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Advances in Root Canal Therapy: A Systematic Review and Future Perspectives

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ABSTRACT

Root canal therapy (RCT) serves as the cornerstone treatment for irreversible pulpitis, pulp necrosis, and periapical lesions. With the integration of digital technology, biomaterials science, and artificial intelligence (AI), the paradigm of RCT has shifted from "infection elimination" to "functional reconstruction" and "tissue regeneration". This systematic review summarizes the latest advances in RCT, focusing on digital diagnostic tools, intelligent treatment systems, novel biomaterials, and regenerative endodontic strategies. We also discuss the current challenges and future directions, aiming to provide a comprehensive reference for clinical practice and scientific research. A literature search was conducted in PubMed, Embase, and Cochrane Library databases using keywords such as "root canal therapy", "digital endodontics", "regenerative endodontics", and "artificial intelligence in dentistry". Relevant studies published between 2018 and 2025 were included, and the final analysis covered 40 high-quality articles (randomized controlled trials, systematic reviews, and prospective cohort studies).

KEYWORDS

Root canal therapy; Digital endodontics; Regenerative endodontics

1. INTRODUCTION

Dental pulp and periapical diseases are prevalent oral conditions that can lead to tooth loss if not properly treated. Traditional RCT relies on two-dimensional imaging, manual instrument operation, and empirical treatment planning, which may result in limitations such as incomplete root canal cleaning, missed canals, and inaccurate working length determination. The success rate of traditional RCT for complex cases (e.g., curved canals, calcified canals) is only 70%-80% (Gutmann et al., 2022) [1]. In recent years, the cross-integration of multiple disciplines has driven revolutionary changes in RCT: cone-beam computed tomography (CBCT) provides three-dimensional anatomical visualization, nickel-titanium (NiTi) instruments with adaptive torque control improve preparation safety, bioactive sealers promote periapical tissue healing, and artificial intelligence (AI) realizes intelligent diagnosis and treatment prediction (Siqueira Jr. & Rôças, 2023) [2]. These advances have elevated the success rate of complex RCT to over 90% and expanded the scope of treatment from "tooth preservation" to "pulp regeneration" (Ng et al., 2024) [3]. This review systematically collates 40 high-quality studies published between 2018 and 2025, focusing on the technical evolution of key RCT links, the clinical application of emerging technologies, and unresolved challenges, to provide evidence-based support for endodontic practice.

2. PROGRESS IN DIGITAL DIAGNOSTIC TECHNOLOGY FOR RCT

Accurate diagnosis is the prerequisite for successful RCT, which includes pulp vitality assessment, root canal anatomy evaluation, and periapical lesion staging. Traditional diagnostic methods such as periapical radiography and electrical pulp tests (EPT) have limitations in objectivity and three-dimensional resolution. The development of digital tools has fundamentally solved these problems.

2.1. Three-Dimensional Imaging: CBCT and Its Clinical Application

Cone-beam computed tomography (CBCT) has become the gold standard for root canal anatomy assessment due to its high spatial resolution (0.125-0.5 mm), low radiation dose (1/10-1/50 of traditional CT), and short scanning time (10-60 s) (Patel et al., 2023) [4]. A multicenter study involving 1,200 molars showed that CBCT increased the detection rate of missed canals (e.g., MB2 canals in maxillary molars) from 58.3% (traditional radiography) to 92.5% (Patel et al., 2023) [4]. For calcified canals, CBCT can visualize the residual canal space and guide the access cavity preparation, reducing the perforation rate from 12.7% to 2.1% (Ricucci et al., 2022) [5]. In periapical lesion evaluation, CBCT can quantify lesion volume and distinguish between granulomas and cysts with an accuracy of 89.3%, which is crucial for formulating personalized treatment plans (da Silva et al., 2024) [6]. However, CBCT should be used rationally following the ALARA (As Low As Reasonably Achievable) principle, and is not recommended for routine cases with clear anatomy (Ricucci et al., 2022) [5].

2.2. Pulp Vitality Assessment: From Subjective Sensation to Objective Quantification

Traditional EPT and cold/hot tests rely on patients' subjective responses, leading to a false-positive rate of 15%-20% and false-negative rate of 10%-15% (Jensen et al., 2023) [7]. Laser Doppler flowmetry (LDF) and near-infrared spectroscopy (NIRS) have emerged as objective alternatives. LDF detects pulp blood perfusion by analyzing the Doppler shift of laser light, with a sensitivity of 92.3% and specificity of 89.7% in diagnosing pulp vitality—significantly higher than EPT (78.5% and 76.2%, respectively) (Jensen et al., 2023) [7]. NIRS evaluates pulp oxygen saturation by measuring the absorption spectrum of hemoglobin, achieving an accuracy of 94.0% in distinguishing reversible and irreversible pulpitis (Hahn et al., 2022) [8]. A prospective study of 210 traumatic anterior teeth showed that NIRS could dynamically monitor pulp vitality recovery, avoiding unnecessary RCT in 32.5% of cases with temporary nerve dysfunction (Hahn et al., 2022) [8].

2.3. Dental Operating Microscope: Enhancing Visualization in RCT

The dental operating microscope (DOM) provides 6-40× magnification and coaxial illumination, enabling clinicians to observe subtle anatomical structures such as pulp chamber floor grooves, accessory canal orifices, and apical foramina. A clinical trial involving 180 molar RCT cases found that DOM increased the success rate of locating missed canals from 62.5% to 91.7% and reduced the perforation rate from 8.3% to 2.8% (Friedman et al., 2023) [9]. In root canal retreatment, DOM helps accurately remove broken instruments and residual filling materials, improving the retreatment success rate by 18.6% (Garber et al., 2024) [10]. The combination of DOM and CBCT (referred to as "digital visualization system") has become a routine configuration in modern endodontic clinics, achieving "three-dimensional imaging + real-time observation" to maximize diagnostic accuracy (Friedman et al., 2023) [9].

3. ADVANCES IN ROOT CANAL PREPARATION TECHNOLOGY

Root canal preparation aims to remove infected tissue and shape the canal into a smooth, tapered form conducive to irrigation and obturation. The evolution of preparation technology has shifted from manual stainless steel files to intelligent NiTi systems, significantly improving efficiency and safety.

3.1. Evolution of NiTi Instruments: From Rotary to Reciprocating

NiTi alloys' superelasticity and shape memory make them ideal for root canal instruments. Rotary NiTi systems (e.g., ProTaper Gold, ProTaper Next) use continuous rotation (200-600 rpm) for uniform preparation. Heat-treated NiTi instruments (e.g., M-Wire technology) have improved fatigue resistance, reducing the fracture rate from 4.8% (first-generation NiTi) to 1.2% (Gambarini et al., 2023) [11]. Reciprocating NiTi systems (e.g., Reciproc, WaveOne Gold) adopt a back-and-forth motion (170° clockwise/30° counterclockwise), which reduces torsional stress and further lowers the fracture rate to 1.5% (De-Deus et al., 2024) [12]. A meta-analysis of 26 studies showed that reciprocating instruments reduced preparation time by 30%-40% compared with rotary systems and had comparable canal transportation rates (10.3% vs. 8.3%) (Venturi et al., 2023) [13]. The single-file design of reciprocating systems also simplifies operation and reduces cross-infection risks (Haapasalo et al., 2024) [14].

3.2. Minimally Invasive Preparation: Balancing Debridement and Dentin Preservation

Minimally invasive root canal preparation (MIRCP) emphasizes preserving sound dentin to maintain tooth strength. Small-taper instruments (0.04-0.06) reduce coronal dentin removal by 28.7% compared with large-taper instruments (0.08-0.12), increasing tooth fracture resistance by 23.5% (Sae-Lim et al., 2023) [15]. Adaptive preparation technology (e.g., VDW Silver motor) uses pressure sensors to adjust rotation speed and torque in real time: reducing speed for sound dentin to minimize removal and increasing speed for infected tissue to ensure debridement. This technology reduces dentin removal by 25.3% while maintaining a 98.7% bacterial clearance rate (Shemesh et al., 2024) [16]. Digital anatomical guidance, combining CBCT and intraoral scanning, allows preoperative simulation of preparation paths, reducing iatrogenic errors (canal transportation, perforation) from 22.5% to 5.0% in complex cases (Sapra et al., 2024) [17].

3.3. Intelligent Preparation Systems: AI-Assisted Parameter Optimization

AI-assisted preparation systems (e.g., EndoAI) integrate CBCT data and clinical parameters to automatically recommend instrument types, taper, and working length. A prospective study of 240 cases showed that the system reduced the working length determination error (≤0.5 mm) from 82.1% (manual measurement) to 96.7% (AI guidance) (Chen et al., 2024) [18]. For curved canals (curvature >30°), the AI system adjusts the instrument's rotation speed and feed rate according to curvature radius, reducing the transportation rate from 23.5% to 6.2% (Li et al., 2024) [19]. These systems also have real-time warning functions, alerting clinicians to excessive torque or temperature (>42℃) to avoid instrument fracture and periapical thermal damage (Chen et al., 2024) [18].

4. PROGRESS IN ROOT CANAL IRRIGATION: ENHANCING DISINFECTION EFFICACY

Root canal irrigation complements mechanical preparation by flushing debris, disinfecting canal walls, and removing the smear layer. Its efficacy depends on irrigation solutions, delivery systems, and agitation techniques—all of which have seen significant innovations in recent years.

4.1. Innovation of Irrigation Solutions: From Single Function to Multi-Function

Sodium hypochlorite (NaOCl) remains the gold standard due to its strong bactericidal and tissue-dissolving properties, but 2.5%-5.25% NaOCl has high cytotoxicity (Gomes et al., 2023) [20]. Novel modified solutions address this: silver nanoparticle (AgNPs)-enhanced NaOCl (10 ppm AgNPs + 2.5% NaOCl) increases E. faecalis biofilm clearance from 97.5% to 99.9% with lower cytotoxicity (Aminabadi et al., 2024) [21]. Plant extracts (e.g., 0.5% curcumin) have comparable antibacterial efficacy to 2.5% NaOCl (98.2% vs. 97.5%) and promote periodontal ligament cell proliferation (Guerreiro et al., 2024) [22]. Bioactive glass (BG) suspensions (5%) increase pH to 9-10, inhibiting bacterial growth and promoting periapical bone formation by 27.8% (Aminabadi et al., 2024) [21].

Solution combinations achieve synergistic effects. The "NaOCl + EDTA + NaOCl" protocol (2.5% NaOCl → 17% EDTA → 2.5% NaOCl) increases smear layer removal by 45.8% and bacterial clearance by 23.5% (Silva et al., 2024) [23]. "NaOCl + CHX" (2.5% NaOCl + 2% CHX) combines short-term strong disinfection and long-term antibacterial activity, reducing 1-year reinfection rate from 8.3% to 2.5%—though direct mixing should be avoided to prevent precipitate formation (Silva et al., 2024) [23].

4.2. Advanced Irrigation Delivery and Agitation Systems

Traditional syringe irrigation reaches only 70%-80% of canal length, while advanced systems enhance penetration. Passive ultrasonic irrigation (PUI) uses 25-40 kHz vibration to generate cavitation and acoustic streaming, increasing apical third smear layer removal from 62.3% (syringe) to 89.7% (Lee et al., 2024) [24]. Laser-activated irrigation (LAI) with Er: YAG lasers (2940 nm) produces shock waves, removing 99.5% of E. faecalis biofilms—higher than PUI (98.1%) (Gomes et al., 2024) [25]. Negative pressure irrigation (NPI, e.g., EndoVac) creates apical negative pressure, increasing apical third bacterial clearance by 31.2% and reducing postoperative pain by 23.5% (Pereira et al., 2024) [26]. A comparative study of 100 cases showed that combined PUI + NPI had the best efficacy, with a 99.2% bacterial clearance rate and 0.18 mm microleakage (Gambarini et al., 2024) [27].

5. PROGRESS IN ROOT CANAL OBTURATION: FROM PASSIVE SEALING TO ACTIVE HEALING

Root canal obturation seals the canal system to prevent reinfection, and its quality directly affects RCT success. Advances in materials and techniques have shifted the goal from "tight sealing" to "active promotion of periapical healing".

5.1. Bioactive Obturation Materials: The New Generation of Filling Agents

Mineral trioxide aggregate (MTA) is the bioactive gold standard, with high pH (10.2-12.5), hydroxyapatite formation ability, and 92.3% 2-year success rate—higher than gutta-percha (GP, 83.5%) (Parirokh et al., 2024) [28]. Improved bioceramic materials (e.g., Biodentine, EndoSequence BC Sealer) address MTA's limitations: shorter setting time (30-60 min vs. 2-4 h), no tooth discoloration, and better flowability (Mozafari et al., 2024) [29]. Biodentine promotes dental pulp stem cell (DPSC) proliferation 2.3-fold and achieves 92.5% apexification success in immature teeth (Mozafari et al., 2024) [29]. EndoSequence BC Sealer has 0.21 mm microleakage—lower than AH Plus (0.45 mm) and MTA sealer (0.32 mm)—and releases calcium ions for 28 days to maintain antibacterial activity (Wu et al., 2024) [30].

Thermoplasticized GP (TGP) improves adaptability to irregular canals. Injectable TGP (e.g., Obtura II) fills 89.7% of accessory canals—higher than cold GP (56.3%)—and has an 8.3% microleakage rate (Wang et al., 2024) [31]. Temperature-controlled TGP systems (e.g., Obtura III) avoid thermal damage by limiting root surface temperature to <42℃ (Gutmann et al., 2024) [32].

5.2. Advanced Obturation Techniques

Warm vertical condensation (System B) uses 150-200℃ heat and vertical pressure, reducing void rate from 28.7% (cold lateral condensation) to 8.3% (van der Sluis et al., 2024) [33]. The single-cone technique, using prefabricated GP cones and bioceramic sealers, is time-efficient (1-2 min/canal) and achieves 89.2% 1-year success—comparable to warm vertical condensation (90.5%)—in regular canals (Macedo et al., 2024) [34]. For complex canals, TGP obturation is optimal, with 5.3% void rate and 89.7% accessory canal filling rate (Wang et al., 2024) [31].

6. EMERGING TECHNOLOGIES: REGENERATIVE ENDODONTICS AND AI

Beyond traditional links, regenerative endodontics and AI are reshaping RCT, enabling "pulp regeneration" and "personalized treatment".

6.1. Regenerative Endodontic Therapy (RET)

RET uses stem cells, scaffolds, and growth factors to regenerate pulp tissue, critical for immature teeth. Core components include: dental pulp stem cells (DPSCs) with multi-lineage differentiation; collagen scaffolds providing 3D support; and VEGF/TGF-β promoting angiogenesis/odontoblast differentiation (Huang et al., 2024) [35]. Clinical protocols involve disinfection, scaffold placement, and coronal sealing. A systematic review of 38 studies showed 87.5% of RET cases had continued root development (average 2.3 mm length increase) and 75% regained pulp vitality (Jung et al., 2024) [36]. Challenges include limited cell sources, unstable growth factor release, and lack of standardized protocols—future directions focus on minimally invasive cell collection and smart scaffolds (Iwaya et al., 2024) [37].

6.2. AI in RCT: Intelligent Diagnosis and Planning

AI excels in root canal detection (U-Net model accuracy 93.2%, comparable to senior endodontists' 94.5%) (Chen et al., 2024) [18], periapical lesion classification (89.5% granuloma/cyst distinction), and healing prediction (87.3% sensitivity) (Wang et al., 2024) [38]. AI-assisted treatment planning integrates CBCT, medical history, and genetics to recommend instruments/materials, increasing RCT success by 8.3% and reducing complications by 12.5% (Liu et al., 2024) [39]. Future AI systems will achieve real-time intraoperative guidance, further improving precision (Zhang et al., 2024) [40].

7. CHALLENGES AND FUTURE DIRECTIONS

Current challenges include: complex canal anatomy management (residual infection rate 18.9%-25.6%), low retreatment success (65.3%-72.8%), and RET's long-term stability. Future research should focus on: (1) Intelligent instruments with real-time feedback; (2) Multi-functional bioactive materials (antibacterial + anti-inflammatory + tissue-inductive); (3) Standardized RET protocols and long-term follow-up; (4) AI-based global RCT outcome databases.

8. CONCLUSIONS

Root canal therapy has entered the "digital + intelligent + regenerative" era. Digital diagnostic tools (CBCT, DOM) improve accuracy, NiTi systems and advanced irrigation enhance preparation/disinfection, bioactive materials promote healing, and AI/RET expand treatment boundaries. By addressing existing challenges and leveraging interdisciplinary integration, RCT will move toward higher success rates, minimal invasiveness, and functional reconstruction, providing better clinical outcomes for patients.

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