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The Evolution of NiTi Endodontic Instruments: A Short Review

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Abstract

The introduction of NiTi endodontic instruments in the early 1990s revolutionized endodontic treatments. Multiple generations of NiTi instruments have been developed, although these generations are a practical classification rather than a universal consensus and are grouped based on their cross-section and kinematics, with innovations in design, metallurgy and surface treatments. The different 5 generations, the surface treatments, alloy properties and the future directives are the four headings used to elaborate on the topic of this review.

Keywords

Surface Treatment, Torsional Fatigue, Phase Transformation, Cyclic Fatigue, Super Elasticity, Shape Memory Alloy, Flexibility, Thermal Treatment

1. Introduction

The development of nickel-titanium (NiTi) endodontic files represented a significant and revolutionary advance in endodontics. Since their introduction in the early 1990s, NiTi instruments have revolutionized root canal preparation, offering greater flexibility, efficiency and cutting capacity than conventional stainless-steel files, facilitating root canal preparation and shaping. Over the years, five generations of NiTi instruments have been developed, each distinguished by advances in design, metallurgy, surface treatments and production methods. Recent advances have led to new manufacturing techniques and instrument designs that significantly improve the performance of NiTi files, sparking an ongoing debate about potential new file generations. This review aims to examine the history of NiTi instruments along with their different generations, the different phases of NiTi alloy transformation, and the various surface treatments used.

2. History of the Various Generations

2.1. First Generation

First-generation NiTi rotary files were introduced in the early 1990s. These files take advantage of the alloy's super-elasticity, making them more flexible and resistant to cyclic fatigue and torsional fracture. Thanks to a continuous rotational movement, they enable mechanical preparation of canals. This generation included innovative instruments such as ProFile, LightSpeed, Quantec, Greater Taper and Hero-642, which introduced new designs to the field [1].

One of the main characteristics of this generation was the geometric design of the files (**Figure 1**), with particular attention to details such as the cross-sectional shape and flute configuration. These instruments also incorporated safety features during use, such as the design of the radial cutting edge, which represents the flattened region parallel to the instrument's central axis throughout the working process, aimed at reducing the risk of procedural errors and improving overall safety during treatment. As a result, an additional number of files is required to achieve optimum shaping [1].

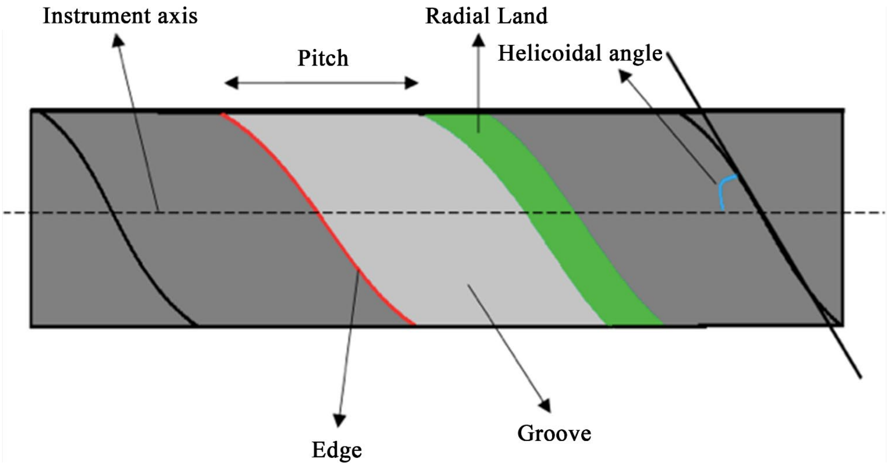


Figure 1. The main parts of the rotary file [2].

2.2. Second Generation

With no radial edges and an improved cutting angle and file taper, second-generation NiTi files are made to cut more efficiently. This generation, which was introduced in the late 1990s and early 2000s, marked a major advancement in technology by introducing exceptional files including ProTaper Universal, K3, Hero Shaper, BioRaCe, and EndoSequence [1].

Fewer tools are required to completely prepare the canal because of the geometric shape alterations, such as the placement of active cutting edges without radial edges, which are intended to provide optimal shaping. Compared to first-generation files, the angle of inclination—the angle formed by the cutting blade and the instrument's longitudinal axis—is smaller. Positive cutting angles have been incorporated into the design of several second-generation systems, increasing their cutting efficiency [3].

2.3. Third Generation

The third generation of NiTi instruments introduced thermomechanically treated alloys designed to improve flexibility and fatigue resistance. One of the earliest examples was M-Wire, introduced in the mid-2000s, which is produced through proprietary thermomechanical processing of conventional NiTi alloy. This treatment results in a microstructure containing austenite, martensite, and R-phase components, thereby improving cyclic fatigue resistance compared with conventional superelastic NiTi alloys [4].

Subsequent developments included CM-Wire, R-phase technology, Blue treatment, Gold treatment, and Max-Wire, each based on different thermomechanical processing methods or proprietary alloy technologies aimed at enhancing flexibility, cyclic fatigue resistance, and clinical performance [1].

2.4. Fourth Generation

Since 2008, fourth-generation NiTi files have steadily improved their design features to optimize clinical performance. These files were created to lower the risk of torsional fatigue and increase cutting efficiency by taking into consideration the alloy type, degree of taper, manufacturing process, mode of movement, and cross-sectional design.

Manufacturing techniques like heat treatments and electropolishing have been used to enhance file performance overall and, as a result, endodontic treatment quality [1].

The balanced force technique, which employs a repeating back-and-forth motion during root canal preparation, has replaced the traditional continuous clockwise rotation. Originally developed for use with stainless steel hand files, this method has been adapted for use with NiTi instruments, leading to more effective cutting and a lower chance of instrument fracture. Additionally, materials like M-wire were used to create files like Reciproc and WaveOne (**Figure 2**) that are intended for reciprocating movements. As a result, the instruments became stronger and more flexible [5].

2.5. Fifth Generation

Since 2010, the fifth generation of NiTi files has ushered in a new era, with significant advances in design, performance and safety. This generation has seen the introduction of NiTi eccentric rotary systems such as ProTaper Next, Revo-S, vortex blue (**Figure 3**), and OneShape. Innovative design, enhanced mechanical performance, and adaptability to various intracanal anatomical differences are what set these fifth-generation files apart [1].

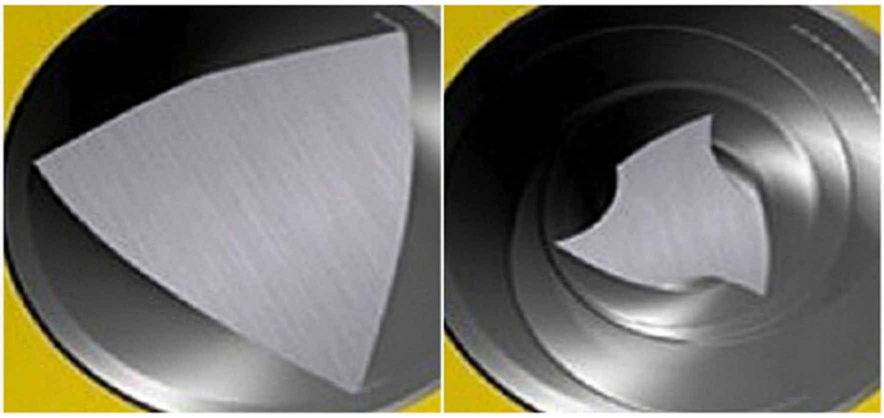


Figure 2. WaveOne file cross-section at 3 mm (right) and 9 mm (left) from the tip of the instrument [1].

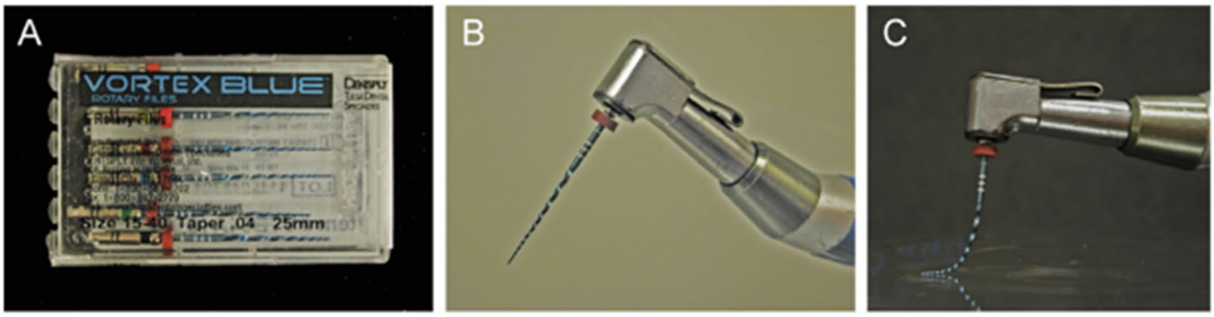


Figure 3. Vortex blue NiTi instruments [3].

This generation of files has better preparation efficiency and increased resilience to torsional fatigue due to advancements in design, manufacture, and heat treatment. This allows the creation of a wave of mechanical movement along the file's active length. Because of this design change, the file's surface engagement with the dentin has decreased, increasing shaping effectiveness and lowering the possibility of mistakes [1].

3. Alloy Properties

3.1. Phase Transformation

The crystalline phase undergoes a reversible temperature-dependent transformation known as phase transformation. At high temperatures, the alloy exists in the austenitic phase, whereas at low temperatures it transforms into the martensitic phase. In certain NiTi alloys, an intermediate rhombohedral phase, known as the R-phase, may appear during the transformation sequence.

During cooling, the transformation generally occurs from austenite to R-phase and then to martensite, whereas during heating the reverse transformation takes place from martensite to R-phase and finally to austenite. These transformations may be induced either by temperature variation or by applied mechanical stress.

According to Guenin (1995), phase transformation is "a first-order displacive structural transformation, presenting a deformation of the homogeneous crystallographic lattice, mainly constituted by shear" (**Figure 4**) When discussing phase transformations, the first phase from which a new phase is formed during the transformation process is referred to as the "mother phase." [6]

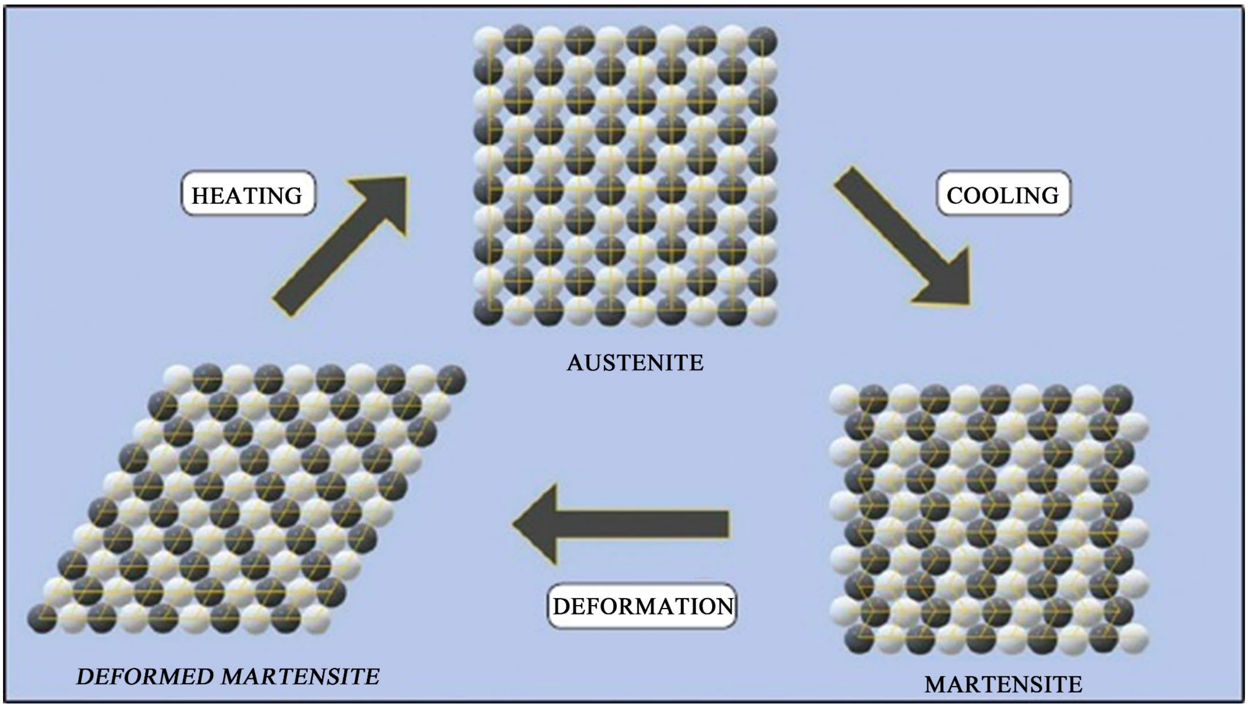


Figure 4. Martensitic transformation: The pseudo-elastic behavior of NiTi is based on the temperature-dependent crystal configurations of austenite and martensite [6].

3.1.1. Austenite

The crystalline structural condition that results from increasing the NiTi alloy's temperature is represented by austenite. Exo-thermia, which is the release of heat, and endo-thermia, known as the absorption of heat, are associated with any physical and/or chemical process that may occur in a material, such as a change in crystalline structure, state, degradation, or deformation.

The mother phase of martensitic transformations in equiatomic NiTi alloys is the austenitic phase, which has unique properties like shape memory and superelasticity. This phase's characteristics include the flexibility of austenitic phases and stability at high temperatures [6].

3.1.2. Martensite

The non-cubic crystal structure described by the martensitic phase typically shows monoclinic distortion of the parent phase's crystal structure.

When external stimuli like temperature changes or higher mechanical loads cause the material to change its crystalline structure without atoms spreading over distances, this phase is unique since it can undergo a diffusion-free metamorphosis.

The martensitic phase exhibits several significant traits and actions. These include superelasticity, flexibility, high strength, and reversible transformation without diffusion [6].

3.1.3. R-Phase

In equiatomic Ni-Ti alloys, a structural, incommensurable, rhombohedral phase known as the "R phase" is a distinct kind of martensitic transformation [7].

Martensite changes from austenite when heated and backward to martensite when cooled. At temperature (Rs), martensite starts to change into the R phase; at temperature (Rf), this change is finished. After additional heating, the R phase starts to change into austenite at temperature (As), and the transformation is finished at temperature (Af). If heated above temperature (Af), it totally turns into austenite. After cooling to a low enough temperature, the alloy then starts to change from austenite to R-phase at temperature (Rs), and this change is finished at temperature (Rf). At temperature (Ms), the R phase begins to transform into martensite through further cooling, ending at (Mf). The alloy is stronger and has a lower modulus of elasticity than stainless steel. R-phase wire instruments are therefore more flexible than stainless steel ones. The wire can be bent to optimize the metal's grain structure after the R-phase has been identified. Grinding damages the metal's structure at the molecular level and creates surface microfractures, which leads to file breaking [7].

In 2008, SybronEndo (Orange, CA, USA) developed Twisted Files (TF) and K3XF by twisting the intermediate alloy and then heat treating it. The R phase has a lower shear modulus than the austenite and martensite phases. Furthermore, transformation strain is less than a tenth of that of martensitic transformation. Recent studies have shown that R-phase instruments provide more flexibility and resistance to bending fatigue, and they are completely austenitic at body and ambient temperatures. However, Park *et al.* claim that there is no beneficial effect of this manufacturing procedure on torsional fracture [7].

3.2. Shape Memory Alloy

One of the special qualities of NiTi alloys is the shape memory effect, which describes their capacity to regain their previous shape following deformation. The shape memory effect is mostly caused by a reversible phase change in the solid state called martensitic transformation. The reversible transition between these phases enables this transformation, which happens when temperature variations cause the crystalline structure to change from austenite to martensite and vice versa. At lower temperatures, NiTi instruments that experience martensitic deformation maintain their original shape. However, the instrument experiences a phase transition that restores its previous shape when heated over a certain degree (the austenitic phase), illustrating the shape memory effect.

The critical temperatures for NiTi alloys are the martensitic start temperature (Ms), martensitic finish temperature (Mf), austenitic start temperature (As), and austenitic finish temperature (Af) (**Figure 5**). These temperatures determine the phase change behavior and therefore the shape memory impact of the alloy [8].

3.3. Superelasticity

Superelasticity, sometimes referred to as pseudoelasticity, highlights the unique manner that NiTi alloys deform and recover while maintaining their shape memory, setting them apart from other kinds of materials. The material changes from an austenite to a martensite crystal structure as a result of external forces, a process known as the reversible stress-induced martensitic transformation (**Figure 6**) [10].

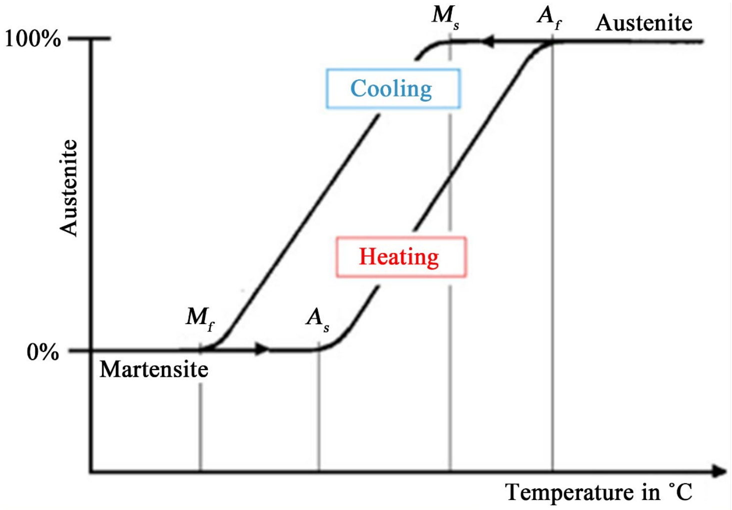


Figure 5. Temperature hysteresis diagram for NiTi alloy: (Ms) martensite start temperature, (Mf) martensite end temperature, (As) austenite start temperature, (Af) austenite end temperature [9].

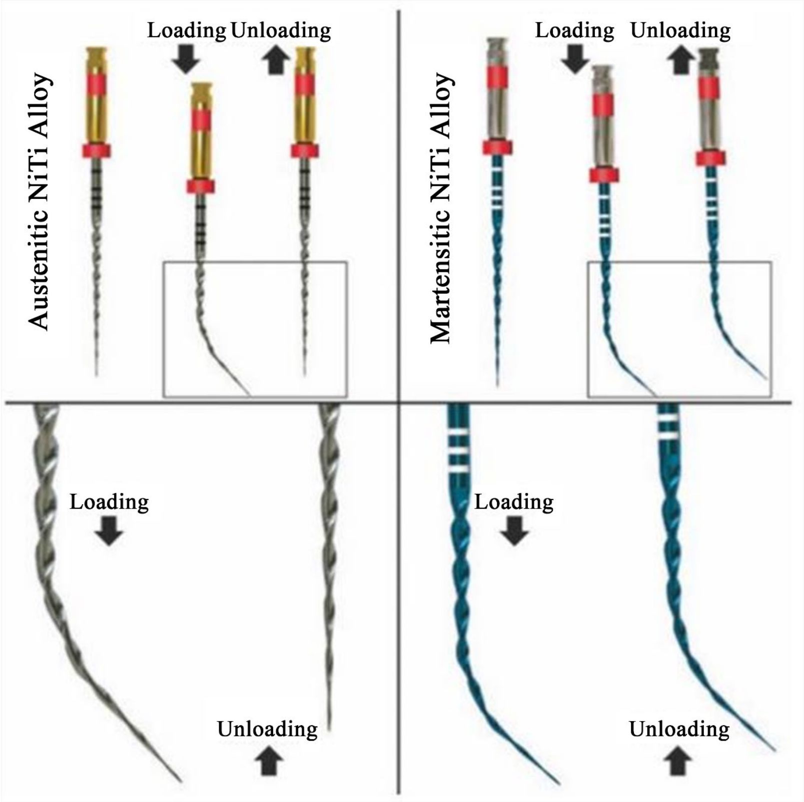


Figure 6. (a) Superelastic effect of austenitic NiTi alloys (b) Controlled memory effect of martensitic NiTi alloys [11].

The mechanical responses of NiTi alloy under particular stresses can be shown via a stress-strain graph (**Figure 7**). The austenitic area, the austenitic/martensitic region (R phase), and the martensitic region are the three discrete zones on the graph that are separated by the three vertical lines (A, B, and C) that divide the stress-strain curve [12].

Under certain loads, the transformation brought on by mechanical stress is completely reversible due to superelasticity (elastic deformation); however, if an elastic limit is exceeded, the deformation becomes irreversible (plastic deformation), resulting in permanent damage to the endodontic instrument [12].

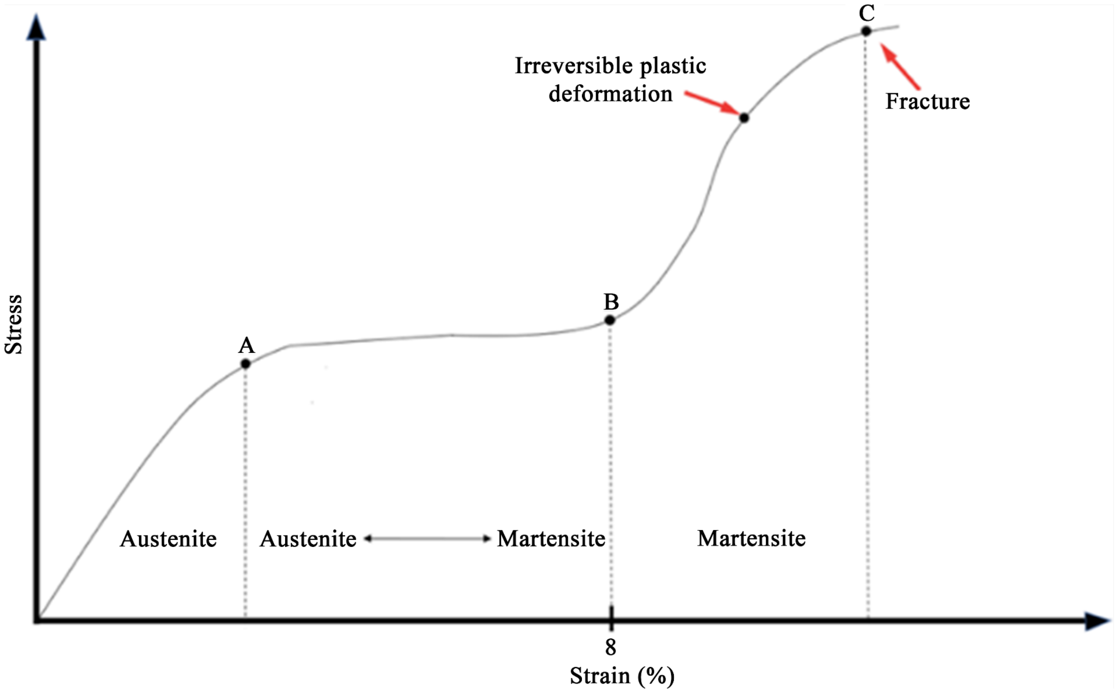


Figure 7. Schematic representation of the stress-strain curve showing crystallographic transformation as a function of induced stress [12].

3.4. Flexibility

NiTi instruments' elastic reaction to bending under loads perpendicular to their axis determines their mechanical property of flexibility [8].

When the temperature falls below the critical transformation temperature range, the NiTi alloy changes into the paired martensitic phase, which is distinguished by a dense hexagonal lattice [12].

With greater flexibility and resistance to cyclic fatigue, this NiTi alloy demonstrates a shape-memory effect when heated and stability at lower temperatures. Increased flexibility is crucial because it lowers the chance of procedural errors like sinking and the risk of instrument breakage during usage [8].

3.5. Cutting Efficiency

Cutting efficiency is defined as the mechanical removal of hard tissue. In the past, cutting efficiency was evaluated exclusively based on the mass that the tested instrument extracted from the tested specimen [13].

Doglas Cecchin *et al.* (2011) assessed the cutting efficiency of a number of equipment, including K3, Profile, Quantec, and NiTi Tee. The K3 instruments' unique cross-sectional design, which includes a relief at the back of the blade, broad radial surfaces, and a positive rake angle for increased cutting efficiency, may be the cause of their higher cutting capacity when compared to Quantec. In contrast to Quantec's two cutting blades, the K3 features a third radial plate to avoid tangling. K3 instruments have remarkable cutting capacity because of the unique helical angle of the file, which quickly displaces and removes the debris created by the cutting action from the work surface [14].

The NiTi Tee instruments' cutting efficiency was comparable to that of the K3 and Profile instruments and better than that of the Quantec instruments (**Table 1**). These instruments had a rounded, non-cutting tip, a positive cutting angle, and no radial land. Additionally, they included two 90˚ cutting blades that made grooves in the inner wall of the canal, allowing dentine waste from the instrument to be removed [14].

In a research, Schafer and Florek assessed how well the K3 system and K-Flexofile files removed debris. Even if the root canal was not completely cleaned, the authors found that the K3 method generated impressive outcomes [14].

Table 1. Summary table of different instrument designs [14].

Instrument	Cross-section	Radial surface	Cutting angle
K3	Complex	Yes	Positive
NiTi Tee	Modified rectangle	No	Positive
Profile	Triangulaire	Yes	negative
Quantec	Helical	Yes	Positive

3.6. Fracture Resistance

In NiTi rotary files, fracture is primarily caused by torsion and cyclic fatigue. Torsional fracture is the result of localized stress concentrations caused by the instrument tip remaining fixed in the canal as the top part rotates. On the other hand, cyclic fatigue occurs when an instrument fails as a result of cumulative damage from repeated bending cycles [15].

It should be emphasized that there are no global standards or recommendations for evaluating the fracture resistance of NiTi endodontic files [15].

3.6.1. Cyclic Fatigue Fracture

On a specially made test fixture, which consists of an artificial channel with a radius of 3 mm and an angle of curvature of 80˚, resistance to cyclic fatigue fracture can be evaluated with a restricted instrument in a highly curved channel (**Figure 8**). The center of curvature is 4 mm from the instrument tip, and the curved portion of the canal is 5.5 mm long (tip no. 30, taper 0.08).

Until breakage occurs, the instruments are utilized as directed by the manufacturer; at that moment, the instrument's time is recorded [15].

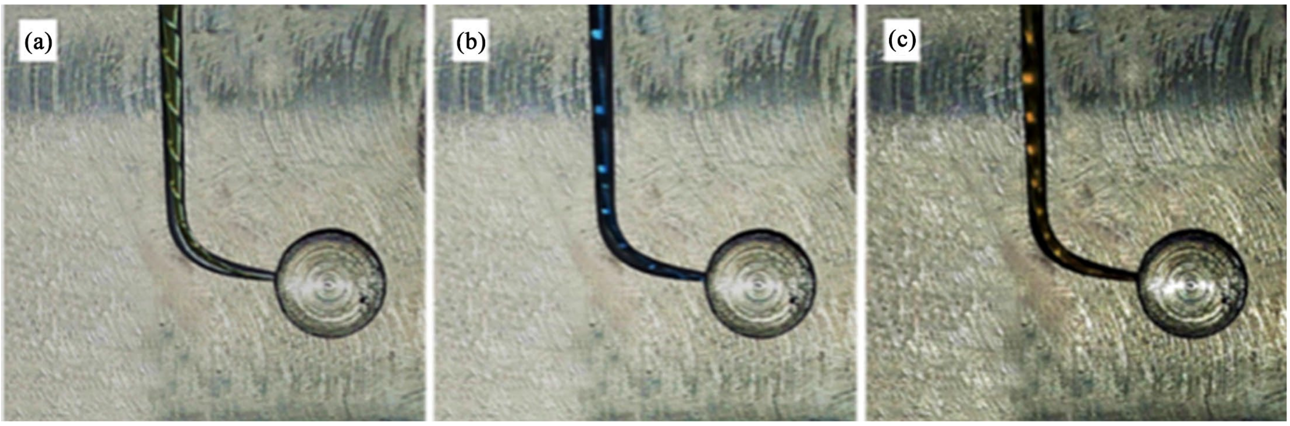


Figure 8. Trajectory of ProDesign R (a), Reciproc Blue (b) and WaveOne Gold (c) in the artificial canal used in the test [15].

3.6.2. Torsional Fracture

When a NiTi instrument rotates inside a canal, it experiences torsional stress. When the instrument's tip rotates and comes into touch with regions of higher resistance, torsional stress may accumulate [15].

A device specifically created in compliance with ISO 3630-1 is used to evaluate the fracture resistance of these instruments. The average ultimate torsional strength is estimated by applying torsional load up to fracture (n = 10 for each system). Each file is clamped at a distance of 3 mm from the tip using a chuck connected to a torque transducer. The file shank is then secured to a second chuck that is motor-rotatable. After then, all of the instruments are rotated counter-clockwise at a speed of two revolutions per minute until the test instrument breaks [15].

3.7. Corrosion Resistance

The corrosion resistance of NiTi endodontic instruments is a critical component of their longevity and performance. The corrosion behavior of NiTi devices is influenced by several parameters, including alloy composition, surface morphology, sterilization procedures, and exposure to irrigating solutions such as sodium hypochlorite and EDTA.

Compared with stainless steel instruments, NiTi alloys generally exhibit superior corrosion resistance due to the formation of a stable titanium oxide layer on their surface. However, repeated sterilization cycles and prolonged exposure to irrigants may alter the surface morphology and increase susceptibility to corrosion and surface defects. Surface treatments such as electropolishing and thermal treatment have been shown to improve corrosion resistance by reducing surface irregularities and enhancing the protective oxide layer.

3.8. Biocompatibility

Biocompatibility refers to the ability of a material to perform its intended function within a biological environment without causing adverse tissue reactions. The biocompatibility of NiTi endodontic instruments depends on several factors, including corrosion resistance, surface quality, chemical composition, and nickel ion release [16].

Although NiTi alloys contain a high percentage of nickel, the presence of a titanium oxide surface layer limits ion release and contributes to their favorable biological behavior. Previous studies have demonstrated that modern thermomechanically treated and surface-treated NiTi instruments exhibit acceptable biocompatibility under clinical conditions. Nevertheless, surface degradation and corrosion may increase nickel ion release, potentially affecting the biological response of surrounding tissues [17].

4. Surface Treatment

4.1. Electro-Polishing

Applying an electrical current while submerging the instrument in an electrolyte bath is known as electrochemical treatment, or electro-polishing [16].

The instrument serves as the anode (positive terminal), while the cathode corresponds to the negative terminal. This process creates a smoother finish, changes the chemistry and morphology of the surface (**Figure 9**), and removes surface flaws. In order to protect the underlying material from corrosive compounds found in the oral environment, such as acids or chemicals used in endodontic treatment, the current causes the metal surface to oxidize and dissolve in the electrolyte, forming a protective layer of titanium oxide [16].

4.2. Thermal Treatment

4.2.1. Thermomechanical Treatment

This method of unique thermomechanical treatment is intended to further enhance the properties of the material by combining heat treatment and hardening in a single stage [19].

Alapati *et al.* discovered that the (Af) temperature of ProFile rose from 45˚C to 50˚C after thermomechanical treatments at 400˚C, 500˚C, and 600˚C. The microstructure recrystallized and lost its superelastic property after treatment at 850˚C [20].

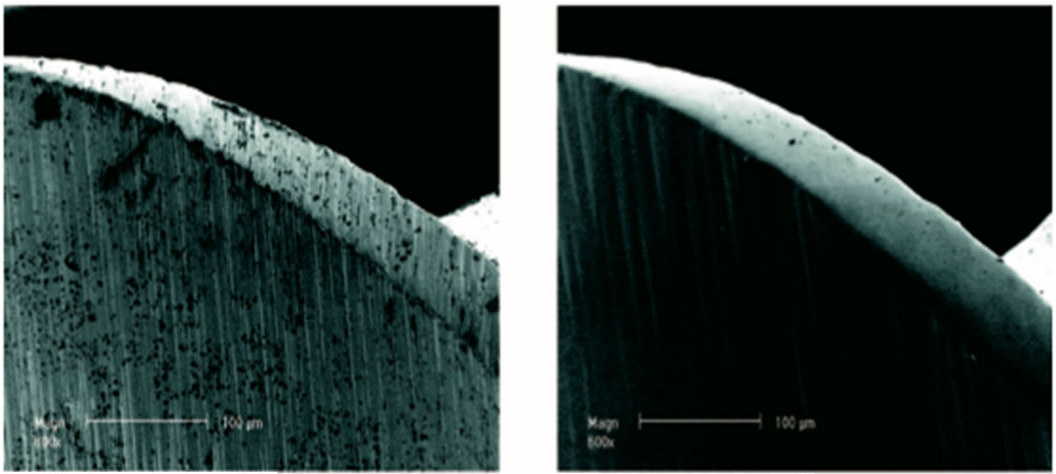
Other studies confirmed these results [21] [22].

In order to increase clinical performance and bring about beneficial changes in mechanical properties, including flexibility, super-elasticity, and fracture resistance, the producer must apply the required heat treatment [19].

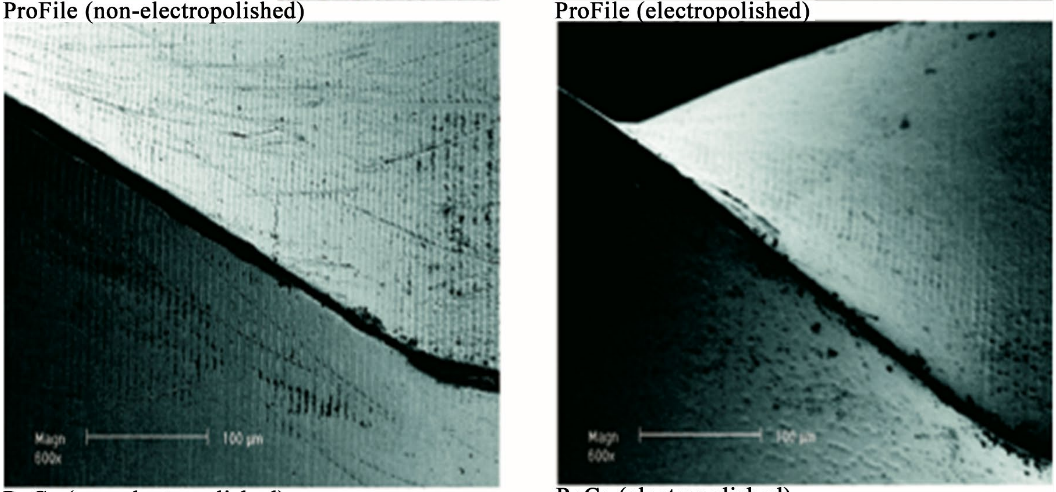
The thermomechanical treatment optimized the structure of NiTi instruments by creating superelastic blanks containing the martensitic phase which is stable in clinical conditions such as ProFile GT Series X, ProFile Vortex, et Vortex Blue [19].

4.2.2. Cryogenic Treatment

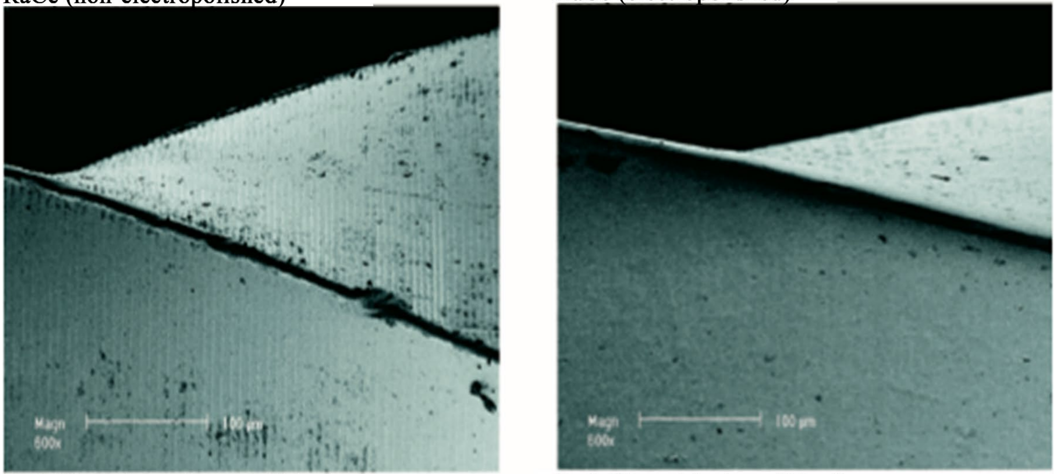
A specific heat treatment technique called cryogenic treatment uses liquid



ProFile (non-electropolished) ProFile (electropolished)



RaCe (non-electropolished) RaCe (electropolished)



EndoWave (non-electropolished) EndoWave (electropolished)

Figure 9. SEM images of electropolished and non-electropolished instruments [18].

nitrogen to expose NiTi files to extremely low temperatures, usually between -100˚C (−148˚F) and −196˚C (−320˚F) [16].

By gradually lowering the instruments to these cryogenic temperatures and then gradually bringing them back to ambient temperature, controlled thermal cycling is made possible (**Figure 10**) [16].

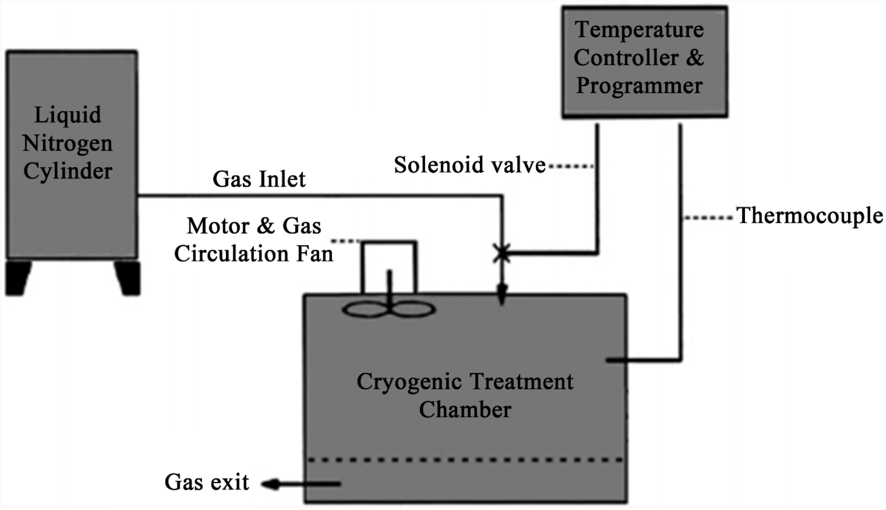


Figure 10. Installation of the cryogenic chamber [23].

Kim *et al.* assessed the effect of the cryogenic treatment on the microhardness, composition, and cutting efficiency of NiTi files. According to their findings, cryogenically treated instruments had a substantially higher microhardness than standard files. Furthermore, 56% Ni, 44% Ti, and 0% Nitrogen made up the majority of the test and control groups, which were in the austenitic phase [18].

According to a different study by Vinothkumar *et al.*, dry cryogenic treatment greatly increased the cutting effectiveness of NiTi files while having no effect on wear resistance [23].

Furthermore, according to George *et al.* deep cryogenic treatment considerably improved the cyclic fatigue resistance of NiTi files [24].

ProFile [23], Procodile (Komet) [25], and Hyflex (Coltene, Altstätten, Switzerland) are examples of cryogenically treated systems [26]. Rotating files of Neoniti and Reciproc NiTi (#25, 6% taper).

4.3. Ion Treatment

NiTi endodontic instruments are treated with ion treatment, a surface engineering method, to increase their corrosion resistance and cutting effectiveness [27].

By introducing high-energy ions, the process alters the surface properties of NiTi files. Ion treatment is the process of applying nitrogen ions at a specific energy level and dosage to the surface of NiTi devices (**Figure 11**) [28].

The utilization of a vacuum atmosphere ensures accurate ion implantation. To accomplish the intended surface alterations, ions are directed at the instrument surface at a high energy of 100 kV, an ion dose of 1017 ions/cm^2, and a current density of 1 mA/cm^2 [29].

During this process, the instruments are rotated to guarantee that each one receives the same quantity of ion exposure. NiTi tools create a layer with superior properties like increased cutting efficiency, harder material, and increased resistance to wear [29].

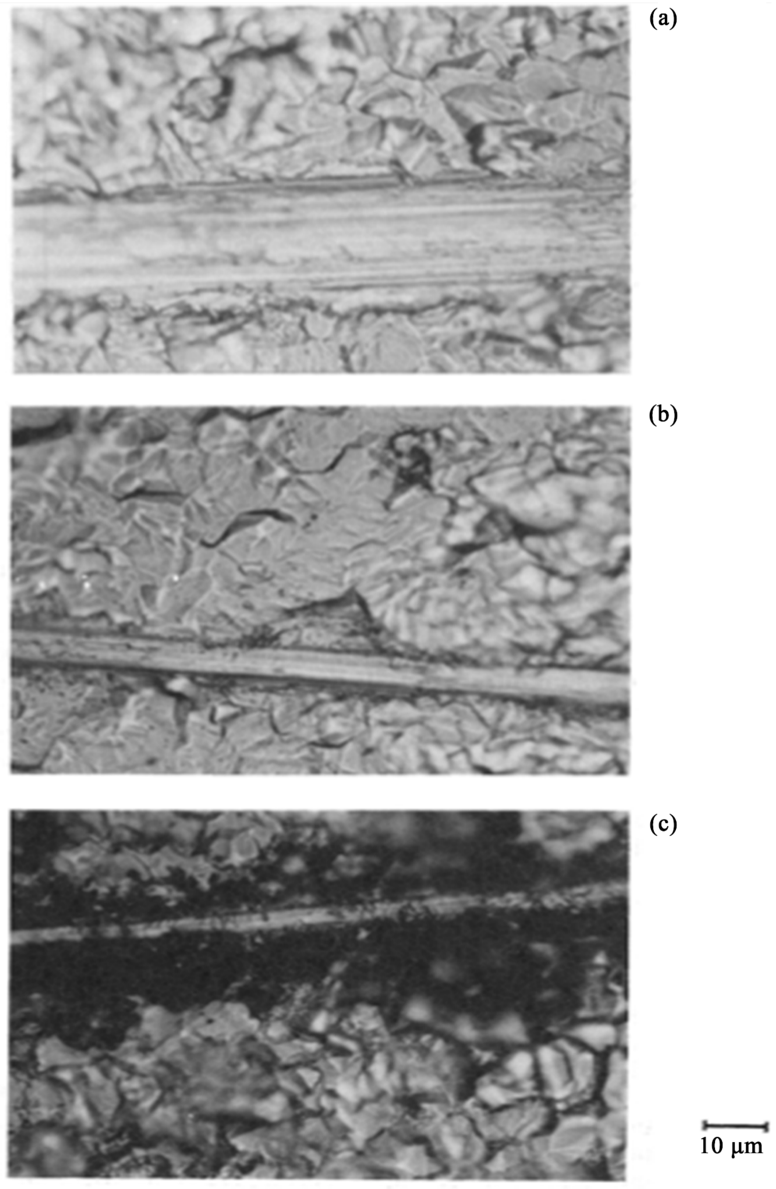


Figure 11. SEM examinations of scratch tests carried out with a 50 g intender on (a) pure titanium; (b) titanium implanted at 5 x 1017 N+/cm2; and (c) titanium annealed at 1100˚C (40 min) [30].

4.4. Thermal Nitriding

By subjecting NiTi instruments to high temperatures—typically about 500˚C—for a predetermined amount of time, the thermal nitriding procedure alters their surface, changing their composition and enhancing properties like flexibility and super-elasticity [28].

The chemical reactions that this treatment causes on the instrument's surface cause nitrogen to infiltrate into the substance. After then, nitride compounds grow on the surface to create a tougher coating that improves wear resistance and cutting efficiency [28].

ProTaper Universal [31], GT (Dentsply Maillefer, Ballaigues, Switzerland) [32], and EasyShape [33], are among the systems that profit from this technology.

5. The Main NiTi Endodontic File Alloys

5.1. M-Wire

In order to produce more flexible NiTi files with a longer life span than ordinary NiTi files and lower the risk of fracture due to cyclic fatigue, Berendt introduced M-Wire (Third Generation), which is a thermomechanically treated NiTi alloy introduced to improve flexibility and cyclic fatigue resistance compared with conventional superelastic NiTi [34].

With enhanced cycle fatigue resistance, M-wire is created by thermomechanically processing raw wire at a particular temperature and tensile tension [35].

Consequently, M wire has greater processing temperatures than NiTi wire that is manufactured traditionally. It has a number of benefits, including reduced apparent modulus of elasticity, reduced transformation stress, and reduced mechanical hysteresis [36].

5.2. R-Phase Wire

R-phase technology refers to a thermomechanical processing method in which the alloy passes through an intermediate R-phase during manufacturing. In order to perform the twisting operation, raw NiTi wire is transformed from the austenitic to the R-phase condition using a special third-generation thermal technology. R-phase instruments, such as Twisted File, Twisted File Adaptive, and K3XF (untwisted), provide more flexibility and resistance to torsional fatigue in addition to resisting cycle fatigue, just like M-Wire instruments do [9].

The Twisted File system's unique feature is that it contains files tailored to different tooth kinds, such as one set for front teeth and another for premolars and molars.

5.3. Blue-File

Blue-file technology, a fifth-generation invention, has a visible titanium oxide layer that gives the surface its distinctive blue color and keeps it that way following heat treatment after machining. This technology is employed in nano-channels and calcification situations because of its controlled memory effect, which increases cutting efficiency while also increasing wire flexibility. Dentsply Tulsa introduced the ProFile Vortex Blue system to the market in 2011.

The primary difference between Profile Vortex Blue and another technique, CM-Wire, is that the latter undergoes a special post-machining heat treatment after being sharpened. Compared to CM-Wire files, Dentsply Tulsa's blue technology provides a smoother surface. In contrast to instruments, this approach provides a stable abundance of martensite phase, resulting in a softer NiTi alloy with a composition of ductile metal [37].

5.4. Controlled Memory Wire

The first thermomechanically modified NiTi alloy that does not display superelastic properties at room temperature is the CM (Controlled Memory) system, a fifth-generation technology that debuted in 2010. CM-Wire (Controlled Memory Wire) is a thermomechanically treated NiTi alloy characterized by reduced shape memory and lower superelasticity at room temperature, resulting in greater flexibility and improved resistance to cyclic fatigue. CM-wires include the Hyflex CM, Hyflex EDM, Thyphoon Infinite, and V-taper systems [9].

This technology is suggested for medium-curvature and narrow canals.

5.5. Superelastic Wire

The high concentration of austenitic phase in SuperElastic wire sets it apart from other types of standard instrumentation systems. Although the grinding process used to make SuperElastic wire instruments maintains their mechanical properties, it may result in surface flaws that impair the instrument's ability to withstand corrosion, cut effectively, and fracture [9].

5.6. Gold Wire

A unique variety of NiTi wire known as "gold-wire" has undergone unique heat treatment processes to enhance its mechanical properties and therapeutic efficacy. This wire's unique austenitic and martensitic transformation properties are primarily responsible for its flexibility and hardness, which makes it useful in curved canals.

Many endodontic tools, such as Dentsply Maillefer's ProTaper Gold, WaveOne Gold, and ProTaper Ultimate, are made from gold wire [38].

5.7. Max-Wire

Max-Wire technology combines shape memory and SuperElastic properties through temperature-dependent phase transformation. At room temperature, the instruments remain relatively straight in the martensitic phase, whereas at body temperature they transform toward the austenitic phase and assume a predefined expanded shape that improves canal adaptation. Max-Wire technology marks a substantial development in endodontic files by integrating shape memory and super-elasticity in a single system. When in their martensitic phase, Max-Wire's XP-endo Shaper and XP-endo Finisher files are made to stay straight at room temperature. However, when exposed to the higher temperatures present inside the channels, these files bend because to the phase shift to the austenitic state. This unique feature allows files to conform to the canals, increasing their efficacy during endodontic treatment [39].

Both straight and curved canals can employ them.

Compared to competing systems like Hyflex CM and Vortex Blue, the XP-endo Shaper has a substantially higher cyclic fatigue resistance, making it a dependable choice. Despite this benefit, we see that Max-Wire files have a lower torsional strength than Vortex Blue [39].

6. Future Directions and Development of NiTi Endodontic Instruments

Despite the development of five generations of NiTi devices by 2013, research has not yet discovered or documented any more generations.

Maintaining the original dentition over the long term is the goal. This suggests that future advancements in endodontic devices will most likely focus on maintaining native tissues using minimally invasive endodontics [40].

6.1. Electrical Discharge Machining

Electrical discharge machining increases cutting efficiency and enhances file performance. Clinical outcomes are enhanced by its improved surface quality and increased dimensional precision. Additionally, EDM increases the instruments' lifetime and tolerance to cyclic fatigue, making the files more flexible and resistant to fracture [40].

There are several crucial steps in the electrical discharge machining process (**Figure 12**). First, the ionization of the dielectric liquid allows an electric current to pass across it [1]. A spark [2] is produced between the tool and the workpiece by this current. The spark causes a small particle of material to vaporize [3]. A small surface crater is left behind when the particle cools and resolidifies [4] after vaporization. EDM allows for extremely precise shaping of the material through repeated sparking [9].

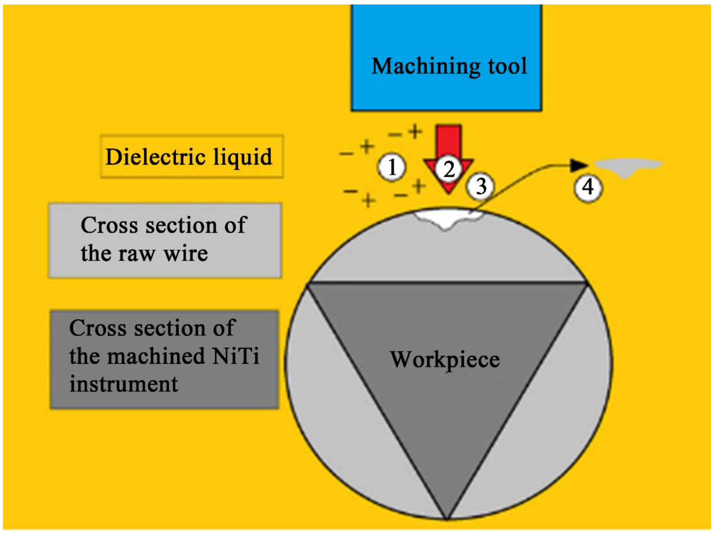


Figure 12. Electrical discharge machining: (1) Ionization of the dielectric liquid (2) Spark (3) Vaporization of a small particle (4) Resolidification [9].

6.2. Mitigating the Dangers of Non-Compliant Endodontic Files

A concerning tendency in recent years has been the development of inexpensive instruments, as producers lacking endodontic experience have started to create bad quality instruments or copy other systems. For the first time, efforts are being focused entirely on "false" financial gain for practitioners rather than better patient outcomes, and practitioners are no longer benefiting from the best quality (**Figure 13**). This is false according to the authors, because low-quality, inexpensive tools can cause early deformity and fracture even in a single treatment session, eventually requiring the use of multiple instruments [5].

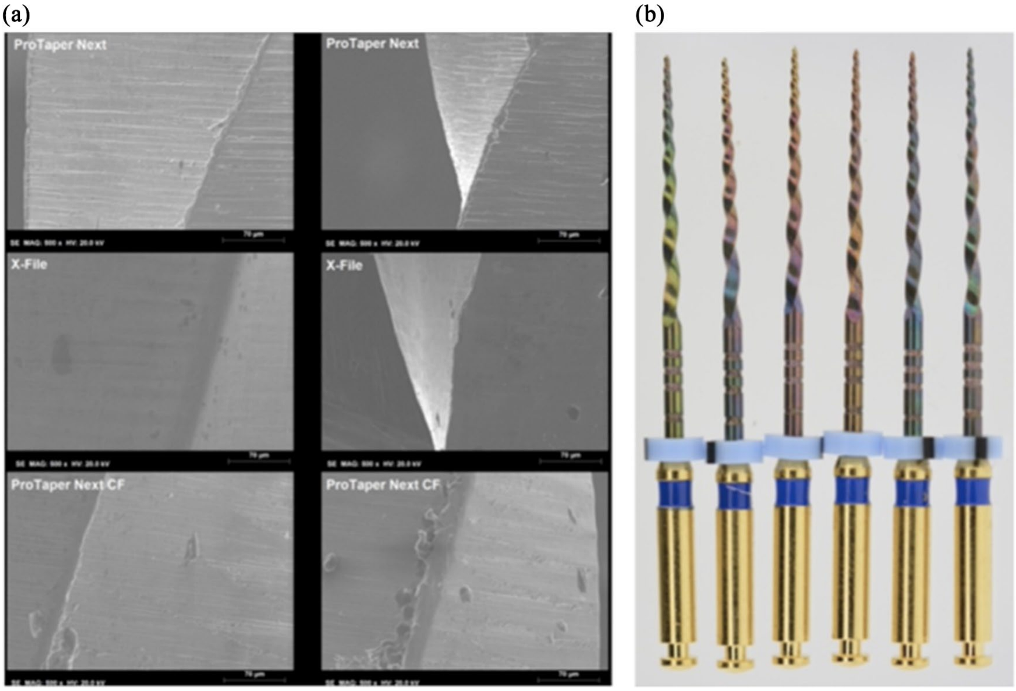


Figure 13. Quality problems in the production of NiTi instruments. (a) SEM images of instrument surfaces in which some minor manufacturing defects were noted, such as slight metal reversal on ProTaper Next, discontinuity on X-File blades and clear metal reversal on the counterfeit ProTaper Next. The smoothest surface can be observed on the X-File instrument. (b) Variable conditions during heat treatment, as indicated by the different colors in a single batch of files taken from a commercial sample [5].

The production of instruments ought to be regulated. Standards that ensure a minimum level of quality prior to the instruments being placed on the market do not exist yet. It would seem reasonable for manufacturers to demonstrate the quality of new instruments before releasing them onto the market once there is a certain level of uniformity. This means that in order to ensure product conformance, all samples that are inspected must meet basic requirements [5].

In 2021, Peters *et al.* made a guideline for quality standards testing for endodontic file cyclic fatigue [41].

It suggests a test based on the instrument alloy's austenite finishing temperature, which will be ascertained using differential scanning calorimetry (DSC). Temperature has a substantial impact on the cyclic fatigue resistance of martensitic alloys, as the literature has demonstrated, but no standard has previously incorporated this criteria [5].

A review of the standards, with correction factors, would probably be necessary for any further developments. Hülsmann [42] [43] stressed the need for manufacturers to validate the reliability of new equipment before it is put on the market [5].

6.3. Minimally Invasive Endodontics

Maintaining as much of the native tooth structure as feasible while treating the root canal system is the goal of minimally invasive endodontics. By removing as little tissue as possible, this technique lowers the chance of issues and enhances long-term outcomes. Cone-beam computed tomography for precise diagnosis and flexible NiTi files for meticulous and effective canal shaping are important technologies. These advancements have made treatments more predictable and less harmful [44].

Artificial intelligence and machine learning are transforming diagnostic and treatment planning by analyzing radiographs and CBCT images, identifying intricate anatomical details, and forecasting the best course of action. These technologies promise fewer procedural mistakes and improved therapeutic outcomes [44].

The evolution of NiTi endodontic instruments has largely been driven by advances in metallurgy, thermomechanical processing, and surface treatment technologies. Modifications such as M-Wire, CM-Wire, R-phase treatment, Blue treatment, Gold treatment, and Max-Wire have improved flexibility, cyclic fatigue resistance, and canal adaptation, thereby reducing the risk of procedural errors and instrument fracture during root canal preparation. However, although many of these systems demonstrate superior mechanical properties in laboratory investigations, most performance claims are primarily based on in vitro studies conducted under standardized experimental conditions. Therefore, clinical outcomes may vary depending on operator experience, canal anatomy, irrigation protocols, and instrumentation techniques. Further long-term clinical studies are required to determine whether the improved metallurgical properties consistently translate into superior clinical performance and treatment outcomes.

7. Conclusion

Since NiTi endodontic instruments' debut, they never ceased to improve. Thanks to their increased flexibility, fatigue resistance, shape memory and superelasticity, they revolutionized endodontic treatments and improved clinical conditions for practiciens. Continious progress aims to develop instruments that are suitable for minimally invasive endodontics, marking a major point when it comes to safety and precison of endodontic care.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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