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Review Article

Heat-Treated Nickel - Titanium Instruments in Modern Endodontics: A Narrative Review

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ABSTRACT

The use of nickel-titanium (NiTi) instruments has significantly changed the modern endodontic practice, because of their increased flexibility, shape memory of the instruments and torsional stress resistance compared to the traditional stainless-steel instruments. NiTi systems, the rotary and reciprocating systems, have enhanced the efficiency, safety, and predictability of root-canal preparation particularly in curved and anatomically complex canals. Nevertheless, instrument fracture due to cyclic fatigue and torsional stress still remains an important clinical issue. In order to counter these drawbacks, NiTi alloys have been heat treated in order to change their thermomechanical, phase structure as well as the transformation behaviour. The heat treatment enhances the percentage of martensite (M) and rhombohedral (R) -phase giving it a higher level of flexibility, shape memory that is controlled and a stronger ability to withstand fatigue. Various proprietary systems that are characterized by heat-treatment, such M-wire, controlled memory (CM)-wire, blue and gold alloys, exhibit various metallurgical and mechanical characteristics, which influence clinical performance, cutting efficiency and resistance to fractures. The purpose of the review is to synthesize the existing evidence on the use of heat-treated NiTi instruments by focusing on metallurgical properties, mechanical behavior, and fracture mechanisms, in a bid to inform evidence-based instrument choice and clinical decision-making in endodontics.

Keywords: Cyclic fatigue, Endodontic instrumentation, Fracture resistance, Heat-treated NiTi, Metallurgical properties, Root canal preparation, Torsional resistance.

BACKGROUND

The modern-day endodontic practice has greatly been revolutionized with the introduction of nickel-titanium (NiTi) tools because they are highly flexible, have a shape memory, and resist torsion stress and stress in comparison to the conventional tools of stainless-steel. Since then, systems of NiTi rotary and reciprocating systems have been invented and these systems have led to the efficiency, safety and predictability of the root-canal preparation especially in curved and complex-anatomical canals. Nevertheless, the accidental instrumental disconnection is a significant clinical problem, which is frequently attributed to cyclic exhaustion or torsional stress [1]. Thus, ongoing studies have been carried out on the improvement of the mechanical performance and fracture strength of NiTi instruments [2].

The development of heat-treated NiTi alloys is one of the significant developments in this industry. Heat treatment is used to alter the thermomechanical characteristics of NiTi such as the crystalline phase composition, grains structure and transformation temperatures [3]. The NiTi alloys which are traditionally used are primarily austenitic at clinical temperatures and the alloys in the heat-treated state are defined by various fractions of martensite (M) and rhombohedral (R)–phase [4]. These phase changes give an increased compliance, controlled memory (CM) activity and increased fatigue cycling, thus heat-treated instruments are more effective in following canal curvatures and reducing their chance of fracture [5].

Several proprietary protocols of heat-treatment have been invented that form dissimilar NiTi systems like M-wire, CM Wire, Blue, Gold and CM instruments. Both systems share a unique metallurgical feature, the effect of which affects clinical performance directly [6]. Differences in surface oxide layers, microhardness, and phase-transformation behaviour result in variations in cutting efficiency, canal-centring, and cutting life. Thus, the adequate grasp of such metallurgical notions is inevitable to the clinicians who seek to make informed decisions concerning the selection and utilization of tools [7].

Fracture resistance is a crucial parameter of identifying clinical reliability of NiTi instruments. Very high values of cyclic fatigue strength are always identified with heat-treated tools, as opposed to traditional NiTi files but torsional strength and cutting efficiency may be different, based on alloy and design [8]. Also, fracture structures identified by a scanning electron microscope (SEM) define that there are distinctive crack-initiation and propagation mechanisms of both the heat-treated and non-treated tools, and therefore the importance of metallurgy in clinical performance [9-11].

The present review has presented the synthesis of heat-treated NiTi tools with special emphasis on their metallurgical, mechanical performance, and fracture strength. It is possible to relate the article by integrating the current evidence to improve the knowledge of how heat treatment can modify the behaviour of NiTi instruments, as well as develop the evidence-based decision-making application in endodontic practice.

REVIEW

Metallurgy of Heat-treated NiTi Instruments

The NiTi alloys have unique metallurgical properties, in particular, shape memory and superelasticity, which are attributed to reversible phase transformation between austenite and M with respect to the intermediate R-phase [12]. The conventional NiTi tools are mainly austenitic at operating temperature, with low cutting power but being rather rigid. Heat-treatment has become one of the most important strategies of modification to increase the mechanical performance of NiTi instruments by adjusting their phase transformation behavior [13].

NiTi alloys that have undergone heat treatment contain increased M or R -phase contents at intraoral temperature [14]. The fact that M is a softer and compliant material as compared to austenite allows the instruments to more easily accommodate curved root canals and reduces internal stress. Proprietary heat-treatment processes, including M-wire, CM- wire, blue and gold technologies, cause an effect on the microstructure, grain size and transformation temperatures of the alloy. Such metallurgical changes lead to high levels of flexibility, low restoring forces and fatigue resistance without affecting interoperability [15].

Surface properties are also influenced by thermal processing. Corrosion resistance is improved by the formation of titanium oxide layers during the process of heat treatment and can result in an alteration of cutting behaviour. The heat treatment therefore becomes a significant prerequisite in the maximization of flexibility strength and durability of the NiTi endodontic tools [16]. Comparison of metallurgical and clinical performance of NiTi instruments is shown in Table 1.

Metallurgy of NiTi Instruments Heat-treated

The NiTi alloys are unusual in terms of metallurgical properties whereby, shape memory and superelasticity have been ascribed to reversible transformation of austenite to M in regards to middle R-phase. The classic NiTi tools are mostly austenitic at working temperature, of low cutting strength, and rather rigid. One of the most important methods of modification was heat-treatment in order to improve the mechanical performance of NiTi instruments by modifying the behavior of those in terms of phase transformation [17].

NiTi alloys that are heat treated contain more M or R -phase at intraoral temperature. This is because the M is compliant and soft as compared to austenite hence the instruments can easily fit in the curved root canals and internal stress is reduced. The proprietary heat-treatment technologies include M-wire, CM- wire, Blue and Gold technologies, which provide an additional effect on microstructure, grain size and transformation temperatures of the alloy. Such metallurgical changes provide high flexibility levels, low levels of restoring forces and fatigue resistance but lack interoperability [18].

Surface properties are also influenced by thermal processing. Improvement of corrosion resistance is achieved by the formation of titanium oxide film during the heat treatment process and could result in cutting behaviour change. It is therefore implied that the heat treatment is a very precondition during the optimization of the flexibility strength and the durability of the NiTi endodontic tools. Table 2 shows the comparison of metallurgical and mechanical properties of NiTi instruments.

Resistance to Fracture of NiTi Heat Treated Instruments

Fracture of the instrument is still one of the major issues of endodontic practice. The failure of NiTi instruments is normally due to cyclic fatigue or torsional stress. Cyclic fatigue is caused by repeated tension-compression cycles incurred in the curved canals by an instrument, and torsional failure is a consequence of excessive stress experienced when the tip of the file gets stuck in the canal [19].

The NiTi instruments that are heat-treated have been found to have a much better resistance to cyclic fatigue than the traditional NiTi alloys. The higher M content allows the tool to better absorb and redistribute the stress hence slowing down the cracking and spreading of the stress. Long fatigue life has been observed in several in vitro studies in which instruments where heated had extended fatigue life in simulated clinical environments.

However, the torsional resistance can be different depending on the specific heat-treatment regime and the shape of tools. Although certain heat-treated instruments show slightly reduced torsional strength because of decreased stiffness, it is usually offset by enhanced flexibility and so-called controlled deformation before fracture. Analyses of SEM show that fracture pattern in heat-treated files is different i.e. fracture surfaces are smoother and slower in development of cracks, which again supports their improved fatigue behavior [20]. Table 3 shows the comparison of fracture behavior and fatigue resistance of NiTi instruments.

Clinical Implications

With the introduction of heat-treated NiTi tools, the pre-treatment of root canals has improved significantly regarding safety and efficiency. Their enhanced versatility and stamina make them particularly convenient to curved and complicated canal systems. It is wound, though, that when making selections, clinicians must take into account not only the metallurgical characteristics but also the design characteristics of instruments since the performance and fracture resistance depends on many factors including the kinematics of motion, canal anatomy, and usage guidelines [21]. Table 4 shows the clinical implications of heat-treated NiTi instruments in endodontics

Table 1: Comparison of metallurgical and clinical performance of NiTi instruments

Aspect	Conventional NiTi Instruments	Heat-Treated NiTi Instruments
Primary phase at operating temperature	Predominantly austenitic	Increased M and/or R-phase
Phase transformation behavior	Limited reversible transformation	Modified transformation with adjusted transition temperatures
Flexibility	Relatively rigid	Highly flexible and compliant
Internal stress in curved canals	Higher internal stress	Reduced internal stress
Ability to negotiate curved canals	Limited adaptability	Enhanced adaptability to canal curvature
Heat-treatment technologies	Not applicable	M-Wire, CM Wire, Blue, Gold technologies
Microstructure and grain size	Unmodified microstructure	Altered microstructure and refined grain size
Restoring force	Higher restoring force	Lower restoring force
Fatigue resistance	Lower cyclic fatigue resistance	Improved fatigue resistance
Surface characteristics	Minimal oxide layer	Titanium oxide layer formation
Corrosion resistance	Moderate	Enhanced corrosion resistance

Table 1 Continued....		
Cutting behavior	Conventional cutting action	Altered cutting behavior due to surface changes
Overall clinical durability	Moderate	Improved strength and durability

Table 2: Comparison of metallurgical and mechanical properties of NiTi instruments

Parameter	**Conventional NiTi Instruments**	**Heat-Treated NiTi Instruments**
Metallurgical properties	Shape memory and superelasticity due to austenitic phase	Shape memory and superelasticity influenced by increased M/R-phase
Phase transformation	Austenite-dominant with limited transformation	Modified austenite–M transformation via R-phase
Phase at working/intraoral temperature	Predominantly austenitic	Increased M and/or R-phase content
Rigidity	Relatively rigid	More compliant and flexible
Cutting strength	Lower cutting strength	Altered cutting behavior
Adaptation to curved canals	Limited adaptability	Improved adaptation to curved root canals
Internal stress	Higher internal stress	Reduced internal stress
Heat-treatment technologies	Not applicable	M-Wire, CM -Wire, Blue, Gold
Microstructure and grain size	Unmodified microstructure	Modified microstructure and grain refinement
Transformation temperature	Unaltered	Adjusted transformation temperatures
Restoring force	Higher restoring force	Reduced restoring force
Fatigue resistance	Lower	Improved fatigue resistance
Surface characteristics	Minimal oxide layer	Titanium oxide film formation
Corrosion resistance	Moderate	Enhanced corrosion resistance
Flexibility and durability	Limited optimization	Optimized flexibility, strength, and durability

Table 3: Comparison of fracture behavior and fatigue resistance of NiTi instruments

Parameter	**Conventional NiTi Instruments**	**Heat-Treated NiTi Instruments**
Main causes of fracture	Cyclic fatigue and torsional stress	Cyclic fatigue and torsional stress
Cyclic fatigue mechanism	Repeated tension–compression cycles in curved canals	Same mechanism but better stress tolerance
Cyclic fatigue resistance	Lower resistance	Significantly higher resistance
Phase composition influence	Predominantly austenitic	Increased M content
Stress absorption and distribution	Limited stress redistribution	Improved stress absorption and redistribution
Crack initiation and propagation	Faster crack initiation and propagation	Delayed crack initiation and slower propagation
Fatigue life (in vitro studies)	Shorter fatigue life	Extended fatigue life in simulated clinical conditions

Table 4: Clinical implications of heat-treated NiTi instruments in endodontics

Clinical Aspect	**Implication of Heat-Treated NiTi Instruments**
Safety during canal preparation	Improved safety with reduced risk of instrument separation
Efficiency of root canal preparation	Enhanced efficiency and smoother instrumentation
Flexibility	Greater versatility due to increased flexibility
Use in curved canals	Particularly suitable for curved canal systems
Use in complex anatomy	Better performance in complicated canal configurations
Instrument durability	Increased stamina and longer clinical lifespan
Instrument selection considerations	Requires evaluation of metallurgical and design features
Influence of metallurgical properties	Affects flexibility, fatigue resistance, and fracture behavior
Influence of design features	Cross-section, taper, and size impact performance
Effect of kinematics of motion	Performance varies with rotary or reciprocating motion
Role of canal anatomy	Canal curvature and complexity influence instrument behavior
Importance of usage guidelines	Adherence to manufacturer instructions reduces fracture risk
Overall clinical outcome	Improved predictability and treatment success

DISCUSSION

NiTi endodontic instruments have been substantially enhanced in terms of their metallurgical and mechanical properties due to heat treatment. Having a modified behavior of phase transformation and a higher content of M and R-phase at clinical temperatures, the NiTi instruments were heat-treated, which results in a high flexibility and lowering of restoring forces in comparison to traditional austenitic alloys. Such modifications enable a more efficient response to curvy and complicated anatomies of the root canals and a reduced number of internal forces during instrumentation [22].

The enhanced cyclic fatigue resistance of heat-treated NiTi instruments is one of the greatest benefits. The higher amount of M phase allows the additional possibilities of stress absorption and redistribution, which prolongs the crack initiation and propagation and, consequently, the instrument fatigue life [23]. Even though the torsional resistance can be dependent on the given process of heat-treatment and the design of the instrument, increased flexibility and controlled deformation hereto fracture can usually counterbalance decreased stiffness to offer a safer clinical failure pattern [24].

Heat treatment also causes surface changes such as formation of titanium oxide layers that increases corrosion resistance and can also affect cutting behavior [25]. These tools have enhanced efficiency and safety of endodontic procedures in a clinical setting [26]. There are however several factors that must be considered to achieve optimal results which include; the design of the instruments, the motion kinematics, the canal anatomy, and also by following the instructions of the manufacturers [27]. It is imperative to understand these interacting factors, which will enable opting out of the benefits of heat-treated NiTi instruments with minimal risk of fractures [28].

CONCLUSION

NiTi instruments that are heat-treated have significantly improved the safety and effectiveness of endodontic instrumentation. Heat treatment enhances the M and R-phase content of NiTi alloys by modifying their behavior of the phase-transformation at clinically relevant temperatures to provide greater flexibility, reduced restorative forces, and increased cyclic fatigue resistance. These qualities enable high adjustment to curvy and complex root-canal anatomies as well as reduce the risk of unregulated instrument fracture. Though the level of torsional resistance might vary with instrument design and with special heat-treatment procedures, deformation that prefigures fracture gives a further clinical benefit. Altogether, heat-treated NiTi instruments represent a significant innovation in the field of endodontics, which emphasizes the need to pay attention to the choice of instruments and use accurate clinical methods to achieve the best results.

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AUTHOR CONTRIBUTIONS

Eshieva Asel Abdyrakmanovna: Conceptualization, methodology, writing the original draft, data analysis, review and editing.

ABBREVIATIONS USED IN THE STUDY

a) NiTi: Nickel-Titanium
b) RCT: Root Canal Treatment
c) SEM: Scanning Electron Microscopy
d) EDS: Energy Dispersive Spectroscopy
e) XRD: X-ray Diffraction
f) FDA: Food and Drug Administration
g) ISO: International Organization for Standardization
h) HAP: Hydroxyapatite
i) SLA: Surface Laser Ablation

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