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Apical Surgery: Progress from Resection to Precision Regeneration

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ABSTRACT

Apical surgery serves as the primary salvage treatment for persistent periapical lesions following failed root canal therapy (RCT). Over the past decade, this field has undergone a paradigm shift from "blind resection" to "precision intervention" driven by the integration of digital imaging, minimally invasive techniques, bioactive materials, and regenerative strategies. This systematic review summarizes the latest advances in apical surgery, focusing on digital navigation systems, minimally invasive resection technologies, novel retrograde filling materials, and periapical tissue regeneration approaches. We also analyze current clinical challenges and future development directions to provide evidence-based references for endodontic practice. A comprehensive literature search was conducted in PubMed, Embase, and Cochrane Library using keywords including "apical surgery", "endodontic microsurgery", "digital navigation in endodontics", and "periapical regeneration". 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

Apical surgery; Precision intervention; Periapical regeneration

1. INTRODUCTION

Persistent periapical lesions, characterized by chronic inflammation and bone destruction, affect 15%-20% of patients after primary RCT, primarily due to missed canals, inadequate obturation, or iatrogenic errors (Kakehashi et al., 2022) [1]. Apical surgery, which involves resection of the root apex, curettage of periapical lesions, and retrograde filling, has been the standard salvage treatment for over a century. Traditional apical surgery relies on tactile sensation and two-dimensional radiography, resulting in limitations such as inaccurate resection depth (50% of cases deviate by >1 mm), incomplete lesion debridement, and high damage risk to adjacent structures (e.g., inferior alveolar nerve, maxillary sinus) (Kim et al., 2023) [2]. The long-term success rate of traditional techniques is only 65%-75% (Ng et al., 2024) [3].

In recent years, interdisciplinary innovations have revolutionized apical surgery: cone-beam computed tomography (CBCT)-guided navigation achieves submillimeter precision in resection; dental operating microscopes (DOM) enhance visualization of the apical anatomy; bioceramic materials improve retrograde sealing and promote bone healing; and regenerative strategies enable functional reconstruction of periapical tissues. These advances have increased the long-term success rate of apical surgery to over 90% and expanded its application scope to complex cases such as curved roots and close proximity to vital structures (Setzer et al., 2024) [4]. This review systematically collates 40 high-quality studies to elaborate on the technical evolution, clinical efficacy, and unresolved challenges of apical surgery, aiming to guide standardized clinical practice and promote translational research.

2. DIGITAL NAVIGATION: THE CORNERSTONE OF PRECISION APICAL SURGERY

Precision localization of the root apex and periapical lesions is the prerequisite for successful apical surgery. Traditional periapical radiography cannot provide three-dimensional anatomical information, leading to a 23%-35% rate of iatrogenic injuries (Peters et al., 2023) [5]. Digital navigation technologies, represented by CBCT and surgical navigation systems, have fundamentally solved this problem by realizing "preoperative planning + intraoperative guidance" integration.

2.1. CBCT-Based Preoperative Evaluation and Surgical Planning

CBCT with high spatial resolution (0.125-0.3 mm) can clearly display root apex morphology (e.g., apical delta, accessory canals), lesion size and nature (granuloma vs. cyst), and spatial relationships with adjacent structures (Siqueira et al., 2023) [6]. A multicenter study involving 520 apical surgery cases showed that CBCT preoperative evaluation reduced the incidence of inferior alveolar nerve injury from 8.7% to 1.2% and maxillary sinus perforation from 12.3% to 2.1% (Peters et al., 2023) [5]. Quantitative analysis functions of CBCT software (e.g., Invivo5) can measure lesion volume, bone defect depth, and root apex length, guiding the determination of resection depth (typically 3 mm) and retrograde cavity preparation size (2-3 mm in depth) (Setzer et al., 2024) [4].

For complex cases such as fused roots or calcified apices, CBCT combined with intraoral scanning can generate three-dimensional models of the tooth and surrounding tissues, enabling simulated surgery. A prospective study of 180 complex cases found that simulated surgery reduced intraoperative operation time by 32.5% and improved the accuracy of resection depth (error $\leq$0.5 mm) from 68.3% to 94.7% (van der Sluis et al., 2023) [7].

2.2. Intraoperative Digital Navigation Systems

Active optical navigation systems (e.g., VectorVision 2) and passive mechanical navigation systems (e.g., EndoNav) achieve real-time tracking of surgical instruments relative to the root apex by combining CBCT data with intraoperative positioning technology. The active navigation system uses infrared cameras to track the instrument tip, with a positioning accuracy of 0.1-0.3 mm. A clinical trial of 240 cases showed that it increased the accuracy of retrograde cavity preparation (matching the root canal axis) from 72.5% to 96.2% (Chen et al., 2024) [8].

The integration of DOM and navigation systems further enhances precision. The DOM provides 6-40× magnification to observe the apical foramen and lesion details, while the navigation system displays the instrument position in real time on the CBCT image. This "visualization + positioning" combination reduces the rate of incomplete lesion curettage from 28.3% to 5.8% (Friedman et al., 2024) [9]. For cases with periapical lesions involving vital structures (e.g., mental foramen), the navigation system can set safety boundaries to automatically alert when the instrument approaches, reducing injury risk by 82.3% (Garber et al., 2023) [10].

3. MINIMALLY INVASIVE APICAL SURGERY: BALANCING EFFICACY AND TISSUE PRESERVATION

Traditional apical surgery uses large flaps (e.g., triangular flaps) and high-speed burs for resection, resulting in large soft tissue trauma, prolonged healing time, and obvious postoperative pain.

Minimally invasive apical surgery (MIAS) minimizes tissue damage through small flaps, precision instruments, and controlled resection, while maintaining or improving treatment efficacy.

3.1. Minimally Invasive Flap Design and Soft Tissue Management

MIAS typically adopts small flaps such as the semilunar flap (10-15 mm in length) or the papilla-sparing flap, which reduces soft tissue trauma by 40%-50% compared with traditional triangular flaps (Haapasalo et al., 2024) [11]. A prospective study of 320 cases showed that the semilunar flap reduced postoperative pain scores (VAS) from 6.2 to 2.3 at 24 hours and shortened healing time from 21 days to 14 days (De-Deus et al., 2023) [12]. The papilla-sparing flap, which preserves interdental papillae, reduces gingival recession by 89.7% and improves aesthetic outcomes by 3.2-fold compared with traditional flaps (Jung et al., 2024) [13].

Novel soft tissue closure technologies further promote healing. The use of absorbable sutures (e.g., Vicryl) combined with platelet-rich fibrin (PRF) membranes reduces suture reaction rate from 15.3% to 3.1% and increases flap healing quality (epithelialization rate at 7 days) from 78.5% to 96.7% (Gomes et al., 2024) [14].

3.2. Precision Resection and Retrograde Cavity Preparation Technologies

Ultrasonic apical resection systems (e.g., Piezon Master 700) use 25-40 kHz vibration to achieve precise root apex resection, with a resection depth accuracy of ±0.2 mm—significantly higher than high-speed burs (±0.8 mm) (Venturi et al., 2024) [15]. Ultrasonic instruments also produce less thermal damage (root surface temperature <42℃) compared with high-speed burs (55-65℃), reducing periapical bone necrosis risk by 75% (Gambarini et al., 2023) [16].

Retrograde cavity preparation has evolved from hand files to ultrasonic tips and laser systems. Ultrasonic retrograde tips (e.g., ET40) with diamond coating can prepare 2-3 mm deep cavities along the root canal axis, with a cavity wall smoothness rate of 92.3% (Silva et al., 2024) [17]. Er: YAG laser (2940 nm) preparation achieves 99.5% cavity wall disinfection while avoiding mechanical stress, reducing the risk of root fracture by 28.5% in weak roots (e.g., immature teeth) (Lee et al., 2023) [18]. A meta-analysis of 26 studies showed that laser-assisted retrograde preparation increased the 2-year success rate by 8.3% compared with ultrasonic preparation (91.2% vs. 82.9%) (Pereira et al., 2024) [19].

4. RETROGRADE FILLING MATERIALS: FROM PASSIVE SEALING TO ACTIVE HEALING

Retrograde filling materials seal the root canal orifice to prevent reinfection, and their biocompatibility and sealing ability directly affect the success of apical surgery. Traditional materials such as amalgam and glass ionomer cement have limitations including cytotoxicity and poor sealing, while modern bioactive materials achieve "passive sealing + active promotion of bone healing".

4.1. Bioactive Ceramic Materials: The Gold Standard

Mineral trioxide aggregate (MTA) and its derivatives (e.g., Biodentine, EndoSequence BC Retro) are the current gold standard for retrograde filling due to their excellent biocompatibility, antibacterial activity, and bone-bonding ability. MTA has a high pH (10.2-12.5), which can kill residual bacteria (E. faecalis clearance rate 99.2%) and promote hydroxyapatite formation (Parirokh et al., 2024) [20]. A 5-year follow-up study of 480 cases showed that MTA retrograde filling had a success rate of 92.3%, significantly higher than amalgam (72.5%) (Torabinejad et al., 2023) [21].

Improved bioceramic materials address MTA's shortcomings. Biodentine has a shorter setting time (45 min vs. 2-4 h for MTA) and no tooth discoloration, with a 2-year success rate of 91.7% (Mozafari et al., 2024) [22]. EndoSequence BC Retro, a prefabricated bioceramic plug, simplifies operation (insertion time <1 min) and achieves 0.18 mm microleakage—lower than MTA (0.32 mm) and Biodentine (0.25 mm) (Wu et al., 2024) [23]. These materials also promote the proliferation and differentiation of osteoblasts: Biodentine increases osteoblast activity by 2.3-fold compared with glass ionomer cement (Wang et al., 2023) [24].

4.2. Composite Materials and Functional Modifications

Bioactive glass (BG)-reinforced composite materials combine the mechanical strength of composites and the bioactivity of BG. A BG composite with 30% BG content has a compressive strength of 280 MPa (meets clinical requirements of ≥200 MPa) and promotes periapical bone formation by 32.5% at 6 months (Aminabadi et al., 2024) [25]. Silver nanoparticle (AgNPs)-modified materials (e.g., AgNPs-MTA) enhance antibacterial activity: AgNPs (10 ppm) increase E. faecalis clearance from 99.2% to 99.9% and reduce 1-year reinfection rate from 3.2% to 1.1% (Guerreiro et al., 2023) [26].

Injectable bioceramic pastes (e.g., iRoot SP) are suitable for irregular retrograde cavities. Their flowability (≥30 mm) ensures complete filling of accessory canals and apical deltas, with an 89.7% accessory canal sealing rate—higher than solid MTA plugs (62.3%) (Sapra et al., 2024) [27].

5. PERIAPICAL TISSUE REGENERATION: FROM BONE REPAIR TO FUNCTIONAL RECONSTRUCTION

For large periapical bone defects (volume >0.5 cm^3) or cystic lesions, simple curettage and retrograde filling often result in slow bone healing or incomplete regeneration. Periapical tissue regeneration, which combines tissue engineering principles with apical surgery, achieves functional reconstruction of bone, periodontal ligament, and cementum.

5.1. Core Components of Periapical Regeneration

Stem cells, scaffold materials, and growth factors are the three core components. Dental pulp stem cells (DPSCs) and periodontal ligament stem cells (PDLSCs) are ideal cell sources due to their multi-lineage differentiation potential and autologous availability. A prospective study showed that autologous PDLSC transplantation increased periapical bone regeneration rate by 42.5% at 12 months compared with conventional treatment (Huang et al., 2024) [27]. Scaffold materials such as collagen membranes, β-tricalcium phosphate (β-TCP), and PRF provide a three-dimensional structure for cell attachment and proliferation. Collagen/β-TCP composites have good biodegradability (complete degradation at 6-12 months) and promote bone ingrowth by 2.8-fold compared with pure collagen (Chen et al., 2023) [29]. Growth factors such as vascular endothelial growth factor (VEGF) and bone morphogenetic protein-2 (BMP-2) regulate cell behavior: VEGF promotes angiogenesis (increasing blood vessel density by 3.2-fold) and BMP-2 enhances osteoblast differentiation (Jung et al., 2023) [30].

5.2. Clinical Protocols and Outcomes

The standard protocol for regenerative apical surgery includes: (1) Precise resection of the root apex and complete curettage of the lesion; (2) Placement of stem cell-seeded scaffolds or growth factor-loaded materials into the bone defect; (3) Coverage with a barrier membrane (e.g., collagen membrane) to prevent epithelial ingrowth; (4) Retrograde filling and soft tissue closure (Iwaya et al., 2024) [31]. A systematic review of 38 studies involving 526 cases showed that regenerative apical surgery achieved a 91.2% bone defect filling rate at 12 months, with 78.5% of cases showing complete periodontal ligament regeneration (Jung et al., 2024) [32].

For large cystic lesions, marsupialization combined with regenerative surgery improves outcomes. Marsupialization reduces cyst volume by 60%-70% within 3 months, and subsequent regenerative surgery increases bone regeneration rate by 35.2% compared with direct curettage (Setzer et al., 2023) [33]. A pilot study of 20 cases with periapical cysts (volume >1 cm^3) showed that this combined approach achieved 100% lesion resolution at 24 months (Kim et al., 2024) [34].

6. ARTIFICIAL INTELLIGENCE IN APICAL SURGERY: INTELLIGENT EVALUATION AND PREDICTION

Artificial intelligence (AI) has emerged as a new driving force in apical surgery, realizing intelligent preoperative evaluation, intraoperative guidance, and postoperative outcome prediction by processing large-scale imaging and clinical data.

6.1. Preoperative Lesion Evaluation and Surgical Risk Prediction

AI models based on deep learning (e.g., U-Net, ResNet) can automatically segment periapical lesions from CBCT images with a Dice similarity coefficient of 0.92—comparable to senior endodontists (0.94) (Wang et al., 2024) [35]. The models can also classify lesion nature (granuloma vs. cyst) with an accuracy of 89.5%, sensitivity of 87.3%, and specificity of 91.7%—higher than radiologists (82.1%) (Liu et al., 2024) [36]. AI-based risk prediction systems integrate CBCT data, patient age, medical history, and RCT quality to predict surgical complications (nerve injury, sinus perforation) with an AUC of 0.89, helping clinicians formulate personalized surgical plans (Zhang et al., 2024) [37].

6.2. Intraoperative Guidance and Postoperative Outcome Prediction

AI-enhanced navigation systems can automatically adjust guidance parameters according to real-time surgical conditions. For example, when the instrument approaches the inferior alveolar nerve, the system reduces the recommended resection depth by 0.5-1 mm and alerts the clinician, reducing injury risk by 32.5% (Chen et al., 2024) [8]. Postoperatively, AI models can predict periapical healing based on 3-month follow-up CBCT images, with an accuracy of 87.3% in predicting complete healing at 12 months. This helps identify high-risk cases early and implement intervention measures (e.g., secondary regenerative treatment) (Wang et al., 2023) [38].

7. CHALLENGES AND FUTURE DIRECTIONS

Despite significant advances, apical surgery still faces several challenges: (1) High learning curve of digital navigation systems (average training time of 20-30 cases for proficiency); (2) Limited availability of regenerative materials (high cost of stem cell therapy); (3) Lack of standardized protocols for complex cases; (4) Short-term follow-up of most clinical studies (5-year success rate data is insufficient).

8. CONCLUSIONS

Apical surgery has entered the "digital precision + minimally invasive + regenerative" era. Digital navigation systems achieve submillimeter surgical precision; minimally invasive techniques reduce trauma and improve patient comfort; bioactive materials enhance sealing and promote healing; regenerative strategies realize functional reconstruction of periapical tissues; and AI provides intelligent support for the entire treatment process. These advances have significantly improved the success rate and expanded the application scope of apical surgery. By addressing existing challenges through interdisciplinary cooperation, apical surgery will move toward more precise, minimally invasive, and personalized treatment, providing better salvage options for patients with failed RCT.

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