ISSN: 2581-5989
PubMed - National Library of Medicine - ID: 101738774

International Journal of Dental Science and Innovative Research (IJDSIR)

IJDSIR : Dental Publication Service

Available Online at:www.ijdsir.com

Volume – 9, Issue – 1, February – 2026, Page No. : 44 – 52

Evolution of Instrumentation in Root Canal Therapy: From Hand Files to AI Assisted Endodontics

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Citation of this Article: Dr Pallavi Thalakola, Dr Pratvi Gour, Dr Harshvardhan Narendra Jain, Dr Komal Chaudhary, Dr Disha Deepak Churi, "Evolution of Instrumentation in Root Canal Therapy: From Hand Files to AI Assisted Endodontics", IJDSIR- February – 2026, Volume – 9, Issue – 1, P. No. 44 – 52.

Type of Publication: Original Research Article

Conflicts of Interest: Nil

Abstract

Endodontic instrumentation has undergone remarkable transformation over the past century, beginning with rudimentary hand-crafted steel tools and progressing to advanced nickel–titanium (NiTi) rotary systems, thermally treated alloys, and, most recently, artificial intelligence (AI)-enhanced technologies. These developments have significantly improved shaping efficiency, safety, and overall treatment outcomes.

This review aims to comprehensively outline the chronological evolution of endodontic instruments—from early hand files to modern AI-augmented systems—highlighting major breakthroughs in material science, manufacturing, kinematics, and digital integration.

A structured electronic search was conducted through PubMed and Google Scholar using the keywords ("evolution" OR "advances") AND ("instrumentation") AND ("artificial intelligence" OR "AI").

Four major phases were identified: (1) early hand instruments fabricated from carbon steel and later stainless steel; (2) the introduction and standardization of instruments between 1955 and 1981; (3) the rise of NiTi files and the progressive evolution of their generations—marked by improved flexibility, fatigue resistance, and shaping capabilities; (4) the emergence of digital and AI-driven systems, including CBCT-based planning, automated radiographic interpretation, outcome prediction models, and early robotic endodontic devices. Each innovation addressed specific limitations of earlier

systems and progressively enhanced clinical efficiency and safety.

Endodontic instrumentation has evolved from simple manual tools to sophisticated, biologically integrated and AI-supported systems. This continuous innovation promises even greater precision, predictability, and personalized treatment in the future.

Keywords: Crucial Role, Flexibility, Nickel–Titanium, Predictability

Introduction

Over the past two decades, significant advancements in both manual and rotary instrumentation have greatly enhanced the predictability and overall success of endodontic procedures[1]. Researchers have increasingly emphasized achieving the technical and biological goals of pulp therapy, recognizing the crucial role of chemo-mechanical preparation. During this period, the continuous refinement of hand and motor-driven systems has contributed substantially to improved treatment outcomes[2,3]. The objective of this review is to discuss key concepts and outline the major developments in the progression of endodontic instruments[2,3,4].

The earliest endodontic files were fabricated from carbon steel. Although these instruments offered notable resistance to fracture and strong cutting ability, their usefulness was compromised by significant susceptibility to corrosion [5,6]. The introduction of stainless-steel instruments, which are still widely used, largely resolved the corrosion issue[3,5,6]. Kerr Manufacturing Co. was the first to produce the well-known K-type instruments, which eventually became the most replicated file design worldwide[3,7]. Despite their advantages, stainless steel files possess limited flexibility, which poses challenges in curved canals and increases the risk of procedural complications such as canal transportation, apical deviation, and perforations due to excessive removal of dentin from the outer curvature. These limitations led to the adoption of nickel–titanium (NiTi) alloys in dentistry[3,8].

NiTi was originally identified in 1963 by metallurgical engineer William Buehler[3,7,9]. The first NiTi endodontic file was developed by Harmeet Walia in 1988, using orthodontic NiTi wire, marking a transformative moment in endodontic instrumentation. Since that time, NiTi systems have become indispensable to contemporary endodontic practice[10].

Technological advancements—including innovations in NiTi metallurgy, heat-treatment protocols, ultrasonic activation techniques, CBCT imaging, and artificial intelligence—have markedly enhanced shaping efficiency, procedural safety, and treatment prognosis[11,12]

Modern applications of artificial intelligence include:[13,14]

1. Automated detection and segmentation of lesions on radiographs/CBCT
2. Classification of root and canal anatomy
3. Identification of vertical root fractures
4. Prediction of treatment outcomes, including likelihood of success or retreatment
5. Workflow optimization (triage, scheduling, task automation)
6. Emerging innovations: robotic endodontic systems that integrate planning and operative execution Recent scoping and review studies have outlined current achievements, existing limitations, and avenues for future research.

This article provides qualitative, descriptive review of literature on evolution of instrumentation in root canal therapy

Methodology

A systematic literature search was conducted, utilizing electronic databases including PubMed and Google scholar without restriction on publication year. The

search criteria consisted of terms such as ("evolution" OR "advances") AND ("instrumentation") AND ("artificial intelligence" OR "AI"). Following elimination of duplicates, 27 articles remained.

Evolution of Endodontic Instruments

ISO grouping of endodontic instruments[15]

The International Standards Organization, together with the Federation Dentaire Internationale, classified endodontic instruments into four major categories.

Group I: Manually operated endodontic instruments

1.Barbed broaches and rasps, 2. K-type reamers and files, 3. Hedström files

Group II: Low-speed stainless-steel rotary instruments with latch-type attachments

1. Gates-Glidden drills, 2. Peeso reamers / Largo drills

Group III: Sonic and ultrasonic instruments

Group IV: Engine-driven nickel–titanium instruments (most widely used today)

1. Rotary systems, 2. Reciprocation-based systems, 3.Canal-adaptive systems: (a) Self-adjusting file (SAF) (b) XP-Endo Shaper and Finisher

Early Hand Instruments (From 1875 to mid-1900s)[14]

The earliest root canal instruments (barbed broaches, early K-files, Hedström files) were handcrafted from thin steel wires. Initially, carbon steel was commonly used, but its high susceptibility to corrosion eventually led to its replacement with stainless steel. Early files were either twisted from wire blanks or produced using rudimentary machining, and their tip designs and flexibility were extremely limited. Standardized sizing came much later.

These instruments made it possible to perform basic canal shaping and obturation; however, they were largely restricted to straight canals and offered little adaptability in curved anatomy.

Stainless-steel files, being considerably harder than dentin, frequently caused complications in curved canals, such as apical foramen distortion, canal transportation, and even perforations—primarily due to excessive cutting on the outer curvature. Their early versions lacked scientific design criteria[5,6,16]

The development of the earliest endodontic tools dates back to 1875. These hand-fashioned steel devices functioned similarly to modern broaches. During that period, clinical emphasis was placed more on canal filling than on thorough cleaning[14]. The introduction of local anesthesia, dental radiology, and bacteriological principles at the end of the 19th century marked the beginning of a new phase in endodontics[15].

Standardization of Instruments (From 1955 to 1981)

In 1955, John Ingle of the University of Washington, together with Levine in 1961, proposed the first comprehensive guidelines for standardizing endodontic instruments as well as gutta-percha and silver cones[3,5,6]. Their recommendations were later adapted by the American Association of Endodontists (A.A.E.), forming the basis of today's ISO norms. In 1976, the American Standardization Association approved Specification No. 28, which defined manufacturing criteria for files and reamers[3,7]. After nearly 26 years of refinement, the final standards for these instruments were established in 1981, creating the modern ISO system[16].

According to these guidelines, the working section of an instrument extends from D1 (file tip) to D2. The diameter at D2 must be exactly 0.32 mm greater than at D1, reflecting a uniform taper of 0.02 mm per mm over a 16-mm active portion[3,7]. Instruments are manufactured in standardized lengths of 21, 25, 28, and 31 mm, and color coding is applied to handles for identification. Their defining features include stainless-steel construction,

plastic handles, and a constant 0.02 taper along the active segment[3,7]

Stainless-Steel Rotary Adjuncts (From mid-1900s to 1980s)

Before the introduction of NiTi, rotary adjuncts made of stainless steel—such as Gates-Glidden drills and Peeso reamers—were routinely used for coronal flaring and post-space preparation. These latch-type instruments had rigid shafts, aggressive cutting behavior, and were efficient for removing dentin coronally. However, their stiffness also posed a higher risk of perforation, particularly when used without caution[14].

Introduction of Nickel–Titanium (From late 1980s to 1990s)

NiTi instruments emerged first as hand-crafted prototypes and later as precision-machined files, including early systems such as LightSpeed and ProFile. The unique material properties of NiTi—shape memory and superelasticity—allowed for unprecedented flexibility, enabling instruments to follow complex canal curvatures with minimal transportation. Manufacturing techniques evolved from simple machining to sophisticated grinding and torsional optimization.

This shift dramatically reduced procedural errors, expanded access to curved canals, and facilitated the adoption of rotary instrumentation worldwide.

This alloy possesses exceptional features, including shape-memory behavior, corrosion resistance, biocompatibility, and affordability[3,6,9]

Nickel–titanium was first developed in 1963 for aerospace applications[14]. William Buehler named the alloy NiTiNOL based on its components—Nickel (Ni) and Titanium (Ti)—and the Navy Ordnance Laboratory (NOL) where it was created [6,9]. Its classification among shape-memory alloys arises from its superelasticity and ability to revert to its original form after deformation.

In dentistry, Andreasen and Hilleman introduced NiTi in 1971 for orthodontic wires due to its excellent elasticity and shape-memory behaviour. Civjan et al. later suggested its use for endodontic instrumentation in 1975. The first functional NiTi endodontic file was manufactured in 1988 by Walia, Brantley, and Gerstein, who machined orthodontic NiTi wire into a handheld instrument. Subsequent technological developments allowed NiTi endodontic files to be produced with varying tapers, helical angles, and cross-sectional designs that diverged from the ISO standards set for stainless-steel files in 1958[17].

Generations of NiTi Rotary Systems[12, 18,19]

The evolution of nickel–titanium rotary file systems can be broadly categorized into multiple generations, each reflecting major advancements in alloy science, instrument geometry, and kinematics:

1. **First generation:** First-generation NiTi systems were the earliest mechanized instruments manufactured from nickel–titanium alloy, providing super elasticity and shape memory. These features offered improved flexibility and strength compared with stainless-steel hand files. Common systems include:

McXim File (NT Company) GT system (Dentsply) LightSpeed (LightSpeed Technology) Pow-R (Moyco) ProFile (Dentsply) ProFile Series 29 (Dentsply) Quantec (Tycom) Quantec 2000 (Tycom) Rapid Body Shaper (Moyco)[7]

Advantages[12]

Excellent flexibility reduce procedural errors such as ledges, transportation, or perforations, Good cutting efficiency , Reduced working time and improved clinical efficiency.

Disadvantages

Higher cost because instruments are recommended for single use. Risk of instrument separation . Limited effectiveness in cleaning flat or oval canal configurations.

2. **Second generation:**

Second-generation systems introduced R-phase NiTi alloy, which offers improved flexibility and reduced fracture risk due to specialized thermal processing. The R-phase allows twisting of the alloy to create cutting surfaces without inducing microcracks.

Systems include:

BioRaCe (FKG) EndoSequence (Brasseler) K3 (Sybron) Mtwo (VDW) ProTaper Universal (Dentsply)[7]

Advantages[12]

Higher resistance to torsional and cyclic fatigue. Improved cutting efficiency and reduced working time. Lower chance of postoperative pain. Greater flexibility than first-generation systems.

Disadvantages

Increased cost due to single-use recommendation. Instrument separation may still occur but at lower frequency.

3. **Third generation**

Focused on new thermally modified alloys (M-Wire, R-phase, CM Wire) and novel manufacturing methods such as twisting rather than grinding, as seen in the Twisted File system. These improvements significantly increased resistance to cyclic fatigue.

HyFlex CM (Coltène) K3XF (Sybron Endo) ProFile GT Series X (Dentsply) ProFile Vortex (Dentsply) ProFile Vortex Blue (Dentsply) ProTaper Gold (Dentsply) Twisted File (Sybron) Typhoon (Clinician's Choice)[7]

Advantages[12]

Markedly increased fatigue resistance. Greater flexibility (approx. 15% more than first generation). Reduced working time and postoperative discomfort. Safer reuse potential (though manufacturers still recommend single use).

Disadvantages

Higher cost. Potential for fracture still exists but is reduced.

4. **Fourth generation:**

Marked the transition to reciprocating and adaptive motion, which reduced torsional stress and improved safety.

Reciproc (VDW) Reciproc Blue (VDW) WaveOne (Dentsply) WaveOne Gold (Dentsply) Twisted File Adaptive (Sybron Endo)[7]

Advantages[12]

Ideal for canals with severe anatomical curvature. Up to 300% greater cyclic fatigue resistance. 80% more flexible than conventional NiTi. Reduced postoperative pain and shorter working time.

Disadvantages

Not recommended for wide or straight canals. Higher material cost.

5. **Fifth and sixth generations:**

Characterized by off-centered, asymmetric cross-sections (e.g., ProTaper Next) and instruments made from shape-changing alloys such as MaxWire (XP-Endo) or adaptive, meshlike systems such as the SAF. These files interact dynamically with the canal and maximize contact with irregular anatomy.

OneShape (MicroMega) ProTaper Next (Dentsply) Revo-S (MicroMega) Rotary Files (VDW) TruNatomy (Dentsply) TruShape (Dentsply) XP-endo Shaper (FKG)[7]

Across all generations, advancements occurred in metallurgy (conventional NiTi → M-Wire → R-phase → CM → MaxWire), cross-sectional design (triangular, S-shaped, offset/rectangular), manufacturing techniques (grinding, twisting, thermal processing), and motion

(continuous rotation → reciprocation → adaptive motion). Collectively, these developments improved file flexibility, cyclic fatigue resistance, and shaping safety. Nonetheless, challenges remain—expense, occasional unexpected fracture, and incomplete cleaning of oval or flattened canals continue to be limitations.

Single-file and Reciprocating Systems (From 2000s to 2010s)[20]

Systems such as Reciprocating- WaveOne, Reciproc and rotary -OneShape, F360, and F6 Sky Taper represented a major shift toward simplified instrumentation. These designs rely on a single shaping file, operated either in full rotary motion or reciprocation, often combined with regressive tapers and motors programmed to deliver specific reciprocating angles. All have **non-cutting tips**

Appropriate case selection, glide-path establishment, and adherence to manufacturer recommendations remain essential for safe use.

Self-Adjusting File (SAF) and Canal-Adaptive Instruments (2010s)[21]

The introduction of true canal-adaptive systems marked a conceptual shift. The SAF, constructed as a hollow, compressible NiTi lattice, allows continuous irrigation during shaping and adapts its geometry to the internal canal form. Operates at 5,000 Hz oscillation. Files clean via scrubbing/brushing action, not cutting flutes.Expands bucco-lingually in oval canals to maximize contact. Recommended use: 4 minutes per canal with small vertical motions.

XP-Endo instruments use a thermomechanically activated alloy that changes phase at body temperature, creating an expanded working configuration once inside the canal.

These designs provide enhanced engagement with irregular or oval canals, minimize unnecessary dentin removal, and improve irrigant penetration. Their non-ISO geometries, however, require modified obturation protocols. Adoption remains limited, and further large-scale clinical research is required to validate long-term outcomes

Advanced Metallurgy and Surface Treatments (From 2000s to Present)[22]

Progressive improvements in alloy processing—such as M-Wire, R-phase, CM Wire, and Gold/Blue thermal treatments—have been accompanied by surface modifications like electropolishing, TiO_2 coatings, nitridation, and cryogenic conditioning. Such processes adjust phase transformation temperatures, increasing the proportion of martensite at working temperatures, thereby enhancing flexibility and resistance to fatigue.

These innovations allow certain files (e.g., CM instruments) to be pre-curved, reduce micro defect formation on the file surface, and improve corrosion resistance. The result is superior cyclic fatigue performance, greater safety margins, and enhanced reliability in daily clinical usage[14].

Early Engine-Driven Devices

Attempts to mechanize canal instrumentation began surprisingly early:

- **Rollins (1889)** introduced the first dedicated endodontic handpiece operating at approximately 100 rpm[23]
- **Oltramare (1892)** developed primitive rotary needle systems for canal shaping[24]
- **The Giromatic (1964)** offered one of the earliest reciprocating instruments, mimicking later modern reciprocation concepts[25]

Although innovative for their time, these early devices lacked adequate flexibility, generated significant mechanical stress, and were prone to operational failure.

Imaging advances that changed instrumentation workflows[26]

Digital radiography and CBCT; higher resolution imaging for canal morphology

More accurate canal anatomy mapping, CBCT enables 3D planning that influences the choice of instruments/approach.

Improved case selection, better anticipation of difficulties, and tailored instrument sequences. (This imaging evolution sets the stage for AI.)

Artificial intelligence

The evolution of endodontic instruments has progressively transitioned from mechanical devices to digitally enhanced systems, influenced by major advances in imaging, computational technologies, and artificial intelligence (AI)[27,28,29]. Early hand and rotary files focused mainly on shaping and debridement, whereas modern endodontics increasingly integrates technologies that enhance diagnostic accuracy, treatment planning, and procedural precision[30,31]. The introduction of cone-beam computed tomography (CBCT) expanded three-dimensional visualization of complex canal morphology, allowing more predictable use of mechanical instruments, particularly in anatomically challenging situations[27,32]. Likewise, ultrasonic activation and magnification systems have improved detection of calcifications, accessory anatomy, and microcracks, thereby strengthening the effectiveness of instrumentation protocols[33].

AI represents a transformative stage in the evolution of endodontic instrumentation. AI-driven platforms can now interpret radiographs, detect periapical pathology, and classify root canal morphology, assisting clinicians in selecting optimal instrumentation strategies[33,35]. Machine-learning models can further support decision-making by predicting treatment outcomes, assessing fracture susceptibility, and guiding retreatment planning[36]. Emerging robotic and semi-autonomous systems extend AI into procedural execution, demonstrating a shift where traditional mechanical instruments are complemented by intelligent, digitally driven technologies[37,38]. This integration marks a new era in which instrumentation is enhanced— and increasingly optimized—through advanced computational systems.

Conclusion

Endodontic instrumentation has progressed from basic hand files to advanced NiTi systems and AI-integrated technologies, each improving safety, efficiency, and anatomical precision. Despite major advancements, challenges such as instrument separation and cleaning complex anatomies persist. Ongoing innovations in metallurgy, kinematics, imaging, and AI will continue refining endodontic care.

Future Perspectives

Future endodontic instrumentation will likely incorporate advanced NiTi alloys, adaptive file designs, and nanotechnology-based manufacturing. AI-driven imaging, automated anatomy recognition, and personalized instrument sequencing will further enhance precision. Emerging robotic systems and sensor-integrated files may provide real-time feedback, reducing errors and improving safety. Together, these innovations promise more predictable, minimally invasive, and fully data-guided endodontic therapy.

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