Review Article

Nanoparticle coatings of Ni-Ti alloy and possibilities in Endodontics: A narrative review

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Abstract: Background: Nickel-titanium (Ni-Ti) endodontic files are revolutionizing root canal therapy because of their remarkable flexibility, shape memory, and corrosion resistance. Nonetheless, cyclic fatigue, corrosion-related fractures, and biofilm development have restricted their clinical efficacy. Recent developments in nanotechnology provide solutions using surface coatings with nanoparticles to enhance the mechanical, chemical, and biological properties of Ni-Ti alloys. Materials and Methods: Current developments in nanoparticle coatings for Ni-Ti alloy are investigated in this narrative study. Of the 57 papers generated from a preliminary literature assessment, only 10 fit the inclusion criteria for relevance, approach, and scientific interest. Results: The selected studies highlight a spectrum of nanoparticles: Titanium dioxide (TiO_2), Zirconia (ZrO_2), Silver (Ag), Silicon carbide (SiC), Graphene oxide (GO), Hydroxyapatite (HA), Carbon nanotubes (CNTs), and Fullerene-like tungsten disulfide (IF-WS_2). Fatigue resistance, wear resistance, corrosion resistance, and antibacterial properties of Ni-Ti alloy coated with these nanoparticles have shown significant development. These coatings not only extend the lifetime of Ni-Ti alloy but also reduce bacterial colonization, therefore improving the possible rates of root canal treatment success. Physical vapor deposition, sol-gel dip coating, electrodeposition, chemical deposition technique and direct current magnetron reactive sputtering have been evaluated among several coating techniques. These coatings have therapeutic value depending on homogeneity, adhesive strength, and biocompatibility. Excellent coating performance is thought to depend critically on the eradication of the natural titanium oxide layer from Ni-Ti alloys. Conclusion: Despite these positive advancements, numerous challenges still exist, including regulatory approval, coating durability, and the need for long-term clinical validation. Self-healing coatings, bioactive layers for regenerative endodontics, and intelligent coatings with antimicrobial release driven by environmental changes should be the main focus of further studies. Bringing these discoveries into practical application depends on cooperation among materials scientists, nanotechnologists, and endodontists, thereby improving the performance and durability of Ni-Ti endodontic files.

Keywords: nanoparticles coating, Ni-Ti endodontic files, surface functionalization, mechanical properties, surface chemistry, nanoparticles coating techniques

Introduction

The primary focus of root canal preparation is to successfully shape and clean the root canal system while respecting the original anatomy and preventing iatrogenic events, including file separation, transportation, ledge formation, or perforation [(1)].

Various techniques for root canal enlargement have been put forward to mitigate errors, like zipping, ledging, loss of working length, and apical transportation [(2)]. Rotary nickel-titanium (Ni-Ti) systems have been invented to preserve the original canal geometry and maintain superior centricity [(2, 3)]. With their great flexibility, shape memory, and corrosion resistance qualities, which are vital to successful root canal instrumentation, nickel-titanium (Ni-Ti) alloys have revolutionized endodontic treatment. Ni-Ti files have some limitations aside from these advantages, which are still major challenges for their long-term clinical dependability, including cyclic fatigue, corrosion-induced breakage, and biofilm development on file surfaces [(4)].

Rotary Ni-Ti files could fail through one of two mechanisms: high torque and flexural fatigue (5-7). Torsional overloading can be mitigated by restricting the maximum torque exerted on the instrument and by regulating the apical force delivered by the practitioner. Fatigue failure may arise when the material experiences cyclic tensile or compressive loading, as occurs when the instrument rotates within a curved canal. The fundamental mechanism of rupture involves the nucleation of microcracks at the material surface, followed by the inward propagation of these cracks until the reduction in cross-sectional area achieves a critical threshold, at which point the tensile stress becomes substantial enough to cause separation of the file (8). Also, Ni-Ti endodontic instruments exhibit susceptibility to failure, as it is widely accepted that the high concentration of surface defects manufactured during the machining process contributes to this failure. These defects in machining are locations for crack nucleation (9). Considering this, some manufacturers have used surface coating with nanoparticles (10, 11), thermal treatment (12), electrochemical polishing (13) and/or electrical discharge machining (EDM) (14) to create a smoother surface, this is intended to improve the fatigue life of the file. Some instruments manufactured using the EDM process achieved improvements of up to 700% (15). Recently, nanotechnology has been used as an appealing response to overcome the limitations associated with Ni-Ti alloys. Recent progress has been made to improve the mechanical, chemical, and biological properties of Ni-Ti alloys through the incorporation of nanoparticles into surface coatings (16). The purpose of these advances is to extend the service life of endodontic files, increase its fatigue resistance and reduce bacterial colonization, leading to better therapeutic action (10, 11). Within this narrative review, the most recent developments in nanoparticle coatings for Ni-Ti alloys are investigated. Specifically, it examines the multiple classes of nanoparticles employed, the effect of nanoparticles on mechanical and antibacterial properties, coating processes, and future use cases.. This review intends to provide insights into the transformative potential of nanoparticle coatings in endodontics by synthesizing information from previous studies and providing a summary of those findings.

Search strategy

Literature search was performed in PubMed, Google Scholar, and ScienceDirect databases based on MeSH terms in the following combinations: “nanoparticles coating” AND (“Nickel-Titanium alloy” OR “Ni-Ti alloy” OR “Ni-Ti endodontic files) AND “surface functionalization “AND “mechanical properties “ AND “surface chemistry“ AND “nanoparticles coating techniques”. The search was conducted for articles published in the English language only from 2014-2024. After an initial search, 57 articles were identified. Screening for duplicates of the selected articles was performed. Hand-searching for the reference list of the selected articles was performed to identify further relevant sources. Articles were included if they were published in English between 2014 and 2024, focused on nanoparticle coatings of Ni-Ti alloys used in endodontics, provided in vitro or in vivo evidence related to mechanical or biological performance and discussed coating techniques relevant to nanoparticle deposition. Articles were excluded if they were review articles or editorials, focused on coatings for dental implants, involved coatings made of non-nanoparticle materials, or lacked relevant mechanical or biological outcomes. Of these, only 10 articles were selected that met the scope of this review. Figure 2 shows a PRISMA search flow chart that used in this review.

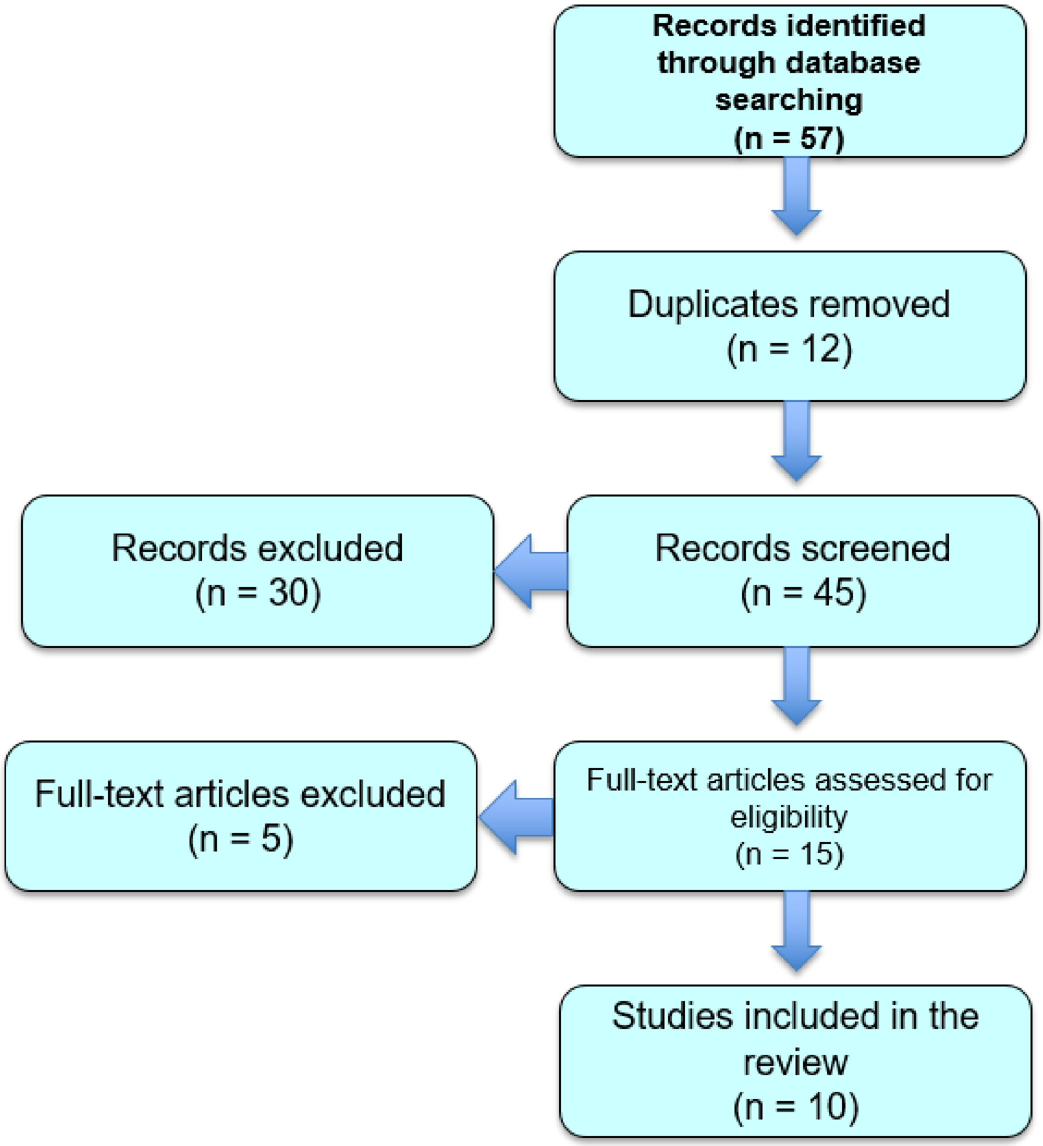


Figure 2: *PRISMA search flow chart*

Selected articles

The selected articles included in this review were summarized, including authors, key focus, and main findings of studies investigating the nanoparticle coatings on Ni-Ti alloy, as listed in Table 1

Classification and properties of nanoparticles

Nanoparticles can be categorized according to many criteria, as shown in Table 2 [22]

Table 1: Summary of the selected articles, including authors, key focus, and main findings of selected studies

Author(s), Year	Key Focus	Main Findings
Adini et al., 2011[11]	The impact of cobalt coatings on fatigue and failure of files.	IF/Co-coated files exhibit reduced friction, phase transition, and mechanical degradation.
Aun et al., 2016[17]	(Ni-Ti) files were coated with a TiO2 layer using a dip-coating sol-gel technique.	Enhanced cutting efficiency and significant resistance to corrosion in NaClO.
Hammad et al., 2020[18]	the impact of ZnO nanocoating on the mechanical properties of Ni-Ti alloy.	ZnO nanocoating may enhance the antibacterial properties of Ni-Ti wires and diminish frictional resistance.
Schäfer, 2002[19]	cutting efficiency of (Ni-Ti) K-files subjected to physical vapor deposition coating.	Exhibit markedly enhanced cutting efficiency relative to traditional, uncoated nickel-titanium files.
Pipattanachat et al., 2021[20]	Assess the antibacterial and anti-biofilm properties of a GO/Ag nanoparticle-coated Ni-Ti alloy.	nanoparticles may serve as an effective coating to mitigate the effects of biofilm formation.
Mahmood et al., 2023[21]	Deposition of tantalum pentoxide (Ta2O5) thin films on (Ni-Ti) alloy substrates	Ta2O5-coated Ni-Ti alloys have superior corrosion resistance, greater biocompatibility, and reduced nickel ion release.
Walkey et al., 2012[22]	Examine the influence of size and surface chemistry on serum protein adsorption to gold nanoparticles .	This research delineates principles for the systematic design of clinically applicable nanomaterials.
Panja et al., 2024a[10]	Examine the surface topography of (Ni-Ti) pediatric rotary file coated with graphene oxide (GO).	GO coatings were successfully deposited on Ni-Ti files.
Panja et al., 2024b[23]	Examine the elemental composition of a(Ni-Ti) pediatric rotary file covered with graphene oxide (GO).	EDX examination confirmed the consistent application of the GO coating on Ni-Ti files.
Kachoei et al., 2016[24]	Application of zinc oxide (ZnO) nanoparticles on (Ni-Ti) wire	The coating facilitate safer and more expedient therapy for the advantage of pateint and physian.

Table 2: Classification types of Nanoparticles.

Origin	Size	Structure	Composition	Shape
Natural Artificial	-Zero-dimensional -One-dimensional nanorods -Two-dimensional thin films -Three-dimensional nanocones	- Carbon-based - Metal - Dendrimers - Composites	- Inorganic - Metals - Polymeric - Quantum dots - Modified	- Particles - Spheres - Rods - Plates

The size or dimensions of nanoparticles (NPs) are crucial. The dimensions range from 10 to 100 nanometers[25]. Nanoparticles smaller than 10 nm and larger than 100 nm do not demonstrate therapeutic efficacy. Minor particles are expelled via the kidneys, but bigger molecules are metabolized by the reticuloendothelial system for excretion [26]. The surface charge of nanoparticles is a critical property that affects their bactericidal potency. Specifically loaded nanoparticles can adhere to the oppositely charged cell walls of microbes, which enhances their efficacy. An increased charge boosts effectiveness, yet it undermines the stability of nanoparticles because of the electric repulsive forces acting between them. Therefore, nanoparticles must be appropriately loaded concerning their negative or positive charge and quantity [26].

Regarding the surface configuration, Nanoparticles demonstrate a hydrophilic coating on their surface. The particles reveal a high surface area to volume ratio. The interaction with cellular receptors is improved by the binding of ligands on the exterior of nanoparticles, making these properties essential for their biological applications [26].

Raw nanoparticles lack characteristics suitable for biological applications. Consequently, they are merged with additional particles to modify their external structure. So, as a result of functionalization, the nanoparticles function as a core with a coating of additional elements [26].

Synthesis of nanoparticles

- Top-down method: Grinding, ablation, etching, or sputtering of the bulk material and reduction to the nanoscale using specialized techniques. It uses mechanical milling employing high-energy ball mills to reduce bulk materials to the nanoscale. Because of this straightforward step, the method is popular and effective by volume. However, it can result in structural weaknesses [24]. High-powered laser pulses are used for laser ablation to vaporize material away from a solid, forming nanoparticles during the cooling process. This technique makes it possible to manufacture pure nanoparticles without chemical substances [27]. Etching is a method to eliminate material from the surface using chemical or physical methods to form nanostructures. Reactive ion etching methods allow for fine tuning and configuration of features [28]. Sputtering is the term for the mechanism of atoms releasing from a target material due to energetic particles, depositing into a thin film on a substrate. This technique can be freely applied in thin film deposition for electronic applications [28]. Bottom-up method: it is the fabrication of nanoparticles with chemical methods using atomic or molecular precursor materials. Remarkable methods include the Sol-Gel Process which allows for the preparation of metal oxide nanoparticles by transitioning from the liquid 'sol' to solid 'gel'. This procedure provides accurate control over the uniformity and composition of the nanoparticles. Composite nanoparticles are prepared by the coprecipitation of several components together from a solution. This process is straightforward and acceptable for industrialization [28]. Hydrothermal Synthesis is another method that allows crystalline nanoparticles of the predetermined size and shape to form within aqueous solutions at elevated temperatures and pressures [28]. The sonochemical production employs ultrasonic vibrations to produce nanoparticles. Specific nanostructures can be developed and reaction rates can be improved by the acoustic cavitation technique [28]. Biosynthesis makes nanosized chemicals by the production of a biological entity such as microbial secretions or plant extracts. This sustainable procedure minimizes the need for hazardous agents, through the use of natural reducing agents and capping agents [28].

Types of Nanoparticles Used for Coating Ni-Ti Alloys

Numerous nanoparticles can coat the Ni-Ti alloy with various nanoparticles to enhance the mechanical properties, especially fatigue resistance, wear resistance, and overall durability, which may encompass [17, 18, 20]. These include:

TiO_2 Nanoparticles: TiO_2 is recognized for its biocompatibility and mechanical strength. Ni-Ti alloy coated with TiO_2 nanoparticles can assist improved corrosion resistance, wear resistance, and file longevity. If nickel ions due to corrosion are liberated, they may induce allergic reactions and toxicity. A coating of TiO_2 nanoparticles imparts a protective oxide layer, acting as a barrier, to reduce the release of nickel ions as well as to increase the corrosion resistance. Studies show that the coating of TiO_2 nanoparticles in nickel matrix through electroplating improves microstructure and corrosion resistance of coating [29]. As reported in research, coatings of nanoporous TiO_2 on NiTi alloys enhance cell growth and lessen cytotoxicity, increasing their applicability to biomedical science tasks [30]. Figure 3 shows the SEM image of the RACE file that was coated with TiO2[17].

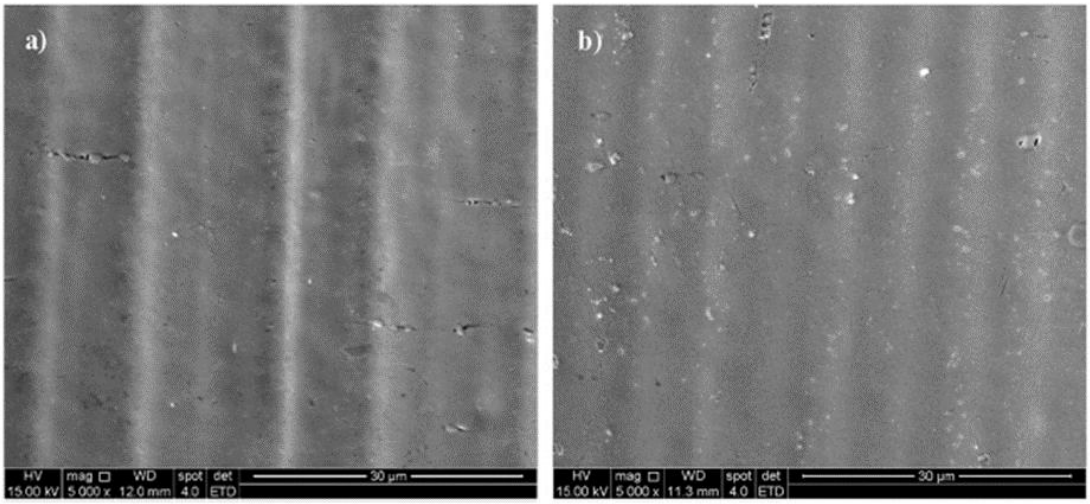


Figure 3: SEM image of RaCa file a)before coating b) after coating with TiO2[17]

Zirconia (ZrO_2) Nanoparticles: Zirconia has exceptional hardness and fracture toughness. Using ZrO_2 nanoparticles in Ni-Ti alloy could be effective in providing them with resistance to cyclic fatigue and in order that fracture damage will be less. It has been demonstrated that it is efficient when ZrO_2 nanoparticles are applied to the NiTi alloys, a stable and highly bonded layer is formed that allows the NiTi alloy to withstand large deformation without fracturing. Such coating serves to delay crack initiation and propagation thereby enhancing NiTi alloy fatigue resistance [31]. Its incorporation of ZrO_2 nanoparticles changes how the alloy crystals are structured, resulting in a more durable and more mechanical tolerant surface, reducing its fracture risk (32).

Silver (Ag) nanoparticles: Although silver nanoparticles are well-known for their antimicrobial properties, it is possible to improve the mechanical behavior of Ni-Ti alloy by reducing corrosion and increasing hardness. Studies have shown that the addition of silver, up to 3 atomic percent, can affect the corrosion resistance as well as biocompatible properties of the alloy. This beneficial effect can be connected to the formation of a solid passive layer on the alloy surface to act as a barrier against the exposure to corrosive impurities (33). Ag added to NiTi alloys increases its antibacterial properties, providing its usefulness in medical devices. Silver exhibits bactericidal activity up to 35 parts per billion concentrations, but is non-toxic to mammalian cells (33).

Silicon Carbide (SiC) Nanoparticles: As SiC is widely used as it is relatively hard and resistant to wear. Nano-deposited coating of Ni-Ti alloy with SiC can improve the hardness in the surface and hence, enhance the wear and deformation resistance that the alloy presents under its application condition. The average hardness level of the coating may be increased from 4.5 GPa (pure Ni-P) to 8.5 GPa (Ni-P/SiC composite) by a process of use of SiC nanoparticles. This remarkable increase may be attributed to the homogenous distribution of SiC nanoparticles that inhibit plastic distortion and improve the hardness of the coating (34). Apart from mechanical benefits, SiC nanoparticle coating has potential to improve corrosion resistance of NiTi alloys. SiC is incorporated in the coating matrix for a finer-grained, surface roughness-reduced formation, which can be used as a counter-corrosion agent. Ni-P/SiC nanocomposite coatings show higher charge-transfer resistance and a lower double-layer capacitance in electrochemical studies, indicating improved corrosion resistance (34).

GO Nanoparticles: Graphene oxide is an electronic composite with superior mechanical properties, flexibility, and biocompatibility. Strong interfacial adhesion from this material and its application through the Ni-titanium alloy promotes the fatigue life of Ni alloy and wears better. GO provides a protective layer of the underlying alloy against corrosive behavior. In addition, GO provides a biocompatibility feature that ensures proper medical use for the coated NiTi alloys, which limits unwanted behaviour on exposure to biological tissues (10).

Hydroxyapatite (HA) Nanoparticles: Hydroxyapatite is mostly investigated for its biocompatibility. Hydroxyapatite coatings can improve surface hardness and decrease friction, therefore enhancing the mechanical properties of Ni-Ti alloy by affecting its surface properties directly. Lower friction at device interface may also occur due to HA coatings. A more homogeneously smooth surface with the basic lubricious characteristics of HA leads to low friction coefficients. In fact, because friction is reduced, wear on the device will be less, extending its operational lifespan. HA-coated Ni-Ti alloys exhibit better wear resistance which significantly increases their durability in physiological parameters (35).

Carbon Nanotubes (CNTs): Carbon nanotubes give good strength and flexibility. CNT coating can improve Ni-Ti alloy fatigue resistance and also reduce wear, eventually increasing the working life of the Ni-Ti alloy. MWCNTs added to Ni coatings can induce a more refined grain structure and improved surface morphology, a major contribution to the nanocompatibility of Ni oxide coatings. The microstructural improvements of these results are reduced friction, wear resistance and coefficient. The uniform distribution of MWCNTs within the metal matrix correlates with enhanced wear resistance of MWCNT/Ni composite coating over pure Ni coating [36].

Zinc Oxide (ZnO) nanoparticles: ZnO coatings enhance hardness, corrosion resistance, and fatigue resistance of Ni-Ti alloy surface, reducing wear and improving the durability of the instrument. The reduction in frictional forces compared to uncoated wires was 34% in ZnO-coated NiTi wires, indicating improved surface hardness and wear resistance. This diminished friction decreases wear and thus prolongs the service life of the alloy [18]. The ZnO-coated NiTi wires show good antibacterial activity against pathogens, such as Staphylococcus aureus, Streptococcus pyogenes, and Escherichia coli. The antimicrobial action is significantly beneficial especially in biomedical applications where the need for bacterial colonization is critical [18].

Fullerene-like tungsten disulfide (IF-WS_2): Coated nickel-titanium (NiTi) alloys have demonstrated improvements in mechanical characteristics, notably through friction reduction, enhanced fatigue resistance, and prolonged durability of NiTi-based devices [11]. The reduction of frictional forces and the enhancement of lubricating qualities afforded by the IF-WS_2 coating enable NiTi instruments to function with less stress, thus augmenting their resistance to fatigue-induced failure. This enhancement is especially advantageous in medical applications where NiTi alloys endure cyclic mechanical strain [11].

Nanoparticle Coating Techniques for Ni-Ti Alloys

Improving the mechanical, biological, and antibacterial characteristics of Ni-Ti alloys depends on the use of nanoparticles. Many methods have been developed to get homogeneous and effective nanoparticle coatings. One might classify these techniques as either physical or chemical ones.

- Electrodeposition: By minimizing surface flaws, electrodeposition helps Ni-Ti alloy to have better fatigue resistance and lessens the sites of cracking starts. Research shows that electrodeposited Ni-Ti alloy performs better in cyclic fatigue tests, hence increasing lifetime and durability over use [11, 20]. Figure 4 shows a schematic diagram of the Electrodeposition technique.

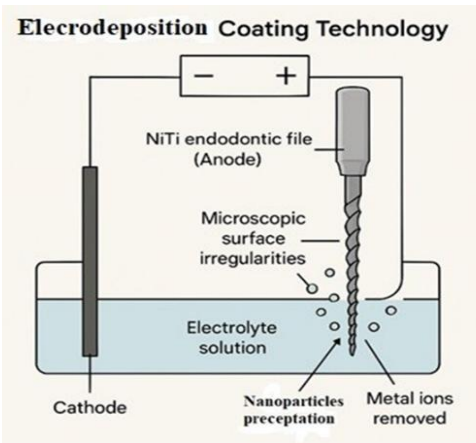
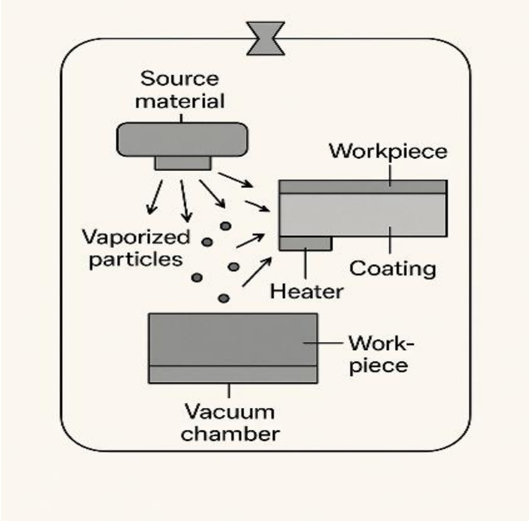


Figure 4: Schematic diagram of the electrodeposition coating technique.

- Physical Vapor Deposition (PVD): stands for physical vapor deposition, which is a technique that involves the vaporization of a material to produce a thin coating on the surface of Ni-Ti. Several techniques, such as thermal metal-organic chemical vapor deposition (MOCVD) and arc evaporation, have demonstrated their ability to produce coatings that are both durable and constant in thickness. These techniques are therefore suitable for the incorporation of nanoparticles to improve mechanical characteristics[19]. Figure 5 shows a schematic diagram of physical vapor deposition technique.

Figure 5 shows a schematic diagram of physical vapor deposition technique



- Dip-Coating with Sol-Gel Technique: Dip-coating in sol-gel solutions makes it possible to create a flexible coating layer, such as titanium dioxide (TiO_2), on the surface of the Ni-Ti alloy and helps to distribute nanoparticles uniformly. Essential for endodontic uses, cutting efficiency and cyclic fatigue resistance are improved by this technique[17]. Figure 6 shows a schematic diagram of Dip-Coating with Sol-Gel Technique.

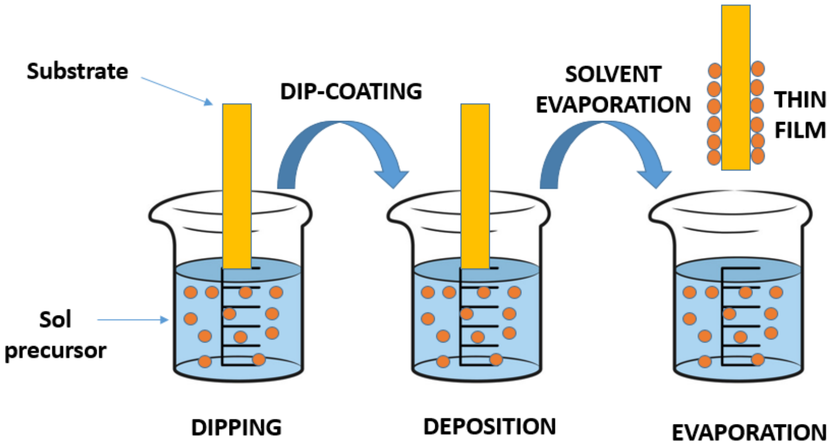


Figure 6 shows a schematic diagram of Dip-Coating with Sol-Gel Technique.

- Chemical Deposition Technique: By use of chemical reactions in a solution, chemical deposition is a technique for coating Ni-Ti alloy with nanoparticles, hence creating a homogeneous and attached thin film on the substrate that leads to enhancement of various mechanical properties, surface quality and corrosion resistance[24].
- DC magnetron reactive sputtering: This approach deposits complex coatings, including nitrides, oxides, or carbide nanoparticles, onto a substrate by combining direct current (DC) sputtering with reactive gas chemistry[21]. The Ni-Ti alloy is stuck in a vacuum chamber with high-energy ions; these ions' kinetic energy moves atoms from the target to be expelled, a process sometimes referred to as sputtering. These

sputtered atoms then pass through the plasma and settle onto a substrate to create a thin coating[21]. Figure 7 shows a schematic diagram of DC magnetron reactive sputtering.

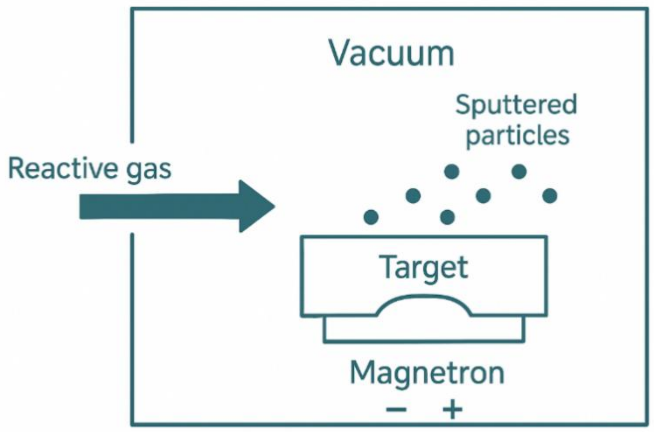


Figure 7 shows a schematic diagram of DC magnetron reactive sputtering

Comparison of Coating Techniques

Each coating process has specific advantages and disadvantages. A number of methods for such coating options have to be carefully selected according to the specific requirements of the Ni-Ti alloy coating such as the desired nanoparticle composition, coating thickness, and application in the endodontic process. Strengths and limitations as demonstrated in Table 3 are summarized the Advantages, limitations, and common applications of Ni-Ti alloy coating techniques.

Removal of the oxide layer

A clean removal of the TiO_2 layer before coating Ni-Ti alloys is an important pre-requisite for ensuring good adhesion and effective coating of their subsequent nanoparticle coatings. The titanium oxide layer that naturally forms on the surface of Ni-Ti alloys when they are exposed to air can create a barrier which may inhibit the adhesion of nanoparticle coatings to the metallic Ni-Ti alloy surface. It is essential to remove this layer to get a strong adhesion, a consistent coating, and an improvement in the performance of the material that has been coated. Methods such as chemical etching, as shown in Figure 8 [10], mechanical polishing, plasma treatment, or laser ablation may be utilized based on the required coating qualities and available resources. Each methodology possesses distinct advantages and limits, and the selection of a method is contingent upon the precise needs of the coating process and the planned application of the coated Ni-Ti alloy in endodontics [10, 23].

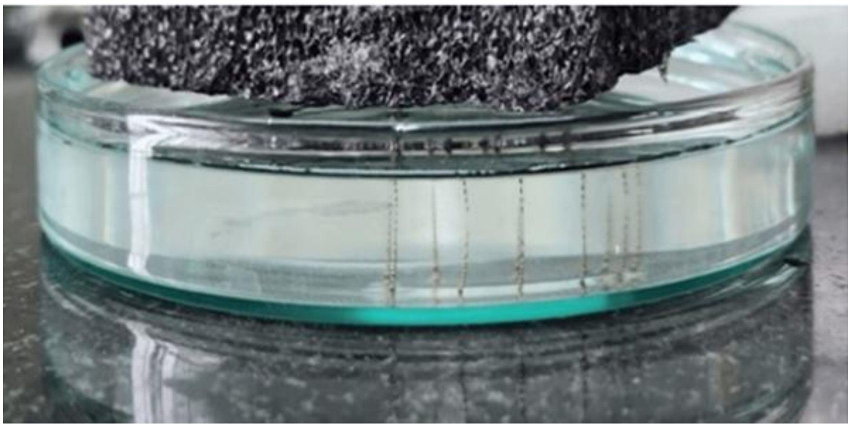


Figure 8: Removal of oxide layer from endodontic file by chemical etching [10]

Table 3: Advantages, limitations, and common applications of Ni-Ti alloy coating techniques.

Technique	Advantages	Limitations	Common Applications
Electrodeposition	Improves surface smoothness and reduces surface flaws. Enhances fatigue resistance by reducing crack initiation. Increases durability and performance.	- May require specialized equipment. Only effective on small parts or complex geometries.	Biocompatible coatings (e.g., HA, TiO_2)
Physical Vapor Deposition (PVD)	Produces uniform, high-quality coatings. Durable and consistent in thickness. Good for nanoparticle incorporation.	High equipment cost and energy consumption. Limited to flat surfaces or geometrically simple parts.	- Medical tools. - Engineering parts. -Endodontic instruments
Dip-Coating with Sol-Gel Technique	Allows uniform distribution of nanoparticles. Flexible and adaptable coating. Improves cutting efficiency and cyclic fatigue resistance.	It can be difficult to control layer thickness. Coating may have lower adhesion strength compared to other methods.	- Endodontic tools. -Biomedical devices. -Aerospace components
Chemical deposition	low cost. simple technique. uniform and well-adhered coating	Restricted impact on crystallinity and film thickness. Possibly include harmful toxins.	- Endodontic files. -Orthodontic wires. -surface modification
DC magnetron reactive sputtering	High density and thick coatings. Great control of composition. strong adherence and homogeneity.	high cost. vacuum chamber required	- orthodontic wire .

Improvements in the properties of the coated Ni-Ti alloy

Using nanoparticle coatings on Ni-Ti alloy aims to enhance certain key mechanical characteristics, which are crucial for prolonging their service life and performance in clinical applications.

- Cyclic Fatigue Resistance

The main cause of fracture in Ni-Ti alloy associated with repeated bending in curved canals is cyclic fatigue. Cyclic fatigue resistance of NiTi instruments has shown improvement after coating with nanoparticles such as titanium dioxide and (IF-WS_2) [11, 17]. (Adini et al., 201) investigated the impact of cobalt coatings with impregnated fullerene-like WS2 nanoparticles on cyclic fatigue of protaper S1 file using electrodeposition and revealed that the coated files may exhibit a 2–3 fold increase in fatigue resistance compared to uncoated controls under work-related strain, as experienced during procedures. Furthermore, the reduced friction and resultant torque may enable the utilization of Ni-Ti files in circumstances presently regarded as excessively hazardous and complex [11].

- Cutting efficiency

In root canal instrumentation, cutting efficiency represents the capacity of an endodontic file to efficiently remove dentin with little effort and time. It is very important to explore whether the nanoparticle coating on endodontic files has an impact on the cutting efficiency that may lead to an increase in the treatment time and impose extra efforts for both the endodontist and the patients. (Aun et al., 2016) explored the effect of coating the Race file with TiO2 nanoparticles on the cutting efficiency of these files. The approach employed to assess cutting efficiency relies on the energy required to penetrate a conventional artificial canal while maintaining constant engine rotation and apical speed. The coated files demonstrated reduced work values necessary for penetrating the artificial canal. This outcome indicates that the coating procedure does not diminish cutting efficiency; rather, it may boost it [17]. (Schäfer, 2002) examined the effect of Titanium nitride coatings on Ni-Ti k-file using the Physical Vapor Deposition technique. The cutting efficiency of the files was evaluated using a computer-controlled testing apparatus in rotational motion. Specialized plastic samples with a circular canal were used, and the highest penetration depth of the tools into the lumen was defined as the measure of cutting efficiency. The researchers concluded that a PVD protocol could produce TiN-coated nickel-titanium instruments demonstrating significantly enhanced cutting efficiency compared to conventional uncoated nickel-titanium instruments. This enhancement is clinically important for reducing instrumentation time and likely to reduce the threat of instrument separation during the instrumentation phase [19].

- Corrosion Resistance

Usually involving the use of chemical irrigants, the specific conditions inside the root canal could cause Ni-Ti files to corrode. Titanium dioxide or nanoparticle coatings based on silver significantly enhance corrosion resistance [17]. This is done by forming a protective surface layer on the file to prevent corrosion. Hence, this leads to a decrease in the deterioration of the alloy and the preservation of structural integrity under adverse conditions, which ultimately improves the biocompatibility and lifetime of the file [11, 37]. Corrosion tests were performed in a galvanostat with a 5.25% NaClO solution (pH=12.3) at a temperature of about 25 °C. Corrosion tests showed a negative hysteresis, which means that the files were resistant to pit and crevice corrosion in NaOCl [17].

- Antimicrobial Properties

The incorporation of antimicrobial nanoparticles, such as silver or zinc, into the coating can inhibit biofilm growth on the alloy surface, but this is not strictly a mechanical feature. This ancillary advantage improves the clinical applicability of the alloy by diminishing bacterial contamination and simultaneously augmenting the coating's durability in operational situations. Hammad et al. (2020) discussed the situation in which Ni-Ti orthodontic wires have been coated with ZnO nanoparticles by an electrochemical deposition technique. The antibacterial efficacy of the coated wires was evaluated against Streptococcus pyogenes (Gram-positive), Staphylococcus aureus (Gram-positive), and Escherichia coli (Gram-negative). The coated wires exhibited no bacterial proliferation. None of the ZnO-coated wires exhibited bacterial growth following a 24-hour incubation at 37°C for all bacterial species tested [18]. Kachoei et al. (2016) studied the effect of ZnO nanoparticles coating on NiTi orthodontic wires using the chemical deposition coating technique. The antibacterial efficacy of the coated wires was evaluated against S. mutans. All plates with ZnO-coated wires exhibited no color changes after 24 and 48 hours of incubation at 37ºC, indicating the absence of bacterial growth. Nevertheless, the color of plates with uncoated wires turns pink, signifying the loss of bacterial proliferation [24].

- Hardness

The smoother surface finish brought about by coatings assists in lowering friction in instrumentation and improves hardness. Improving the overall efficiency and effectiveness of the root canal treatment, a smoother surface reduces the potential of file locking in the canal. Mahmood et al. (2023) examined the effect of tantalum pentoxide Coatings on Ni-Ti alloy using DC magnetron reactive sputtering. Ta2O5 coatings exhibit exceptional stiffness and directly support the load applied to the Ni-Ti substrate. Hardness testing was conducted at a load of 0.24N at three separate locations on the specimen's surface. The microhardness value increased from approximately 204 HV for an uncoated Ni-Ti sample to around 254 HV for a Ni-Ti sample coated with sputtered Ta2O5. This significant enhancement highlights the beneficial effect of Ta2O5 coatings on the mechanical performance of the Ni-Ti substrate [21].

Future Possibilities and Challenges

Nanoparticles' coatings have remarkable opportunities for enhancement of the mechanical qualities, antibacterial action, and biocompatibility of Ni-Ti endodontic files. Before these developments get accepted as standard practice in endodontic instrument manufacturing, concerns such as coating durability, authorization from regulators, toxicity concerns, and validation in clinical trials have to be sorted out.

Incorporation of self-healing materials into the coatings can enhance the longevity of Ni-Ti instruments by repairing microcracks that form due to cyclic stress. Smart coatings with stimuli-responsive properties (e.g., pH-sensitive or temperature-responsive coatings) could improve the efficiency of antimicrobial release and corrosion resistance.

The promising antibacterial properties of silver (Ag), zinc oxide (ZnO), and graphene-based coatings reduce the risk of secondary infections by preventing biofilm formation on Ni-Ti files. Designed to release antimicrobial ingredients only if bacterial contamination is detected, functionalized surface nanoparticles may contribute to reducing unnecessary injury.

Calcium phosphate, bio-glass, and other types of bioactive nanoparticle coatings could help to remineralize dentinal tubules and enable regenerative endodontic treatments. Coatings that include growth factors or stem cell attractants might assist in encouraging dentin regeneration, hence expanding the spectrum of Ni-Ti file uses. Still, major issues include the adhesion and wear resistance of nanoparticle coatings, as continuous mechanical stress and exposure to irrigant solutions cause the coatings to degrade over time.

Advanced nanoparticle deposition processes, such as Atomic Layer Deposition and Pulsed Laser Deposition, tend to be expensive and challenging to scale for mass production. The clinical usefulness of nanoparticle-coated Ni-Ti instruments vs common thermomechanically treated Ni-Ti alloys necessitates an assessment of cost-effectiveness and manufacturing difficulty.

Finally, although in vitro studies show great promise, till now, no long-term clinical data proving the advantages of nanoparticle coatings in actual patient settings exist. To evaluate the efficacy, security, and cost-effectiveness ratio of nanoparticle-coated Ni-Ti files, it is necessary to conduct long-term clinical research, including randomized controlled trials, to assess the benefits/drawbacks of nanoparticle coatings on the Ni-Ti endodontic instruments.

Limitations

Most of the included studies were in vitro experiments, which do not fully replicate the complex conditions of the oral environment. Variables such as salivary flow, masticatory forces, temperature changes, and microbial diversity in vivo are difficult to simulate in laboratory settings, leading to questions about the clinical relevance and translatability of these findings (11,20).

In addition, sample sizes in many studies were relatively small, often fewer than 10 specimens per group, limiting statistical power and the generalizability of the results (24). Variability in experimental design, such as the use of different test solutions (e.g., NaOCl concentrations), rotational speeds, and canal curvature in fatigue tests, further complicates direct comparisons between studies (19,21).

As a major problem, there is heterogeneity in coating techniques. Numerous methods of deposition were used (e.g., sol-gel dip coating, physical vapor deposition, electrophoretic deposition) with different parameters including but not limited to temperature, duration, and post-treatment methods. The differences in coating thickness, adhesion and surface morphology directly have an effect on the mechanical and antibacterial properties of the finished product (17,22).

In addition, the concentration, particle size, and surface chemistry of the nanoparticles showed inconsistent properties between studies. These variations influence dispersion of the nanoparticles, their interfacial adhesion with the Ni-Ti substrate, and the corresponding biological response (23).

In addition, there is no standardized testing protocol especially for cyclic fatigue resistance, and anti-bacterial activity. Various fatigue-testing machines, torque values, and types of motion (reciprocation vs. continuous rotation) pose challenges for reproducibility and a meta-analysis in reproducible and statistical analysis. Antibacterial assays differed in microbial strains, incubation time and criteria for evaluation and therefore the effectiveness could not be accurately measured across studies (20,24).

Lastly, long-term biocompatibility and cytotoxicity or systemic properties of these coatings are still not well understood. Although numerous nanoparticles (e.g., silver, ZnO) have great antibacterial activity, the release and potential bioaccumulation of such nanoparticles in human tissues is not completely known (25). This is a serious clinical safety problem for long-term usage or recurring exposure.

Conclusion

There is an optimistic development that endeavors to address the intrinsic drawbacks of traditional Ni-Ti alloys: the implementation of nanoparticle coatings on Ni-Ti endodontic files. These coatings have indicated their capability to modify mechanical properties (cycle fatigue resistance, hardness, and flexibility), improve corrosion resistance, and provide antibacterial action to reduce biofilm development. Notwithstanding these developments, concerns such as coating adherence, long-term stability, potential cytotoxicity, and scalability of production techniques remain major challenges for clinical translation. Moreover, there is an absence of established protocols to assess the durability and efficacy of nanoparticle-coated instruments in practical endodontic treatments. Further work is needed to explore intelligent coatings which contain regulated drug release, self-repairing characteristics, and bioactive effects to improve regenerative endodontics. Major clinical studies and regulatory endorsements will need to be carried out in order to assure their safety, efficacy, and cost-effectiveness of advanced coatings such that they can go through clinical trials before standard application in practice. To summarize, although nanoparticle coatings have great potential to increase both the success and the effectiveness of Ni-Ti endodontic instruments, additional interdisciplinary collaboration among materials scientists, nanotechnologists, and endodontists is needed to turn these innovations into clinically appropriate and economically feasible solutions.

Conflict of interest

The authors have no conflicts of interest to declare.

Author contributions

A.I.A and A.H.A. Conceptualization and data collection; A.I.A., A.H.A.and F.M., Formal analysis; A.I.A., A.H.A.and F.M. Project administration; A.H.A.and F.M. Supervision; A.I.A., A.H.A.and F.M. Roles/Writing - original draft; A.I.A., A.H.A.and F.M. Writing - review & editing. All authors have read and agreed to the published version of the manuscript.

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طلاءات الجسيمات النانوية على سبيكة النيكل والتيتانيوم وإمكانياتها في حشوات الجذ مراجعة سردية

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المستخلص:

الهدف:تُحدث ملفات علاج الجذور المصنوعة من النيكل والتيتانيوم (Ni-Ti) ثورة في علاج قنوات الجذر بفضل مرونتها اللافتة، وذاكرة الشكل، ومقاومتها للتآكل ومع ذلك، فإن التعب الدوري، والكسور الناتجة عن التآكل، وتكوُّن الأغشية الحيوية قد حدّت من فعاليتها السريرية توفر التطورات الحديثة في تكنولوجيا النانو حلولًا من خلال الطلاءات السطحية بجزيئات نانوية لتعزيز الخصائص الميكانيكية والكيميائية والبيولوجية لسبائك النيكل تيتانيوم. تستعرض هذه الدراسة السردية التطورات الحالية في طلاءات الجسيمات النانوية لسبائك .Ni-Ti من بين 57 ورقة بحثية تم الحصول عليها من التقييم الأولي للأدبيات، تم اختيار 10 فقط وفقًا لمعايير الشمول من حيث الصلة، والمنهج، والأهمية العلمية .تسلط الدراسات المختارة الضوء على مجموعة من الجسيمات النانوية، مثل ثاني أكسيد التيتانيوم(TiO_2) ، وأكسيد الزركونيوم(ZrO_2) ، والفضة(Ag) ، وكربيد السيليكون(SiC) ، وأكسيد الغرافين(GO) ، وهيدروكسي أباتيت(HA) ، وأنابيب الكربون النانوية(CNTs) ، وثنائي كبريتيد التنغستن الشبيه بالفوليرين .($IF-WS_2$) وقد أظهرت الطلاءات بهذه الجسيمات تحسنًا كبيرًا في مقاومة التعب، ومقاومة التآكل، ومقاومة التآكل الكيميائي، والخصائص المضادة للبكتيريا لسبائك .Ni-Ti لا تعمل هذه الطلاءات على إطالة عمر سبائك النيكل تيتانيوم فحسب، بل تقلل أيضًا من استعمار البكتيريا، مما يعزز من معدلات نجاح علاج قنوات الجذر .وقد تم تقييم عدة تقنيات للطلاء، منها الترسيب الفيزيائي للبخار، وتقنية الغمس بطريقة السول جيل، والترسيب الكهربائي، والترسيب الكيميائي، والرش الممغنط التفاعلي بالتيار المستمر وتختلف القيمة العلاجية لهذه الطلاءات حسب تجانسها، وقوة التصاقها، وتوافقها الحيوي ويُعتقد أن الأداء المثالي للطلاء يعتمد بشكل كبير على إزالة طبقة أكسيد التيتانيوم الطبيعية من سبائك .Ni-Ti على الرغم من هذه التطورات الإيجابية، لا تزال هناك تحديات عديدة، تشمل الموافقات التنظيمية، ومتانة الطلاء، والحاجة إلى التحقق السريري طويل الأمد ينبغي أن تركز الدراسات المستقبلية على الطلاءات ذاتية الشفاء، والطبقات النشطة بيولوجيًا لعلاج الجذور التجديدي، والطلاءات الذكية التي تطلق مواد مضادة للميكروبات استجابة للتغيرات البيئية يعتمد تحويل هذه الاكتشافات إلى تطبيقات عملية على التعاون بين علماء المواد، وخبراء تكنولوجيا النانو، وأخصائيي علاج الجذور، مما يعزز من أداء ومتانة ملفات Ni-Ti المستخدمة في علاج الجذور.