinical conditions. While M-Wire and R-phase instruments maintain an austenitic state, CM Wire, as well as the Gold and Blue heat-treated instruments, is composed of substantial amounts of Martensite form. The austenitic instruments possess superelastic properties and reveal high torque values at fracture. Thus, these files are appropriate to shape straight or slightly curved root canals. Additionally, eccentric rotary motion, produces more balanced points of contact with the root dentin, contributes to greater instrument cyclic fatigue resistance and ensures greater contact with the canal walls.

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