



ISSN: 2230-9926

Available online at <http://www.journalijdr.com>

IJDR

International Journal of Development Research
Vol. 15, Issue, 09, pp. 69101-69106, September, 2025
<https://doi.org/10.37118/ijdr.30116.09.2025>



REVIEW ARTICLE

OPEN ACCESS

THE ROLE OF NICKEL-TITANIUM IN MODERN ENDODONTICS: A COMPREHENSIVE REVIEW

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ARTICLE INFO

Article History:

Received 11th June, 2025
Received in revised form
26th July, 2025
Accepted 08th August, 2025
Published online 30th September, 2025

Key Words:

NiTi alloys, Root Canal Therapy,
Superelasticity.

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ABSTRACT

The introduction of rotary Nickel-Titanium (NiTi) instruments has changed root canal therapy by improving the predictability and quality of root canal shaping. These instruments offer superior flexibility and help maintain the original curvature of the canal, which is particularly useful in complex root canal anatomies. Traditional stainless-steel hand files often lead to procedural errors, such as canal transportation and perforation. However, challenges still exist even with rotary NiTi systems. Issues like instrument separation, inadequate cleaning of canal irregularities, and incomplete removal of dead tissue and microbial biofilms remain. Therefore, while automated instrumentation marks an essential change in endodontic practice, careful case selection and clinical judgment are still necessary. The main goals of canal preparation, such as centered shaping, preservation of the canal's natural path, and thorough cleaning, must work with proper irrigation methods to ensure successful treatment. Ultimately, adequate root canal preparation requires a combination of mechanical precision and biological insight, supported by ongoing research and technological improvements.

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Citation: **Krishna Prasada L, Naveen Kumar K and Nakshathra Abraham. 2025.** "The role of Nickel-titanium in modern endodontics: a Comprehensive Review". *International Journal of Development Research*, 15, (09), 69101-69106.

INTRODUCTION

Evolution of instrumentation: from stainless steel to NiTi systems:

The evolution of root canal instrumentation has brought significant progress in modern endodontic practice. Traditional techniques using stainless steel hand files faced complications like canal transportation and perforation, especially in curved or anatomically complex canals. The introduction of rotary Nickel-Titanium (NiTi) systems changed root canal preparation by providing better flexibility and a greater ability to maintain the original canal curvature. These advances led to more conservative and centered canal shaping, improving endodontic treatment's precision, safety, and efficiency. The shift to automated tools has also reduced procedural errors and allowed for quicker, more predictable canal shaping. Despite these improvements, several clinical challenges persist. Instrument separation, inadequate cleaning of complex canal anatomies, and anatomical differences still make achieving the best treatment outcomes hard. Proper debridement in root canals depends on mechanical shaping and chemical irrigation to remove tissue remnants and disrupt microbial biofilms. While advancements in endodontic tools have improved clinical success, achieving ideal results still requires a balanced approach that combines mechanical precision, effective chemical disinfection, and a clear understanding of root canal shapes¹.

Traditional stainless-steel instrumentation: limitations and complexity: Before the development of NiTi technology, root canal

shaping mainly relied on the sequential use of many stainless-steel instruments. Each file served a specific purpose within a complicated stepwise technique - larger instruments were used for coronal enlargement while progressively smaller ones advanced toward the apical third. This method aimed to create a continually tapering canal while preserving the original canal anatomy. However, the rigidity of stainless steel meant that achieving ideal canal shaping, especially in curved or anatomically complex canals, required great care². Multiple shaping strategies were often needed to avoid procedural issues like canal transportation and perforation.

NiTi instrumentation: A technological breakthrough: Significant advancements in NiTi endodontic tools have altered root canal preparation in recent years. Improvements in instrument design, surface treatments, and thermal processing have enhanced mechanical properties such as flexibility, cutting efficiency, and resistance to cyclic fatigue and fracture. These changes have greatly improved the safety and efficiency of canal shaping procedures. NiTi instruments display unique qualities like better flexibility, shape memory, and resistance to cyclic fatigue. These features allow them to follow the natural curvature of root canals and navigate narrow or curved pathways more effectively than stainless steel files. Consequently, NiTi instruments reduce the risk of procedural errors and support safer, more reliable root canal preparation³. Nickel-titanium (NiTi) alloy instruments have revolutionized endodontic practice due to their unique mechanical properties. Compared to stainless steel, NiTi files are two to three times more elastic, allowing them to keep canal curvature better and lowering the risk of procedural errors in

challenging canals⁴. A key feature of NiTi instruments is their low elastic modulus, enabling them to be pre-bent for insertion into curved canals while returning to their original shape after use. This flexibility and shape memory combination ensures the files retain their form and working diameter throughout use, allowing efficient and consistent canal shaping¹. Furthermore, nitinol files are remarkably resilient and durable under clinical stress, as they can recover their shape after bending. This quality helps maintain canal integrity during treatment⁵. However, despite these benefits, NiTi instruments have limitations. Clinical use carries potential risks, such as cyclic fatigue, torsional failure, and progressive wear. These issues require careful handling, regular inspection, and following usage guidelines to avoid instrument separation during procedures⁶. Recent innovations aim to address these limitations with developments like heat-treated NiTi alloys such as M-Wire, Controlled Memory (CM) Wire, and Blue Wire. These alloys undergo special thermal processing that changes the material's behavior, significantly improving flexibility, cyclic fatigue resistance, and fracture risk⁷⁻⁹. Integrating NiTi instruments into everyday endodontic practice has significantly raised root canal therapy's quality, safety, and predictability. Their use has also led to more consistent shaping with fewer procedural errors, especially in anatomically complex cases¹⁰. Advancements in alloy treatment, tool design, and motion continue to enhance the performance of NiTi instruments. These innovations contribute to more efficient procedures, better clinical outcomes, and greater long-term success in endodontic treatment.

Super elasticity -NiTi revolution in endodontics: The introduction of superelastic nickel-titanium (NiTi) instruments represented a significant turning point in endodontic practice. These instruments provided more efficient, reliable, and safer canal shaping, significantly lowering the chance of procedural errors linked to traditional stainless-steel tools¹. Switching from stainless steel to super elastic NiTi instrumentation marked a vital progression in root canal therapy. NiTi instruments featured several advantages, including better flexibility, improved fracture resistance, and a heightened ability to conform to and shape complex root canal anatomies⁴. These benefits stem mainly from the unique mechanical properties of NiTi alloys, particularly super elasticity and shape memory¹. Because of these exceptional properties, NiTi rotary systems have become popular in modern endodontics. They are now essential to contemporary treatment protocols, offering better performance, increased safety, and consistent clinical results. Removing debris and shaping the root canal is critical for effective endodontic treatment. Key goals include thoroughly clearing organic material and forming a continuously tapered shape that respects the natural anatomy of each canal¹¹. Accomplishing these objectives is vital for ensuring disinfection and the long-term success of root canal therapy. Rotary NiTi instruments have greatly improved the precision and predictability of canal shaping, particularly in complex or curved canals. These instruments provide the mechanical efficiency needed to navigate complex canal systems while lowering the risk of procedural errors. NiTi files, made from the shape-memory alloy nitinol, exhibit better resistance to torsional fracture. Moreover, nitinol instruments can endure bending and torsional stress while returning elastically to their original shape. This resilience decreases the chances of permanent distortion or instrument failure during clinical use, further supporting their effectiveness in canal preparation. Even with significant advancements in NiTi instrument technology, issues such as cyclic fatigue and torsional failure still pose challenges. Surface and bulk changes were introduced to boost these instruments' mechanical properties, with varying success levels¹². Thermal treatments and electropolishing have proven particularly effective in enhancing fatigue resistance. By encouraging R-phase changes within the alloy, these treatments can nearly double the cyclic fatigue life of NiTi files compared to untreated ones. However, NiTi instruments remain vulnerable to failure even with these improvements under repetitive clinical stress.

Material properties of Nickel-Titanium alloys

Physical properties: Nickel-titanium alloys have unique physical properties that make them very useful in endodontics. These

properties have significantly changed root canal treatment by improving safety and clinical outcomes. One of the most remarkable features of NiTi alloys is their super elasticity, which lets instruments bend significantly and return to their original shape. This characteristic allows for smooth navigation through curved and complex canal anatomies without permanent deformation or loss of cutting efficiency. NiTi also exhibits shape memory, letting the alloy return to its pre-deformed shape when subjected to certain temperatures. This feature ensures consistent instrument performance during use, especially when body temperature triggers a phase change from martensite to austenite. The high flexibility of NiTi improves its ability to navigate challenging canal shapes without breaking or transporting¹³. This flexibility makes NiTi instruments especially suitable for anatomically complex cases. Additionally, NiTi instruments demonstrate excellent fatigue resistance, strength, and durability. Their high corrosion resistance extends the instrument lifespan and reduces the risk of material breakdown during use¹⁴. A key aspect of NiTi is its capacity for thermally prompted phase changes, which improve its mechanical properties. The alloy becomes stiffer at body temperature, enhancing tactile feedback and clinical control during canal shaping. Moreover, NiTi's low elastic modulus allows it to conform to canal curvature more effectively than stainless steel, reducing problems such as canal transportation and zipping. The properties such as superelasticity, shape memory, flexibility, fatigue resistance, and corrosion resistance make NiTi ideal for modern root canal tools.

Mechanical properties: The NiTi instruments achieve outstanding mechanical performance through a unique metallurgical property called stress-induced phase transformation, especially between the austenite and martensite phases. This transformation allows NiTi instruments to flex within curved canals without permanent deformation, preserving the canal's original shape¹³. NiTi's super elasticity comes from a reversible stress-induced martensitic transformation, which lets files return to their original shape after navigating complex canal curves⁸. Along with super elasticity, NiTi has high tensile strength and excellent fatigue resistance, enabling it to handle repetitive mechanical stress during root canal preparation without failing. These properties are vital in preventing cyclic fatigue, a common cause of instrument separation in practice. The introduction of R-phase NiTi alloys has further improved endodontic instrument performance. These alloys have a lower Young's modulus than austenitic NiTi or stainless steel, providing greater flexibility and allowing the instruments to better conform to the natural curvature of root canals¹⁵. Additionally, NiTi alloys show high resistance to wear and corrosion, ensuring the instruments remain functional and intact even under the harsh conditions of root canal therapy. Together, the characteristics¹⁶ of NiTi—super elasticity, shape memory, high fatigue and tensile strength, corrosion resistance, and low modulus of elasticity—make it an ideal material for endodontic tools. These features improve the safety and efficiency of root canal shaping and lead to better clinical outcomes.

The NiTi alloys are widely considered suitable for endodontic tools due to their exceptional compatibility with biological tissues, super elasticity, and shape memory properties. These traits improve mechanical performance and ensure safety and compatibility with tissues during clinical procedures. A key benefit of NiTi alloys is their high corrosion resistance, caused by creating a stable passive oxide layer on the surface¹⁷. This layer effectively limits the release of nickel ions, thus reducing the risk of cytotoxic or inflammatory responses in surrounding tissues. The low ion release associated with NiTi tools is essential in minimizing adverse biological reactions. A stable chemical interface reduces the chances of peri-apical irritation or allergic reactions, even in sensitive tissues. While some individuals may have nickel sensitivities, the overall safety profile of NiTi is excellent, primarily due to its stable passivation and low systemic reactivity. Surface-treated NiTi instruments—especially those that are electropolished or passivated—also show reduced surface roughness¹⁸. This smoothness helps lessen mechanical irritation to nearby tissues and encourages better healing after surgery. Therefore, despite hypersensitivity in a few people, NiTi alloys are considered

biologically safe and non-toxic for endodontic use¹⁷. Their resistance to corrosion, low ion release, and stable surface chemistry supports their effectiveness and favourable biological results in root canal therapy.

NiTi in endodontic instrumentation: Using NiTi as the material for endodontic rotary instruments has significantly changed clinical practice. Since NiTi became the preferred alloy for rotary tools, endodontic therapy has improved considerably, with higher success rates, better efficiency, and more predictable root canal outcomes¹⁹. NiTi rotary files transformed root canal preparation by utilizing their super elasticity and shape memory to keep the original canal anatomy intact during the shaping procedure. These mechanical features allow the tools to experience considerable deformation and revert to their original form, safely navigating even the most complicated canal curves²⁰. Moreover, the torsion-resistant quality of NiTi boosts its capacity to navigate intricate root systems with a lower risk of instrument separation. These characteristics enhance the technical success of root canal procedures and minimize complications, which improves long-term success rates²¹. NiTi rotary files are now essential to modern endodontic practice due to their exceptional mechanical properties, which allow for safer and more efficient root canal shaping, especially in anatomically complex cases. A significant benefit of these instruments is the unique behaviour of the nitinol alloy, which combines super elasticity, shape memory, and high resistance to fatigue. Thenitinol alloy has a very low modulus of elasticity, about one-fourth to one-fifth that of stainless steel¹. This property provides it with a much wider range of elastic deformation. This capability allows NiTi rotary files to bend extensively without breaking, maintaining structural integrity even when working with curved or narrow canals. Metal fatigue is a significant concern for the clinical performance of rotary NiTi instruments. It arises from repeated loading cycles, leading to irreversible structural changes and eventual metal fracture. Microscopic analysis of broken rotary NiTi instruments suggests that metal fatigue often results in ductile fracture after prolonged mechanical stress^{22,23}. To tackle this issue, thermo-mechanically treated NiTi alloys have been developed that offer better flexibility, improved resistance to cyclic fatigue, and a greater angle of deflection before failure compared to standard NiTi²⁴. These advancements come from modified phase compositions, including various amounts of R-phase and martensite, which enhance the alloy's mechanical performance. NiTi instruments made from austenitic alloys have superelastic properties due to stress-induced martensite transformation, bringing them back to their original shape following deformation⁷. In contrast, martensitic-phase instruments are more easily deformed but show shape memory behaviour when heated, which can also provide clinical benefits. Since the arrival of NiTi rotary instruments, various systems have been created that maintain the original canal curvature while reducing procedural mistakes and improving the speed and efficiency of root canal preparation²⁵. Modern endodontics has seen significant advantages from standardizing canal shaping protocols that utilize advanced NiTi systems. These changes have led to better-filling quality and, as a result, higher success rates and tooth survival. Design improvements such as non-cutting tips, radial lands, varied cross-sectional shapes, and progressive tapers have further enhanced modern rotary tools' safety, efficiency, and shaping results.

NiTi file designs: The creation of nickel-titanium instruments has changed root canal preparation by allowing for more predictable shaping of complex canal anatomies due to their superior flexibility and cutting efficiency¹. Differences in the design features of NiTi rotary tools, including cross-sectional shape, taper, and motion kinematics, are crucial in determining their flexibility, cutting efficiency, and resistance to breaking, which affects clinical performance and safety during root canal procedures. Innovations in NiTi file design focus on improving cutting efficiency, increasing flexibility to manage curved canals and reducing the risk of instrument separation to ensure safer and more effective root canal treatment¹⁰. The design factors of NiTi tools, such as cross-sectional shape, taper, flute pitch, and thermomechanical processing, greatly affect their mechanical performance, cutting efficiency, and safety

during root canal procedures. The cross-sectional shape is vital for how instruments perform. Designs like triangular or convex cross-sections offer better-cutting efficiency, while more intricate shapes, like S-shaped profiles, provide greater flexibility and more resistance to cyclic fatigue¹⁹. The instrument's taper also significantly impacts the shaping dynamics. Larger tapers are linked to better cutting ability and faster shaping in wider canals, while smaller tapers reduce wall contact, lowering the risk of canal transportation and over-instrumentation. Flute pitch, defined as the distance between spirals along the file's shaft, affects flexibility and the ability to remove debris. A decreased pitch improves cutting smoothness and flexibility, which helps in curved canals, while an increased pitch enhances debris removal, especially in straight or wider canals²⁶. Moreover, the thermomechanical processing of NiTi alloys has significantly improved instruments' flexibility and cyclic fatigue resistance. Heat-treated options are better suited for navigating curved and complex root canals, helping lower file separation chances. When chosen and applied carefully, differences in instrument design directly impact the quality of canal shaping, particularly in the apical third, and are crucial for minimizing procedural complications and ensuring positive endodontic outcomes⁷.

Performance and limitations of rotary NiTi instruments in root canal preparation: Rotary NiTi instruments have become essential in modern endodontics because they are highly efficient for root canal preparation. Their continuous rotation allows for quick and consistent shaping of canals, especially in straight or moderately curved ones²². This helps clinicians achieve the desired canal shape and size more quickly and reliably. During rotation, particularly in curved canals, these instruments face tensile and compressive stresses that peak at the point of maximum curvature. The mechanical stress on NiTi files depends on the canal curvature, dentin hardness, and motor torque settings. These stress factors can substantially raise the risk of cyclic fatigue, which can cause instrument separation if not carefully managed. Despite these challenges, rotary glide path files are widely used because they reduce treatment time and improve efficiency, particularly in straightforward canal shapes²⁷. However, in complex anatomies, clinicians must be cautious and practice proper technique and torque control to lessen the chances of file breakage and ensure safe instrumentation²⁸. Introducing reciprocating motion in NiTi instruments has significantly improved canal preparation, especially in curved and complex anatomies²⁹. Unlike continuous rotation, reciprocation switches between clockwise and counterclockwise motion, effectively lowering stress on the instrument. This motion greatly improves the instrument's resistance to cyclic fatigue, reducing the fracture risk. By closely following the natural canal curvature, reciprocating files decrease the likelihood of canal transportation and zipping, which helps to maintain the root canal's original anatomy. This action also enhances how NiTi instruments feel in the hand, giving clinicians better control and safety, which is especially valuable for less experienced practitioners. Additionally, reciprocating instruments show better shaping ability and improved fatigue resistance in highly curved canals, leading to more predictable, efficient, and safer root canal therapy²⁹.

Clinical challenges and evolving solutions in NiTi instrumentation: Over the last few decades, NiTi rotary instruments have become the most effective and widely used tool for root canal shaping among endodontists. Their popularity arises from their superior flexibility, strength, and cutting performance, which supports safer and more predictable canal preparation, particularly in complex anatomies³⁰. However, certain limitations persist. Cyclic fatigue, a common cause of instrument separation, strongly depends on canal curvature³¹. For instance, files working in a 3 mm radius of curvature fail much sooner than those in a 5 mm curvature, highlighting the increased mechanical stress in sharply curved canals. Moreover, the cost of NiTi instruments remains a practical concern. These files are substantially more expensive than traditional stainless-steel files, which can deter clinics from operating with tight budgets or in resource-limited settings. Despite these challenges, the clinical benefits of NiTi instruments keep them at the forefront of modern endodontic practice. While NiTi instruments offer many advantages in flexibility, efficiency, and canal

preservation, their use poses challenges, especially for inexperienced practitioners²¹. Successful use of NiTi rotary systems involves a steep learning curve, as effective handling requires a good understanding of how the instruments behave in complex root canal anatomies. Less experienced clinicians often find it hard to master the precise techniques needed to optimize performance, which increases the risk of procedural errors like instrument separation or canal transportation. Although NiTi alloys are known for their flexibility, they can still deform if misused, particularly in severely curved or narrow canals. Another factor to consider is the potential biological impact of nickel, a part of the alloy. While nickel allergies are uncommon, they may be a concern for some patients, requiring careful assessment of patient history. Fortunately, ongoing advancements in NiTi alloy processing and file design have led to significant improvements in durability, flexibility, and safety, addressing many earlier limitations and reinforcing the value of NiTi systems in modern endodontics³⁰.

Recent advances in NiTi alloy technology and instrument design: In the last decade, NiTi instruments have significantly improved cutting efficiency and safety during procedures. These improvements come from refinements in instrument design, such as changes in cross-sectional geometry, taper, and tip shape, which lead to better-shaping performance and fewer procedural errors. At the same time, advances in surface treatment technologies, like electropolishing and ion implantation, have enhanced corrosion resistance and reduced surface defects that might lead to instrument failure. Furthermore, thermal treatments have changed how the NiTi alloy behaves during phase transformations, increasing flexibility and fatigue resistance greatly improving clinical performance⁵. In recent years, we have seen remarkable progress in NiTi technology, significantly improving root canal instruments' clinical performance and safety. These innovations address long-standing issues regarding instrument durability, shaping accuracy, and procedural risks. One key development is the introduction of thermo-mechanically treated NiTi alloys. These exhibit better flexibility, greater resistance to cyclic fatigue, and a higher deflection angle at failure than conventional NiTi. This improved performance comes from a modified phase composition that includes different amounts of R-phase and martensitic structures²⁴. Instruments in the martensitic phase are particularly beneficial because they can easily deform and return to their original shape when heated, allowing for greater adaptability in complex procedures. Beyond alloy innovations, advancements in file design have been critical. Modern instruments now have altered cross-sectional shapes, optimized tapers, and better flute pitches. These changes improve cutting efficiency, enhance debris removal, and lower the risk of canal transportation or over-instrumentation. Another advancement is using reciprocating motion, which switches the direction of instrument rotation. This method reduces stress on the file, significantly improving its resistance to cyclic fatigue compared to continuous rotary systems²⁸. As a result, reciprocating files are more durable and better equipped for navigating complex and curved canals with lower chances of separation. Further enhancements include surface treatments like thermal nitridation, which creates titanium nitride (TiNi) coatings¹⁸. These coatings improve corrosion resistance, improved cutting efficiency, and a longer instrument lifespan. These advancements have revolutionized the practice of endodontic instrumentation, empowering clinicians to carry out root canal treatments with heightened accuracy, shorter procedure durations, and improved patient comfort. The ongoing combination of material science, instrument engineering, and clinical ergonomics continues to shape a more effective and efficient future for endodontic treatment. Thermomechanical processing techniques, like those used to create M-Wire and Controlled Memory (CM) wire, have further boosted the mechanical properties of NiTi alloys. These specially processed alloys show superior flexibility and much higher cyclic fatigue resistance than traditional NiTi, making them suitable for safely working in curved canals³.

Emergence of single-file reciprocating systems: A new approach to root canal preparation has come forward, promoting using a single NiTi rotary instrument to complete the entire shaping process instead of using a series of larger files. This method employs a reciprocating

motion, switching between clockwise and counterclockwise rotations, to lower torsional stress and improve safety during canal preparation. Applied to curved canals in extracted human molars, this technique was evaluated for its efficiency in shaping, ability to maintain canal curvature, and safety in procedures. The results showed that root canals could be effectively shaped using just one NiTi file, with minimal canal transportation and no cases of instrument separation. The reciprocating motion reduced file contact with the canal walls, lowering the chance of taper lock and instrument breakage. This simplified method significantly reduced instrumentation time and eliminated the need for multiple files, offering clinicians a more efficient and cost-effective option. It also introduced the fundamental idea of single-file canal preparation systems, which later developed into commercially available reciprocating instruments now commonly used in clinical practice³². While these initial results were promising, further studies were recommended to confirm this technique across different tooth types, canal shapes, and clinical situations to ensure its long-term safety and effectiveness.

The future of NiTi instrumentation: personalization, robotics, and AI integration: Over the decades, many NiTi rotary instruments have been introduced, with each generation building on the last to meet the changing needs of root canal shaping¹⁰. These generations aimed to improve flexibility, safety, and clinical efficiency, resulting in significant changes in endodontic practice. A key breakthrough was the development of thermo-mechanically treated NiTi wires, which provide much greater flexibility than conventional superelastic wires⁵. This added flexibility is crucial for navigating complex and curved canal anatomies and reduces the chance of instrument separation. The design of NiTi rotary instruments is also essential for their performance and resistance to fracture. Factors such as cross-sectional shape, pitch, taper, radial lands, rake angle, and off-center mass distribution affect stress distribution and the risk of cyclic or torsional failure³³. Recent technological progress has focused on improving procedural control and safety. For instance, real-time torque and stress sensors are added to endodontic files, allowing clinicians to monitor mechanical loads in realtime and detect excessive forces early, which minimizes the risk of file separation and improves procedural safety. Looking ahead, machine-assisted and robotic technologies are being explored to lessen the reliance on manual skills. These systems intend to enhance precision, consistency, and treatment outcomes by automating key parts of the instrumentation process. Robotic systems can manage fine motor control and integrate sensor feedback. This means the future of endodontics may lean toward more predictable and minimally invasive methods, especially in complex or anatomically challenging cases^{34,35}.

Advances in imaging and manufacturing have led to customized instruments designed for specific canal anatomies. Using three-dimensional imaging techniques like cone-beam computed tomography (CBCT), clinicians can produce accurate, detailed models of a patient's root canal system. These digital reconstructions are used in CAD/CAM-based design and manufacturing of endodontic instruments, allowing for a more personalized approach to root canal therapy. This patient-specific customization improves the fit and performance of instruments, enhancing their ability to adapt within the canal. It also significantly lowers the chance of procedural complications such as canal transportation, instrument separation, and over-instrumentation while improving cutting efficiency and debris removal. As technology advances, integrating robotic systems and automation into the design and manufacturing process increases the precision, safety, and predictability of treatment. These innovations represent a strong shift toward more anatomically accurate and minimally invasive root canal therapy, redefining the standards of care in modern endodontics. Combining NiTi instruments with digital technologies transforms endodontic procedures by improving precision, efficiency, and patient outcomes. Through 3D imaging methods like cone-beam computed tomography (CBCT) and CAD/CAM systems, clinicians can create highly accurate, patient-specific models of the root canal system^{36,37}. These digital models aid in designing and making customized NiTi instruments tailored to each canal's unique anatomy. This individualized approach enhances the fit

and cutting performance of the files while reducing the risk of canal transportation, over-instrumentation, and instrument separation. In practice, specialized endodontic motors with real-time torque monitoring allow clinicians to track the stress on the files throughout the procedure. These intelligent endodontic engines automatically adjust the torque to keep a steady rotational speed, no matter the variations in canal anatomy or dentin hardness³⁸. Understanding torque and stress dynamics is key to preventing file fractures and structural damage to the tooth. Additionally, integrating artificial intelligence (AI) systems offers excellent potential for further personalization. AI can help select the best file sequence based on root canal complexity and provide insights to support clinical decision-making. Overall, merging NiTi instrumentation with digital technologies streamlines treatment, enhances safety, and reduces errors. This combination provides a more predictable, efficient, patient-centered approach to modern endodontic therapy.

CONCLUSION

The NiTi alloys have changed the endodontic practice by offering better flexibility, resistance to fracture, and improved navigation of complex root canal anatomies. Introducing NiTi instruments has greatly improved root canal treatment outcomes by lowering the risk of complications like file breakage and canal transportation. Despite these advantages, challenges such as file fatigue, fracture, and the learning curve associated with NiTi use remain. However, ongoing innovations in NiTi alloy treatments, improved file designs, and digital technologies like CAD/CAM and 3D imaging lead to further progress in endodontic instrumentation. These developments, alongside emerging techniques like robotic systems and AI monitoring, aim to deliver more personalized, efficient, and predictable treatments. NiTi's role in endodontics is expected to grow as technology advances, offering even more potential to enhance clinical outcomes and patient care.

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