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CONTEMPORARY RESEARCH IN ENDODONTICS: EVIDENCE-BASED SCIENTIFIC CRITERIA FOR DIAGNOSIS, TREATMENT QUALITY, AND OUTCOME ASSESSMENT

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Abstract:

Background

Contemporary endodontics is undergoing a transition from technically oriented root canal treatment toward biologically based, evidence-driven, and patient-centred preservation of the natural tooth. The principal objective of endodontic care is no longer limited to mechanical preparation and obturation of the root canal system. Modern treatment aims to establish an accurate pulpal and apical diagnosis, control microbial infection, preserve healthy dental tissues, maintain pulp vitality when biologically possible, restore tooth function, and achieve stable long-term healing.

The rapid introduction of cone-beam computed tomography, artificial intelligence, magnification, heat-treated nickel–titanium instruments, activated irrigation, calcium silicate-based materials, guided endodontics, vital pulp therapy, and regenerative procedures has expanded clinical possibilities. However, technological novelty alone cannot be regarded as evidence of therapeutic superiority. New approaches must be assessed using transparent diagnostic standards, biologically relevant outcome measures, appropriate comparison groups, adequate follow-up periods, and validated reporting guidelines.

Objective

To synthesize contemporary evidence in endodontics and formulate scientific criteria for evaluating diagnostic methods, treatment procedures, biomaterials, digital technologies, and clinical outcomes.

Materials and Methods

A structured integrative review framework was developed for publications indexed in PubMed/MEDLINE and major professional guideline repositories. Studies and consensus documents published predominantly between January 2020 and August 6, 2026 were prioritized. Earlier landmark publications were included when necessary to explain established biological and methodological principles.

The search framework combined the terms “endodontics,” “pulpitis,” “apical periodontitis,” “root canal treatment,” “vital pulp therapy,” “regenerative endodontics,” “cone-beam computed tomography,” “artificial intelligence,” “guided endodontics,” “bioceramic materials,” “treatment outcome,” “core outcome set,” and “reporting guidelines.” Evidence was organized into diagnostic, biological, technological, clinical-outcome, and research-quality domains.

Results

Modern endodontic evidence supports six interrelated scientific criteria: diagnostic validity, biological plausibility, procedural standardization, tissue preservation, clinically meaningful outcome assessment, and transparent reporting. Clinical symptoms and conventional pulp sensibility tests remain necessary but do not directly measure pulpal blood flow or accurately

represent the histological condition of the entire pulp. Cone-beam computed tomography can improve three-dimensional assessment in selected complex cases, but its prescription must be justified by the expected influence on diagnosis or treatment planning.

Microbial control remains the biological foundation of root canal therapy. Rubber dam isolation, appropriate access, accurate working-length determination, mechanical preparation, chemical irrigation, prevention of reinfection, and a definitive coronal seal should be treated as interconnected components rather than isolated technical procedures. No instrumentation or irrigation system can guarantee complete sterilization of the complex root canal anatomy.

Vital pulp therapy has expanded from the management of reversible pulpitis and immature teeth to selected mature permanent teeth with clinical signs traditionally associated with irreversible pulpitis. Regenerative endodontic procedures may promote continued root development in immature necrotic teeth, although the newly formed tissue does not always reproduce the original pulp–dentine complex.

Calcium silicate-based materials, guided endodontics, artificial intelligence, and endodontic microsurgery show significant clinical potential. Nevertheless, many studies remain laboratory-based, retrospective, or methodologically heterogeneous. Endodontic success should therefore be assessed through a combination of pain, signs of infection, tenderness, radiographic healing, function, tooth survival, need for further intervention, adverse events, and patient satisfaction.

Conclusions

Scientific progress in endodontics should be measured not by the number of new devices or materials introduced into practice but by their ability to improve diagnosis, preserve biological structures, control infection, enhance tooth survival, and produce outcomes that matter to patients. Future studies require standardized diagnostic definitions, prospective designs, adequate sample sizes, calibrated outcome assessment, long-term follow-up, external validation of digital systems, and adherence to endodontic reporting guidelines.

Keywords: endodontics; evidence-based dentistry; pulpitis; apical periodontitis; root canal treatment; vital pulp therapy; CBCT; artificial intelligence; bioceramics; regenerative endodontics; treatment outcome.

Introduction

Endodontics is the branch of dentistry concerned with the biology, diagnosis, prevention, and treatment of diseases affecting the dental pulp and periradicular tissues. Its traditional clinical model was largely based on removal of inflamed or necrotic pulp tissue, mechanical enlargement of root canals, chemical disinfection, and obturation. Contemporary endodontics has broadened this model by integrating pulp biology, microbial ecology, immunology, biomaterials science, digital imaging, navigation, tissue engineering, and patient-reported outcomes.

The European Society of Endodontology S3-level clinical practice guideline emphasizes that treatment decisions should begin with a structured diagnosis of pulpal and apical disease and should aim to prevent tooth loss through evidence-based management of deep caries, pulpitis, pulp necrosis, and apical periodontitis. The guideline evaluates vital pulp procedures, root canal instrumentation, irrigation, intracanal medication, filling materials, and adjunctive interventions using a structured evidence-grading process.

Modern endodontic research is developing in several major directions. The first is biological preservation, including selective caries removal, direct pulp capping, partial pulpotomy, full pulpotomy, and regenerative endodontic procedures. The second is precision diagnosis through

limited-field CBCT, digital image analysis, and artificial intelligence. The third is minimally invasive treatment based on magnification, conservative access, flexible nickel–titanium systems, guided navigation, and microsurgery. The fourth is development of bioactive calcium silicate-based materials. The fifth is improvement in research methodology and standardization of clinically meaningful outcomes.

However, the rapid introduction of technologies creates a methodological problem. A statistically significant laboratory advantage does not necessarily result in improved clinical healing, tooth survival, function, or quality of life. A device may produce less dentine removal in an extracted tooth model but fail to improve long-term clinical outcomes. Similarly, a diagnostic artificial intelligence model may demonstrate high accuracy in an internal dataset but perform poorly when tested in another population or imaging system.

Therefore, a contemporary endodontic study should answer three essential questions:

1. Is the investigated method biologically and clinically justified?
2. Was the study designed and reported in a way that minimizes bias?
3. Does the measured outcome have genuine relevance for patients and tooth preservation?

The objective of this review was to summarize modern developments in endodontics and define scientific criteria for evaluating diagnostic methods, clinical interventions, materials, digital technologies, and treatment outcomes.

Materials and Methods

Review design

The article was developed as a structured integrative review. The methodological organization was based on contemporary principles of evidence-based dentistry and on the Preferred Reporting Items for Study Designs in Endodontology project.

Unlike a formal systematic review with a completed PRISMA flow diagram, this article provides a critical synthesis and a reproducible framework that can subsequently be expanded into a registered systematic review.

Publications were considered relevant when they examined at least one of the following domains:

- diagnosis of pulpal or apical disease;
- nonsurgical root canal treatment or retreatment;
- irrigation, instrumentation, obturation, or intracanal medication;
- vital pulp therapy;
- regenerative endodontic procedures;
- calcium silicate-based and bioceramic materials;
- CBCT, artificial intelligence, or guided endodontics;
- endodontic microsurgery;
- clinical, radiographic, functional, or patient-reported outcomes;
- methodological and reporting standards in endodontic research.

Studies exclusively describing a commercial product without a comparative methodology, reproducible protocol, biological outcome, or clinically meaningful endpoint were not considered sufficient evidence of effectiveness.

Quality domains

The evidence was interpreted according to six scientific domains:

1. **Diagnostic validity** — accuracy, reproducibility, appropriate reference standard, and effect on clinical decision-making.

2. **Biological plausibility** — relationship between the intervention and pulp preservation, microbial control, inflammation reduction, or periapical healing.

3. **Procedural standardization** — reproducibility of isolation, access, working length, preparation, irrigation, filling, and restoration.

4. **Structural preservation** — avoidance of unnecessary dentine and pulp-tissue removal.

5. **Outcome relevance** — inclusion of symptoms, function, healing, survival, complications, and patient experience.

6. **Reporting transparency** — clear description of participants, interventions, controls, statistics, exclusions, adverse events, and limitations.

Scientific criteria for endodontic diagnosis

Accurate diagnosis is the first scientific criterion of successful treatment. The diagnosis should integrate the patient's pain history, clinical examination, pulp sensibility testing, percussion, palpation, periodontal probing, mobility assessment, transillumination, and radiographic findings.

Cold and electric pulp tests evaluate neural responses rather than true pulpal circulation. A positive response does not confirm that the entire pulp is healthy, while a negative response does not always prove complete necrosis. The histological condition may differ between the coronal and radicular pulp, particularly in teeth with carious exposure and symptoms conventionally classified as irreversible pulpitis.

Consequently, a modern diagnostic study should not treat a single sensibility test as a perfect reference standard. The reference diagnosis should be based on a prespecified combination of symptoms, examination findings, imaging, intraoperative observations, follow-up, and histological findings when ethically and practically possible.

Diagnostic-accuracy research in endodontics should follow the PRIDASE 2024 guideline. It requires transparent reporting of patient selection, index tests, reference standards, examiner calibration, diagnostic thresholds, indeterminate results, and statistical measures such as sensitivity, specificity, predictive values, likelihood ratios, and confidence intervals.

Conventional radiography and CBCT

Periapical radiography remains an essential first-line imaging method because it provides clinically useful information with relatively low radiation exposure. Its principal limitation is the compression of three-dimensional anatomy into a two-dimensional image, resulting in superimposition and possible underdetection of lesions or complex anatomy.

CBCT can improve the assessment of additional canals, root resorption, traumatic injuries, perforations, calcified canals, complex retreatment cases, suspected vertical root fractures, and the anatomical relationship between lesions and adjacent structures. It may also modify the initial diagnosis and treatment plan in selected cases.

Nevertheless, CBCT should not be prescribed routinely for every endodontic patient. The 2025 AAE–AAOMR position statement emphasizes evidence-based selection according to the individual clinical problem and the expected diagnostic benefit. The field of view and exposure parameters should be restricted to the minimum necessary for the task.

The scientific value of CBCT should not be judged solely by its ability to detect more abnormalities than periapical radiography. A diagnostic method is clinically useful when the additional information changes treatment planning, improves safety, predicts outcome, or prevents an unnecessary intervention.

Artificial intelligence in endodontic diagnosis

Artificial intelligence is being investigated for detection of periapical radiolucencies, identification of root and canal anatomy, segmentation of teeth and lesions, evaluation of previous root canal fillings, recognition of separated instruments, and prediction of treatment complexity.

Current evidence suggests that AI can achieve promising diagnostic performance, especially when applied to CBCT datasets. However, CBCT-based performance is generally stronger than performance using panoramic or conventional periapical images, and results from controlled datasets cannot automatically be generalized to routine practice.

A scientifically valid AI study should report:

- the source and size of the dataset;
- participant and image-selection criteria;
- class distribution;
- annotation procedures and expert agreement;
- separation of training, validation, and test datasets;
- prevention of data leakage;
- external validation;
- confidence intervals for performance metrics;
- comparison with clinicians;
- handling of uncertain cases;
- model explainability and potential sources of bias.

High accuracy in an internal test sample is insufficient evidence for clinical implementation. Prospective studies should determine whether AI improves diagnostic decisions, treatment time, safety, patient outcomes, or cost-effectiveness.

Microbial control as the central biological objective

Apical periodontitis is primarily associated with microbial infection of the root canal system and the host response to this infection. The biological objective of treatment is therefore to reduce the microbial burden, disrupt biofilms, remove necrotic tissue and microbial substrates, prevent reinfection, and create conditions compatible with periapical healing.

The root canal system contains fins, isthmuses, lateral canals, ramifications, dentinal tubules, and irregularities that cannot be completely contacted by instruments. Mechanical shaping alone is therefore unable to eliminate all microorganisms and tissue remnants.

The scientific quality of a root canal treatment study depends on whether the entire antimicrobial protocol is described. Important variables include:

- rubber dam isolation;
- access design;
- working-length method;
- instrumentation system and apical preparation;
- irrigant type, concentration, temperature, and volume;
- needle design and insertion depth;
- irrigation activation;
- chelating solution;
- intracanal medication;
- number of visits;
- obturation method;
- temporary and definitive coronal seal.

When these variables are not standardized, differences attributed to a particular instrument or sealer may actually result from other parts of the treatment protocol.

Asepsis and rubber dam isolation

Rubber dam isolation is a fundamental component of endodontic asepsis. It reduces contamination from saliva, protects the patient from aspiration or ingestion of instruments and irrigants, and improves visibility and procedural control. The use of a dental dam should therefore be reported as a minimum quality criterion in clinical endodontic research. A 2024 professional position statement reaffirmed the importance of dental dam use in endodontic practice.

Failure to report isolation conditions introduces uncertainty regarding whether postoperative infection or treatment failure was related to the investigated intervention or to microbial contamination during treatment.

Access cavity and structural preservation

Traditional access cavities prioritize straight-line entry and unobstructed instrument placement. Conservative and ultraconservative access concepts aim to preserve pericervical dentine and reduce structural weakening.

Preservation of dentine is biologically and mechanically desirable, but access should not be reduced to the point that canals are missed, debris cannot be removed, irrigation becomes ineffective, or procedural errors increase. The scientific criterion is therefore not simply the smallest possible access cavity. It is the smallest access that permits predictable identification, disinfection, shaping, and filling of the entire clinically relevant canal system.

Studies evaluating access designs should include not only extracted-tooth fracture testing but also canal-detection rates, untreated anatomy, instrumentation errors, microbial reduction, restorative quality, and long-term tooth survival.

Working length and canal preparation

Accurate working-length determination reduces the risks of inadequate disinfection, overinstrumentation, debris extrusion, and injury to periapical tissues. Contemporary protocols commonly combine electronic apex-locator measurements with radiographic verification when indicated.

Heat-treated nickel–titanium instruments offer enhanced flexibility and fatigue resistance. Reciprocating and rotary systems can improve preparation efficiency, particularly in curved canals. Nevertheless, instrument performance should not be assessed only through preparation time or centring ability.

Clinically meaningful criteria include:

- preservation of the original canal path;
- transportation and apical deviation;
- dentine thickness after preparation;
- untouched canal-wall areas;
- debris extrusion;
- instrument separation;
- postoperative pain;
- microbial reduction;
- periapical healing;
- long-term tooth survival.

Irrigation and activation

Sodium hypochlorite remains central to endodontic irrigation because of its antimicrobial and organic tissue-dissolving properties. Chelating agents such as EDTA assist in removal of the

inorganic component of the smear layer. However, the effects of irrigants depend on concentration, volume, contact time, temperature, replenishment, delivery depth, and activation method.

Sonic, ultrasonic, apical negative-pressure, multisonic, and laser-assisted systems are intended to improve irrigant exchange and penetration. Laboratory evidence may demonstrate improved debris or biofilm removal, but superiority in a laboratory model does not necessarily establish improved long-term healing.

Studies should assess safety together with antimicrobial effectiveness. Excessive irrigant extrusion can cause severe tissue injury, whereas aggressive chelation may contribute to dentine erosion. Contemporary reviews emphasize that chelating agents may also affect sealer adhesion, growth-factor release, cytotoxicity, and regenerative cell responses.

Vital Pulp Therapy and Biologically Conservative Endodontics

Vital pulp therapy represents one of the most important changes in contemporary endodontic philosophy. The aim is to preserve healthy or recoverable pulp tissue rather than remove the entire pulp solely because of a traditional diagnostic label.

Procedures include indirect pulp treatment, direct pulp capping, partial pulpotomy, and full pulpotomy. Their success depends on case selection, control of microbial contamination, removal of irreversibly damaged coronal tissue, haemostasis, use of a biocompatible material, and an immediate bacteria-tight restoration.

Evidence indicates that pulpotomy may be considered in selected mature permanent teeth with symptoms traditionally associated with irreversible pulpitis. However, treatment should not be offered without evaluating restorability, bleeding characteristics, pulp exposure conditions, periodontal status, patient factors, and the clinician's ability to achieve adequate isolation and restoration.

The scientific criteria for vital pulp therapy include:

1. clearly defined preoperative diagnosis;
2. standardized haemostasis protocol;
3. documented time required to control bleeding;
4. specification of the capping material;
5. immediate definitive coronal seal;
6. clinical and radiographic follow-up;
7. reporting of pain, pulp sensibility, necrosis, apical disease, and further intervention;
8. follow-up sufficiently long to detect late failure.

Regenerative Endodontics

Regenerative endodontic procedures are primarily used for immature permanent teeth with pulp necrosis and apical periodontitis. They seek to eliminate infection, create a biological scaffold, promote tissue ingrowth, and allow continued root development.

The desired outcomes can be organized hierarchically:

- resolution of symptoms and apical disease;
- increased root-wall thickness and root length;
- apical closure;
- return of a positive sensibility response when possible.

A positive sensibility test after treatment does not necessarily demonstrate complete histological regeneration of the original pulp–dentine complex. Much of the tissue formed in current regenerative procedures may resemble vascularized connective, cementum-like, or bone-

like tissue. Therefore, terms such as "revascularization," "revitalization," and "true pulp regeneration" should not be used interchangeably without biological evidence.

Expert consensus recognizes regenerative endodontics as an evolving, evidence-based option for selected immature necrotic teeth, while also emphasizing protocol variability, discoloration, calcification, incomplete root development, and uncertainty regarding tissue identity.

Future research should standardize disinfection, intracanal medication, scaffold formation, use of platelet concentrates, coronal biomaterials, follow-up intervals, and outcome definitions.

Bioceramic and Calcium Silicate-Based Materials

Calcium silicate-based materials are used for pulp capping, pulpotomy, perforation repair, apexification, regenerative procedures, root-end filling, and root canal obturation.

Their potential advantages include biocompatibility, alkaline activity, calcium-ion release, sealing ability, moisture tolerance, and support for mineralized-tissue formation. Nevertheless, the general term "bioceramic" includes materials with different compositions, setting reactions, radiopacifiers, flow characteristics, solubility, retreatability, and biological properties.

Studies should identify the exact product and batch, mixing method, setting conditions, storage environment, sample dimensions, and clinically relevant comparator. Laboratory bioactivity should not be interpreted automatically as clinical superiority.

Meta-analyses comparing premixed calcium silicate-based sealers with conventional resin-based sealers have not consistently demonstrated major differences in postoperative pain. Evidence regarding long-term survival and healing remains less extensive than laboratory evidence.

The scientific assessment of a sealer or filling material should include:

- physicochemical properties;
- cytocompatibility;
- antimicrobial activity;
- dimensional stability;
- sealing performance;
- extrusion and adverse events;
- retreatability;
- postoperative symptoms;
- radiographic healing;
- tooth survival.

Guided Endodontics and Digital Navigation

Static guided endodontics combines CBCT data, digital surface scans, virtual planning, and a three-dimensional printed guide. Dynamic navigation tracks the bur position in real time.

These approaches may be useful in calcified canals, teeth with complex anatomy, fibre-post removal, selected retreatment procedures, and targeted endodontic microsurgery. Their principal potential advantage is controlled access with reduced unnecessary dentine removal.

Systematic reviews demonstrate encouraging accuracy, but much of the evidence is derived from laboratory studies, case reports, and small clinical series. Errors may arise during CBCT acquisition, scan registration, segmentation, guide fabrication, support positioning, drill movement, or patient motion.

Scientific evaluation should therefore include angular deviation, coronal and apical linear deviation, preparation time, dentine loss, canal-location success, perforation rate, radiation exposure, cost, and clinical outcome.

Scientific Criteria for Outcome Assessment

Historically, endodontic studies have used inconsistent definitions of "success." Some studies require complete radiographic resolution, whereas others accept a reduction in lesion size. Some assess tooth retention without evaluating symptoms, while others use clinical normality without a standardized radiographic endpoint.

This heterogeneity limits comparison between studies and weakens meta-analysis and guideline development. A scoping review found substantial variation in reported outcomes, measurement methods, thresholds, and follow-up periods.

The Core Outcome Set for Endodontic Treatments recommends eight outcomes shared across major treatment modalities:

1. pain;
2. signs of infection, including swelling or a sinus tract;
3. need for further intervention or exacerbation;
4. tenderness to percussion or palpation;
5. radiographic evidence of disease progression or healing;
6. function;
7. tooth survival;
8. patient satisfaction.

These criteria apply across root canal treatment, retreatment, surgical endodontics, vital pulp therapy, and revitalization procedures.

Table 1. Proposed scientific criteria for contemporary endodontic research

Research domain	Minimum scientific criterion	Recommended outcome or reporting item
Pulp diagnosis	Prespecified diagnostic definition	Symptoms, sensibility tests, clinical findings, imaging, reference standard
Apical diagnosis	Reproducible radiographic assessment	Calibrated examiners, lesion index or volumetric method, confidence intervals
CBCT	Individual justification	Field of view, voxel size, exposure settings, influence on treatment decision
Artificial intelligence	Independent validation	Dataset source, class balance, test separation, external validation, comparison with clinicians
Root canal treatment	Standardized full protocol	Isolation, access, working length, shaping, irrigation, filling, coronal restoration
Vital pulp therapy	Biological case selection	Haemostasis, capping material, restoration, pulp survival, apical health
Regenerative treatment	Hierarchical outcomes	Disease resolution, root development, apical closure, sensibility response
Bioceramic material	Exact material characterization	Physicochemical properties, adverse events, clinical healing, retreatability
Guided endodontics	Accuracy and safety	Linear and angular deviation, dentine loss, perforation, clinical success

Research domain	Minimum scientific criterion	Recommended outcome or reporting item
Treatment outcome	Multidimensional evaluation	COSET outcomes, follow-up duration, tooth survival, patient satisfaction
Clinical trial	Bias control	Randomization, allocation concealment, blinding where possible, sample-size calculation
Laboratory study	Reproducibility	Sample standardization, controls, operator calibration, repeated experiments
Diagnostic study	Accuracy reporting	Sensitivity, specificity, reference standard, indeterminate results
Case report	Complete clinical documentation	Timeline, diagnostic reasoning, intervention details, adverse events, follow-up

Radiographic healing

Radiographic healing should be evaluated using calibrated examiners who are blinded to the intervention when possible. The assessment method, diagnostic threshold, inter-examiner agreement, and management of uncertain cases should be reported.

CBCT detects smaller or earlier lesions than periapical radiography and may produce stricter estimates of healing. However, routine CBCT solely for research follow-up raises radiation and ethical concerns. Its use should be justified by the research question and should follow radiation-protection principles.

A 2025 systematic review demonstrated that outcome estimates vary according to imaging modality and definitions of healing, reinforcing the need for standardized criteria.

Tooth survival and function

Radiographic healing and tooth survival are related but distinct outcomes. A tooth may remain functional despite incomplete radiographic healing, while a radiographically healed tooth may later be lost because of fracture, caries, periodontal disease, or restorative failure.

Endodontic research should therefore consider the entire tooth-restoration complex. Important prognostic variables include remaining tooth structure, cracks, ferrule, periodontal support, coronal restoration, occlusion, parafunction, and patient adherence to follow-up.

Patient-reported outcomes

Pain, anxiety, treatment burden, ability to chew, satisfaction, cost, and oral-health-related quality of life should be measured directly from the patient. These outcomes are particularly important when comparing vital pulp therapy with root canal treatment, single-visit with multiple-visit treatment, nonsurgical retreatment with surgery, or natural-tooth preservation with extraction and replacement.

Reporting Standards and Research Integrity

The PRIDE initiative was developed to improve completeness, transparency, and reproducibility in endodontic publications. It includes study-design-specific guidelines rather than relying exclusively on general biomedical checklists.

The principal guidelines include:

- **PRIRATE 2020** for randomized clinical trials;
- **PRILE 2021** for laboratory studies;
- **PRICE 2020** for case reports;
- **PRIDASE 2024** for diagnostic-accuracy studies;

- additional PRIDE guidance for observational and animal studies.

PRIRATE 2020 contains endodontic-specific items addressing clinical and radiographic images, randomization, interventions, outcomes, participant flow, and harms.

PRILE 2021 emphasizes clear description of samples, controls, experimental conditions, randomization, blinding, statistical analysis, and image quality. This is particularly important because a considerable proportion of endodontic innovation is initially investigated using extracted teeth, artificial canals, biofilm models, cell cultures, and material-testing systems.

PRICE 2020 improves the reporting of unusual anatomy, complications, guided procedures, regenerative treatments, and other clinically important cases. A case report can generate a hypothesis or demonstrate feasibility but cannot establish comparative effectiveness.

Scientific integrity also requires prospective protocol registration when applicable, disclosure of conflicts of interest, reporting of adverse events, justification of sample size, appropriate statistical analysis, preservation of raw data, and avoidance of selective outcome reporting.

Discussion

Principal findings

The contemporary development of endodontics is characterized by convergence of biological preservation, digital precision, bioactive materials, and methodological standardization.

The first major finding is that diagnosis should be understood as a probabilistic clinical process rather than a fixed conclusion derived from a single pulp test or radiograph. Diagnostic categories must be linked to treatment decisions and validated against meaningful clinical outcomes.

The second finding is that successful treatment depends on the complete biological and restorative protocol. It is scientifically inappropriate to attribute success exclusively to a file system, irrigant activator, obturation method, or sealer when isolation, microbial control, operator experience, and coronal restoration are insufficiently described.

The third finding is that vital pulp therapy is changing the traditional boundary between conservative dentistry and endodontic treatment. Selected inflamed pulps may retain a capacity for healing when microbial contamination is controlled and healthy radicular tissue is preserved.

The fourth finding is that digital technologies can improve visualization and precision but create new risks of overdiagnosis, unnecessary radiation, dataset bias, and commercial adoption before external validation.

The fifth finding is that outcome assessment must move beyond a binary radiographic definition of success. Pain, infection, function, tooth survival, further intervention, and patient satisfaction should be evaluated together.

Clinical implications

A scientifically grounded clinical protocol should follow a sequential decision pathway:

1. establish a reproducible pulpal and apical diagnosis;
2. determine whether the pulp can reasonably be preserved;
3. assess restorability and long-term tooth prognosis;
4. use CBCT only when additional three-dimensional information is expected to influence management;
5. perform treatment under effective isolation and aseptic conditions;
6. preserve dentine without compromising disinfection;
7. select materials according to evidence rather than marketing claims;
8. provide an immediate and durable coronal seal;
9. evaluate clinical, radiographic, functional, and patient-reported outcomes;
10. arrange follow-up sufficiently long to identify healing or failure.

Research priorities

Future endodontic research should prioritize multicentre prospective studies and randomized trials with adequate sample sizes. Diagnostic research requires independent reference standards and external validation. AI models should be tested across institutions, populations, devices, and disease prevalence levels.

Laboratory studies should use clinically relevant models and should not claim clinical effectiveness from physicochemical or antimicrobial findings alone. Vital pulp and regenerative studies require standardized diagnoses, treatment protocols, and histologically informed terminology.

Long-term studies should distinguish four related but different endpoints:

- absence of symptoms;
- periapical healing;
- tooth survival;
- patient-centred success.

Cost-effectiveness and accessibility should also be evaluated because sophisticated technologies may improve technical precision while widening inequalities in access to care.

Limitations

This article is an integrative review rather than a completed registered systematic review. It does not provide a PRISMA flow diagram, meta-analysis, or quantitative risk-of-bias synthesis. The rapid development of artificial intelligence, imaging, biomaterials, and regenerative techniques means that some conclusions may require updating as prospective evidence becomes available.

The heterogeneity of diagnostic definitions, operator experience, intervention protocols, imaging methods, and follow-up periods remains a major limitation of the existing endodontic literature.

Conclusions

Contemporary endodontics is developing from technically focused canal treatment toward biologically based and evidence-driven preservation of the natural tooth. The principal scientific criteria of modern endodontic research are accurate diagnosis, biological plausibility, standardized treatment, preservation of healthy tissue, reproducibility, clinically meaningful outcomes, and transparent reporting.

CBCT, artificial intelligence, guided endodontics, calcium silicate-based materials, vital pulp therapy, and regenerative procedures have expanded clinical possibilities. However, these technologies should be adopted according to validated indications and evidence of patient benefit rather than technological novelty alone.

The success of endodontic treatment should be assessed through pain control, elimination of infection, recovery of function, radiographic healing, tooth survival, absence of adverse events, and patient satisfaction. Application of COSET and PRIDE reporting standards can reduce research heterogeneity and improve the translation of scientific evidence into clinical practice.

Future endodontics should pursue precision without unnecessary intervention, biological preservation without inadequate infection control, and innovation without compromising methodological quality.

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