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Thermally Treated NiTi Endodontic Instruments and its Application in Root Canal Cleaning and Shaping

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Abstract

Objective: This Review aims to clarify how efficient thermally treated NiTi instruments are in root canal cleaning and shaping and if they are superior to other File Systems or not. What is the status of the development of thermally treated instruments? Are there any new thermal treatment processes, and how effective are they compared to each other?

Methods: Narrative Literature Review

Conclusion: Thermally treated endodontic NiTi instruments show very good results in root canal cleaning and shaping due to their highly improved properties, such as cyclic fatigue resistance, corrosion resistance and cutting efficiency. The results in root canal cleaning and shaping are shown as better with thermally treated NiTi instruments. Differences in the efficiency between the thermally treated instruments are related to different types of thermal treatments on the Files.

1. Introduction

Endodontics is an important part of dentistry and also belong to the most complicated working fields for many decades. The root canal treatment is mostly the last chance to keep a tooth in the mouth before its extraction may be considered. Therefore, very efficient instruments which work accurately and are very resistant to fracture to point to the best possible results are needed. A broken instrument inside the root canal is a big problem and should be prevented. Thermally treated Nickel Titanium (NiTi) endodontic instruments are now the most advanced and best instruments for the root canal cleaning and shaping. The so-called Nickel-Titanium alloy was first invented by the U.S. space program in 1963. In 1971 it found the first use in the dental field, strictly speaking in the orthodontic treatment for producing the orthodontic wires. For the Endodontic treatment, the first handheld NiTi endodontic instrument was invented and used in 1988 [1]. The NiTi compound consists of approximately 56% Nickel and 44% of Titanium[2]. The NiTi instruments still have problems with fracturing today during the treatment, although they have many advantages in comparison to the Stainless-Steel instruments. Due to the missing flexibility of Stainless-Steel Instruments, especially in curved Canals, they tend to straighten them. Also, a risk of perforation and transportation is likely with Stainless Steel instruments. This fact makes them less practical for root canal treatment compared to NiTi instruments[21]. Since their invention, the NiTi instruments have been improved and "optimized" further. Through different kinds of production processes, one tried to improve the performance of these instruments and kept trying to improve the characteristics of the Instruments always on. To fulfil this process, the NiTi Instruments were treated with thermal, mechanical, electropolishing or electric discharge mac procedures [3]. However, this Review will focus on the impact of different types of thermal treatment methods on the properties and efficiency of NiTi instruments and the outcome of the root canal cleaning and shaping procedures related to these instruments. Are there better results that can be achieved with the thermally treated instruments, and what influence does the thermal treatment have on the properties and characteristics of the NiTi instrument? This is an important question for clinicians and needs to be clarified because the practitioner needs to know which instrument can provide the best treatment outcome.

2. Review

2.1 Literature Search methodology

A comprehensive literature search was performed searching in the databases of Google Scholar, PubMed and Web of Science between the 1st January 2017 and 22nd April 2023. To find the acceptable papers, the following search strategy was used to find the most relevant studies to the topic: (thermal-treated NiTi instruments or heat-treated NiTi instruments) OR (conventional NiTi instruments or Nitinol Instruments) OR (NiTi alloys in endodontics or NiTi alloys) AND (root canal treatment or root canal or endodontics or root canal filling) OR (root canal cleaning or root canal shaping) Laboratory and clinical studies evaluating the minimum of one Thermal treatment or characteristic on NiTi instruments were included in this Review. The reference lists of the studies and previously published reviews were also searched. The studies performed on animal teeth were excluded.

2.2 Root Canal Cleaning and Shaping

The root canal cleaning and shaping is one of the most important steps of the root canal treatment. It is the basic work to maintain a damaged or infected tooth. During the cleaning process, the infected pulp tissue in the root canal is removed. During the shaping process, the root canal system gets shaped to a good and wide shape to be open enough for the filling while all infected tissue rests at the canal wall gets removed[4]. Cleaning and shaping are the two main steps of the root canal treatment. The root canal system is shaped using special instruments, which are usually made of Nickel-Titanium alloys. These instruments are inserted into the root canal and rotate/reciprocate to remove tissue, bacteria and other debris. The size and shape of the instruments vary depending on the shape of the root canal System and the individual needs of the patient. Shaping the root canal system refers to creating a clean, shaped canal that meets the needs of root canal treatment. As mentioned before, this is accomplished by removing tissue and bacteria from the walls of the canal and shaping them to a specific size and shape. The NiTi instruments are tailored to a specific size and shape to completely clean and shape the root canal. Care is taken to ensure that the shape and size of the canal is designed in such a way that later filling and sealing is possible [5].

2.3 Characteristics of conventional and heat-treated NiTi endodontic instruments

Comparing the two types of NiTi endodontic instruments, conventional NiTi instruments and the thermally treated NiTi instruments. They both have specific characteristics which differ from each other. These characteristics are very important and affect the outcome of the root canal treatment

2.3.1 Flexibility

Starting with the conventional NiTi instruments, one of their biggest characteristics is their flexibility. This so-called super elasticity is based on its unique Nickel and Titanium alloy. This alloy guarantees that the instruments bend and deform under pressure before they move back into their normal previous form. They are able to adapt to the curved shape of root canals without breaking or deforming. Due to this characteristic, the Dentist is able to clean and shape the root canal much better, which supports a better disinfection and healing of the root canal.[6] The heat-treated NiTi Instruments are characterized by their higher flexibility compared to conventional NiTi instruments. They gain their higher flexibility by a heat treatment process followed by a fast cooling down. The higher flexibility results from a changed crystalline structure of the instruments. The instruments adapt better to the curved shape of root canals, cause less tension on the walls of the root canal and ensure less risk of perforation and other damage on the root canal wall [8].

2.3.2 Shape Memory Effect

Another superior characteristic of NiTi instruments is their Shape Memory effect. They are able to return to their previous shape after they have been bent and deformed. That means even if they are moved through tiny, narrow and curved root canals, they guarantee the memory effect of their original shape. This is a big advantage to stainless steel instruments which often break and bend when moved through narrow curves. This shape memory effect is activated by the body temperature. When the instrument is heated to body temperature, it remembers and keeps its original shape. Another advantage of the memory shape effect is that the amount of instrument exchange is reduced due to a longer usability because it moves back to its original shape [9].

2.3.3 The Resistance to Fracture

The resistance to fracture is one of the most important Characteristics of the NiTi instruments because a broken instrument inside the root canal is a big Problem. The quality of the alloy is important when it comes to the fracture of instruments. A higher quality in the alloy offers a greater resistance to the breaking point [8]. The manufacturing technique can also influence the breaking resistance; some production techniques can offer a higher density and a higher homogeneity of the instrument [10]. Another very important point to mention is the experience of the operator. An operator with many years of experience is able to control the stress on the instrument better and to reduce the possibility of breaking. Nevertheless, the breaking of the instrument is a big problem, especially in curved canals [11]. Heat-treated NiTi instruments have a higher resistance to breaking. Again, this bigger resistance is to be traced back to the changed crystal structure of the NiTi alloy. The heat-treated Instruments can be used with higher speed and pressure [12].

2.3.4 The cutting and shaping efficiency

The cutting/shaping efficiency of the NiTi instruments plays another important role, or the instrument should clean and form the root canal fast and effectively way without leaving unnecessary damage on the root walls or the instr in the augment itself. Instruments with a higher efficiency are able to clean the root canal in less time and with less number of movements. The method of instrumentation can have a big influence on the efficiency. A study compared the efficiency of reciprocating and rotating movements and came to the result that the reciprocating movement showed better results than the rotating movement [12].

2.4 Cyclic fatigue resistance and Fracture of NiTi Endodontic Instruments

Without a doubt, NiTi Endodontic Instruments are much better and result in less Instrument failure than Stainless Steel Instruments. But still, the NiTi Instruments are not perfect and tend to fracture inside of the root Canal. Especially curved root canals are a very big challenge for the Instruments. If the Instrument is not flexible enough and straightens in the Canal, it leads to high pressure on the Wall of a root canal. Therefore, these NiTi Instruments always get developed for Better Results in root canal treatment. The Niti Alloys can be divided into two different types. There is an austenite and martensite alloy phase. The austenite Phase is conventional and not heat-treated NiTi alloy. These are not as flexible as the Martensic Instruments. One of the biggest advantages of the Martensic alloys is the shape memory of Material. They are able to stay kind of in the shape of the root canal, which reduces the pressure on the root wall in curved canals. Also, they are less likely to fracture due to their huge flexibility. Two Phases of a fracture in the NiTi Instruments can be outpointed. The fracture begins with an initial crack which means that micro-cracks are forming. These micro-cracks grow preferentially on the side of crystallographic planes and gain connections with the micro-cracks. The second Phase is the final fracture of the instrument. The Cyclic fatigue resistance of these Instruments is counted by the time and cycles the Instruments are used until the fracture occurs. From the clinical point of view, the fracture, in most cases, happens due to the same Problems. The NiTi Instruments stick at some part inside of the root canal while the Instrument is still turning and causes torsional stress on the Instrument. Also, the high flexibility of these NiTi alloys comes to an end. When the limit of its elasticity is reached, a fracture of the Instrument occurs. Another Problem which occurs due to the clinical part is the temperature. The inside temperature of the canal and as well the outside temperature which has an effect on the properties of the Instrument [6,49]. A study by Drukteinis et al. (2020) compared different kinds of thermal-treated NiTi Endodontic instruments related to their properties during root canal shaping. The aim was to find out how resistant the NiTi Files are to cyclic fatigue. The root canals were shaped by using three different thermally treated NiTi Files: HyFlex CM, HyFlex EDM and EdgeFile. The HyFlex CM is made from a new type of NiTi wire. The CM means controlled memory; they have no shape memory but are very flexible. HyFlex EDM is the first Instrument produced by the new electric discharge machining. During this process, the wire surface gets melted and evaporated by pulsed electrical discharge. This process makes the instrument harder and more resistant to fracture. Edge Files are made from Fire-Wire, which is an annealed heat-treated NiTi alloy. This provides the instruments with more flexibility, flexural strength and resistance to cyclic fatigue. The study showed that the Edge Files were the most resistant to fracture, measured by the time to fracture or the number of cycles to fracture in 672 seconds. HyFlex EDM files with 376 seconds and HyFlex CM files with 136 seconds to fracture. This shows that the EdgeFiles are the most resistant files to cyclic fatigue [7]. The study of Gianluca Plotino et al. compared Vortex Blue Rotary files and ProFile Vortex instruments, made of M-Wire, which have the same Properties but only differ in their manufacturing Process. They found that ProFile Vortex had a great increase in cyclic fatigue by approximately 150% when compared to conventional NiTi instruments. The Vortex Blue file had an increased cyclic fatigue resistance and flexibility compared to the ProFile Vortex instruments [22].

2.5 Different types of treatment on NiTi instruments

Regarding the material, NiTi instruments are “softer” than stainless steel instruments. They have a higher flexibility but therefore are also more likely to fracture. This is due to surface defects, and due to this, the cutting efficiency is decreased in NiTi instruments. To solve this problem, one tried to improve the properties of the NiTi instruments through different types of treatments on the NiTi Alloy. These methods are

Plasma immersion ion implementation, thermal nitridation, Cryogenic treatment and Electropolishing [13].

2.5.1 Plasma immersion ion implementation

In the process of the Plasma immersion ion implementation, the sample is immersed in the plasma in a chamber and applied on the sample is a highly negative pulsating voltage. The hardness, friction coefficients and wear resistance of the instruments should be improved. The ion implantation is a process during which ions are extracted from plasma and then accelerated and bombarded in a device. This method showed a very good effect on the Cycle to fracture (CTF) with 510 cycles compared to annealed Instruments with 428 cycles [5,13,19].

2.5.2 Thermal nitridation

During the thermal nitridation procedure, NiTi samples with a phase transformation temperature of 15 degrees Celsius are annealed at 900 degrees Celsius for 1.5 hours and then at 1000 degrees Celsius for 1 hour in sealed containers. The Nitrogen atoms diffuse into the samples, and atmospheric oxygen is stopped by a steel foil consisting of a notable amount of Cr. The modified surface consists of a thin outer layer of TiN and a thicker layer of TiNi underneath. This process is increasing the cutting efficiency and corrosion resistance of the instrument in contact with sodium hypochlorite [13].

2.5.3 Cryogenic treatment

In this process during which, the Instrument is put in a very cold bath of liquid which has a temperature of -196 degrees Celsius, and after this bath, the instrument is slowly heated up to room temperature. The process is increasing the overall strength of the metals and also its cutting efficiency [5].

2.5.4 Electropolishing

Typically, the instrument is immersed in a temperature-controlled bath of electrolyte and serves as the anode when it is connected to the positive terminal of a direct current power supply, and the negative terminal is attached to the cathode. As the current passes, the surface of the metal oxidizes and dissolves in the electrolyte. A reduction reaction occurs at the cathode, which normally produces hydrogen. The advantages of the Instrument of this process are the elimination of defective surface layers through surface oxidization. The life of the NiTi instruments can be prolonged by this method due to the reduction of surface irregularities which are very sensitive points for stress and then crack initiation [5,13].

2.6 Comparison of different thermal Treatment effectiveness on NiTi Instruments

2.6.1 Corrosion Resistance

In the following, the different kinds of thermal treatments on the NiTi Instruments will be evaluated and compared regarding their advantages. Starting from the Plasma Immersion Ion Implementation, there was a study by Shanaghi et al. (2021) that tested the influence of this procedure on the corrosion of the Alloy and its antibacterial effect. The study came to the Result that a coating with 1.7-micrometer micrometre and the roughness of the surface of 17 +- 2 nanometers provided better corrosion resistance. Regarding the antibacterial effect after culturing for 6 and 24 hours, it increased by 76.7% and 98.9% on the Nitrogen hydroxyapatite coating (NHA) and Nitrogen hydroxyapatite ciprofloxacin coating (NHACip). NHA is a NiTi alloy with hydroxyapatite coating (HA), and NHACip is the same but with additional ciprofloxacin (Cip) [17]. Another Study by Shanagi et al. (2022) about the mechanical Properties of NiTi, which is modified by Carbon Plasma Immersion ion implantation, found that the service life of these NiTi alloys can be prolonged by this process [18]. The study of Justyna Witkowska et al. (2017) investigated the corrosion resistance, structure and surface roughness of NiTi alloy after using low-temperature plasma as surface treatment. The glow discharge oxidizing process was performed at 290 degrees Celsius in an atmosphere of air with a pressure of 1.6 hPa for 30 minutes in the working chamber. The study concluded that the corrosion resistance of NiTi alloy is increasing by the formed layer of titanium oxynitride and 40nm-thick amorphous carbon as the surface coating [23]. A study performed by UeiMing et al. (2007) tried to put argon ions alongside nitrogen ions while inserting them into the surface of NiTi Instruments during the Plasma Immersion Ion implementation. After analyzing the results, it showed that there was no significant difference in the surface layer of the NiTi instrument after the conventional Plasma Immersion ion implantation and the trial in the study [19]. Another study focusing on corrosion resistance published by Sui et al. (2006) assessed the Plasma immersion ion implantation. It is found that a diamond-like carbon film of approximately 200 nm thickness formed, and no pores are found on this Diamond-like carbon (DLC) coated area. It was concluded that the DLC coating is improving the corrosion resistance of the NiTi alloy compared to the uncoated sample. Also, the Ni-ion release was more or less not present in the DLC-coated sample. Which is a very important property [24]. The study of Rapisarda et al. compared how effective the ionic Implementation and thermal nitridation are on the wear and cutting efficiency of NiTi instruments. The study came to the result that the ionic implantation showed the highest increase in cutting efficiency. The thermal nitridation also showed an increase in the cutting ability compared to the control group, which underwent no surface treatment. Another Key point was the fact that the control groups cutting ability was decreased after a usage time of 240 seconds, separated into three cycles of 80 seconds. The NiTi instruments receiving thermal nitridation or Ion implantation were not losing their cutting efficiency [20].

2.6.2 Cyclic Fatigue Resistance and Bending Resistance

The Plasma Nitriding treatment is examined regarding the cyclic fatigue resistance of NiTi instruments in the study performed by Michal Bumbalek et al. (2021) by comparing nontreated and two kinds of plasma nitrided instruments. Two different processes were used, one with 550 degrees Celsius for 20 hours and the other one with 470 degrees Celsius for 4 hours. In process one, a layer of 2-2.7 micrometer thickness was reached, and in process two, a 3-3.8 micrometre layer thickness was reached. Process number 2 showed significantly better results regarding the cycles until fracture at the taper sizes 10/.04 and 20/.06 compared to Process 1. For taper size 15/.05 Process number 1 showed better results regarding the cycles to fracture than Process number 2. This indicates that for different types of Taper sizes, different kinds of plasma nitridation processes could be better when it comes to cyclic fatigue [25]. Another study by Chih-wen Chi et al. (2017) also evaluated the cyclic fatigue and the cutting efficiency as well of ProTaper Universal

F2 instruments. Three groups of files were divided, no treatment, heat treatment at 400 degrees Celsius and another group at 600 degrees Celsius. The study concludes that files receiving the 600-degree Celsius treatment had a higher cyclic fatigue increasing from 1.7 to 5.5, but the cutting efficiency was decreasing compared to the control and 400-degree Celsius group. The 400-degree Celsius group could improve in cutting efficiency and in cyclic fatigue, increasing from 2.1 to 2.8 compared to both other groups. Therefore, it indicates that the thermal treatment at 400 degrees Celsius is the better choice for use in clinical practice [26]. Also, the bending properties are important for NiTi instruments in the root canal treatment. The study performed by Yahata et. al. (2009) investigated this with an additional heat treatment. There were five groups, test group, heat-treated groups by 440 degrees Celsius for 10 and 30 minutes and 500 degrees Celsius for 10 and 30 minutes as well. The study found that the time frame of 10 minutes had better results regarding the bending properties compared to the 30-minute samples. These bending properties were related to their transformation behaviour. The 440 degrees Celsius treatment showed the best result in improving the bending properties, and therefore, it can be suspected that the flexibility of the NiTi instruments can be improved by the treatment with 440 degrees Celsius for 10 minutes [27]. A study by Khalil et al. (2019) compared the ProTaper Gold and EdgeEvolve files in terms of cyclic fatigue, bending resistance and surface roughness. Both instruments are heat treated but by different kinds of treatments and were tested in root canals with single and double curvatures. The EdgeEvolve file showed better results in all three tested properties. The flexibility was higher compared to ProTaper Gold, and the surface roughness was lower; the EdgeEvolve has a very nice smooth surface which seems to prevent the initiation of cracks. Also, the Cyclic fatigue resistance was higher in the EdgeEvolve files. The EdgeEvolve files were treated by a cryogenic heat treatment, which indicates that the cryogenic heat treatment shows better results on the NiTi instruments [28]. To find out if cryogenic treatment is providing NiTi instruments with better properties, the study performed by Vinothkumar et. al. (2016) investigated this regarding the cyclic fatigue resistance and cutting efficiency. Therefore, three groups of 25 NiTi instruments were taken, one control group and two experimental groups. One group underwent Deep cryogenic treatment at -185 degree Celsius for 24 hours, and the other group at -185 degree Celsius for 6 hours. The study result shows that the deep cryogenic treatment for 24 hours showed the best result in cycles to failure. The instruments took 2280 +-205 cycles till failure, while the control group and 6 hours deep cryogenic treated group had more or less the same cycles to failure of 2011+-219 and 2026+-93. In the cutting efficiency, there was no significant difference between all three groups. This result shows that the deep cryogenic treatment of NiTi instruments can improve their cyclic fatigue resistance with no loss of cutting efficiency, but the duration of the treatment is important, and a too-small duration has no effect on the instrument [29]. Another study investigating the effect on the cyclic fatigue resistance of deep cryogenic treatment was performed by Yazdizadeh et. al.. (2017). The 40 NiTi instruments were divided into 2 groups of the RaCe and Mtwo systems, subdivided into 2 groups each, control and cryogenic treated group. Cryogenic treatment was done at -196 degrees Celsius for 24 hours. It concludes that there is a difference between the two different types of NiTi Systems in the cycles to fail and time to fail, RaCe 4175.4 and Mtwo 1248.2 cycles to fail. The time to fail was 274.8 for Mtwo and 313.2 for RaCe. But there was no difference between the cryogenic treated and none treated instruments. This indicates that there is a difference between the different NiTi instrument systems, but there is no effect of the Cryogenic treatment on the cyclic fatigue resistance. The results of this study stand in contrast to the results of the previous study, which showed an increase in cyclic fatigue resistance [30]. To evaluate the effect of Cryogenic treatment, more studies need to be examined. The study performed by Maamoun Ataya et al. (2018) evaluated the cyclic fatigue resistance and bending resistance by comparing the heat-treated OneFlare system and the conventional OneFlare system. Therefore 90 instruments were taken and evaluated regarding the cycles to failure for the cyclic fatigue resistance and at a 45-degree bending moment for the bending resistance. The result showed that the OneFlare system produced from a heat-treated NiTi wire showed a better cyclic fatigue resistance and a better-bending resistance due to less stiffness [32]. To investigate if different thermally treated NiTi instruments or conventional NiTi instruments have better cyclic fatigue resistance and bending stiffness, the study by Hye-Jin Goo et al. (2017) compared those instruments. The five instrument systems compared are V-Taper 2, V-Taper 2H, Hyflex CM, HyFlex EDM and ProTaper Next X2. The study indicated that instruments produced by CM-wire have the highest cyclic fatigue resistance, even higher than the instruments produced by M-wire. CM-wire and Mwire are both thermally treated NiTi alloys. CM- and M-wire showed both a higher cyclic fatigue resistance than conventional

NiTi files [38]. The study of Pirani et al. (2015) compared the HyFlex Cm and HyFlex EDM instrument systems. HyFlex EDM is manufactured by an electric discharge machining process. For this reason, thirty HyFlex EDM files were compared to 20 HyFlex CM files regarding their cyclic fatigue resistance in artificial canals with a 70-degree angle and a radius of 5 mm of curvature. The files were all rotated until the fracture occurred, and the time to fracture and cycles to fracture were recorded. The study concluded that the HyFlex EDM files have a much higher cyclic fatigue resistance. The taper 25.04 of the CM file has 696 +-271 cycles to failure compared with the taper 25.08 of the EDM files, they have 981 +-329 cycles to failure. The difference is bigger at the taper 40.04 for both instruments. The CM files have 257 +-100, and the EDM files 2013 +-425 cycles to failure. This means that the HyFlex EDM file has an increased cyclic fatigue resistance of up to 700% when compared to HyFlex CM instruments [39]. The study by Weber Schmidt Pereira Lopes et al. (2021) tested three thermal-treated NiTi instruments about their flexibility and cyclic fatigue resistance. The three file systems are Reciproc R25, Reciproc Blue R25 and WaveOne Gold Primary. Therefore the flexibility was tested by 45-degree bending, and the cyclic fatigue resistance in a stainless steel canal with 86 degrees angle and 6 mm was the radius of curvature. The flexibility was the best for the Reciproc Blue R25. Also, the cyclic fatigue resistance is the best for the Reciproc Blue R25. The WaveOne Gold Primary showed the most bad result in all tests [40]. The results of the discussed studies always show that the Reciproc Blue R25 file has the best properties for cyclic fatigue resistance and bending resistance. This can be traced back to the special blue thermomechanical treatment. This was investigated by the study of De-Deus et al. (2017), which aimed to evaluate the blue thermal treatment on conventional M-Wire Reciproc files. This was tested at a 60-degree angle and 5 mm of curvature radius in stainless steel artificial canals for the cyclic fatigue resistance and a 45-degree bending test for the bending resistance. In the cyclic fatigue test, the instrument treated with the blue thermomechanical treatment showed better results. The time to fracture in the conventional Reciproc file is between 210 and 225 seconds, while this time for the Reciproc Blue file is 300 to 340 seconds. But in the test for the bending resistance, the conventional Reciproc file shows a better result. The maximum strength on the Reciproc Blue file is 350 to 375 gf, and on the conventional Reciproc file, 400 to 460 gf. The results of this study show that the Blue thermal treatment has a good influence on some properties of the files but, on the other hand, lowers other properties [41]. The study from Xiao-Mei Hou et al. (2021) investigates the mechanical properties of NiTi instruments after receiving the blue or gold heat treatments. Therefore, the file systems WaveOne Gold, ProTaper Gold, Reciproc Blue, ProTaper Next, WavoOne and ProTaper are compared. To test the cyclic fatigue resistance, a stainless-steel artificial canal with a 60-degree angle and 3.5 mm curvature radius was used. The tests showed that WaveOne Gold has the highest fatigue resistance with 560 +-111 cycles to failure; the second best is ProTaper Gold with 222 +-36 cycles to failure. Reciproc Blue showed less fatigue resistance with 153 +- 41 cycles to failure, and ProTaper Next had 158 +- 22 cycles to failure. Both conventional M-Wire files, WaveOne and ProTaper, showed the least cyclic fatigue resistance with 128 +-18 and 65 +-20 cycles to failure. The results of the study showed that the NiTi instruments treated with the gold or blue heat treatment showed improved properties for cyclic fatigue resistance, which leads to the conclusion that these treatments have a big influence on the properties. The Gold heat treatment indicates to have a better influence on the cyclic fatigue resistance than the blue heat treatment [42]. To find out if different kinds of thermal treatments on NiTi instruments can affect cyclic fatigue resistance in different ways, the study by Miccoli et al. (2017) investigated exactly this by comparing two similar NiTi instruments which undergo different thermal treatments. The test is performed in an artificial stainless steel canal with a 60-degree angle and a 5mm curvature radius. The cycles and time to failure is evaluated. The M3 ProGold files show much better results in both tests, 1012 +-77 cycles to failure and 173.5 +-14.7 seconds to failure. The M3 files have lasted 128.3 +-11.6 seconds to failure and 748 +-62 cycles to failure. This result shows the different effects of different thermal treatments on NiTi instruments since both instruments have the same design and same alloy because they are produced by the same manufacturer. The cyclic fatigue resistance in the NiTi instruments is different due to the different thermal treatments they undergo [43].

2.6.3 Cutting efficiency

The study published by Gingu Koshy George et al. (2011) evaluated the cutting efficiency of three NiTi instruments after deep dry cryogenic treatment. 20 files were used, 10 untreated and 10 cryotreated files. The instruments were cooled down to -184 degrees

Celsius for 2 hours and 18 minutes and then for 36 hours at a temperature of -88.44 degree Celsius. The cryogenically treated instruments showed a much longer time to fracture and a number of cycles to fracture. Groups B1, B2 and B3 showed better properties in all categories. The results were as follows: Group A1 had a number of cycles to fracture of 352 +-2, and Group B1 had 405 +-3. Group A2 has 452 +-3 compared to group B2 with 708 +-4. Group A3 has 268 +-7 cycles to fracture, and group B3 is 359 +-10. These results show clearly that the deep dry cryotherapy can highly improve the cyclic fatigue resistance of NiTi instruments and should be researched more [31]. A study performed by Pedulla et al. (2019) concluded the cutting efficiency of conventional and heat-treated NiTi rotary and reciprocating instruments at an angle of 45, 70 and 90 degrees. Instruments compared are the HyFlex EDM Glidepath file, One G, R-Pilot and WaveOne Gold Glider. The study concluded that the R-Pilot and WaveOne Gold Glider had the best cutting efficiency in all different angles and therefore showed better properties [35]. Another study from Eugenio Pedulla et al. (2021) compared the Reciproc R25 and the Reciproc blue R25 and did this also at the angle of 45, 70 and 90 degrees. For testing the cutting efficiency, the weight loss of a gypsum block was taken after 120 seconds of cutting. The Reciproc Blue showed a much higher cutting efficiency at an angle of 45 degrees compared to the Reciproc R 25. At the angle of 70 and 90 degrees, there was no difference detected between both instruments. The cutting efficiency and depth was shown to be the most efficient with Reciproc Blue at the angle of 45 degrees. This leads to the conclusion that some thermal-treated NiTi instruments show better properties at different curvature angles of the root canal [36].

2.7 The influence of thermal treatment on corrosion of NiTi files in Sodium Hypochlorite

Sodium Hypochlorite is a very important irrigating solution in the root canal cleaning and shaping. It can have a negative effect on the NiTi files and cause a lower life expectation. Therefore, the influence of the thermal treatment on NiTi files can be investigated in having a positive influence on the NiTi alloy. The study performed by Han-Hsing Lin et al. (2020) compared the effect of sodium hypochlorite on conventional and thermally treated NiTi instruments. Five different file systems, two conventional and three thermally treated, were taken. They were put for 5, 10 and 20 minutes and 1, 6 and 24 hours in the sodium hypochlorite. The result of this test concluded that the thermally treated NiTi instruments except for one show better corrosion resistance than the other NiTi instruments. This result indicates that thermal treatment on NiTi instruments can increase their corrosion resistance when immersed in sodium hypochlorite, but some thermal treatment may also have no positive effect on this property. It needs to be said that under shorter time periods of sodium hypochlorite immersion, there was no difference between all test groups. To evaluate the effect of heat treatment on corrosion resistance in connection with contact with sodium hypochlorite, more studies need to be evaluated [44]. Another interesting study is observing thermal treated NiTi instruments submerged in sodium hypochlorite regarding its cyclic fatigue resistance afterwords. Artificial canals were used and submerged into distilled water, 2.5% sodium hypochlorite and 5.25& NaOCL and the temperature was set at 25, 37 and 60 degrees Celsius. The best cyclic fatigue resistance was shown in 5.25% NaOCL and highest in distilled water at 25 degrees Celsius. This indicates that the irrigation solution and temperature have also an influence on the cyclic fatigue resistance [34]. Another study was performed by Ahmet Keles et al. (2019) and focused on the effect of different sodium hypochlorite temperatures and the effect on the cyclic fatigue resistance of NiTi files and heat-treated NiTi files by this. Therefore 5 samples were taken, control, distilled water at 37 degrees Celsius and 60 degrees Celsius, sodium hypochlorite at 37 degrees Celsius and 60 degrees Celsius. Stainless steel artificial canals were taken with a 60-degree angle and 5-mm radius. It was concluded that the Reciproc Blue file showed the highest cyclic fatigue resistance compared with all other file systems. All instrument's cyclic fatigue resistance except for Reciproc Blue was decreased by sodium hypochlorite of 60 degrees Celsius. Distilled water at 60 degrees Celsius increased the cyclic fatigue resistance of Reciproc Blue. Overall, the heat-treated files showed better cyclic fatigue resistance in all tests. This result indicates that, at first, all heat-treated files have a better cyclic fatigue resistance and also that some heat-treated NiTi files have a better cyclic fatigue resistance, which depends on the heat treatment they undergo [37].

2.8 Results in Root Canal Cleaning and Shaping with thermally treated NiTi Instruments

It is very important that the root canal cleaning and shaping leads to a good result. This is the basis of the prognosis of the tooth, if it is long-lasting or not. Therefore, some studies will be compared to show which thermally treated NiTi files show the best result and how these results are. One study performed by Keskin et al. (2018) compared the WaveOne Gold file with the Reciproc Blue R25 file. The ability of the instruments to shape the canal was evaluated by the amount of resin material removed, canal transportation and errors during the treatment like perforations, ledges, zips and elbows. During the procedure, none of the before-mentioned errors occurred. Five measurement points were taken to evaluate the instrument at the Canal orifice, halfway between the orifice, the beginning of the curve, the apex of the curve and the endpoint of the canal. The reciprocal blue instruments showed a better widening of the root canal at the first four points of measurement, and the Wave One Gold instruments showed a much better widening just at the end point of the canal. Again, the same five measurement points were taken, but the amount of resin removed was measured. This time the Reciproc Blue and WaveOne Gold were not significantly different at the four last measurement points. The Reciproc Blue instrument was only removing much more resin at the Canal orifice. There was only a difference in the transportation in three measurement points, at the halfway point between the orifice and the beginning of the curve, the apex of the curve and the end-point of the canal. At these three points, the Reciproc Blue instruments caused much more transportation than the Wave One Gold instrument. Both instruments were safe to use, and the anatomy of the root canal was preserved in its original shape. The WaveOne Gold was responsible for a more conservative enlargement with less apical transportation [14]. The study from Kesim et. Al. focused on cracks in dentin by thermally treated NiTi instruments. Therefore, it cut the teeth on 3mm, 6mm and 9mm. The study came to the result that all thermally treated NiTi instruments were responsible for cracks of the dentin in the root canal. Two systems, the Reciproc and K3XF, were causing much fewer cracks than the other systems, TF Adaptive and ProTaper Next, on the level of 3mm and 9mm [15]. A Review from Xi Wei et al. (2017) compared seven studies, including the Protaper, Reciproc and WaveOne file systems. It was found that the Reciproc and WaveOne systems produced fewer cracks in the dentin than the ProTaper Rotary system, which was found by one study to cause 2.4-fold higher dentinal crack risk than the WaveOne system. The Review came to the Result that the Rotary movement shows a higher risk of dentin

Cracks than the Reciprocating movement. This is due to the continuous pressure on the Instrument during the Rotary movement. During the Reciprocating movement, the stress is always released by time [16]. An in vitro study by Jack Han-Hsing Lin et al. (2020) investigated the influence of Sodium hypochlorite on heat-treated NiTi instruments compared to conventional ones. The study found that the heat-treated NiTi instruments showed greater resistance to corrosion from Sodium hypochlorite than conventional NiTi instruments, but this feature can not only be attributed to the heat treatment and depends on many other factors such as file cross-section geometry or design [21]. The study of Kataia et al. (2021) compared the shaping ability of two different thermal-treated NiTi instruments during rotational and reciprocating movement. Therefore 40 resin blocks with a 30-degree angle and 16mm length the Blocks were separated into 4 groups regarding the file used and the movement used. The result shows that there was no significant difference found on the apical level, but it was shown that a much lower transportation was shown using the reciprocating movement [33]. The study by Belladonna et al. (2018) assessed the shaping ability of the Reciproc Blue NiTi instrument by comparing it to the Reciproc M-Wire instrument. Therefore, 105 mandibular first and second molars from humans with moderate curvatures in the mesial root canals were taken for the test. This study concludes that there is no difference in the root canal shaping between the Reciproc and Reciproc Blue instruments. Both instruments show more or less the same canal transportation and changes in dentin volume with no statistically significant difference. This leads to the conclusion that the Reciproc Blue file shows the same result in root canal shaping as Reciproc files, although the blue thermal treatment has a positive effect on the properties of the Instrument. It should be mentioned that this can also be because of the same design of the instruments [45]. The study performed by Bayram et al. (2017) compared the HyFlex CM, HyFlex EDM, Vortex Blue and TRUShape thermally treated NiTi instruments regarding the formation of microcracks in the dentin. For this reason, forty mandibular incisors with straight root canals were assessed. Before and after the root canal preparation, cross-section pictures were taken. There was no formation of new dentinal microcracks after the root canal preparation; the 4452 microcracks were already present before. The result of this study indicates that thermally treated NiTi instruments are not causing microcracks in the dentin and may be better in root canal cleaning and shaping than conventional instruments [46]. The study done by Filizola de Oliveria et al.

(2019) compared the shaping ability of four different thermally treated NiTi instruments. Thirty-two mandibular molars with severe curvature were taken and tested with the ProTaper Next, Reciproc, Reciproc Blue and TRUShape files. Through all tests performed, it is shown that the instruments with a greater taper performed bigger morphological changes in the root canal; these systems were the Reciproc and Reciproc Blue instruments. Regarding transportation, there is no statistically significant difference between all four tested NiTi systems. It can be concluded that there might be some small areas where some instruments show small advantages, but the movement type, thermal treatment, and design of the instruments did not result in showing a statistically significant difference in dimensional changes and canal transportation in the apical area of the root canal [47]. The study of Yu Gu et al. (2016) tested different thermally treated NiTi instruments in S-shaped resin canals. Therefore, the Twisted files, WaveOne, HyFlex CM and V Taper 2H were compared. The study concludes that all instruments caused transportation more at the coronal than at the apical curvature. The Twisted files showed the highest transportation among all instruments. HyFlex CM files produced the best preparations of the resin canals. Comparing all instruments, the files produced by CM-Wire showed the most conservative and best cleaning and shaping of the root canal [48].

3. Conclusion

This narrative literature search aimed to review the properties of thermally treated NiTi instruments in the process of root canal cleaning and shaping. The thermal treatment of NiTi instruments affects the NiTi alloy in many different and positive ways. The flexibility, shape memory effect, breaking strength, cyclic fatigue resistance and cutting efficiency is improved by the thermal treatment. The cyclic fatigue resistance is extremely improved by up to 700%, according to studies that show a positive influence of thermal treatments on NiTi instruments. The breaking strengths and cutting efficiency are also extremely improved, and the same with the flexibility. There are many kinds of thermal treatments on the NiTi instruments, which vary from exposure to -196 degrees Celsius up to +500 degrees Celsius. These different thermal treatments all have different influences on the NiTi files, but all show extremely positive effects. It cannot be concluded that this one thermal treatment is the best compared to all others. Different treatments show better results in different properties of the instrument. Some instruments show slightly better results in apical curvatures than others or have a higher cyclic fatigue resistance than others. But it can be stated that all thermal treatments show a very positive effect on the properties of NiTi instruments, and these instruments show much better results in root canal cleaning and shaping than conventional instruments. It needs to be said that the endodontist should decide in every particular case for the right instrument for this specific case.

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