



GRADUATION PROJECT

Degree in Dentistry

ANALYSIS OF ADVERSE EVENTS IN ENDODONTICS

Madrid, academic year 2025/2026

RESUMEN

Introducción: Los eventos adversos en endodoncia siguen siendo una preocupación clínica relevante a pesar de los importantes avances en instrumentación, imagen y técnicas de obturación. Los errores procedimentales e iatrogénicos pueden ocurrir antes, durante o después del tratamiento de conductos y afectar negativamente la cicatrización periapical, el éxito del tratamiento y la supervivencia dental a largo plazo; **Objetivo:** El objetivo principal de este estudio fue analizar, a través de la literatura científica, los principales eventos adversos asociados al tratamiento endodóntico, sus causas subyacentes y las estrategias preventivas necesarias para reducir el riesgo clínico; **Material y Métodos:** Se realizó una revisión bibliográfica sistematizada siguiendo los principios PRISMA utilizando MEDLINE Complete. Se consideraron estudios publicados en inglés durante los últimos 10 años que incluían pacientes adultos. Tras el proceso de cribado y evaluación de elegibilidad, se incluyeron 14 estudios; **Resultados:** La evidencia revisada mostró que los eventos adversos siguen siendo frecuentes, especialmente en molares y en casos de alta dificultad. Las complicaciones más reportadas fueron la subobturación, la sobreobturación, los conductos omitidos, la separación de instrumentos y la restauración coronal inadecuada. Estos factores se asociaron de forma consistente con una mayor prevalencia de enfermedad periapical postratamiento, peor cicatrización radiográfica y una reducción del éxito global del tratamiento; **Conclusiones:** Los eventos adversos en endodoncia son multifactoriales y continúan influyendo en los resultados del tratamiento. Una evaluación preoperatoria cuidadosa, una ejecución técnica rigurosa y un adecuado sellado coronal son esenciales para minimizar las complicaciones y mejorar el pronóstico.

PALABRAS CLAVE

Odontología, endodoncia, eventos adversos, periodontitis apical, tratamiento de conductos.

ABSTRACT

Introduction: Adverse events in endodontics remain a relevant clinical concern despite major advances in instrumentation, imaging, and obturation techniques. Procedural and iatrogenic errors may occur before, during, or after root canal treatment and can negatively affect periapical healing, treatment success, and long-term tooth survival; **Objective:** The main objective of this study was to analyse, through scientific literature, the principal adverse events associated with endodontic treatment, their underlying causes, and the preventive strategies required to reduce clinical risk; **Material and Methods:** A systematised literature review following PRISMA principles was performed using MEDLINE Complete. Studies published in English within the last 10 years and involving adult patients were considered. After screening and eligibility assessment, 14 studies were included; **Results:** The reviewed evidence showed that adverse events remain frequent, particularly in molars and high-difficulty cases. The most commonly reported complications were underfilling, overfilling, missed canals, instrument separation, and inadequate coronal restoration. These factors were consistently associated with a higher prevalence of post-treatment periapical disease, poorer radiographic healing, and reduced overall treatment success; **Conclusions:** Adverse events in endodontics are multifactorial and continue to influence treatment outcomes. Careful preoperative assessment, rigorous treatment execution, and adequate coronal sealing are essential to minimise complications and improve prognosis.

KEY WORDS

Dentistry, endodontics, adverse events, apical periodontitis, root canal treatment.

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ABBREVIATIONS

RCT: Root Canal Treatment

CBCT: Cone-Beam Computed Tomography

PAI: Periapical Index

SS: Stainless Steel

AP: Apical Periodontitis

PTED: Post-Treatment Endodontic Disease

OR: Odds ratio

NSRCT: Non-Surgical Root Canal Treatment

NiTi: Nickel Titanium

MB2: Second MesioBuccal Canal

CDAF: (modified) Case Difficulty Assessment Form

AAE: American Association of Endodontists

HR : Hazard Ratio

1. INTRODUCTION

1.1. Background and significance of endodontics

1.1.1. Advances in endodontic techniques and their associated challenges

A fully established branch of dentistry, endodontics is a specialised field focused on the study of dental pulp function, morphology and health, as well as the prevention and management of injuries and diseases (Figure 1). As a result of bacterial infiltration through enamel, dentin and, ultimately, the pulp, inflammation of the pulp tissue can develop, leading to various pathologies such as pulpitis or pulpal necrosis. Understanding the etiology and diagnosis of dental pain and pulp-periapical disease is a fundamental aspect of endodontic practice (1).

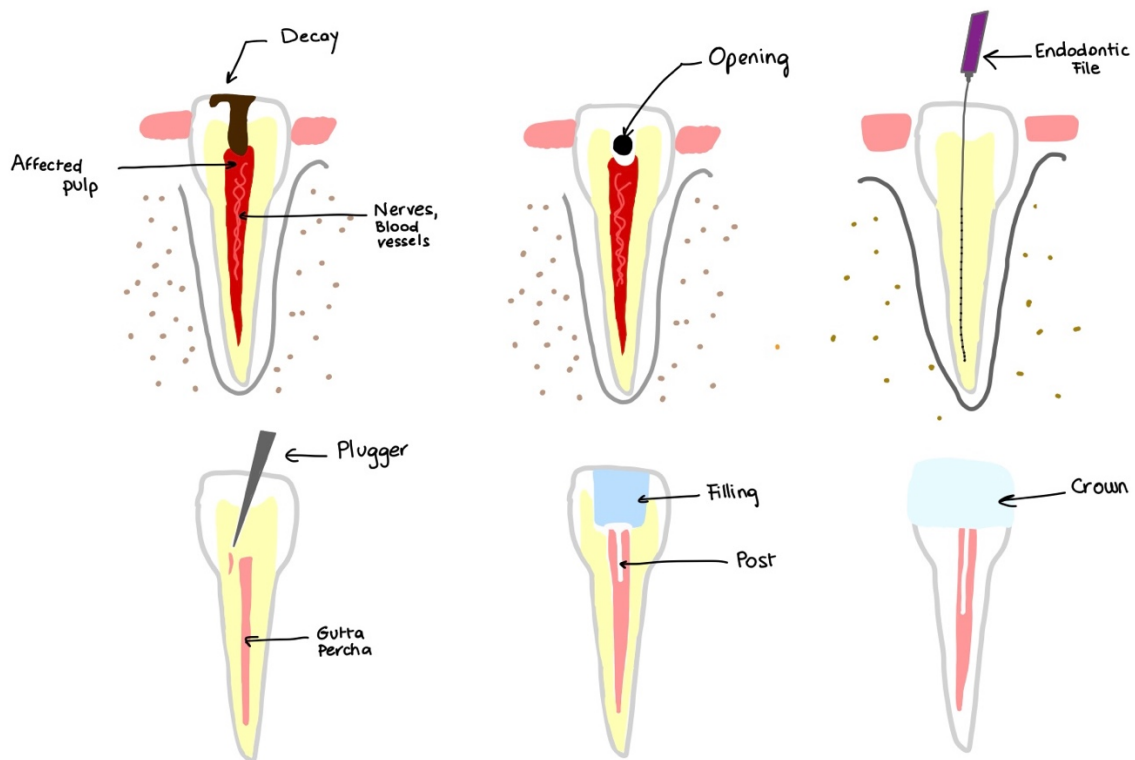


Figure 1. Overview of endodontic treatment sequence. Source: Personal work.

As many other fields in dentistry, endodontics has undergone many changes in recent years. Advances in materials, instrumentation methods and obturation techniques, together with the integration of digital imaging and new technologies, have significantly influenced endodontic instrumentation, improving precision and safety (2).

Single-file systems have improved procedural efficiency without compromising treatment effectiveness, while NiTi rotatory instruments have significantly changed contemporary endodontic practice (3). However, despite these new technological advances, the growing complexity of modern systems may also introduce complications, particularly in cases with challenging anatomy or limited operator experience (4).

1.1.2. Importance of patient safety and clinical quality

Patient safety is a fundamental component of dental care, aiming to prevent errors and adverse outcomes during clinical procedures. It relies on evidence-based protocols and strategies designed to minimise risk, strengthen team communication, and promote high-quality, patient-centred care. By identifying potential hazards and encouraging a culture of transparency and ongoing improvement, dental professionals can safeguard patient well-being and reduce the likelihood of preventable incidents (2).

1.2. Adverse events in endodontics according to treatment phase

Adverse events in endodontics may occur at different stages of treatment, from diagnosis and access preparation to obturation and post-treatment follow-up (Figure 2).

1.2.1. Pre-treatment phase

Pre-treatment adverse events in endodontics mainly arise from diagnostic and treatment-planning errors (5). Accurate pulpal and periapical diagnosis is essential because it directly influences case selection, therapeutic decisions, and prognosis. Incomplete assessment of symptoms, inadequate interpretation of radiographic findings, or insufficient use of pulp vitality tests may lead to misdiagnosis, treatment of the wrong tooth, or underestimation of case difficulty. Such errors may compromise the whole treatment sequence from the outset and increase the risk of subsequent procedural complications. Therefore, careful clinical and radiographic examination, together with an evidence-based diagnosis, is essential to reduce pre-treatment risks and improve the predictability of endodontic therapy (6).

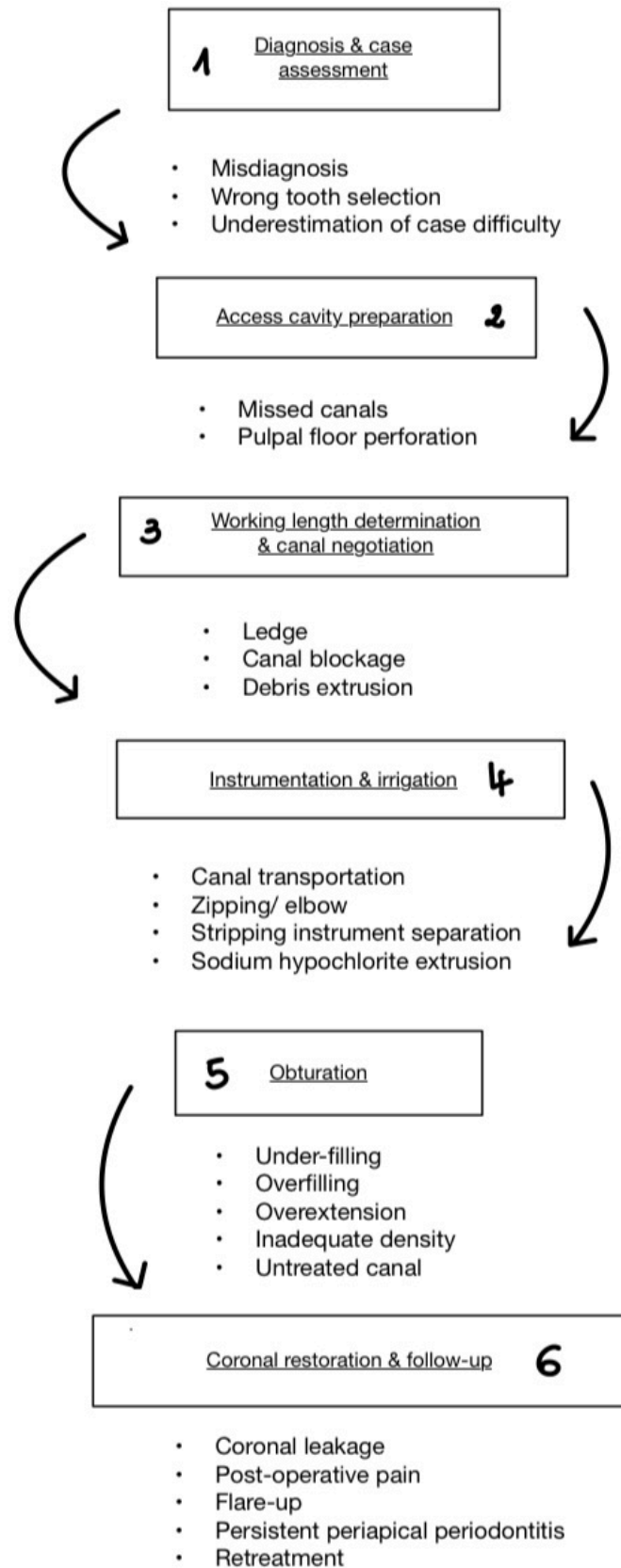


Figure 2. Main adverse events in endodontics according to treatment phase. Source : Personal work.

1.2.2. Intra-treatment phase

Intra-treatment adverse events may occur throughout root canal therapy, from access cavity preparation to obturation, and are particularly relevant because they may compromise disinfection, technical quality, and long-term prognosis (5,6).

Endodontic access cavity preparation is a critical and technically demanding stage of root canal therapy. An inadequate access cavity may limit proper visualisation of canal anatomy and increase the likelihood of missed canals (Figure 3), especially in molars, where the number of canals may exceed the number of roots (7,8). At this stage, pulpal floor perforation may also occur as an iatrogenic communication between the pulp chamber and the external root surface, usually associated with improper use of instruments during access opening and canal location (9).



Figure 3. Periapical radiograph illustrating a missed mesial canal in tooth 37. Source: Personal archive.

Another important source of complications concerns working length determination, canal negotiation, and irrigation. Ledge formation (Figure 4) may result from inadequate maintenance of original canal path, creating an artificial deviation that limits apical cleaning and obturation (9).

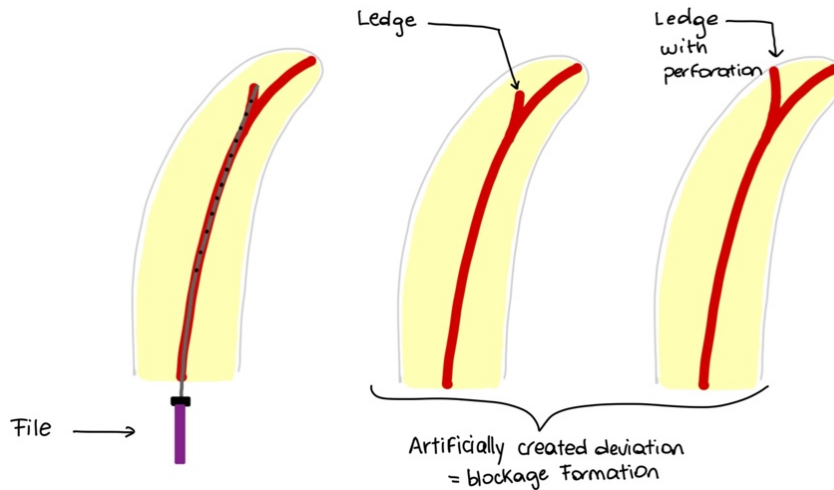


Figure 4. Ledge formation. Source: Personal work

Sodium hypochlorite extrusion beyond the apical foramen represents a more severe event, as it may cause acute pain, edema, and soft-tissue injury. Nevertheless, sodium hypochlorite remains indispensable because of its antimicrobial and tissue-dissolving properties when used cautiously and with appropriate irrigation control. In addition, apical extrusion of infected debris may occur during canal exploration or irrigation and, although often transient, has been associated with postoperative pain and inflammation (10).

Canal instrumentation itself is also associated with several interconnected adverse events. Loss of working length or improper canal negotiation may lead to blockage and subsequent ledge formation, whereas overinstrumentation in curved canals may distort apical anatomy and predispose to zipping or elbow defects (Figure 5) that complicate obturation and sealing (11). When instrumentation extends beyond canal walls, perforation may occur, allowing bacterial contamination and negatively affecting periapical healing (12).

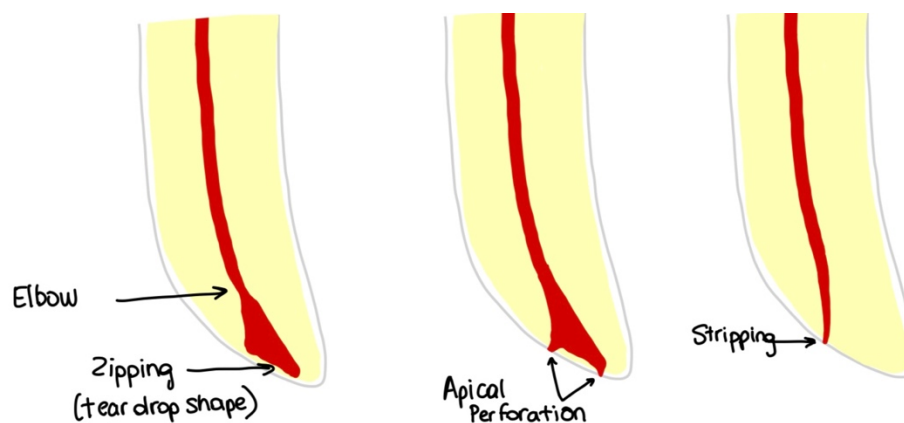


Figure 5. Zipping, apical perforation, stripping schema. Source: Personal work.

More severe shaping errors, such as strip perforation, may also develop in curved canals and significantly compromise prognosis if not detected early (13,14). Instrument separation is another relevant intraoperative complication and is considered multifactorial, being related to mechanical stress, technical errors, and operator-dependent factors such as excessive pressure, inadequate anatomical assessment, or improper use of NiTi instruments (11,15,16).

Adverse events occurring during obturation and after treatment completion may have important biological, clinical, and psychological consequences, influencing treatment outcomes, patient well-being, and professional responsibility. Inadequate obturation, including overextended or underfilled root fillings (Figure 6), as well as untreated canals, may sustain residual biofilm or trigger periapical inflammation through foreign body reactions, thereby compromising long-term prognosis (4,9).

Overextension of filling materials (Figure 7) is particularly relevant because, in addition to impairing prognosis, it may cause serious complications when vital anatomical structures are involved. Likewise, sodium hypochlorite extrusion or root perforations may result in chemical burns, inflammation, or secondary infections, thereby impairing periapical healing (17). Post-endodontic flare-ups, commonly manifested by pain and swelling, should also be considered among the main post-treatment complications. More broadly, root-filled teeth are more prone to structural failure due to tissue loss and inadequate restoration, which highlights the importance of strict infection control and a well-sealed coronal restoration to ensure durable treatment success (4,8,11,18).



Figure 6. Radiographic example of severe overfilling associated with extensive structural damage to the treated tooth. Source: Personal archive.

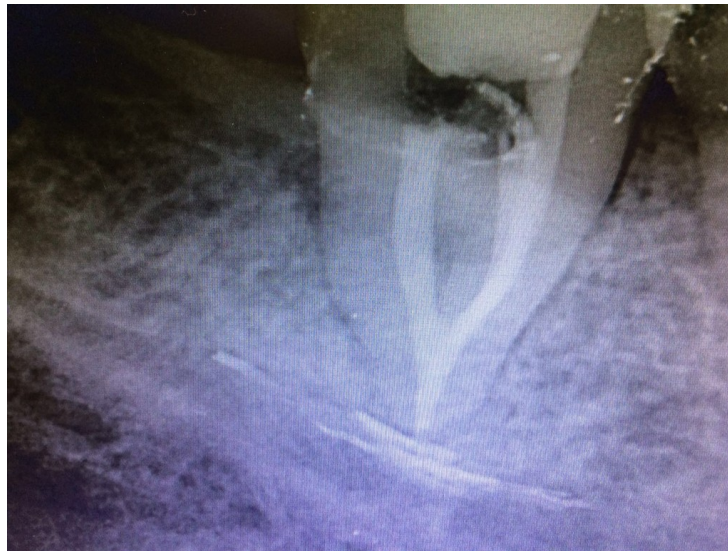


Figure 7. Extrusion of endodontic sealer beyond the root canal system. Source: Personal archive.

1.2.3. Post-treatment phase

Post-treatment adverse events become evident after completion of root canal therapy and often represent the clinical consequence of pre-treatment or intra-treatment deficiencies. They may include post-endodontic pain, swelling, flare-ups, persistent or newly detected periapical pathology, and, in some cases, structural complications affecting the long-term survival of the treated tooth. These events are particularly relevant because they directly influence treatment outcomes, patient well-being, and the need for retreatment (4,11).

Persistent post-treatment disease is frequently associated with technical deficiencies such as inadequate disinfection, untreated canals, underfilled or overextended root fillings, and insufficient coronal sealing. In these situations, residual microorganisms or persistent leakage may compromise periapical healing and maintain chronic inflammation. Extrusion-related accidents, including sodium hypochlorite extrusion or root perforation, may also contribute to secondary tissue injury, inflammation, or infection, thereby worsening the biological response after treatment (17). Post-endodontic flare-ups, commonly manifested by pain and swelling, should also be considered among the main post-treatment complications, as they may reflect acute exacerbation of periapical inflammation after canal instrumentation or obturation. Beyond these immediate consequences, root-filled teeth are more prone to structural failure due to cumulative tissue loss and inadequate restoration (18).

For this reason, post-treatment prognosis depends not only on the biological quality of endodontic therapy, but also on appropriate restorative management and the achievement of a well-sealed coronal restoration to ensure durable treatment success (4,8,11,18).

1.3. Scientific and clinical relevance of adverse events in endodontics

1.3.1. Clinical impact and prognosis

Adverse events in endodontics are clinically relevant because they may compromise the biological and technical objectives of RCT, namely effective canal disinfection, adequate obturation, periapical healing, and long-term tooth retention. Even with contemporary materials and techniques, procedural and iatrogenic errors remain a recurring part of clinical practice and may negatively influence treatment outcomes (19,20).

Their prognostic impact on treatment outcomes is multifactorial and depends on variables such as the type and severity of the complication, root canal anatomy, preoperative periapical status, and the quality of both the root filling and the coronal restoration. Rather than isolated technical incidents, adverse events should be viewed as factors capable of affecting the whole treatment sequence and reducing predictability (4,5).

Furthermore, their consequences may extend beyond radiographic failure, as they can also result in pain, inflammation, retreatment, and structural weakening of the tooth. For these reasons, understanding the clinical implications of adverse events is essential to improve prognosis and support safer, more predictable endodontic care (8,19).

1.3.2. Relevance for education and prevention

The persistence of complications in endodontics also highlights an important educational and preventive issue. They may arise from anatomical complexity, operator-related variables, or limitations of the instruments and techniques used, which underlines the importance of risk assessment, careful planning, and strict adherence to clinical protocols (3,21).

In addition, iatrogenic errors are not limited to experienced practitioners and have also been reported during undergraduate clinical training, emphasising the need to strengthen endodontic education and adapt teaching methods to contemporary clinical challenges (22).

From this perspective, preventive measures must start before complications arise, through accurate diagnosis, appropriate case selection, preoperative difficulty assessment and careful technical execution. Therefore, a structured and critical analysis of the literature is justified not only to improve patient safety and treatment outcomes, but also to promote prevention-oriented clinical training and continuous improvement in endodontic practice (2,17).

Justification

Although recent technological and scientific advances have considerably enhanced the quality and predictability of endodontic treatment, complications remain a recurring issue in daily clinical practice. Despite the evolution of modern endodontics, retreatment is still frequently required to address incidents or failure of primary therapy (13). This confirms that these events are multifactorial, involving anatomical complexity, operator-related factors, and mechanical limitations of current systems. For instance, instrument separation during canal shaping remains one of the most troublesome iatrogenic complications, highlighting the need to identify all causal factors and to develop valid preventive guidelines to minimise their recurrence (13).

Moreover, iatrogenic errors are not limited to experienced practitioners; they are also frequently observed among undergraduate dental students during their clinical training, highlighting the need to improve the quality of endodontic education and to adapt curricula to contemporary clinical challenges (21). Therefore, from both scientific and pedagogical perspectives, it becomes essential to systematise and update existing knowledge, through a structured and critical synthesis of literature. Such an approach not only contributes to improving patient safety and treatment outcomes, but also strengthens the clinical training of dental students, fostering a culture of prevention, precision and continuous improvement in endodontic practice.

2. OBJECTIVES

2.1. Main objective

To analyse, through scientific literature, the main adverse events that may occur during endodontic treatment, their underlying causes, and the preventive strategies required to minimise clinical risk.

2.2. Secondary objectives

1. To identify and classify the different types of adverse events described in endodontic literature (instrument fracture, perforation, under and overfilling...)
2. To determine the most frequent risk factors associated with these events, including operator experience, anatomical complexity, and procedural technique.
3. To review preventive and management strategies aimed at improving patient safety and treatment outcomes.

3. MATERIAL AND METHODS

3.1. Methodological design

This study was designed as a systematised literature review. PRISMA guidelines were used as a reporting framework to support the transparent presentation of the study selection process, without classifying the study as a systematic review. The review focused on the main procedural and iatrogenic errors, their clinical impact, and the preventive strategies proposed to reduce clinical risk. A structured and reproducible methodological approach was used to ensure transparency and scientific rigour.

3.2. Search strategy and study selection

The literature search was carried out through MEDLINE Complete, selected for its relevance and broad coverage of biomedical and dental literature. As no single search equation was sufficient to retrieve all relevant studies, five complementary searches were performed using different combinations of MeSH terms, keywords, and Boolean operators (AND, OR).

The search strategy was progressively refined to identify studies addressing procedural and iatrogenic errors during RCT, as well as their clinical consequences. The main concepts explored included Root Canal Therapy, endodontics, adverse events, technical quality, obturation, instrument separation, perforation, prognostic factors, retreatment, and treatment outcomes. The five searches were combined, duplicates were removed, and studies were screened according to predefined eligibility criteria. Titles and abstracts were reviewed for relevance and full-text articles were then assessed for final inclusion.

3.3. Data collection and synthesis

The studies retained after full-text assessment were analysed using a qualitative approach. Data was extracted according to the main objectives of the review, including: type of adverse event, study design, population characteristics, outcomes, and prognostic implications. The findings were grouped and synthesised thematically in order to identify recurring patterns, areas of agreement, and discrepancies across studies. This approach allowed a structured comparison of results and supported the narrative interpretation of the current literature on adverse events in endodontics.

3.4. Determination of PICO question

To guide the review and ensure focused and structured analysis, the research question was formulated using the PICO framework. This approach allowed for an identification of relevant literature and facilitated the comparison between cases involving procedural or iatrogenic errors and adequately performed endodontic treatment.

- P (Population): adult patients undergoing root canal therapy
- I (Intervention/Exposure): presence of iatrogenic or procedural errors
- C (comparison): adequately performed treatments
- O (outcome): treatment outcomes, including treatment failure, postoperative complications, periapical healing, persistence of symptoms, retreatment, and long-term prognosis

The formulated research question is :

In adult patients undergoing root canal therapy, how does the presence of iatrogenic or procedural errors, compared with adequately performed treatments, influence treatment failure and clinical outcomes ?

3.5. Eligibility criteria

3.5.1. Inclusion criteria

Studies were included if they met the following criteria:

- Published in English
- Conducted on adult patients (≥ 19 years) undergoing root canal treatment
- Evaluated iatrogenic and/or procedural errors related to endodontic treatment
- Reported clinical, radiographic, or prognostic treatment outcomes
- Included observational or analytical study designs, such as cohort studies, case control studies, or randomised controlled trials
- Published within the last 10 years

3.5.2. Exclusion criteria

Studies were excluded if they met any of the following criteria:

- Lack of full-text availability
- Animal studies or in vitro studies
- Studies involving pediatric patients (≤ 18 years of age)
- Meta-analysis or systematic reviews
- Editorials, expert opinions or conference abstracts
- Publications not reporting clinical outcomes related to procedural or iatrogenic errors in endodontics

3.6. Search equations

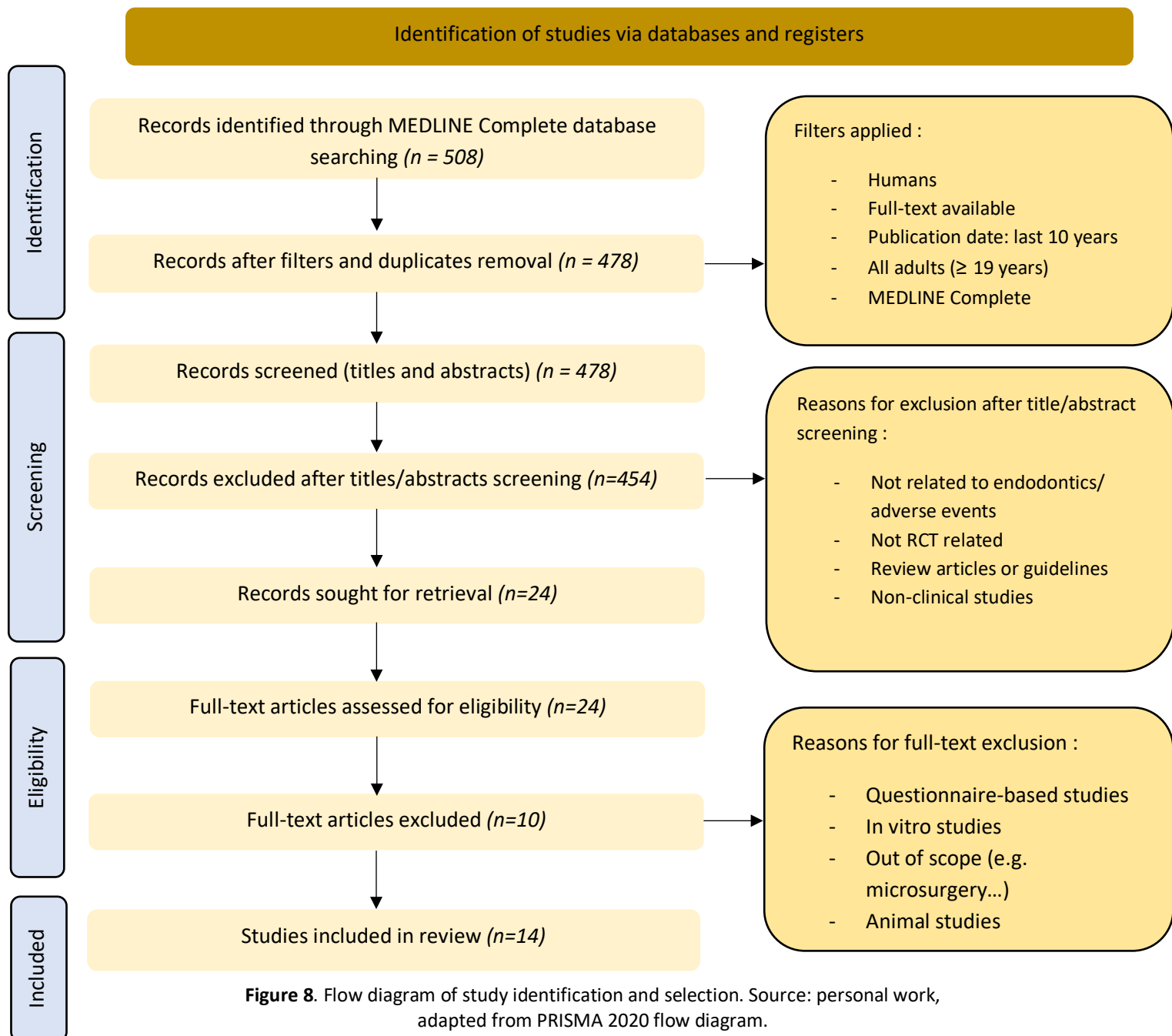
Given the broad scope of the topic, the final sample was obtained through five search equations rather than a single broad search. The different equations were designed to improve sensitivity and to capture studies addressing distinct categories of complications and outcomes.

1. MH (Root Canal Therapy) AND TX (treatment outcomes OR success OR healing OR prognosis) AND TX (procedural errors OR iatrogenic OR technical quality)
2. MH (Root Canal Therapy) AND TX (technical quality OR obturation OR filling length OR density) AND TX (periapical OR healing OR outcome)
3. MH (Root Canal Therapy) AND TX (perforation OR instrument separation OR ledge OR transportation) AND TX (outcomes OR healing OR prognosis OR success)
4. MH (Root Canal Therapy) AND TX (prognostic factors OR predictors) AND TX (success OR failure OR healing)
5. MH (Root Canal Therapy) AND TX (retreatment OR failed root canal OR previous endodontic treatment) AND TX (prevalence OR outcome)

4. RESULTS

4.1. Study selection

A total of 508 records were identified through MEDLINE Complete database searching (Figure 8). After removal of approximately 30 duplicates, 478 records were screened based on titles and abstract. Of these, 454 records were excluded for being out of scope or not meeting inclusion criteria. Twenty-four full-text articles were assessed for eligibility, and 10 studies were excluded due to inappropriate study design or lack of relevant clinical outcomes. Finally, 14 studies were included in the review.



4.2. Summary of results

The results are shown in Table 1.

Table 1. Characteristics of the studies reviewed.

Author (Year)	Study type	Population / Sample size	Adverse events / procedural error studied	Outcome measure	Main findings / conclusions
Keratiotis et al. (23), 2024	Cross-sectional observational study	614 adults; 14,655 teeth	Quality of root canal filling (density and length), coronal restoration quality, and presence of caries	Prevalence of apical periodontitis (panoramic radiographic assessment)	High AP prevalence (45% in RCT); inadequate coronal restoration, caries, and poor filling density were associated with AP, with no improvement in RCT quality over 22 years.
Kaya Mumcu et al. (24), 2025	Prospective observational study	200 patients, 200 root canal-treated teeth	Endodontic mishaps (e.g., over-instrumentation, working length loss, under/over filling, apical transportation, instrument fracture, perforation)	Incidence and number of procedural errors and number of treatment visits according to case difficulty (AAE)	Procedural errors occurred in 37% of cases and were more frequent in high-difficulty cases and molars, which also required more visits.`

Teerawanitsan et al. (19), 2025	Retrospective cohort study	142 teeth (343 roots); follow-up $\approx$ 36 months	Errors during instrumentation (e.g., canal deviation, lateral/apical/strip perforation, ledge formation, instrument separation)	Radiographic healing and presence of post-treatment disease	Healing: 72.5% teeth / 80.5% roots. Under-instrumentation errors were the only significant predictors of poorer outcomes, increasing the risk of disease by up to eightfold.
Vieira et al. (25), 2024	Retrospective clinical study	218 patients, 304 teeth (treatment/retreatment)	Overextension, overfilling, preoperative lesion, lesion size, number of visits, restoration quality	Radiographic outcome using Periapical Index (PAI; rigid and lenient criteria)	Success: 74% rigid/ 82% lenient; overextension, preoperative lesions, large lesion size, and multiple visits reduced treatment success.
Johnsen et al. (26), 2023	Prospective clinical follow-up study (4-6 years)	149 patients; 160 teeth at recall	Case difficulty, instrumentation methods, procedural errors (e.g., over instrumentation, loss of working length, short obturation, canal transportation...)	Clinical signs/symptoms, radiographic success/failure + PAI measurement	Combined success was 78.8%; radiographic success 87.5% and clinical success 88.8%. High-difficulty cases and procedural errors were associated with more symptoms and higher PAI scores.

Handa et al. (27), 2024	Retrospective cohort study	2,911 endodontic treatments screened	Incidence of instrument separation and related factors	Frequency and Instrument separation incidence was 6%, occurring significantly in molars, MB canals, and the apical third, especially with SS files.
Nascimento et al. (20), 2018	Cross-sectional CBCT study	618 teeth; 1,146 root canals	Technical errors (under/overfilling, voids, non-filled canal, deviation, fracture) and restoration quality	Presence of periapical radiolucency on CBCT Periapical lesions in 59.3% of canals; technical errors increased lesion risk (OR $\approx$ 7.6), rising to OR $\approx$ 9.9 when combined with poor restorations. Underfilling is the most frequent error.
Alkis & Kustarci (28), 2019	Retrospective cross-sectional study	245 adults; 6,064 teeth (541 roots canal-treated teeth)	Adequate versus inadequate RCT quality and restoration quality	Periapical status (PAI index) AP prevalence was 40.5%. Adequate RCT strongly associated with healthier periapical status (77.5% healthy), confirming the impact of treatment quality on outcome.

Aysal et al. (29), 2022	Retrospective cross-sectional study	1,069 patients; 20,646 teeth endodontically treated (1,604 teeth)	Procedural errors (short/long filling, inhomogeneous filling, missed canals, perforation, ledge formation, fractured instrument)	Post-treatment endodontic disease (PTED)/apical lesion	PTED prevalence was 56.8%; 54.1% of root canal-filled teeth had at least 1 procedural errors. Procedural errors were strongly associated with PTED (76.2% with errors vs 34% without), particularly missed canals, short and inhomogeneous fillings.
Alamoudi et al. (30), 2020	Retrospective cross-sectional study	1,000 undergraduate-treated RCT cases	Iatrogenic errors (perforation, ledge formation, fractured instrument, over/underfilling) related to case difficulty (AAE)	Incidence of iatrogenic errors	Iatrogenic errors occurred in 22.1% of cases and were significantly associated with higher case difficulty. Underfilling (8.4%) was the most frequent error; molars showed highest error rates.
Law et al. (31), 2025	Prospective cohort study	1,860 enrolled; 1,698 analysed, treated by 104 general dentists and 49 endodontists	Case difficulty factors and treatment complications (short obturation, overextension, instrument separation, overfilling, perforation)	Incidence of complications and predictors (OR)	Complications in 16% of RCTs and were significantly less frequent when treatment was performed by endodontists (13%) than general dentists (19%). The most common complications were short obturation and overextension (6% each).

Prati et al. (32), 2018	Prospective cohort study	72 patients/196 RCTs	Root filling quality, coronal restoration quality, perioperative periapical status	Tooth survival and periapical healing after 20 years	Tooth survival was 79%; most extractions were due to non-endodontic causes, and retreatment was required in only minority of cases.
Gökdoğan et al. (33), 2025	Retrospective cohort study (≥ 5 years of follow-up)	943 teeth from 740 patients were treated/ 408 teeth from 376 patients were included	Pre-retreatment obturation quality, restoration type/quality	Survival and treatment success (clinical + radiographic criteria)	Overall survival : 73.5% and success: 79% after 78 months. Restoration type and initial obturation quality significantly influenced both survival and success.
Şahin P, Gündüz H (34), 2026	Retrospective cross-sectional radiographic study	396 teeth from 282 patients	Treatment quality factors (filling length, homogeneity, coronal seal, missed canals)	Presence and severity of periapical radiolucency	Among 396 molars, adequate treatment was associated with 72.9% healthy teeth, whereas short or inadequate fillings significantly increased lesion prevalence, lesion size and bone destruction.

5. DISCUSSION

5.1. Prevalence of adverse events

5.1.1. Frequency of procedural errors

Procedural and technical deficiencies remain common in contemporary endodontic practice. In a prospective clinical study, procedural mishaps were reported in 37% of cases, with obturation-related errors, particularly overfilling and underfilling, among the most frequent events (24). Consistent with this, CBCT-based assessments indicate that underfilling is a prevalent technical deficiency in treated canals and that three-dimensional imaging enables a more sensitive detection of both technical shortcomings and associated periapical changes. Cross-sectional CBCT data also show that more than half of root-filled teeth (54.1%) present at least one procedural error, reinforcing the substantial impact of technical deficiencies in endodontically treated teeth (20,29). Similar patterns are observed in training settings, where iatrogenic errors were identified in 22.1% of treated teeth, predominantly involving obturation and instrumentation-related complications (30). In parallel, a prospective practice-based cohort reported a lower overall complication rate (16%), particularly when treatment was performed by endodontists rather than general dentists, suggesting that operator profile and case management may partly explain variations in the reported prevalence (31).

Together, these findings suggest that, beyond technology, advances in materials, anatomical complexity, and technique-sensitive steps such as working length control, canal shaping, obturation quality, and coronal sealing remain key sources of error. This burden is not uniformly distributed and appears strongly influenced by tooth type, case difficulty, and possibly operator profile.

5.1.2. High-risk cases: tooth anatomy and complexity

Case difficulty provides a useful framework to explain why adverse events cluster in specific clinical situations. In a prospective postgraduate study, procedural mishaps were significantly more frequent in molars and high difficulty cases, and increasing case difficulty correlated positively with both the number of mishaps ($r = 0.344$) and the number of treatment visits ($r = 0.433$), indicating that more complex cases tend to generate more technical errors and require additional appointments (24).

This trend is consistent with undergraduate clinical data using difficulty classification, where the distribution of iatrogenic errors was strongly skewed toward high-difficulty cases (71%), and errors occurred predominantly in molars (73%), with mesiobuccal roots of maxillary molars representing a particularly frequent error location (26%) (30). Practice-based data further show that complications were less frequent when treatment was carried out by endodontists, which further suggests that complex anatomy and case difficulty require greater technical control and case selection.

Apart from difficulty categories, anatomical features help explain this concentration of adverse events. Posterior teeth with narrow and curved canals, especially mesiobuccal canals, and instrumentation in the apical third are more prone to procedural complications, including instrument separation; a large retrospective series reported separation events occurring predominantly in molars and most often in the apical third (27).

Importantly, these increased procedural challenges have potential clinical consequences: in a 4 to 6-years follow-up study from an undergraduate clinic, high-difficulty cases and molars presented more clinical signs/symptoms and higher combined failure rates than minimal or moderate cases, suggesting that case complexity is linked not only to intraoperative mishaps but also to less favourable long-term outcomes (26). These data support a continuum from anatomical complexity and case difficulty to a higher procedural error frequency and, in some settings, worse long-term clinical outcomes.

5.1.3. Association with periapical lesions

Evidence from population-based surveys supports a persistent association between technical quality and periapical status in root-filled teeth. In a Belgian cross-sectional study, apical periodontitis remained frequent and more than half of root canal treatments were rated as technically inadequate; importantly, inadequate coronal restoration and poor root-filling density were strongly associated with apical disease (23).

CBCT studies further highlight the cumulative effect of endodontic and coronal factors on periapical radiolucency. In particular, apical radiolucency was substantially more likely when technical errors were present and increased further when poor coronal restoration coexisted, with the highest risk observed when inadequate endodontic quality and inadequate coronal restoration occurred together (OR 9.86) (20).

This interpretation is supported by CBCT-based studies showing that technical deficiencies are associated not only with the presence of periapical lesions but also with increased lesion severity. In molars treated at least four years earlier, inadequate technical quality was linked to both higher lesion prevalence and more advanced radiographic features, including larger lesion size, cortical bone destruction, and furcation involvement, indicating a more severe periapical condition when treatment quality is compromised (34).

To enable meaningful comparisons across studies, outcome definitions and imaging modalities should be considered. In PAI-based panoramic assessments, “healthy” generally corresponds to PAI = 1, whereas apical periodontitis is defined as PAI $\geq$ 2. Using this threshold, a panoramic cross-sectional study reported an AP prevalence of 40.5% in root-filled teeth, and periapical health was significantly better when RCT quality was adequate ($p < 0.001$). However, panoramic radiography is less sensitive than CBCT and may underestimate periapical changes, which can partly explain differences in reported prevalence (28). This interpretation is also supported by the European Society of Endodontology position statement on the use of CBCT in endodontics. These CBCT-based studies suggest that periapical pathology may be detected more frequently when assessed three-dimensionally (29,35).

These observations emphasise that “success” and “disease” rates depend strongly on how outcomes are defined and measured, which provides a rationale for the next section addressing the impact of technical factors on treatment success.

5.2. Impact on treatment outcomes

5.2.1. Effect on treatment success

Building on the association between technical quality and periapical status discussed above, treatment success should be interpreted according to the outcome criteria used. In the long-term retrospective study by Vieira et al. (25), radiographic success varied depending on whether strict (rigid) or less strict (lenient) PAI criteria applied, with overall success reaching 74% under rigid criteria and 82% under lenient criteria. Similar patterns were observed for both primary treatments and retreatments, indicating that studies using different thresholds may report varying “success” rates, even when clinical improvement is present (25).

Follow-up data combining radiographic and clinical endpoints further support this interpretation. In a 4 to 6-years undergraduate recall study, radiographic success was 87.5% (PAI ≤ 2) and clinical success 88.8%, whereas overall success decreased to 78.8% when both criteria were required, highlighting the impact of composite definitions on reported outcomes (26).

In addition to medium-term success rates, very long-term data suggest that RCT should also be evaluated according to tooth retention over time. In a 20-year prospective cohort, 79% of root-filled teeth were still present at recall (tooth survival), while 65% were classified as periapically healthy (PAI ≤ 2). Most extractions were attributed to non-endodontic causes (e.g., fracture, caries, and periodontal disease), whereas endodontic post-treatment disease was less frequent, suggesting that long-term prognosis depends not only on periapical healing but also on structural and restorative factors (32). Similarly, long-term nonsurgical retreatment cohorts (≥ 5 years) report favourable outcomes, indicating that treatment success is not limited to primary RCT and can also be achieved after retreatment (33). Together, these findings suggest that success in endodontics should be considered as a multidimensional concept, including radiographic healing, absence of symptoms, and long-term tooth survival.

5.2.2. Risk of post-treatment disease

Post-treatment disease refers to persistent or newly detected periapical pathology after root canal therapy, and is influenced by both baseline status and specific technical deficiencies. In a retrospective cohort of molars treated by sixth-year students, multivariable analysis identified under-instrumentation as a key independent predictor of post-treatment disease (OR 5.33), along with preoperative radiolucency (OR 7.12) and inadequate coronal restoration quality (OR 16.54). Subgroup analyses confirmed this pattern: when a preoperative radiolucency was present, under-instrumentation further increased disease risk, and greater uninstrumented canal length was associated with a higher probability of disease (19). Cross-sectional CBCT evidence supports these associations at the population level. Among teeth diagnosed with PTED, procedural deficiencies such as short or inhomogeneous root fillings, untreated canals, and overextended fillings are frequently observed, suggesting that post-treatment pathology commonly coexists with identifiable technical shortcomings at the time of imaging (29).

In addition, CBCT data indicate that technical deficiencies may influence not only the presence but also the severity of disease. In molars treated ≥ 4 years earlier, inadequate obturation and insufficient coronal restoration were associated with larger lesions and more advanced bone involvement (e.g. cortical destruction and furcation involvement) (34). Although these data help explain the persistence of periapical pathology after treatment, they do not fully reflect long-term prognosis in terms of tooth retention. This highlights the need to distinguish between the persistence of periapical disease and the broader concept of long-term tooth survival.

5.2.3. Long-term survival

Long-term prognosis after root canal therapy should be interpreted not only in terms of radiographic healing, but also according to the ability to retain the tooth in function over time. After 20 years, 79% of root-filled teeth remained present, and 65% were classified as periapically healthy (PAI ≤ 2). Importantly, tooth loss during long-term follow-up is often related to non-endodontic causes such as structural failure, caries and periodontal breakdown. This suggests that long-term success is best understood as a combination of effective infection control, preservation of tooth structure, and adequate restorative management (32).

Additional long-term evidence is also available for nonsurgical root canal retreatment (NSRT). In a cohort study with a follow-up of at least 5 years, treated by experienced endodontists, overall tooth survival reached 73.5% and among surviving teeth, 79% fulfilled strict success criteria based on combined clinical and radiographic assessment. The main reason for non-survival was extraction due to crown/root fracture, again suggesting that long-term retention after retreatment is often limited by structural and restorative factors rather than by persistent infection alone (33). Taken together, these findings suggest that long-term success should not be reduced to radiographic healing alone, but should also include functional tooth retention over time.

Preventing technical complications, particularly those affecting apical disinfection, obturation quality, missed anatomy, and structural integrity, is therefore critical and justifies a focused analysis of the main procedural complications.

5.3. Main procedural complications

5.3.1. Obturation errors

Obturation-related complications have a measurable impact on endodontic outcomes, particularly when filling materials extend beyond the apical foramen. In the long-term retrospective study by Vieira et al. (25), overextension was one of the strongest negative predictors of strict radiographic success (OR 0.197) (25). Similarly, a 4 to 6-years undergraduate follow-up study found that gutta-percha overfill (7.5% of cases) was associated with unfavourable radiographic outcomes, including higher PAI scores and increased total failure rates (26).

CBCT evidence further supports the clinical importance of obturation quality, showing that technical obturation deficiencies are frequently associated with apical radiolucency (20). This interpretation is reinforced by CBCT cross-sectional data on PTED where obturation deficiencies (e.g., short and inhomogeneous fillings, as well as overextended fillings) are commonly observed in affected teeth, highlighting their role in persistent periapical pathology (29).

Beyond lesion presence, CBCT analyses in molars treated ≥ 4 years earlier indicate that short and inhomogeneous fillings are associated not only with lesion presence but also with increased lesion severity, with larger lesions more frequently linked to advanced bone involvement (34). This suggests that obturation quality may influence not only the presence of post-treatment disease, but also its radiographic severity. Finally, undergraduate clinical data confirm that obturation errors remain common in practice, with underfilling (8.4%) and overfilling (4.0%) among the most frequent iatrogenic events (30).

5.3.2. Instrumentation errors

Instrumentation-related errors can compromise canal debridement and apical control, thereby increasing the likelihood of post-treatment disease. In a cohort study of molars treated by sixth year dental students, under-instrumentation was identified as an independent predictor of post-treatment disease in multivariable analyses (OR 5.33). In teeth with a preoperative radiolucency, under-instrumentation further increased disease risk (OR 8.05), and greater uninstrumented canal length was associated with a higher probability of disease, underscoring

the clinical importance of maintaining working length and avoiding apical blockage or deviation during canal shaping (19).

Supporting the clinical relevance of instrumentation mishaps in practice, undergraduate clinical data identified ledge formation (4.2%) and root perforation (2.5%), confirming that canal negotiation and shaping remain vulnerable steps, particularly in complex anatomy (30).

In addition, medium-term follow-up data indicate that certain instrumentation errors may translate into patient-centred outcome. Over-instrumentation was associated with a higher frequency of pain and clinical signs (e.g. sinus tracts and endodontic pockets), and canal transportation was also linked to pain, highlighting that deviations from original canal anatomy may contribute to persistent symptoms and less favourable outcomes (26). Collectively, these studies suggest that instrumentation errors may affect not only periapical healing but also the patient's clinical experience after treatment.

5.3.3. Instrument separation

Instrument separation remains a clinically relevant procedural complication, particularly in complex posterior anatomy. In a large retrospective series conducted in a postgraduate setting, separation occurred in 6% of treatments and was predominantly located in the apical third (80%), with fewer events in the middle (12%) and coronal thirds (8%). Separation was most frequently observed in molars, especially mesiobuccal canals, and was more commonly associated with stainless-steel files (62.86%) than NiTi instruments, highlighting apical negotiation in narrow and curved canals as a high-risk stage (27). This pattern is consistent with the broader association between molar anatomy, case complexity, and procedural mishaps discussed above.

Similarly, undergraduate clinical data also reported file separation as a recurring complication, with instrument fracture identified in 3% of treated teeth (30). Although the reported frequency was lower in the undergraduate setting, both studies support the view that instrument separation is not an isolated event, but a complication that tends to concentrate in anatomically demanding cases.

5.3.4. Missed canals

Missed canals are closely linked to molars and their complex anatomy, reinforcing the relationship between case complexity and persistent infection risk. CBCT data show that untreated canals are particularly frequent in the MB2 canal of maxillary molars (78.4%) and are also common in the distobuccal canal of mandibular molars (30%), highlighting untreated anatomy as a major technical deficiency in posterior teeth (20).

These observations indicate that failure to identify and treat additional canals represents one of the most critical technical limitations in endodontic therapy. Finally, it also indicates that failure to locate and treat additional canals is strongly associated with persistent periapical radiolucency in root-filled molars (34). This interpretation is supported by external CBCT-based evidence showing that root-filled teeth with at least one untreated canal have a markedly higher prevalence of post-treatment apical periodontitis, with the odds of apical disease being substantially increased compared with teeth in which all canals were adequately treated (36).

5.4. Factors influencing prognosis

5.4.1. Operator experience

Operator experience appears to meaningfully influence the occurrence of intraoperative complications. In a practice-based cohort study, complications were observed in 16% of cases overall and included clinically relevant events such as short or overextended obturation, inability to negotiate canals to working length, instrument separation, perforation, and related procedural mishaps (31). Importantly, complication rates were significantly higher among general dentists than endodontic specialists (19% vs 13%; $p < 0.001$). Despite managing cases with higher difficulty profiles according to the CDAF, endodontists still experienced fewer complications, indicating that specialist training and experience may mitigate procedural risk even in complex cases and support case selection and referral for high-risk situations (31). This interpretation is consistent with the broader pattern observed in the present review, in which high-difficulty cases and molars were more frequently associated with procedural mishaps. Together, these findings suggest that operator experience may influence outcomes not only through technical skill itself, but also through more appropriate case selection, planning, and referral decisions.

5.4.2. Preoperative difficulty assessment

Case difficulty should be assessed systematically before initiating RCT, as it supports risk stratification and treatment planning. Practice-based evidence indicates that clinicians can rate case complexity using a preoperative 10-point difficulty scale (0 = minimal, 10 = high), and these pre-treatment ratings are strongly consistent with post-treatment ratings ($r = 0.79$; $p < 0.001$), indicating that case complexity can be anticipated with reasonable accuracy before treatment. (31). In addition, pre-treatment difficulty ratings correlate with the number of objective difficulty features recorded in a modified Case Difficulty Assessment Form (CDAF) ($r = 0.57$; $p < 0.001$), supporting the idea that subjective judgement aligns with measurable clinical and anatomical challenges (31). Overall, these findings reinforce the practical value of structured difficulty assessment tools (AAE/CDAF) to guide scheduling, supervision, and referral decisions, particularly for cases presenting high-risk features such as molars, limited canal visibility, calcifications, or marked curvature (24,31). This also emphasises the role of preoperative assessment as a key step in preventing procedural complications and improving treatment outcomes.

5.4.3. Major prognostic factors

When confounding factors are considered, multivariable analyses help identify the variables that remain independently associated with post-treatment outcomes. In a cohort of molars treated by sixth-year students, under-instrumentation was identified as a key procedural predictor of post-treatment disease (OR 5.33), along with strong clinical predictors reflecting baseline and restorative conditions, including preoperative radiolucency (OR 7.12) and inadequate coronal restoration quality (OR 16.54) (19). Subgroup analyses refined this interpretation: in teeth with preoperative radiolucency, under-instrumentation further increased disease risk (OR 8.05), whereas in teeth without preoperative radiolucency, restoration quality remained the main determinant, highlighting the importance of preventing coronal recontamination when initial infection was absent (19).

Complementary long-term outcome data support the prognostic relevance of baseline periapical status and lesion characteristics. Vieira et al. found that preoperative apical periodontitis reduced strict radiographic success (OR 0.326), and lesion size further stratified prognosis, with smaller lesions (< 5 mm), showing better outcomes than lesions > 10 mm (OR 4.759) (25).

Cross-sectional radiographic evidence also emphasises the role of technical quality: in a panoramic study using PAI definitions, periapical health was significantly more frequent when RCT met radiographic adequacy criteria compared with inadequate treatment ($p < 0.001$), supporting technical quality as an important prognostic indicator, although the apparent influence of coronal restoration was weaker in that dataset (28). Finally, retreatment cohorts further highlight the importance of both baseline technical conditions and restorative integrity. In a ≥ 5 -year NSRT cohort, pre-NSRT obturation quality influenced outcomes (survival $p = 0.007$; success $p = 0.035$), and short pre-NSRT fillings were associated with higher failure risk (HR 2.10), indicating that initial technical deficiencies remain relevant even after retreatment (33).

This section reinforces the association between RCT technical quality and periapical health, while CBCT-based evidence and outcome studies in this review indicate that prognosis is likely multifactorial, combining endodontic quality, coronal sealing, and baseline infectious status (e.g., preoperative apical periodontitis).

5.5. Role of coronal restoration

Coronal sealing plays a central role in endodontic prognosis by limiting bacterial recontamination of the root canal system after treatment. In a cohort study assessing procedural errors and outcomes, inadequate restoration quality was a strong independent predictor of post-treatment disease (OR 16.54), and, in teeth without preoperative radiolucency, restoration quality emerged as the main determinant of outcome (19).

CBCT-based evidence supports this relationship, showing that even when endodontic treatment is classified as adequate, poor coronal restoration remains associated with a higher likelihood of apical radiolucency (OR 3.23), and that risk is greatest when inadequate endodontic quality and poor restoration coexist (20). Similarly, CBCT findings in molars indicate that insufficient coronal restorations are associated not only with lesion presence but also with larger lesions and more advanced features such as cortical bone destruction and furcation involvement, suggesting that inadequate coronal integrity may contribute to a more severe apical condition over time (34).

However, the strength of this association may vary across studies and may be influenced by methodological factors such as imaging modality and diagnostic criteria, since panoramic cross-sectional analyses are less sensitive than CBCT for detecting periapical changes (28).

From an outcome perspective, long-term data further indicate that restoration-related variables remain clinically relevant, particularly in retreatment scenarios (25). In a 5-year NSRT cohort, poor coronal restoration quality was independently associated with a markedly higher risk of failure, with hazard ratios of 6.89 for composite restorations and 7.21 for full-coverage restorations (33).

Very long-term cohort evidence indicates that maintaining teeth over decades is often limited by non-endodontic structural or restorative causes, reinforcing that endodontic success should be considered within an endodontic-restorative continuum rather than as an isolated technical procedure (32). Coronal sealing appears to be a key modifiable determinant of prognosis, highlighting the importance of integrating endodontic and restorative management in clinical practice.

5.6. Clinical implications

5.6.1. Risk assessment and planning

From a clinical perspective, structured risk assessment is essential to reduce adverse events and optimise treatment planning. The AAE case difficulty assessment provides a practical framework to anticipate procedural mishaps and treatment duration, particularly in molars and high-difficulty cases, and may therefore support informed case selection and referral decisions (24). In undergraduate training settings, incorporating this difficulty assessment can also improve patient safety by aligning case complexity with operator experience and supervision level, thereby promoting timely referral of high-difficulty molars to more experienced clinicians or endodontists when appropriate (30).

5.6.2. Patient-centred outcomes

Outcome evaluation should incorporate patient-centred endpoints rather than relying on radiographic findings alone. Practice-based evidence indicates that complication rates are higher among general dentists than endodontists, despite specialists managing more complex cases, which supports timely referral for high-risk situations such as molars with calcifications or limited canal visibility (31). Furthermore, follow-up data show that clinical signs and symptoms may have a stronger negative impact on oral health-related quality of life than radiographic findings alone, emphasizing the importance of symptom control and functional recovery when defining treatment success (26).

Long-term cohort evidence suggests that the ultimate clinical endpoint extends beyond radiographic healing and includes maintaining the tooth in function over time. Because tooth loss is often driven by non-endodontic causes, endodontic care should be integrated with definitive restorative management and long-term maintenance to maximise tooth survival. These patient, and function, oriented considerations highlight the need for prevention strategies that minimise avoidable procedural errors and reduce the risk of reinfection.

5.7. Prevention strategies

From a preventive perspective, risk reduction should begin before instrumentation through structured case assessment. Early identification of high-difficulty cases may support appropriate planning, supervision, and timely referral, thereby limiting avoidable iatrogenic errors, particularly in training environments (23,24).

During treatment, preventive strategies should focus on high-risk steps and anatomically challenging areas. With regard to instrument separation, targeted measures are especially relevant in molars, mesiobuccal canals, and the apical third: careful scouting with minimal apical pressure, early recognition of canal restriction or curvature, and strict file inspection and replacement rules, particularly for stainless-steel instruments, may help reduce torsional stress during canal negotiation and apical instrumentation (27).

This interpretation supports prevention strategies based on risk stratification, careful technical execution, and appropriate case selection. However, these implications should be interpreted with caution because the included evidence remains methodologically heterogeneous, particularly regarding study design, outcome definitions, and imaging-related assessment.

5.8. Limitations

Meta-analysis was not performed because the aim of this review was to provide a clinically interpretable synthesis of primary studies on adverse events in endodontics. In addition, the included studies differed substantially in design, populations, imaging modalities, outcome definitions, follow-up periods, and reported variables, which would have limited the validity and interpretability of quantitative pooling.

The search strategy relied on MEDLINE Complete, accessed through the university library. Although this database provides broad coverage of biomedical literature and overlaps considerably with PubMed indexing for endodontic publications, restricting the search to a single database may have led to the omission of relevant studies indexed in other sources, thereby increasing the risk of selection and publication bias. Future updates could strengthen the completeness of the review by including additional databases.

Another important limitation concerns the design of several included studies. Cross-sectional imaging studies provide only a single time-point assessment and therefore cannot determine whether a detected periapical lesion is healing, stable, or progressing. As a result, these studies are useful for estimating prevalence and identifying associations between technical factors and periapical status, but they cannot establish temporal relationships or confirm that specific procedural errors caused treatment failure over time. This limitation is further compounded by heterogeneity in imaging modalities, since CBCT is more sensitive than conventional two-dimensional radiography for detecting periapical pathology and may partly explain variations in reported prevalence across studies (32).

In CBCT-based studies, the assessment of coronal restoration quality may also be limited by imaging artefacts, particularly beam hardening from radiopaque materials, which can obscure restoration margins and surrounding tooth structure (29). Finally, very long-term cohort studies, including retreatment cohorts, provide valuable survival data but may be influenced by recall and selection effects, as well as by specialist treatment settings, which may reduce generalisability of their estimates to broader clinical populations (32,33).

6. CONCLUSIONS

In adult patients undergoing root canal therapy, iatrogenic and procedural errors are consistently associated with less favourable clinical and radiographic outcomes compared with adequately performed procedures. Across the included literature, these adverse events remain frequent in both routine practice and training settings, contributing to persistent post-treatment periapical pathology, increased symptoms, and reduced rates of radiographic healing and overall treatment success.

These events can be classified according to the treatment phase in which they occur. Pre-treatment events mainly include diagnostic and treatment-planning errors, whereas intra-treatment events include access, instrumentation, irrigation, and obturation-related complications, particularly missed canals, perforation, instrument separation, and filling deficiencies. Post-treatment events are mainly represented by persistent periapical disease, flare-ups, postoperative pain, and retreatment. Among these adverse events identified, obturation-related errors, especially underfilling and overfilling, were among the most frequently reported complications.

The findings of this review confirm that prognosis in endodontics is multifactorial and largely influenced by preoperative periapical status, technical quality of RCT, and coronal restoration integrity. Case complexity also plays a central role, with molars and high-difficulty cases showing a higher concentration of procedural mishaps and less favourable outcomes.

From a clinical perspective, effective prevention strategies should combine structured preoperative risk assessment (AAE/CDAF), appropriate case selection and referral, and meticulous technical execution during treatment, including accurate working length control, careful canal negotiation, and adequate obturation and coronal sealing. Integrating these measures into routine clinical practice may reduce avoidable procedural errors and improve endodontic treatment outcomes.

7. SUSTAINABILITY

This analysis of adverse events in endodontics contributes to sustainability from economic, environmental, and social perspective. From an economic point of view, the analysis of adverse events in endodontics may help reduce avoidable costs associated with procedural errors, retreatments, extra appointments, and tooth loss requiring more complex rehabilitation. By identifying the main cause of treatment failure and promoting prevention, this work supports a more efficient use of clinical time and healthcare resources. From an environmental perspective, improving the quality and predictability of RCT may reduce the unnecessary consumption of single-use materials, irrigants, filling materials, radiographs, and energy linked to repeated procedures. Fewer retreatments and extractions may also decrease patient travel and the overall environmental impact of care. Finally, from a social perspective, this study promotes patient safety, better treatment outcomes, and preservation of natural teeth, which has a direct impact on quality of life and trust in dental care. In addition, by reinforcing prevention-oriented education, this work may support better clinical training and more equitable, responsible and patient-centred healthcare.

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9. ANNEXES