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Contemporary surgical endodontics: Current concepts, microsurgical advances and future perspectives with special considerations for paediatric patients: Narrative review

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Abstract
Surgical endodontics has evolved considerably with advances in diagnostic imaging, microsurgical techniques, biomaterials, and regenerative strategies, offering a predictable treatment option for teeth with persistent periapical disease when conventional root canal treatment or non-surgical retreatment is unlikely to achieve success. The integration of operating microscopes, cone-beam computed tomography, ultrasonic root-end preparation, and bioceramic root-end filling materials has enhanced surgical precision, reduced postoperative complications, and improved long-term treatment outcomes. More recently, emerging technologies such as dynamic navigation, three-dimensional printing, artificial intelligence, and regenerative approaches have further expanded the scope of endodontic microsurgery. This narrative review critically examines the biological principles, indications, contemporary microsurgical procedures, prognostic factors, clinical outcomes, and recent technological advances in surgical endodontics by synthesising evidence from current scientific literature. Particular emphasis is placed on evidence-based clinical decision-making, microsurgical protocols, and biomaterials that influence healing and treatment success. Special considerations for paediatric patients, including growth and developmental factors, anatomical variations, behavioural management, and preservation of immature permanent teeth, are also discussed. Furthermore, the review highlights current limitations in the literature and explores future directions that may improve the predictability, biological outcomes, and minimally invasive nature of surgical endodontic procedures. Contemporary endodontic microsurgery, when performed using evidence-based principles and modern technologies, remains a valuable treatment modality for preserving the natural dentition and promoting favourable long-term clinical outcomes.

Keywords: Endodontic surgery, apicoectomy, cone-beam computed tomography, microsurgery, bioceramics, pediatric dentistry

Introduction
Surgical endodontics has become an integral component of contemporary endodontic practice, providing a predictable treatment option for teeth with persistent apical disease when conventional root canal treatment or orthograde retreatment cannot achieve complete resolution of infection. The primary objective of surgical intervention is to eliminate persistent periradicular pathology, establish an effective apical seal and preserve the natural dentition while maintaining function and aesthetics. Advances in microsurgical techniques, biological understanding and biomaterials have transformed surgical endodontics into a highly predictable treatment modality supported by substantial clinical evidence [1].
Persistent apical periodontitis develops when microorganisms and their by-products remain within the root canal system despite previous treatment. Anatomical complexities, untreated accessory canals, apical ramifications, resistant microbial biofilms, extraradicular infection, foreign-body reactions and true radicular cysts may prevent complete healing following nonsurgical treatment. In such cases, surgical endodontics enables removal of pathological tissues, management of anatomical irregularities and placement of a biocompatible root-end filling to promote periapical healing [2, 3].
The introduction of the operating microscope, ultrasonic retropreparation, microsurgical instruments and calcium silicate-based root-end filling materials has revolutionised endodontic surgery by improving visualisation, surgical precision and healing outcomes [1, 4]. In parallel, cone-beam computed tomography (CBCT) has enhanced diagnosis and treatment planning by providing three-dimensional assessment of periapical lesions, root morphology and their relationship to adjacent anatomical structures [5, 6] Advances in biomaterials, including mineral trioxide aggregate (MTA), Biodentine and newer calcium silicate-based bioceramics, have further improved biological outcomes through superior sealing ability, biocompatibility and bioactivity. Digital technologies such as guided endodontic surgery, dynamic navigation, three-dimensional printing and artificial intelligence have further expanded the scope of contemporary microsurgical practice [7, 11].
Although endodontic microsurgery is less commonly performed in paediatric patients, it remains an important treatment option in selected cases involving immature permanent teeth affected by persistent apical pathology

following trauma, developmental anomalies, failed apexification or unsuccessful regenerative endodontic procedures. Preservation of immature permanent teeth is essential for continued root development, maintenance of alveolar bone and normal craniofacial growth; therefore, treatment planning should consider behavioural management, stage of root development and minimally invasive surgical principles [13, 13].

Recent systematic reviews have demonstrated favourable long-term outcomes when evidence-based case selection, microsurgical techniques and bioactive root-end filling materials are employed. Continued advances in regenerative medicine, digital navigation and artificial intelligence are expected to further improve treatment predictability and expand opportunities for conservative tooth preservation [4, 14].

The aim of this narrative review is to critically evaluate the biological principles, indications, contemporary microsurgical techniques, prognostic factors and recent technological advances in surgical endodontics, with particular emphasis on evidence-based clinical practice and special considerations for paediatric patients [2].

Literature Search Strategy

A literature search was conducted using PubMed/MEDLINE, Scopus, Web of Science and Google Scholar to identify English-language publications on surgical endodontics. Search terms included surgical endodontics, endodontic microsurgery, apicectomy, root-end surgery, cone-beam computed tomography, bioceramics, guided endodontic surgery, dynamic navigation, artificial intelligence, regenerative endodontics and paediatric endodontics. Priority was given to systematic reviews, meta-analyses, clinical practice guidelines, randomised controlled trials, prospective clinical studies and landmark publications. Additional references were identified through manual screening of reference lists. As this is a narrative review, no formal systematic review methodology, risk-of-bias assessment or statistical meta-analysis was performed.

Indications and Contraindications

Appropriate case selection is fundamental to the success of surgical endodontics. Endodontic microsurgery should be considered only after comprehensive clinical and radiographic assessment when predictable healing cannot be achieved through conventional root canal treatment or orthograde retreatment. Treatment planning should integrate biological, restorative and patient-related factors to maximise long-term tooth preservation [1, 15].

Indications

Contemporary endodontic microsurgery is indicated when persistent apical periodontitis remains despite well-executed nonsurgical root canal treatment or retreatment. Persistent periapical radiolucencies associated with symptoms such as pain, swelling or sinus tract formation often indicate residual intraradicular infection or extraradicular pathology requiring surgical intervention [2, 3].

Surgery is also indicated when orthograde retreatment is impractical or likely to compromise existing restorations. Teeth restored with well-functioning crowns, extensive fixed prostheses, cast posts or intracanal obstructions may be more appropriately managed surgically, thereby preserving tooth structure and avoiding unnecessary restorative procedures [1, 16].

Anatomical and iatrogenic complications—including separated instruments extending beyond the root apex, inaccessible ledges, perforations, apical transportation, persistent root-end resorption and complex apical anatomy—may also necessitate surgery. Endodontic surgery additionally permits biopsy of persistent periapical lesions when histopathological examination is required to exclude non-endodontic pathology [17, 18].

Surgical endodontics may also be indicated following dental trauma, particularly in cases of horizontal root fractures, persistent apical pathology after luxation injuries or failed healing following previous endodontic treatment. In selected cases, microsurgery may facilitate preservation of traumatised permanent teeth when conservative treatment has failed [19].

Although uncommon in paediatric practice, carefully selected children and adolescents may benefit from surgical intervention when immature permanent teeth exhibit persistent periapical disease following failed apexification, regenerative endodontic therapy or trauma-related complications. Because preservation of developing permanent teeth is essential for continued root maturation and craniofacial growth, surgery should be considered only after multidisciplinary assessment and when less invasive alternatives are unlikely to succeed [12, 13].

Contraindications

Surgical endodontics should not be undertaken when the tooth has a hopeless long-term prognosis. Teeth with vertical root fractures, non-restorable coronal destruction, severe periodontal attachment loss, advanced mobility or inadequate remaining root length generally have limited potential for long-term retention and are better managed by extraction followed by appropriate prosthetic rehabilitation [1, 20].

Patient-related factors must also be considered. Uncontrolled diabetes mellitus, immunosuppression, bleeding disorders, recent myocardial infarction, head and neck radiotherapy, antiresorptive medication-associated osteonecrosis risk and inability to tolerate surgery may significantly compromise treatment outcomes or increase postoperative complications. Appropriate medical consultation should be obtained whenever indicated [21].

Certain anatomical situations represent relative contraindications, including limited surgical access, proximity to the inferior alveolar nerve, mental nerve, maxillary sinus or nasal floor, and inadequate mouth opening. In such cases, CBCT plays an important role in assessing surgical feasibility and minimising procedural complications [5, 6].

Successful treatment depends on evidence-based decision-making that balances biological feasibility, restorative prognosis, patient expectations and long-term tooth preservation. Whenever predictable healing can be achieved through orthograde retreatment, it should remain the preferred treatment, with surgical endodontics reserved for cases in which conventional approaches are unlikely to resolve disease [16, 4]. (Table 1.)

Table 1: Clinical Indications and Contraindications for Contemporary Surgical Endodontics

Clinical Scenario	Indications	Contraindications	Clinical Consideration
Persistent apical periodontitis	Persistent lesion after RCT	Vertical root fracture	Surgical removal of persistent infection
Failed non-surgical retreatment	Persistent disease despite retreatment	Non-restorable tooth	Tooth preservation when feasible
Orthograde retreatment impractical	Cast post, fractured instrument, calcified canal	Predictable orthograde retreatment possible	Avoid unnecessary removal of restorations
Apical procedural errors	Perforation, transportation, ledge	Severe periodontal disease	Direct correction of apical pathology
Persistent periapical lesion	Suspected cyst or foreign-body reaction	Medication-related osteonecrosis risk	Histopathological examination when indicated
Dental trauma	Horizontal root fracture with persistent pathology	Uncontrolled systemic disease	Preserve traumatised permanent teeth
Paediatric patients	Failed apexification/regenerative endodontics	Inadequate patient cooperation	Preserve immature permanent teeth and support growth

Abbreviations: RCT, root canal treatment.
Source: Published literature [1, 3, 15, 21].

Case Selection and Treatment Planning

Successful surgical endodontics begins with meticulous case selection and comprehensive pre-operative assessment. Despite advances in microsurgical techniques and biomaterials, favourable outcomes depend primarily on accurate diagnosis, appropriate patient selection and careful treatment planning. Evaluation should integrate clinical findings, radiographic assessment, restorative prognosis, periodontal status and patient-related factors before surgery is considered [1, 15].

The initial assessment should include the presenting complaint, previous endodontic treatment, symptom duration and relevant medical history. Clinical examination should assess pain on percussion or palpation, swelling, sinus tract formation, periodontal probing depths, tooth mobility, occlusion and the integrity of the coronal restoration. The restorability of the tooth remains a key determinant of long-term success because surgery offers little benefit if an adequate coronal seal cannot be achieved [17, 20].

Radiographic assessment is fundamental to treatment planning. Conventional periapical radiographs provide information on root canal fillings, root morphology and periapical lesions, whereas cone-beam computed tomography (CBCT) offers three-dimensional visualisation of untreated canals, root fractures, apical resorption, cortical defects and the relationship of the surgical site to adjacent anatomical structures. This improves diagnosis, surgical planning and the prevention of intraoperative complications [5, 6, 15].

The biological cause of treatment failure should be identified before surgery. Persistent disease may result from intraradicular infection, extraradicular biofilms, foreign-body reactions, cholesterol crystals, apical cysts or procedural errors. Distinguishing cases suitable for orthograde retreatment from those requiring surgery is essential for evidence-based decision-making [2, 3, 18].

Restorative considerations are equally important. Teeth restored with well-fitting crowns, bridges or cast post-and-core systems may be better managed surgically when orthograde retreatment risks damaging existing restorations. Conversely, nonsurgical retreatment remains the preferred option whenever it can eliminate the source of infection without compromising the tooth [4, 16].

Patient-related factors, including age, systemic health, smoking, oral hygiene, compliance and expectations, influence treatment outcomes. Conditions associated with impaired healing require appropriate medical consultation. Informed consent should include discussion of treatment alternatives, potential complications, prognosis and the possibility of future extraction if healing is unsuccessful [12, 15].

Special consideration is required in children and adolescents. Preservation of immature permanent teeth is essential for continued root development and craniofacial growth. Behavioural maturity, stage of root formation, proximity of developing tooth germs and the possible need for sedation or general anaesthesia should be assessed, while regenerative endodontic procedures and other conservative options should be considered before surgery [12, 13].

Modern treatment planning increasingly incorporates digital technologies. CBCT-based planning, dynamic navigation and patient-specific surgical guides improve localisation of the root apex, minimise osteotomy size and reduce unnecessary bone removal, particularly in anatomically challenging cases [9, 11].

Successful case selection requires integration of biological, restorative, anatomical and patient-centred factors. Surgical endodontics should be undertaken only when the tooth has a favourable long-term restorative prognosis, the cause of treatment failure has been identified and current evidence supports microsurgical intervention as the best option for preserving the natural tooth [4, 15].

Contemporary Surgical Endodontic Techniques

The introduction of microsurgical principles has transformed surgical endodontics by improving precision, reducing surgical trauma and enhancing long-term treatment outcomes. Contemporary endodontic microsurgery is based on minimally invasive surgery, meticulous tissue handling and biologically driven treatment. Compared with conventional apical surgery, modern techniques employ magnification, enhanced illumination, ultrasonic root-end preparation and bioactive root-end filling materials to maximise healing while preserving healthy tissues [1, 4].

1. Pre-operative Preparation

Successful microsurgery begins with careful pre-operative planning. Medical history, systemic health, medications, allergies and previous dental treatment should be reviewed. Clinical examination should confirm the diagnosis and assess periodontal health, restorability and occlusion. CBCT is recommended in anatomically complex cases to evaluate lesion size, root morphology, cortical bone thickness and adjacent anatomical structures. Appropriate patient counselling and written informed consent are essential before surgery [5, 15].

2. Magnification and Illumination

The operating microscope is the standard of care in contemporary endodontic microsurgery. Magnification (×4–×25) enables identification of root apices, accessory canals, isthmuses and microfractures, while coaxial illumination enhances visualisation and instrument control. Clinical studies have demonstrated superior healing rates with microsurgical procedures performed under magnification [1, 4].

3. Microsurgical Instruments

Specially designed microsurgical instruments minimise tissue trauma and improve surgical precision. Micro-mirrors, micro-scalpels, micro-curettes and fine tissue forceps facilitate atraumatic soft tissue management, whereas ultrasonic retro-tips allow conservative root-end preparation. Microsurgical needle holders and fine monofilament sutures contribute to accurate wound closure and favourable healing [1].

4. Flap Design

Flap design should provide adequate surgical access while preserving blood supply and promoting wound healing. Selection depends on lesion size, tooth location, periodontal status and aesthetic requirements.

The triangular flap provides good access for anterior teeth and premolars, whereas the rectangular flap offers greater visibility for larger lesions but may increase postoperative swelling. The submarginal (Ochsenbein–Luebke) flap preserves the marginal gingiva in aesthetically demanding cases with adequate attached gingiva but should be avoided in patients with periodontal disease. The papilla-base flap minimises gingival recession and papillary shrinkage and is increasingly recommended in the anterior maxilla [22, 23].

5. Osteotomy

The objective of osteotomy is to obtain adequate surgical access while preserving cortical bone. Conservative osteotomy, typically 3–5 mm in diameter, reduces postoperative discomfort and promotes faster osseous healing. Piezoelectric surgery offers a selective alternative to rotary burs by minimising injury to adjacent soft tissues [24, 25].

6. Periapical Curettage

Following osteotomy, pathological tissue should be removed to eliminate inflammation, improve visualisation and permit histopathological examination when indicated. Persistent lesions should be submitted for biopsy to exclude non-endodontic pathology [18].

7. Root-End Resection (Apicectomy)

Root-end resection removes the apical portion containing accessory canals, apical ramifications and infected dentine. Current evidence recommends resection of approximately 3 mm with a bevel angle of 0–10°, thereby reducing exposed dentinal tubules while maintaining an effective apical seal [1].

8. Root-End Preparation

Ultrasonic retrograde preparation has largely replaced conventional micro-handpieces because it permits centred root-end cavities approximately 3 mm deep with minimal bevel. Careful irrigation and intermittent instrumentation reduce heat generation and minimise dentinal microcracks [27].

9. Root-End Filling Materials

An ideal retrograde filling material should provide an effective seal, excellent biocompatibility, dimensional stability and bioactivity. Mineral trioxide aggregate (MTA) remains the reference standard because of its superior sealing ability and osteogenic potential. Biodentine and premixed calcium silicate bioceramics demonstrate favourable handling and biological properties, with higher success rates than conventional materials such as amalgam or intermediate restorative material (IRM) [7, 8, 28].

10. Wound Closure and Suturing

Primary wound closure should be achieved without tension using microsurgical techniques. Monofilament sutures (6-0 or 7-0 polypropylene or nylon) are preferred because they accumulate less plaque and produce minimal tissue reaction. Early suture removal (48–72 hours) promotes favourable soft tissue healing [1].

11. Post-operative Care

Postoperative management includes appropriate analgesia, oral hygiene instructions, chlorhexidine mouth rinses when indicated and advice regarding diet and physical activity. Clinical and radiographic follow-up at 6 months, 12 months and annually thereafter is recommended, with CBCT reserved for selected cases where conventional radiographs are inconclusive [5, 29, 30]. (Table 2.)

Table 2: Contemporary Microsurgical Protocol and Recent Technological Advances

Stage	Contemporary Recommendation	Recent Advancement	Clinical Benefit
Diagnosis	Clinical examination + CBCT	Three-dimensional imaging	Improved diagnosis and treatment planning
Magnification	Dental operating microscope	Enhanced illumination	Improved visualisation and precision
Flap design	Papilla-base/Submarginal flap	Microsurgical flap concepts	Better soft tissue preservation
Osteotomy	Conservative (3–5 mm)	Piezosurgery	Minimal bone removal
Root-end resection	3 mm resection with 0–10° bevel	Microsurgical techniques	Removal of apical ramifications
Root-end preparation	Ultrasonic retro-tips	Precision retropreparation	Conservative dentine removal
Root-end filling	MTA, Biodentine, Bioceramics	Bioactive calcium silicate materials	Superior apical seal and healing
Digital guidance	Dynamic navigation	3D-printed surgical guides	Increased surgical accuracy
Artificial intelligence	AI-assisted diagnosis	Machine-learning algorithms	Decision support and prognosis prediction
Follow-up	Clinical + radiographic evaluation	CBCT when indicated	Accurate assessment of healing

Abbreviations: AI, artificial intelligence; CBCT, cone-beam computed tomography; MTA, mineral trioxide aggregate.

Source: Published literature [1, 5, 7, 11, 22, 30].

Assessment and Prognostic Factors

The success of contemporary endodontic microsurgery depends on accurate diagnosis, appropriate case selection, meticulous surgical technique and effective long-term follow-up. Advances in microsurgical techniques, magnification, ultrasonic root-end preparation and bioactive root-end filling materials have substantially improved outcomes, with systematic reviews reporting favourable healing in approximately 90–94% of appropriately selected cases [4, 14].

1. Assessment of Treatment Outcome

Outcome assessment should include both clinical and radiographic evaluation, as healing cannot be determined solely by the absence of symptoms. Clinical success is characterised by the absence of pain, tenderness, swelling, sinus tract formation, pathological mobility and functional discomfort [15].

Radiographic healing has traditionally been assessed using the criteria of Rud *et al*., later modified by Molven *et al*.,

which classify healing as

- Complete healing
- Incomplete (scar tissue) healing
- Uncertain healing
- Unsatisfactory healing

These criteria remain widely accepted for evaluating postoperative healing and comparing clinical outcomes.[29, 30]

Although conventional periapical radiographs remain the standard follow-up method, their two-dimensional nature may underestimate persistent disease. Cone-beam computed tomography (CBCT) provides superior three-dimensional assessment of osseous healing and is recommended selectively when conventional radiographs are inconclusive or clinical findings do not correlate with radiographic appearance [5, 6].

2. Prognostic Factors

Prognosis is influenced by lesion size, duration of infection, quality of previous root canal treatment, periodontal status and the presence of root fractures. Teeth with adequate coronal restorations, minimal periodontal destruction and well-executed root canal fillings generally demonstrate more favourable healing. Although large periapical lesions do not necessarily reduce success rates, cystic lesions, extensive cortical bone destruction and true extraradicular infections may require prolonged healing [1, 2, 18].

Intra-operative Factors

The quality of the surgical procedure is a major determinant of long-term success. Microsurgical techniques performed under magnification improve visualisation and facilitate precise root-end management. Current evidence supports conservative osteotomy, approximately 3 mm root-end resection, minimal bevel (0–10°), ultrasonic retropreparation and placement of calcium silicate-based root-end filling materials to optimise healing [1, 4].

Root-End Filling Material

The choice of retrograde filling material significantly influences treatment success. Mineral trioxide aggregate (MTA) remains the reference standard because of its excellent sealing ability, biocompatibility and bioactivity. Biodentine and premixed calcium silicate bioceramics also demonstrate favourable clinical performance, whereas amalgam has largely been abandoned because of inferior biological and sealing properties [7, 8, 28].

Operator Experience

Operator experience and adherence to microsurgical principles contribute significantly to treatment success. Appropriate use of the operating microscope, ultrasonic instruments and microsurgical techniques reduces procedural errors and improves clinical outcomes [1, 4].

Patient-related Factors

Patient compliance, smoking, poorly controlled diabetes mellitus, oral hygiene and other systemic conditions affecting wound healing influence prognosis. Regular clinical and radiographic follow-up enables early detection and management of persistent disease [15].

3. Healing Following Endodontic Microsurgery

Successful healing is characterised by resolution of inflammation, regeneration of alveolar bone, periodontal ligament formation and cementum deposition over the resected root surface. Calcium silicate-based materials enhance these biological processes by promoting mineralised tissue formation. Complete radiographic healing may require 6–24 months, depending on lesion size, patient age and systemic health [7, 8].

4. Future Concepts in Outcome Assessment

Emerging technologies, including CBCT-based healing indices, artificial intelligence-assisted image interpretation and quantitative volumetric analysis of periapical lesions, may provide more objective and reproducible assessment of healing than conventional two-dimensional radiography and are expected to improve long-term outcome evaluation [11].

Recent Advances and Future Directions in Surgical Endodontics

Advances in digital imaging, microsurgical instrumentation, biomaterials and regenerative biology have transformed surgical endodontics into a minimally invasive, biologically driven discipline. These innovations have improved diagnostic accuracy, surgical precision, patient comfort and long-term treatment outcomes while supporting greater preservation of the natural dentition [1, 4].

1. Cone-Beam Computed Tomography (CBCT)

CBCT is an essential adjunct in contemporary endodontic microsurgery, providing three-dimensional assessment of lesion size, cortical bone perforation, root morphology, untreated canals and the relationship of the surgical site to adjacent anatomical structures. Compared with conventional radiography, CBCT improves diagnosis and surgical planning, particularly in anatomically complex cases. Its use should comply with the ALARA (As Low as Reasonably Achievable) principle to minimise radiation exposure [5, 6].

2. Dynamic Navigation and Guided Endodontic Microsurgery

Dynamic navigation integrates CBCT imaging with real-time tracking to improve localisation of the root apex during surgery. Similarly, three-dimensional printed surgical guides enable accurate osteotomy and root-end resection while preserving surrounding bone. These technologies improve precision, reduce operator-dependent variability and are particularly valuable in anatomically challenging cases [9, 10].

3. Advances in Biomaterials

Calcium silicate-based biomaterials have substantially improved the biological success of endodontic microsurgery. Mineral trioxide aggregate (MTA) remains the reference standard because of its excellent sealing ability and bioactivity. Biodentine and premixed bioceramic materials provide favourable handling characteristics and comparable biological performance, while ongoing research aims to develop materials with enhanced regenerative and antimicrobial properties [7, 8, 10].

4. Regenerative Endodontics and Tissue Engineering

Stem cell research, growth factors and tissue engineering are expanding the biological scope of surgical endodontics by promoting regeneration of the pulp–dentine complex and periapical tissues. Platelet-rich fibrin (PRF), platelet-rich plasma (PRP) and bioactive scaffolds have shown promising results in enhancing healing following periradicular surgery, although further clinical evidence is required [13, 31].

5. Artificial Intelligence

Artificial intelligence (AI) is emerging as a valuable adjunct for detecting periapical lesions, analysing root canal morphology, assisting CBCT interpretation and supporting treatment planning. Although promising, AI should complement rather than replace clinical judgement, and further prospective clinical validation is required before routine clinical implementation [11].

6. Laser-assisted Endodontic Surgery

Laser technology may enhance soft-tissue incision, haemostasis and surgical-site decontamination while reducing postoperative discomfort. However, current evidence does not support its routine use as a substitute for conventional microsurgical techniques, and additional randomised clinical trials are required [15].

7. Future Perspectives in Paediatric Patients

Although surgical endodontics is rarely required in children, advances in regenerative medicine, stem cell-based therapies and bioengineered scaffolds may improve management of immature permanent teeth. When surgery is indicated, digital navigation and minimally invasive techniques may help preserve alveolar bone, adjacent tooth germs and craniofacial development.

Critical Appraisal

Despite significant technological advances, many emerging techniques are supported mainly by laboratory studies, observational research and limited clinical series. High-quality multicentre randomised controlled trials with long-term follow-up are still needed to establish their effectiveness, cost-effectiveness and reproducibility. Until stronger evidence is available, new technologies should be integrated alongside established evidence-based microsurgical principles. (Table 3.)

Table 3: Prognostic Factors and Future Perspectives in Contemporary Surgical Endodontics

Factor/Innovation	Current Evidence	Clinical Significance	Future Perspective
CBCT	Standard of care	Precise diagnosis and treatment planning	Automated image interpretation and AI-assisted diagnostics
Operating microscope	Standard of care	Enhanced visualisation and surgical precision	Integration with digital workflows and augmented visualisation
Bioceramic root-end materials	High-level evidence	Superior sealing ability, biocompatibility, and bioactivity	Development of smart bioactive biomaterials with regenerative potential
Dynamic navigation	Emerging evidence	Accurate osteotomy and root-end resection with minimally invasive surgery	Routine clinical implementation and improved navigation accuracy
Three-dimensional (3D) printing	Increasing evidence	Patient-specific surgical guides and enhanced treatment planning	Personalised microsurgical procedures and customised surgical templates
Regenerative endodontics	Limited clinical evidence	Biological regeneration of periapical tissues	Stem cell-based therapies and tissue engineering applications
Artificial intelligence	Early clinical application	Diagnostic support, treatment planning, and prognostic prediction	Predictive precision endodontics with automated clinical decision support
Paediatric considerations	Conservative approach preferred	Preservation of immature permanent teeth and continued root development	Growth-preserving regenerative strategies and minimally invasive surgical approaches

Abbreviations: AI, artificial intelligence; CBCT, cone-beam computed tomography.
Source: Published literature [4, 5, 9, 15, 31].

Clinical Implications

The contemporary management of persistent apical periodontitis has evolved into an evidence-based, patient-centred approach. Advances in diagnostic imaging, microsurgical techniques and bioactive materials have improved the predictability of endodontic microsurgery, allowing preservation of teeth that might previously have been extracted. Treatment decisions should therefore be guided by biological, restorative and patient-related factors rather than radiographic findings alone [1, 15].

Accurate diagnosis remains fundamental to successful treatment. Comprehensive assessment, including clinical examination, periodontal evaluation and cone-beam computed tomography (CBCT) when indicated, facilitates identification of the cause of treatment failure and optimises treatment planning. CBCT is particularly valuable for detecting missed canals, root fractures, apical resorption and the relationship of the surgical site to adjacent anatomical structures [5, 6].

Appropriate selection between orthograde retreatment and endodontic microsurgery is essential. Whenever retreatment can predictably eliminate infection without compromising the tooth, it should remain the preferred option. Surgical intervention is indicated when orthograde retreatment is unlikely to achieve predictable healing because of restorative limitations, procedural complications or persistent extraradicular disease [4, 16].

Routine use of the operating microscope, ultrasonic retropreparation and calcium silicate-based root-end filling materials has improved surgical precision, reduced tissue trauma and enhanced long-term healing. These advances have established microsurgical techniques as the preferred approach for contemporary surgical endodontics [1, 7].

Digital technologies, including CBCT-guided planning, dynamic navigation and three-dimensional printed surgical guides, further improve surgical precision while minimising unnecessary bone removal, particularly in anatomically challenging cases. Nevertheless, favourable outcomes continue to depend primarily on sound biological principles, careful case selection and operator competence rather than technology alone [9, 11].

Preservation of the natural dentition remains the principal objective of endodontic treatment. Long-term success depends on maintaining an effective coronal seal, periodontal health and regular postoperative review [20].

Although surgical intervention is uncommon in paediatric patients, it may be indicated in carefully selected immature permanent teeth with persistent periapical disease following trauma or failed endodontic treatment. Treatment planning should consider behavioural management, stage of root development, restorative prognosis and the possible need for sedation or general anaesthesia. Whenever feasible, regenerative endodontic procedures should be considered before surgery [12, 13].

Future advances in regenerative medicine, biomaterial science and artificial intelligence are expected to further refine clinical practice. However, their routine adoption should continue to be guided by robust clinical evidence and long-term outcome data.

Future Perspectives

The future of surgical endodontics will be shaped by advances in digital technologies, biomaterial science, regenerative medicine and artificial intelligence. Although contemporary microsurgical techniques already achieve high clinical success, ongoing innovations are expected to improve treatment precision, minimise surgical morbidity and enhance biological healing, supporting more personalised and minimally invasive care.

Artificial intelligence has emerged as a promising adjunct in endodontics. Machine-learning algorithms have demonstrated encouraging performance in detecting periapical lesions, analysing root canal morphology and assisting CBCT interpretation. Future AI systems may support treatment planning, predict surgical outcomes and estimate procedural complexity using patient-specific clinical and radiographic data. However, these technologies should complement rather than replace clinical judgement and require further prospective clinical validation [11].

Digital navigation and three-dimensional printing are expected to become increasingly integrated into microsurgical practice. Patient-specific surgical guides and real-time navigation systems can improve the accuracy of osteotomy, minimise unnecessary bone removal and reduce operator variability, particularly in anatomically challenging cases [9, 10].

Future biomaterials are likely to evolve from passive root-end filling materials towards biologically active regenerative scaffolds incorporating antimicrobial agents, bioactive molecules and controlled-release growth factors to promote angiogenesis, cementogenesis and osseous regeneration [8, 11].

Regenerative medicine, including stem cell therapy, tissue engineering and gene-based approaches, may eventually restore the pulp–dentine complex and periapical tissues, reducing the need for surgical intervention in selected cases. Although current clinical applications remain limited, continued research is expected to expand their therapeutic potential [13, 31].

In paediatric patients, regenerative therapies may enhance continued root maturation and strengthen immature permanent teeth following trauma or pulpal necrosis, thereby reducing the need for apical surgery. When surgery is required, minimally invasive microsurgical techniques supported by digital planning may better preserve alveolar bone, adjacent developing tooth germs and craniofacial growth.

Despite these advances, robust multicentre randomised controlled trials with long-term follow-up are still required to establish the effectiveness, cost-effectiveness and generalisability of emerging technologies. Future research should also emphasise patient-reported outcomes, quality of life, economic evaluation and standardised outcome reporting.

Ultimately, continued collaboration between clinicians, researchers, biomaterial scientists and biomedical engineers will be essential to translate emerging innovations into safe, predictable and evidence-based patient-centred care.

Conclusion

Surgical endodontics has evolved into a predictable microsurgical discipline founded on biological preservation, minimally invasive intervention and evidence-based clinical practice. Advances in magnification, cone-beam computed tomography, ultrasonic root-end preparation and calcium silicate-based biomaterials have substantially improved the precision, predictability and long-term success of endodontic microsurgery. Contemporary evidence demonstrates that, with appropriate case selection and meticulous surgical technique, endodontic microsurgery is an effective treatment for persistent apical periodontitis and other conditions in which orthograde treatment is unlikely to achieve predictable healing.

Long-term success depends not only on surgical expertise but also on accurate diagnosis, identification of the cause of treatment failure, careful restorative and periodontal assessment, and evidence-based treatment planning. Although digital technologies continue to improve diagnostic accuracy and surgical precision, they should complement rather than replace sound biological principles and clinical judgement.

Future developments in bioactive materials, digital navigation, artificial intelligence and regenerative endodontics are expected to further enhance treatment outcomes and support more conservative tooth preservation. However, their routine implementation should be guided by robust clinical evidence and long-term outcome data.

Although endodontic microsurgery is performed less frequently in paediatric patients, it remains an important treatment option in carefully selected cases involving immature permanent teeth with persistent periapical disease. Whenever feasible, regenerative and other conservative approaches should be prioritised, with microsurgery reserved for situations in which it offers the most predictable opportunity for long-term tooth preservation.

In conclusion, contemporary surgical endodontics is a biologically sound, minimally invasive and predictable treatment modality. Continued integration of technological innovation with evidence-based clinical decision-making will further improve patient-centred care while supporting preservation of the natural dentition.

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