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Revitalization Treatment in Endodontics: A State-Of-The-Art Review

M. Widbiller[1] | X. Petridis[2,3] | G. Krastl[4] | N. Meschi[5,6] | J. Camilleri[7] | H. F. Duncan[8] | M. T. Arias-Moliz[9,10] | J. G. Leprince[11] | G. Van Gorp[12] | M. Arnold[13] | K. M. Galler[14] | S. Simon[15] | B. Kahler[16]

[1]Department of Conservative Dentistry and Periodontology, University Hospital Regensburg, Regensburg, Germany | [2]Department of Endodontics, Section of Dental Pathology & Therapeutics, School of Dentistry, National and Kapodistrian University of Athens, Athens, Greece | [3]Department of Endodontology, Section of Fundamental Dentistry, Center for Dentistry and Oral Hygiene, University Medical Center Groningen, University of Groningen, Groningen, the Netherlands | [4]Department of Conservative Dentistry and Periodontology, University of Würzburg, Würzburg, Germany | [5]Department of Oral Health Sciences, Endodontology, Ghent University, Ghent, Belgium | [6]Department of Oral Health Sciences, Université Libre de Bruxelles, Brussels, Belgium | [7]School of Dentistry, College of Medicine and Health, University of Birmingham, Birmingham, UK | [8]Division of Restorative Dentistry & Periodontology, Dublin Dental University Hospital, Trinity College Dublin, Dublin, Ireland | [9]Department of Microbiology, School of Dentistry, University of Granada, Granada, Spain | [10]Instituto de Investigación Biosanitaria ibs.GRANADA, Granada, Spain | [11]Division of Cariology & Endodontology, University Clinics of Dental Medicine, Geneva, Switzerland | [12]Department of Oral Health Sciences, KU Leuven and Pediatric Dentistry and Special Dental Care, University Hospitals Leuven, Leuven, Belgium | [13]Praxis für Endodontie und Zahnerhaltung, Dresden, Germany | [14]Department of Conservative Dentistry and Periodontology, University Hospital Erlangen, Erlangen, Germany | [15]Private Dental Practice, Rouen, France | [16]School of Dentistry, University of Sydney, Camperdown, New South Wales, Australia

Correspondence: M. Widbiller (matthias.widbiller@ukr.de)

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ABSTRACT

Ten years after the European Society of Endodontology (ESE) issued its inaugural Position Statement in 2016, revitalization (BrE: revitalisation) treatment has progressed from an experimental approach to a cornerstone of contemporary endodontic practice. This state-of-the-art review provides a comprehensive synthesis of the biological and clinical advances that have redefined the treatment options for permanent teeth with incomplete root formation after loss of pulp vitality, as well as broader applications beyond these cases. The review refines case selection by integrating biological potential with clinical aetiology and extended applications for revitalization, while evaluating the role of modern diagnostic and operative aids in enhancing procedural precision. It details technical protocols ranging from evidence-based irrigation to the precise placement of barriers and definitive restorations, ensuring a seamless transition from disinfection to long-term structural stability. Beyond methodological refinements, there is growing awareness of prognosis in relation to specific case constellations, accompanied by clearer articulation of realistic treatment aims. These aims prioritize the absence of signs and symptoms of infection and long-term tooth survival, while increasingly emphasizing patient-centred outcomes. Furthermore, the review explores the practical intersection of revitalization and orthodontic management and presents a proactive framework for early recognition and management of complications and procedural failures. By delineating these clinical boundaries, it offers a contemporary basis for clinical decision-making and supports the upcoming update of the ESE Position Statement.

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ESE-Approved Definitions and Terminology

Revitalization

A biologically based endodontic procedure that induces bleeding from periapical tissues into the disinfected root canal to create a blood clot, serving as a scaffold for the ingrowth of reparative tissue.

Endodontic Tissue Engineering (ETE)

A biologically based endodontic procedure following tissue engineering principles—scaffolds, signalling molecules and stem cells—involving orthograde placement of natural (autologous, allogenic or xenogenic) or synthetic biomaterials, with (cell-based) or without cells (cell-free), into the disinfected root canal to promote formation of regenerative or reparative tissue.

Regenerative and Reparative Endodontic Procedures (REP)

A collective term encompassing biologically based endodontic treatment strategies, including revitalization and endodontic tissue engineering, that aim to replace irreversibly damaged pulp tissue and restore the structure and function of the pulp-dentine complex, resulting in the formation of regenerative or reparative tissue.

Revascularisation

Restoration of vascular supply to the pulp space, typically following traumatic dental injuries, leading primarily to the ingrowth of reparative tissue.

Endodontic Tissue Repair

Formation of tissue within the root canal that differs structurally and/or functionally from the original pulp tissue. This typically involves fibrous connective tissue lacking odontoblastic cells, with atypical cells lining the dentine and depositing cementum-like or bone-like tissue instead of tubular dentine.

Endodontic Tissue Regeneration

Restoration of the original structure and function of the pulp tissue through the formation of new tissue containing odontoblastic cells capable of depositing tubular dentine and re-establishing the pulp-dentine complex.

1 | Introduction

It has been 10 years since the European Society of Endodontology (ESE) first issued its Position Statement on Revitalization in 2016, which introduced revitalization as a biologically-based alternative to apexification, such as apical barrier techniques or long-term calcium hydroxide placement, in immature teeth, aiming to promote tissue formation within the root canal, continued root development, increased dentine thickness, thereby improving long-term prognosis of the tooth (Galler et al. 2016).

Since then, revitalization has emerged as an established component of contemporary clinical endodontic practice (Anna et al. 2024; Lee et al. 2018). The preclinical and clinical evidence base for this biologic and regenerative approach continues to expand, with ongoing developments refining case selection, procedural protocols, and clinical outcomes.

Revitalization represents a biologically-based extension of traditional endodontic treatment. Rather than simply obturating the root canal, the procedure is designed to create a microenvironment within the canal that allows ingrowth of blood vessels, nerve fibres, and other tissue components, ultimately leading to the formation of new tissue (Widbiller and Schmalz 2021). Histologically, this tissue is best described as pulp-like reparative connective tissue rather than true regenerated pulp (Digka et al. 2020; Minic et al. 2022). However, it can restore many vital pulp functions, providing both biological and clinical benefits to patients (Diogenes and Ruparel 2017; Meschi et al. 2023; Panda et al. 2022; Xie et al. 2021).

Since the publication of the ESE position statement on revitalization procedures, a growing body of clinical evidence supports the reproducibility and efficacy of revitalization, while long-term outcomes are currently being elucidated (Alghamdi and Alsulaimani 2021; Meschi et al. 2023; Panda et al. 2022; Torabinejad et al. 2017). Clinical experience has expanded and diversified, while several conceptual and practical uncertainties remain that are potentially critical to procedural success, including careful case selection, disinfection protocols, scaffold application, and coronal sealing and restoration. In addition, practical issues such as evaluating treatment outcomes, integrating revitalization into routine orthodontic care, and managing complications have become increasingly apparent.

In response to these developments, the purpose of this state-of-the-art review is to critically synthesize the current preclinical and clinical knowledge underlying revitalization treatment in endodontics, and to delineate unresolved issues that require clarification. This work is intended to provide the scientific basis for an updated ESE Position Statement on Revitalization treatment.

2 | Clinical Considerations and Case Selection

2.1 | Indication

Revitalization procedures, according to the ESE S3-level Clinical Practice Guidelines (Duncan et al. 2023), are primarily indicated for immature permanent teeth at Cvek stages I and II with pulp necrosis or (a)symptomatic irreversible pulpitis, with or without apical periodontitis, apical abscess, or condensing osteitis. Although not explicitly recommended in the guidelines, treatment at Stage III may be considered in selected cases where the root canal walls are thin and further development is desirable, particularly when apical barrier placement is considered technically challenging (Figure 1; Kahler et al. 2024). Conversely, in teeth with more mature roots or complete root formation (Cvek stages IV–V), the rationale for revitalization is less compelling, as these conditions are unlikely to derive meaningful clinical benefit from the procedure. Since there is currently no long-term comparative evidence demonstrating superiority over apexification or root canal filling in these cases, revitalization is not advocated.

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FIGURE 1 | Revitalization of an immature maxillary right central incisor (Cvek Stage III). The tooth was clinically diagnosed as having a necrotic, infected pulp, making endodontic intervention necessary. (a) Preoperative periapical radiograph showing a complicated crown fracture with necrotic pulp. The apex is wide open and the root canal walls are thin. (b) Postoperative periapical radiograph following revitalization. (c) Periapical radiograph at the 1-year follow-up demonstrating thickening of the canal walls and near-complete apical closure. (d) Periapical radiograph at the 7-year follow-up showing marked narrowing of the canal space and normal periapical tissues. Courtesy of Dr. Jing Lu (Kahler et al. 2024).

The ESE S3 guideline is primarily based on systematic reviews of RCTs, which provide high-quality evidence but are limited by strict inclusion criteria. Accordingly, the following explanations on indications and treatment requirements are based on a critical appraisal of the broader scientific literature (Garcia-Godoy and Murray 2012; Murray 2023; Wei et al. 2022).

2.2 | Prognostic Factors

2.2.1 | Aetiology

Traumatic dental injuries (TDI), anatomical anomalies such as dens invaginatus/evaginatus, and caries are the most commonly reported etiological reasons for revitalization (Alghamdi and Alsulaimani 2021; Diogenes and Ruparel 2017).

Among these, dental trauma is predominant (Alghamdi and Alsulaimani 2021), affecting almost one in five children before the age of 12, when most permanent teeth in the maxillary anterior region are still immature (Petti et al. 2018). Importantly, trauma-related factors appear to influence revitalization outcomes to a high degree, with prognosis being closely linked to the type and severity of injury. In particular, luxation injuries with severe displacement are associated with a higher risk of pulp necrosis and other sequelae that compromise the outcome of revitalization compared to uncomplicated injuries (Meschi et al. 2019). Beyond restorative challenges, severe trauma may negatively affect healing and continued development through increased mobility, disruption of Hertwig's epithelial root sheath (HERS), and trauma-induced root resorption (Murray 2023). These unfavourable outcomes are therefore likely driven by the initial traumatic insult and its biological consequences, rather than by the revitalization procedure itself (Meschi et al. 2019).

Several studies have explored whether aetiology influences treatment outcome; however, the evidence remains inconsistent and does not currently permit firm conclusions regarding the specific contribution of any single aetiological category (Chrepa et al. 2020; Koç and Fabbro 2020; Vitali et al. 2025). While multiple studies report less favourable outcomes in teeth affected by trauma (Hu et al. 2023; Li, Pan, et al. 2017; Lin et al. 2017; Theekakul et al. 2024; Vitali et al. 2025; Zeng et al. 2022), comparisons across aetiologies are substantially confounded because cases vary in both microbial burden and the extent of trauma-related tissue damage. Consequently, variation in outcome parameters may reflect these accompanying biological and clinical factors, and current evidence does not yet allow a clear conclusion as to whether aetiology exerts an independent, causal effect on revitalization failure.

2.2.2 | Infection and Periapical Inflammation

Although short- and medium-term success and survival rates for revitalization appear high (< 5 years), consistent evidence indicates that pre-existing infection and apical periodontitis adversely affect outcomes (Meschi et al. 2023; Song et al. 2025; Vitali et al. 2025). Teeth with pulp necrosis and apical periodontitis show less predictable root development and, in some cases, lead only to the formation of reparative hard tissue within the canal rather than physiological root development (EzEldeen et al. 2015; Meschi et al. 2018, 2021; Shetty et al. 2021; Song et al. 2025). Even when clinical and radiological healing occurs, residual bacteria can compromise continued root development and lead to re-exacerbation of infection (de-Jesus-Soares et al. 2020; Leprince et al. 2025). Analyses of failed revitalization cases consistently show that persistent infection is the primary cause of failure, with many cases showing delayed symptoms more than 2 years after treatment (Almutairi et al. 2019; Leprince et al. 2025). Therefore, accurate diagnosis and infection prevention during and after revitalization are critical.

2.3 | Extended Clinical Applications of Revitalization

2.3.1 | Revitalization in Mature Teeth and Adults

Practically, revitalization can also be applied successfully to mature teeth after root development is complete, but no mechanical advantages over conventional treatments are expected

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(Al-rawhani et al. 2024; Glynis et al. 2021; He et al. 2017; Kasper et al. 2025; Murad and Cooper 2023; Scelza et al. 2021). In contrast to immature teeth, the potential for revascularisation decreases with reduced apical foramen width, and important biological prerequisites, such as the presence of mesenchymal stem cells in the apical papilla (Abada et al. 2021; Estefan et al. 2016; Fang et al. 2018; He et al. 2017; Laureys et al. 2013) and an intact HERS required for physiologic root development (Huang et al. 2009), are lost after maturation. Even in immature permanent teeth with arrested root development in adults, further root growth is unlikely (Hilkens et al. 2015). Current clinical evidence is limited to short-term observations and reports solid success rates (Barbosa et al. 2025; Li et al. 2023), however, protocols are not yet standardized for mature teeth and apical foramen widening remains controversial due to the potential risk of structural damage (Figure 2; He et al. 2017; Nakashima et al. 2017).

2.3.2 | Revitalization in Multi-Rooted Teeth

Multirooted teeth in adults generally show a favourable prognosis following conventional root canal treatment. However, microbial infection and the presence of apical periodontitis significantly compromise long-term treatment outcomes (Bürklein et al. 2020; Martins et al. 2025). This is partly attributable to the complex root canal anatomy of multirooted teeth, including isthmuses and canal ramifications that are difficult to adequately disinfect (Hernández et al. 2024; Siqueira et al. 2024).

Despite advances in preventive strategies, posterior teeth remain particularly susceptible to caries, often from a young age (Creeth et al. 2013; Krol et al. 2022). In such cases, conventional root canal obturation may be challenging due to limited patient compliance and, in some instances, incomplete root development.

In revitalization procedures for multirooted teeth, bleeding is typically induced in each canal to allow formation of an intracanal blood clot, while the access cavity is kept free of coagulum (Figure 3). Several case reports have demonstrated successful application of these approaches in molars and premolars with immature roots, resulting, despite heterogeneity, in continued root development and apical closure (Feli et al. 2024; Heck et al. 2021; Lee et al. 2020; Martin et al. 2013; Subash et al. 2016; Tzanetakis et al. 2021). Notably, some reports also suggest that biologically-based endodontic approaches may be feasible in multirooted teeth with apical periodontitis and fully developed roots (Nakashima and Tanaka 2024; Saoud et al. 2015; Saoud, Martin, et al. 2016; Terauchi et al. 2021).

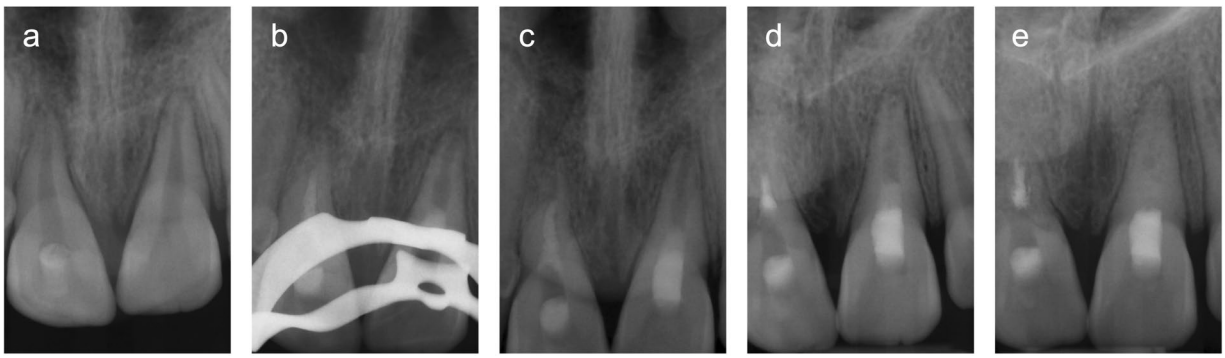


FIGURE 2 | Revitalization of a maxillary left central incisor with mature root development and clinical findings consistent with pulp necrosis after luxation (Cvek stage V). (a) Preoperative radiograph showing nearly complete apical development and thick canal walls. (b) Postoperative radiograph following revitalization and apical widening to ISO size 50. (c) Radiograph at the 6-month follow-up showing absence of periapical pathology. (d) Radiograph at the 9-month follow-up demonstrating mineralization in the apical third of the canal. (e) Radiograph at the 36-month follow-up showing complete mineralization and normal periapical tissues.



FIGURE 3 | Revitalization of a mandibular left first molar. (a) Preoperative radiograph showing apical periodontitis associated with clinically diagnosed pulp necrosis. (b) Postoperative radiograph following revitalization. (c) Radiograph at the 3-month follow-up showing residual periapical pathology. (d) Radiograph at the 6-month follow-up demonstrating periapical healing. (e) Radiograph at the 12-month follow-up. (f) Radiograph at the 12-month follow-up showing normal periapical tissues.

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However, the currently available evidence is largely limited to case reports and is heterogeneous regarding root maturation. Therefore, the reproducibility and clinical effectiveness of these outcomes in multirooted teeth still need to be confirmed.

2.3.3 | Revitalization Following Traumatic Dental Injury

Revitalization appears to be a particularly advantageous treatment option in specific TDI-related scenarios, especially in young patients with immature teeth (Cvek stages I–III), where preservation of the affected teeth and/or alveolar bone is desired until full skeletal growth.

Importantly, in immature teeth affected by TDI, the indications for endodontic intervention must be carefully considered, and such treatment should be deferred until all regenerative capacities capable of achieving spontaneous revascularisation have been exhausted (Bourguignon et al. 2020; Fouad et al. 2020; Krastl et al. 2021b).

In particular, teeth that have lost pulp vitality for example, due to severe luxation or transplantation (Krastl et al. 2021a; Plotino et al. 2021) may benefit from revitalization treatment compared to conventional endodontic approaches, both in terms of treatment outcomes and in the management of complications such as pathological resorption, as further described below.

Another trauma-related indication for revitalization is an intra-alveolar root fracture with pulp necrosis in the coronal fragment. Pulp necrosis may occur even if the fragment remains in place and is generally unavoidable when extensive displacement leads to separation of the pulp tissue. In such cases, revitalization may offer a more biologically oriented treatment approach compared with conventional management using HCSs as a barrier at the apical end of the coronal fragment, which is technically demanding and often complicated by unclear fracture patterns (Heithersay and Kahler 2013; Lu and Kahler 2022; Saoud, Mistry, et al. 2016). Here, the remaining vital pulp in the apical fragment can be purposefully stimulated to initiate controlled bleeding into the coronal canal space.

2.3.4 | Revitalization in Teeth With Pathological Root Resorption

After traumatic dental injury, not only pulp necrosis but also external root resorption are common sequelae (Kahler et al. 2024). Following cementum damage, the root is often degraded by bone-derived clastic processes, which may be stimulated by necrotic pulp tissue or infectious cues within the root canal (Galler et al. 2021; Patel et al. 2023).

Over the past decade, an increasing number of case reports have demonstrated that revitalization may represent a useful treatment option for external inflammatory (infection-related) resorption (EIR; A. Chaniotis 2016; Erdogan et al. 2024; Khourdaji et al. 2026; Santiago et al. 2015; Saoud, Mistry, et al. 2016; Tzanetakis 2018). Stringent disinfection of the root canal space during revitalization may arrest resorptive progression via mechanisms similar to traditional EIR management (Fouad et al. 2020; Kahler et al. 2024). Interestingly, besides removing infectious stimuli, it has been hypothesized that bioactive compounds released from dentine may diffuse into resorptive lacunae and attract local periodontal ligament- or bone-derived stem cells, thereby halting the resorptive process (Figure 4; Rostami et al. 2026; Silva et al. 2004). This mechanism could lead to repair at the resorption sites and restoration of a functional periodontal ligament with cementum deposition (Kaufman and Kahler 2024; Lu et al. 2023). Despite promising reports, revitalization of teeth with EIR remains a developing treatment modality and evidence is limited to case reports, which carry a risk of reporting bias. Therefore, careful follow-up is essential to detect potential complications early (Lee and Song 2022; Lin et al. 2022).

Furthermore, revitalization may prevent the development of external replacement resorption (ERR) and ankylosis in cases where periodontal healing would otherwise be unlikely due to severe cementum damage, although evidence is similarly limited (Lu et al. 2023; Sheikhnezami et al. 2022; Sheng et al. 2025; Yoshpe et al. 2020). ERR is typically associated with severe luxation injuries, such as delayed replantation after avulsion, and often results in tooth loss due to mechanical failure or infraposition associated with ankylosis (Figure 5). Since prognosis is closely related to the severity of the trauma, it appears

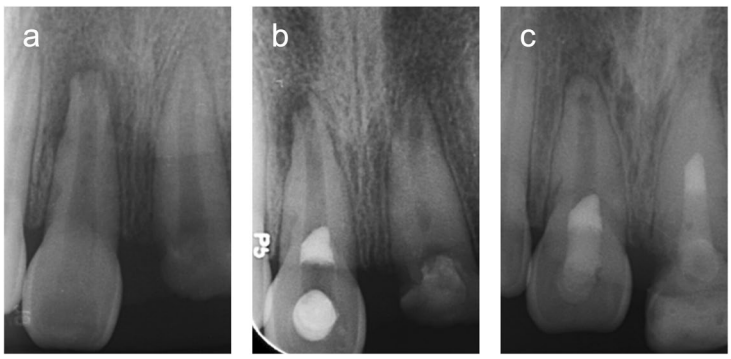


FIGURE 4 | Revitalization of a maxillary right central incisor with external inflammatory resorption (EIR) after avulsion (3 h extra-oral dry time). (a) Preoperative radiograph showing infection-related external inflammatory resorption, apical periodontitis, and an immature apex. (b) Postoperative radiograph following revitalization. (c) Radiograph at the 5-year follow-up showing arrest of resorption, resolution of radiolucency, hard tissue deposition within defects, an intact periodontal ligament space, and apical closure. Courtesy of Dr. Jing Lu (Lu et al. 2023).

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unlikely that revitalization will have a decisive effect on ERR. Nevertheless, revitalization may offer procedural advantages over conventional root canal filling, particularly in the management of complications requiring re-entry or decoronation procedure. Delaying any intervention may offer advantages, including greater patient maturity and cooperation, while postponing the functional and aesthetic consequences associated with early tooth loss. Overall, ERR treatment with revitalization should be approached cautiously, with careful consideration of the individual tooth prognosis.

External cervical resorption (ECR), external surface resorption (ESR), or minor transient resorptions typically follow other treatment strategies or do not require treatment, so revitalization is generally not recommended.

Regarding internal root resorption (IR), which is often associated with chronic inflammatory processes, a limited number of reports suggest that revitalization may arrest disease progression in selected cases (Arnold 2021; Kaval et al. 2018; Saoud, Mistry, et al. 2016). Unlike the conventional treatment, pulpectomy and root canal filling, revitalization is a biological approach that seeks to harness residual vital, uninflamed pulp tissue to support tissue repair and maintain vitality. This approach may offer procedural advantages in cases where conventional treatment is challenging or not feasible—for example, in teeth with perforating defects (Figure 6; Arnold 2021).

Retention of teeth affected by pathological root resorption represents a key clinical outcome with significant impact on patient quality of life. Revitalization may offer practical advantages, particularly in cases of complex resorption defects with possible perforations, which can pose significant challenges for conventional approaches. In addition, in terms of complication management, removal of root filling materials is not required even in progressing resorption, reducing potential risks. Further systematic research is needed to elucidate the mechanisms by which revitalization may modify or arrest both internal and external inflammatory resorption, particularly with respect to its potential immunomodulatory effects.

2.3.5 | Revitalization as a Retreatment Option

More recently, case reports and series have documented retreatment with revitalization in both immature and mature permanent teeth after failed revitalization (Figure 7) or failed nonsurgical and surgical root canal treatment (Figures 8 and 9), showing favourable survival and periapical healing (Arnold 2025; Chaniotis 2017; Nakashima and Tanaka 2024;



FIGURE 5 | Revitalization of a maxillary left central incisor with external replacement resorption (ERR) after avulsion (non-physiological storage for > 1 h). (a) Preoperative radiograph following avulsion. (b) Postoperative radiograph after revitalization performed 1 month after injury. (c) Radiograph at the 2-year follow-up showing replacement resorption. (d) Radiograph at the 6-year follow-up demonstrating progression. (e) Radiograph at the 8-year follow-up. Despite progressive resorption and infraocclusion, decoronation was deferred until 16 years of age.

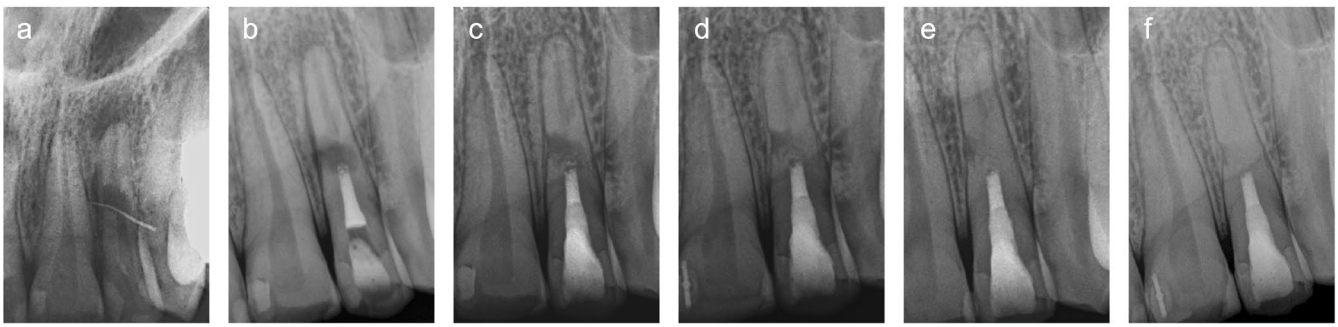


FIGURE 6 | Revitalization of a maxillary left lateral incisor with perforating internal root resorption (IR). (a) Preoperative radiograph with guttapercha tracing of a sinus tract. (b) Radiograph 8 weeks after revitalization. (c) Radiograph at the 1-year follow-up showing healing of the lateral defect. (d) Radiograph at the 2-year follow-up demonstrating mineralization of the resorptive defect. (e) Radiograph at the 3-year follow-up. (f) Radiograph at the 8-year follow-up showing complete healing and total mineralization (Arnold 2021).

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FIGURE 7 | Retreatment of a maxillary left central incisor after revitalization failure due to reinfection. (a) Preoperative radiograph of the tooth with clinically diagnosed pulp necrosis following crown fracture. (b) Radiograph at the 32-month follow-up after initial revitalization showing normal periapical tissues and secondary caries treated immediately. (c) Radiograph at the 77-month follow-up showing apical periodontitis indicating reinfection. (d) Radiograph at the 20-month follow-up after retreatment demonstrating restored periapical health. Courtesy of Dr. Rita Yoshpe.



FIGURE 8 | Retreatment of a maxillary left central incisor after failed root canal treatment using revitalization. (a) Preoperative radiograph showing apical periodontitis. (b) Postoperative radiograph following revitalization. (c) Radiograph at the 28-month follow-up demonstrating normal periapical tissues. Courtesy of Dr. Rita Yoshpe.

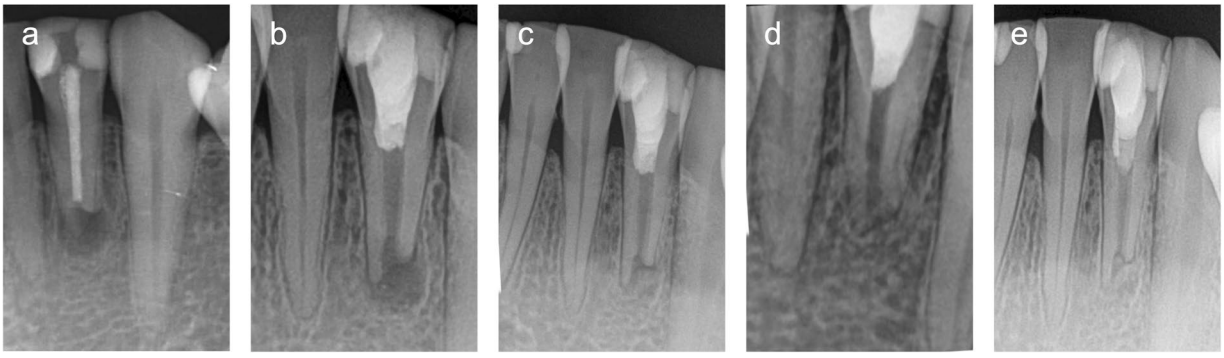


FIGURE 9 | Revitalization of a mandibular left lateral incisor after previous apicoectomy and inadequate root filling. (a) Preoperative radiograph showing apical periodontitis and root-end resorption. (b) Postoperative radiograph after regenerative and reparative endodontic procedure (REP) using PRF. (c) Radiograph at the 6-month follow-up demonstrating healing of the periapical lesion. (d) Radiograph at the 2-year follow-up. (e) Radiograph at the 3-year follow-up after successful tissue formation was confirmed by re-entry (Arnold 2025).

Nosrat et al. 2021). In immature permanent teeth (Cvek stages I–III), where primary apexification or revitalization has failed, revitalization as a secondary approach may represent a viable last resort. In contrast, for mature permanent teeth, non-surgical root canal retreatment remains the current standard of care (Duncan et al. 2023). Notably, in selected mature teeth with a wide apical foramen, for example, following previous apicoectomy (Arnold 2025) or apical resorptions, revitalization may represent a feasible salvage strategy—an aspect that warrants further investigation. Overall, although revitalization in mature permanent teeth seems technically feasible, current evidence does not justify its routine clinical use, as it has not yet demonstrated a meaningful advantage over conventional treatment.

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3 | Diagnostic and Operative Aids

3.1 | Radiographic Assessment

Typically, pulp necrosis and apical periodontitis are diagnosed by a combination of clinical findings and periapical radiographs. The supplemental use of cone beam computed tomography (CBCT) is generally not required to make a treatment decision for revitalization, unless specific diagnostic uncertainties exist (Melo et al. 2026; Patel et al. 2019). In the absence of such uncertainties, periapical radiographs remain the standard imaging modality due to their lower radiation dose, availability and broad clinical applicability, particularly in paediatric patients. In children, tissues are considerably more sensitive to ionizing radiation and the likelihood of radiation-induced stochastic effects is markedly higher than in adults (Krastl et al. 2021a; Kühnisch et al. 2020; European Commission: Directorate-General for Energy and Transport 2004). Although CBCT is widely used in clinical research studies—where quantitative assessment of root development and detailed evaluation of periapical healing modalities are essential (Meschi et al. 2018)—it has limited relevance for revitalization in routine clinical practice. While CBCT provides more sensitive, accurate and reproducible data in research contexts, the primary aim during follow-up in daily practice is to determine whether healing has occurred and whether reintervention is necessary. In general, standardized techniques for periapical radiography, such as the use of a positioning holder and the paralleling technique, are recommended (Basrani 2025; Galler et al. 2022). These approaches help minimize variations in angulation between pre- and postoperative images, thereby improving quality, comparability and diagnostic accuracy during follow-up.

3.2 | Asepsis and Magnification

The critical importance of asepsis, technical quality, and enhanced visual control—achieved by rubber dam isolation, adequate illumination, and magnification—has been strongly emphasized in recent ESE clinical practice guidelines. These factors are recognized as fundamental to the success of all endodontic procedures, including revitalization (AAE 2024; Duncan et al. 2019). Maintenance of an aseptic working field throughout the procedure is essential. Rubber dam isolation represents the standard of care, effectively minimizing salivary contamination and thereby enhancing the predictability and overall success of treatment outcomes (AAE 2024; Cochran et al. 1989; Lin, Huang, et al. 2014).

The use of magnification is strongly advised during revitalization procedures to improve clinical precision and reduce operator strain. At a minimum, high-magnification dental loupes with a coaxial light source should be considered standard, as they are widely accessible and commonly used in general dental practice (Perrin et al. 2019). However, the use of a dental operating microscope (DOM), when available, is considered best practice and provides superior visualization. In addition to visual benefits, magnification devices have also been associated with reduced musculoskeletal symptoms, further emphasizing their importance in routine clinical care (AAE 2012; Liu et al. 2023; McLean et al. 2025).

3.3 | Assessment of Sensibility and Perfusion

Radiographic findings such as mineralization, apical closure, or continued root development provide important indirect evidence of tissue formation following revitalization procedures. From a clinical perspective, however, non-invasive assessment of tissue vitality—specifically neuronal sensibility and blood perfusion—is essential, as aside from the absence of inflammatory signs, it constitutes the only specific clinical indicator for a vital tissue.

Sensibility testing using thermal stimuli (hot or cold) or electrical pulp testing (EPT) remains the most widely applied clinical approach, but it is associated with several inherent limitations. These methods rely on patient cooperation, which is frequently reduced in children, and their diagnostic validity may be limited by ongoing neuronal maturation (Jafarzadeh and Abbott 2010; Krastl et al. 2021a). Moreover, insulating coronal restorations, including composite resins and barrier materials, can attenuate thermal stimuli, thereby increasing the risk of false-negative results. Importantly, the absence of sensibility does not indicate treatment failure, as vital but non-innervated or insufficiently innervated tissue may exist within the root canal system. To minimize diagnostic uncertainty, sensibility test results should always be interpreted in comparison with adjacent healthy reference teeth. In particular, baseline EPT measurements obtained prior to revitalization may support longitudinal assessment.

Objective perfusion-based methods including magnetic resonance imaging (MRI), laser Doppler flowmetry (LDF), ultrasound Doppler flow measurement, and pulse oximetry are not yet part of routine clinical practice in most dental settings, but they enable direct assessment of pulpal blood supply and can substantially improve diagnostic accuracy (Balevi 2019; El-Kateb et al. 2020; Ghouth et al. 2019; Han et al. 2025). Their broader implementation is currently limited by technical complexity, susceptibility to motion artefacts, limited availability, and the lack of standardized protocols for routine dental use (Alghaithy and Qualtrough 2017).

3.4 | Local Anaesthesia and Bleeding Management

Induction of bleeding from the apical tissues is a critical step in achieving a blood clot, but the over-instrumentation required to induce bleeding causes discomfort or pain. Therefore, the use of local anaesthesia is essential. Avoiding a vasoconstrictor is generally preferred because it does not reduce blood flow in the periapical tissues and facilitates more predictable bleeding induction (Kijsamanmith et al. 2022; Yoon et al. 2012). However, even in its absence, bleeding failure occurs in approximately 40% of revitalization cases (Wikström et al. 2022). Furthermore, the duration of anaesthesia without a vasoconstrictor is significantly shorter (Ford et al. 1993), which is particularly challenging in paediatric patients, where inadequate pain control can compromise the revitalization procedure. Consequently, vasoconstrictor-containing agents are preferable when deep or prolonged anaesthesia is a priority, especially in anxious or young patients (Kühnisch et al. 2017). If plain anaesthetic is used initially, clinicians should be ready to supplement with a vasoconstrictor-containing anaesthetic if analgesia proves insufficient.

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FIGURE 10 | Revitalization of maxillary central incisors with insufficient bleeding in one tooth and normal clot formation in the contralateral tooth. The right incisor suffered from subluxation, the left incisor from avulsion (2 h in saliva) (a) Postoperative radiograph showing bleeding limited to the apical third of the right incisor. (b) Radiograph at the 3-year follow-up demonstrating normal periapical tissues. (c) Radiograph at the 7-year follow-up showing resorption in the left incisor and root thickening in the right. (d) Radiograph at the 10-year follow-up after decoronation and root submergence of the left incisor, with continued maturation of the right, despite initial procedural problems.

Despite careful preparation and an appropriate anaesthetic strategy, there may be difficulty in inducing bleeding, resulting in either incomplete or complete filling of the root canal with coagulum. In the case of incomplete bleeding, revitalization may be continued if a stable clot can be established in the apical or mid-root portion of the canal (Figure 10), or the procedure may be discontinued and converted to a conventional apexification approach. If no bleeding can be induced at all, a classical revitalization protocol is not feasible and an alternative scaffold-based strategy or conventional apexification should be selected. These potential intraoperative deviations and fallback options should therefore be anticipated in the treatment plan and explicitly addressed during informed consent.

3.5 | Behavioural Management

Additionally, in paediatric patients, behavioural guidance should be used, when necessary, to reduce anxiety and improve cooperation, in accordance with current recommendations from the American Academy of Pediatric Dentistry (AAPD) and the European Academy of Paediatric Dentistry (EAPD). Non-pharmacologic approaches are preferred, but conscious sedation by inhalation nitrous oxide-oxygen or oral drugs, for example midazolam, may be considered if administered by a trained and competent team, in accordance with local regulations and with informed parental consent (Ashley et al. 2021; AAPD 2024; Dhar et al. 2023). Collaborative efforts between endodontists and paediatric dentists are encouraged (Wilson 2013).

4 | Clinical Procedure

4.1 | Irrigation and Activation

Unlike conventional root canal treatment, revitalization seeks to restore vital tissue within the canal. This biological goal requires more effective disinfection protocols, as residual bacteria can colonize the entire canal space, whether it is filled by a blood clot or another scaffold, turning it into a potential reservoir for reinfection (Fouad 2011). Insufficient disinfection has been reported as a leading factor associated with clinical failure (Almutairi et al. 2019; Meschi et al. 2019; Shetty et al. 2021) and has been linked to impaired root maturation (de-Jesus-Soares et al. 2020; Verma et al. 2017; Yoo et al. 2021). Effective disinfection of immature teeth is particularly challenging due to their anatomical characteristics, such as wide canal diameters and deep, permeable dentinal tubules (Ahmed et al. 2023; Kakoli et al. 2009), combined with the limited use of mechanical instrumentation, which increases the reliance on chemical irrigation and intracanal medication.

4.1.1 | Disinfection

Microbiological studies indicate that the microbial composition of teeth with necrotic pulp and immature apexes is largely comparable to that in teeth with mature apices (Fouad et al. 2022; Manoharan et al. 2020; Nagata et al. 2014). Consequently, sodium hypochlorite (NaOCl) irrigation remains the gold standard in revitalization procedures due to its potent antimicrobial properties and ability to dissolve organic matter (de-Jesus-Soares et al. 2020; Ashraf F. Fouad et al. 2022; Sellami et al. 2023; Wikström et al. 2025).

Since effective disinfection is fundamental to achieving the primary aim of revitalization—namely periapical healing and resolution of clinical symptoms—it must be sufficiently potent while preserving essential biological structures, including periapical cells, dentine matrix proteins, and root canal surface integrity. Accordingly, NaOCl at concentrations of 3%-6% is considered an appropriate standard, with a recommended volume of at least 20 mL per canal and a contact time typically ranging from 5 to 20 min, ideally with periodic replenishment (Chrepa et al. 2020; Galler et al. 2022; Martin et al. 2014; Silva et al. 2026; Trevino et al. 2011).

Alternative disinfectants such as chlorhexidine (CHX) have been investigated, but limitations including insufficient antibiofilm activity, lack of tissue-dissolving capacity, and cytotoxicity restrict their applicability in revitalization protocols (Busanello

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et al. 2019; Ruiz-Linares et al. 2017; Trevino et al. 2011; Widbiller et al. 2019, 2022).

4.1.2 | Conditioning

Following disinfection, the root canal dentine should be conditioned with a demineralizing agent to neutralize cytotoxic NaOCl residues, remove surface debris, and expose dentine tubules and dentine matrix proteins. A 17% EDTA solution is recommended, as it effectively meets those requirements (Aspesi et al. 2021; Diogenes et al. 2014; Hashimoto et al. 2018; Morago et al. 2019; Widbiller et al. 2022) and promotes the formation of a cytocompatible surface that supports cell attachment and subsequent tissue development (dos Reis-Prado et al. 2022). A minimum volume of 5 mL per canal is recommended, however, in clinical practice, emphasis should be placed on using a sufficient volume to ensure thorough irrigation, with continuous replenishment throughout a 1–5 min application period.

Citric acid (CA) has been considered as an alternative; however, evidence does not show consistent advantages over EDTA regarding smear layer removal, cytocompatibility, or bioactive molecule release (Galler and Widbiller 2020; Tavares et al. 2021; Zhao et al. 2000). In contrast, CA is linked to greater dentine erosion and structural compromise, particularly at higher concentrations and prolonged exposure times (AlBatati and AbuMostafa 2024; Bosaid et al. 2020; Gandolfi et al. 2018). Because of these drawbacks and the limited evidence, citric acid is not considered for routine use in revitalization procedures at this time.

Regardless of the conditioning agent used, a final rinse with sterile physiological saline is advised to remove any remnants and minimize adverse effects on cells, blood clot formation, and subsequent tissue development (Meeprasert et al. 2023; Taweewattanapaisan et al. 2019).

4.1.3 | Activation of Irrigants

In order to reduce the risk of apical extrusion of the irrigating solutions, close-ended needles placed 1–3 mm from the working length are recommended (Boutsioukis and Arias-Moliz 2022; Savitha et al. 2023). During revitalization procedures, the activation of irrigants in immature root canals can serve different purposes depending on whether the agent is disinfecting or demineralizing.

For NaOCl, activation can enhance penetration into dentinal tubules, disrupt biofilms, and achieve superior microbial reduction compared to conventional needle irrigation (Vieira, de-Jesus-Soares, et al. 2024; Virdee et al. 2020), potentially improving treatment outcomes. However, there are significant risks associated with activation in immature teeth (Abat et al. 2025; Abdellatif et al. 2024). Concerns include apical extrusion, which can cause periapical tissue dissolution and local cell damage, as well as increased dentine surface damage and degradation of organic components (Karasu et al. 2022; Ribeiro, Bueno, et al. 2022; Widbiller, Rosendahl, et al. 2023; Widbiller et al. 2022). The literature also indicates that the concentration of sodium hypochlorite and the duration of exposure are at least as important as activation for achieving effective disinfection (Virdee et al. 2020). Given the delicate balance between improved disinfection and procedural risk in immature teeth, irrigant activation may be considered, but should be applied conservatively to minimize the risk of apical extrusion and dentinal damage.

Following NaOCl disinfection, activation of EDTA can enhance the release of dentine matrix proteins (Hancerliogullari et al. 2021; Widbiller et al. 2017) without impairing blood clot formation on conditioned dentine surfaces (Vieira, Kitamura, et al. 2024). While this may contribute to solubilization of dentine matrix proteins, it does not necessarily increase their surface availability and current evidence shows no consistent clinical benefit for disinfection (Herrera et al. 2017; Widbiller, Rosendahl, et al. 2023). Therefore, routine use of EDTA activation in standard revitalization protocols is not advised.

4.2 | Intracanal Dressing

In multivisit revitalization procedures, intracanal medication is used to enhance disinfection and support periapical healing (Ashraf F. Fouad et al. 2022; Alina Wikström et al. 2025; Wikström, Vestman, et al. 2024). The most commonly employed agents are calcium hydroxide ($Ca(OH)_2$) and antibiotic pastes. Ideally, these medicaments should provide effective antimicrobial activity while maintaining cytocompatibility and preserving dentine matrix proteins.

Antibiotic pastes have historically been widely used in revitalization (Galler et al. 2022) and demonstrate stronger antimicrobial activity than $Ca(OH)_2$ (Hoshino et al. 1996; Sathorn et al. 2007; Sato et al. 1996). They are commonly used as triple antibiotic paste (TAP; ciprofloxacin, metronidazole, and minocycline), modified formulations in which minocycline is replaced by another antibiotic (e.g., cefaclor or clindamycin), or as double antibiotic pastes (DAP) without minocycline, typically mixed at ratios of 1:1:1 or 1:1 and applied using water-based carriers such as saline to facilitate placement and removal (Hwang et al. 2018; Montero-Miralles et al. 2018). Their use is associated with several notable drawbacks, including cytotoxicity and adverse effects on dentine matrix proteins and their release (Braido et al. 2026; Diogenes et al. 2014; Galler et al. 2015; Kitikuson and Srisuwan 2016; de Oliveira et al. 2025), a high risk of tooth discoloration (Chrepa et al. 2020; Kahler and Rossi-Fedele 2016; dos Santos et al. 2018), difficulties in complete removal from the root canal system (Berkhoff et al. 2014), as well as potential sensitization and the development of bacterial resistance (Barbosa-Ribeiro et al. 2024; Segura-Egea et al. 2018). The optimal concentration balancing antimicrobial efficacy and cytotoxicity has not yet been established, but concentrations of 0.1–1.0 mg/mL have been shown to reduce cytotoxicity (Labban et al. 2014; Sabrah et al. 2015). However, lowering concentrations to achieve this effect may also compromise antimicrobial potential (Jacobs et al. 2017; Latham et al. 2016; Phumpatrakom and Srisuwan 2014).

In contrast, $Ca(OH)_2$ does not impair cell survival (Althumairy et al. 2014; Braido et al. 2026; Gougousis et al. 2019; Rahhal

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et al. 2019; Ruparel et al. 2012) and preserves the biological activity of dentine surfaces (Widbiller et al. 2022). Experimental and clinical evidence indicates that it sufficiently reduces bacterial load (de-Jesus-Soares et al. 2020; Fouad et al. 2022; Wikström et al. 2025) and promotes periapical healing in immature permanent teeth (Sellami et al. 2023). However, the risk of revascularisation-associated intracanal mineralization has been reported to be higher with $Ca(OH)_2$ intracanal dressings than with antibiotic pastes (Almutairi et al. 2019).

Despite these biological differences, both antibiotic pastes and $Ca(OH)_2$ have demonstrated acceptable clinical effectiveness in revitalization (Nagata et al. 2014), with clinical studies reporting comparable antimicrobial efficacy and treatment outcomes, sometimes showing advantages for one or the other (Báez et al. 2022; Chrepa et al. 2020; Fouad et al. 2022; Wikström et al. 2025; Alina Wikström, Vestman, et al. 2024; Yoo et al. 2021). Based on the current body of evidence, $Ca(OH)_2$ is regarded as the preferred intracanal medicament in revitalization procedures, offering effective disinfection alongside superior biocompatibility and lower risk for discoloration. Antibiotic pastes may be considered as alternatives outside routine use, reserved for exceptional cases where persistent or severe infection necessitates stronger antimicrobial action (AAE 2025; European Parliament 2010).

4.3 | Scaffold

A three-dimensional framework is fundamental for supporting tissue formation in the root canal, as it facilitates stem cell migration, attachment, and proliferation—key requirements for new tissue ingrowth. By mimicking the natural extracellular matrix, biological scaffolds provide a structural environment that allows cells to organize and differentiate into functional tissues. During revitalization procedures, the induced blood clot serves as a simple and effective autologous scaffold to support tissue formation in the root canal (Meschi et al. 2023). Alternatively, a variety of scaffolds or biomaterials—natural or synthetic; autologous, allogenic or xenogenic; cell-based or cell-free—can be introduced through the access cavity within the concept of endodontic tissue engineering (ETE; Widbiller, Knüttel, et al. 2023). Examples of scaffolds include blood-derived matrices, such as platelet-rich fibrin (PRF), platelet-rich plasma (PRP), or platelet pellet (PP), as well as other hydrogels that can be further functionalized with antibiotics, signalling molecules or decellularized tissue components (Ribeiro, Münchow, et al. 2022; Ribeiro, Bueno, et al. 2022; Song, Takimoto, et al. 2017; Viswanath et al. 2017; Widbiller et al. 2022).

Whether specific scaffolds provide a clinical advantage over the blood clot in immature teeth remains unclear (Yang et al. 2024). Although several studies have reported favourable or even superior outcomes with blood-derived scaffolds such as PRF, PRP, and concentrated growth factors (CGF; Abo-Heikal et al. 2024; Elheeny and Tony 2024; Kavitha et al. 2022; Narang et al. 2015; Rizk et al. 2019; Santhakumar et al. 2018; Shivashankar et al. 2017), some have noted disadvantages (Cheng et al. 2022; Meschi et al. 2021), and the majority of clinical studies found no significant differences between blood clot and alternative scaffolds (Alshahhoud et al. 2024; Darwish et al. 2025; El-Hady and Badr 2022; ElSheshtawy et al. 2020; Jiang et al. 2017; Mittal et al. 2021; Nagy et al. 2014; Ulusoy et al. 2019; Zhang and Sheng 2024).

The use of scaffolds other than the patient's own blood clot must be justified by demonstrating either significantly improved clinical outcomes or clear advantages in terms of practicality, safety, or cost-effectiveness. For most cases, alternative scaffolds require additional treatment steps and increased cost. Blood-derived scaffolds may be considered when there is no bleeding in the canal (El-Hady and Badr 2022), however, their use requires patient consent, compliance, venipuncture, and longer processing. Consequently, induction of bleeding from the root apex, as applied in the revitalization, leading to the formation of a stable blood clot, remains the most practical scaffold for REPs.

4.4 | Barrier

In revitalization procedures, the barrier material is placed over the scaffold to fulfil both protective and functional roles. Its primary purpose is to establish a hermetic seal that prevents bacterial leakage and contamination of the root canal system. Additionally, it protects the underlying scaffold from mechanical disruption and, as a biomaterial, provides a favourable environment for tissue formation.

The barrier should be thick enough to fulfil its function, yet sufficiently thin to preserve space for reparative tissue formation and the definitive adhesive restoration. A thickness of ≥ 2 mm is generally considered an appropriate compromise.

Ideally, the barrier material should set rapidly in contact with the underlying scaffold and attain sufficient hardness before placement of the final restoration. It should not cause any adverse effects, particularly tooth discoloration. To enhance scaffold stability during barrier placement, an intermediate membrane or sponge, such as collagen, may be placed over the blood clot or scaffold (Kontakiotis et al. 2015).

The vast majority of reported revitalization procedures have used hydraulic calcium silicate (HCS)-based cements, such as mineral trioxide aggregate (MTA) or materials based on lab-manufactured tricalcium silicate that are modified to exhibit short setting times and improved mechanical properties as barrier materials (Galler et al. 2022; Kontakiotis et al. 2015), primarily due to their favourable biological properties. These HCSs have been shown to induce growth factor release from dentine (Graham et al. 2006; Schmalz et al. 2017; Tomson et al. 2007) and positively influence cell behaviour (Seo et al. 2013; Tomson et al. 2017; Widbiller et al. 2016).

Although direct evidence demonstrating their capacity to enhance regenerative processes within the blood clot is lacking, these biological effects provide sufficient rationale to consider HCS-based cements as the primary barrier material of choice. Hydraulic cements are available in different chemistries and include additives that modify their properties. To date, only materials releasing calcium hydroxide as a by-product of hydration have been shown to have associated biological activity (Camilleri 2020; Cardinali and Camilleri 2023).

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Within the category of hydraulic calcium silicate cements, clinical comparisons between MTA and Biodentine as barrier materials over a blood clot have shown similar clinical outcomes (Al-rawhani et al. 2024; Sareen et al. 2025). Notably, the shorter setting time of HCS-based materials such as Biodentine offers a clinical advantage (Camilleri et al. 2013; Setbon et al. 2014). Furthermore, tooth discoloration has been reported with the use of MTA in REPs and represents the most frequent complication in this context (Li et al. 2023; Lin et al. 2017; Meschi et al. 2023). Discoloration is primarily attributed to bismuth oxide which is added as radiopacifer in MTA and its interaction with collagen in the tooth (Marciano et al. 2015), contamination with blood (Guimarães et al. 2015), or interaction with sodium hypochlorite (Camilleri 2014; Camilleri et al. 2020). The colour change is caused by a phase change in bismuth oxide, which changes from the α-phase to the δ-phase when in contact with sodium hypochlorite, a reaction that is reversible only at 500°C (Camilleri et al. 2025). Newer calcium silicate materials such as Biodentine incorporating alternative radiopacifiers, such as zirconium oxide, have demonstrated reduced discoloration and improved long-term tooth colour stability (Kayaci et al. 2024; Palma et al. 2019; Pednekar et al. 2021; Shokouhinejad et al. 2020). The main disadvantage of Biodentine is the reduced radiopacity (Grech et al. 2013; Oliveira et al. 2021) making detection of the barrier material difficult post-operatively.

Hydraulic calcium silicate cements with a short setting time and free of bismuth oxide are the barrier materials of choice. Consequently, materials containing bismuth oxide should be avoided in REPs for aesthetic reasons. The discolouration effect can be minimized by the use of dentine bonding agents applied to the internal walls of the access cavity thus providing an additional safeguard (Ateş and Aydın 2023; Shokouhinejad et al. 2018).

4.5 | Coronal Restoration

The coronal restoration following revitalization procedures serves to prevent reinfection and to strengthen structurally compromised immature teeth, which are particularly prone to fracture (Cvek 1992; Wikström, Brundin, et al. 2024).

With respect to reinfection, it must be recognized that the root canal space is occupied by a blood clot, and prevention of bacterial recolonization relies entirely on the integrity of the coronal seal—initially provided by the tricalcium silicate barrier (see previous section) and subsequently by the adhesive restoration.

Although revitalization aims to reinforce the tooth through continued root maturation (Bucchi et al. 2019), gains in root length and dentinal wall thickness remain unpredictable, and no consistent improvement in long-term survival has so far been demonstrated (Meschi et al. 2023; Panda et al. 2022; Torabinejad et al. 2017). Furthermore, as traumatic dental injury represents the predominant aetiology (Kahler et al. 2024; Koç and Fabbro 2020), pre-existing infractions are frequent. While root maturation during revitalization may contribute to some reinforcement, mineralization at the cemento-enamel junction (CEJ), where fractures most commonly occur (Brito-Júnior et al. 2014; Bucchi et al. 2019; Hassouneh et al. 2023; Talati et al. 2007), is typically minimal. In this context, adhesive restorations placed over the barrier material play a critical role in enhancing fracture resistance after revitalization (Sutam et al. 2026).

Restorative strategies are therefore a central concern in the management of immature permanent teeth (Chotvorrarak et al. 2024; Cvek 1992; Seghi et al. 2013; Wikström et al. 2021; Wikström, Brundin, et al. 2024). These primarily involve adhesive approaches, such as intracanal placement of composite below the CEJ or fibre posts. Evidence suggests that deep adhesive restorations or fibre posts may increase fracture resistance or promote more favourable fracture patterns (Brito-Júnior et al. 2014; Chun et al. 2022; Crozet et al. 2023; EL-Ma'aita et al. 2014; Hassouneh et al. 2023; Ree and Schwartz 2017; Schmoldt et al. 2011; Seto et al. 2013; Sutam et al. 2026), however, outcomes and their clinical relevance should be interpreted with caution (Danwittayakorn et al. 2019; Vieira et al. 2022). Overall, this underscores a genuine restorative-regenerative dilemma, as intracanal placement of adhesive materials inevitably reduces the space available for tissue formation.

Considering this evidence, a permanent coronal restoration should be placed over the barrier material immediately after the revitalization procedure. If placement in the same appointment is not feasible, the cavity may be temporarily sealed with a fast-setting tricalcium silicate cement or with a resin-modified glass ionomer cement over the barrier. Conventional glass ionomer cements are not recommended, as they exhibit poor bonding to hydraulic calcium silicate cements (Cengiz and Ulusoy 2016; Meraji and Camilleri 2017) and interfere with their physical properties, hydration, and setting (Camilleri 2011; Tulumbaci et al. 2017).

Given the restorative-regenerative dilemma, the intracanal adhesive restoration should extend as deeply as clinically feasible, at least to the CEJ and better below, to provide mechanical reinforcement and aesthetic integrity, while maintaining a minimum thickness of barrier material of 2 mm. Placement of a fibre post is generally not indicated.

Before restoration, all surfaces must be thoroughly cleaned to remove contaminants such as blood, irrigant residues, or material remnants using minimally invasive methods, such as ultrasonication, air abrasion, or gentle mechanical cleaning with fine-grit burs. Adhesive procedures should employ selective enamel etching with phosphoric acid (30%–40%) to enhance the long-term stability of the adhesive interface (Meerbeek et al. 2020). Although total-etch adhesive strategies have been reported to provide advantages over self-etch systems in experimental studies, it remains advisable to avoid etching hydraulic calcium silicate cements, as acid conditioning may alter their surface characteristics and potentially compromise the material (Camilleri 2013; Meraji and Camilleri 2017). Therefore, when adhesive systems are used, etching should be restricted to the tooth structure, while ensuring adequate polymerization of the adhesive layer. The adhesive should be thoroughly light-cured, with optimal positioning of the polymerization light and a minimum curing time of 20 s to compensate for light attenuation at depth (Cadenaro et al. 2019).

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Resin-based composite should then be placed incrementally to minimize interfacial stress, with each layer light-cured for 20–40 s. Bulk placement in high C-factor cavities, such as access cavities, should be avoided. In narrow access cavities, highly filled flowable composites may facilitate adaptation and controlled placement.

5 | Outcome Evaluation and Success Criteria

5.1 | Treatment Aims

In contrast to conventional endodontic treatment, revitalization is a biologically-based approach that allows treatment outcomes to be framed beyond long-term tooth survival alone. In this context, three hierarchical aims can be defined (Table 1).

The primary aim of revitalization is disease control, namely healing of apical periodontitis in line with the traditional objectives of endodontic treatment (Duncan et al. 2023). This is reflected by the absence of clinical signs and symptoms and radiographic evidence of periapical healing (Table 1).

The secondary aim focuses on patient-related parameters, particularly improvement of oral health-related quality of life (OHRQoL). This includes functional tooth integrity and aesthetic acceptability, with preservation of natural tooth colour and avoidance of discoloration contributing substantially to overall treatment satisfaction (Cushley et al. 2022).

The tertiary aim encompasses both structural and functional recovery, including continued root development (root lengthening, thickening of canal walls, and potential apical closure) and restoration of neurogenesis, indicated by a positive response to sensibility testing (Meschi et al. 2023).

This hierarchical framework integrates traditional disease-oriented outcomes with patient-reported and biological parameters.

5.2 | Definition of Success

Histological evidence indicates that tissues formed after revitalization are most often reparative rather than truly regenerative, frequently lacking the microanatomy of native pulp and sometimes containing ectopic components (Kim et al. 2018; Minic et al. 2022). Nevertheless, such endodontic tissue repair can fulfil clinical requirements and support the achievement of defined aims even in the absence of true pulp regeneration (Diogenes and Ruparel 2017; Panda et al. 2022; Xie et al. 2021).

From a clinical standpoint, treatment success is primarily defined by the achievement of the primary aim, namely resolution of apical disease and absence of complications requiring further intervention, even if secondary or tertiary aims are not fully met. This prioritization is clinically justified because tertiary aims remain variable and unpredictable, whereas infection control and symptom resolution are consistently achievable and most directly linked to long-term tooth survival. Consequently, treatment outcomes after revitalization should be interpreted hierarchically: fulfilment of the primary aim represents clinical success, whereas achievement of secondary and tertiary aims reflects increasing levels of therapeutic benefit rather than mandatory criteria for success.

From the patient's perspective, sustained relief from pain and other symptoms, reliable functional integrity, and an acceptable aesthetic result, particularly the absence of tooth discoloration matter (Kahler and Rossi-Fedele 2016). These patient-centred parameters (secondary aim), particularly those impacting

TABLE 1 | Aims of revitalization treatment.

Aim	Description	Outcomes
Primary aim	Absence or healing of apical periodontitis	– Resolution of clinical signs and symptoms (e.g., pain, swelling, sinus tract, tenderness to percussion or palpation) – Radiographic evidence of periapical healing (e.g., reduction or resolution of periapical radiolucency) – Absence of adverse events or complications requiring additional intervention
Secondary aim	Patient-centred outcomes	– Improvement in oral health-related quality of life (OHRQoL), including: • Functional tooth integrity (e.g., ability to chew without discomfort), • Aesthetic acceptability (e.g., preservation of natural tooth colour, absence of discoloration) • Relief from pain and discomfort – Cost-effectiveness of treatment – Treatment burden (e.g., number of visits, invasiveness) – Overall patient satisfaction
Tertiary aim	Structural and functional regeneration	– Continued root development: • Lengthening of the root • Thickening of the root walls • Apical closure – Positive response to pulp sensibility testing – Evidence of tissue functionality (e.g., vascularization, mineralization)

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OHRQoL, should be explicitly acknowledged and incorporated into outcome evaluation as core measures of revitalization, alongside clinical disease resolution (Cushley et al. 2022; Doğramacı and Rossi-Fedele 2023).

If intracanal tissue formation remains uncertain in mechanically compromised immature teeth (Cvek I–III) due to a lack of structural or functional evidence, a re-entry procedure after 2 years may be considered—even in asymptomatic cases—to verify tissue development and mitigate potential risks associated with unsuccessful revitalization, such as infection or fracture. This does not imply failure of revitalization but rather indicates that the anticipated regenerative benefits may not have been realized. If no intracanal tissue is present, alternative treatment options, including repeat revitalization or conventional apexification, may be considered depending on the clinical context.

5.3 | Follow-Up Recommendations and Outcome Reporting

The evaluation of primary, secondary, and tertiary aims in revitalization treatment requires a structured clinical and radiological follow-up. Clinical assessment should include inspection for discoloration, sinus tracts, and swelling, alongside palpation to evaluate mobility and pain. Percussion testing is used to detect tenderness and ankylosis, while pulp sensibility is assessed through thermal or electrical stimulation (Donnermeyer et al. 2023). Radiographic monitoring should focus on resolution of periapical radiolucency, root development, and apical closure. For increased accuracy, especially in clinical research, three-dimensional imaging, particularly CBCT, can provide valuable quantitative insights into root maturation and healing (Hilmi et al. 2023; Meschi et al. 2018).

According to the ESE Clinical Practice Guidelines, a minimum follow-up period of 12 months is recommended (Duncan et al. 2023), although longer-term monitoring may be necessary to detect delayed changes in root development and late complications (Duncan et al. 2023). In the specific case of revitalization procedures, follow-up for at least 2 years with semi-annual examinations is advisable. In situations with an increased risk of complications—such as dental trauma with potential risk of pathological root resorption—the monitoring period should be extended to at least 5 years (Bourguignon et al. 2020).

In clinical research, adoption of standardized outcome reporting would improve comparability and evidence quality in revitalization studies (Cushley et al. 2022; Galler et al. 2022; Meschi et al. 2023; Widbiller, Knüttel, et al. 2023; Zanjir et al. 2025). The defined treatment aims—particularly the primary aim of infection resolution—should be reported in all clinical investigations as a minimum requirement. Patient-centred outcomes (secondary aim) should also be documented to capture the broader impact of treatment. While core outcomes provide a common framework for comparison, clinical trials may define additional outcomes aligned with their specific research objectives. These may also include parameters related to tertiary aims, such as structural and functional regeneration, or other study-specific measures. Clinical parameters must be comprehensively assessed and documented using objective, standardized, and blinded methods. Radiographic changes should be evaluated with reproducible techniques, such as individualized bite blocks or registration devices, or three-dimensional imaging where ethically appropriate (EzEldeen et al. 2017; Patel et al. 2019).

6 | Orthodontic Considerations

Orthodontic movement of revitalized permanent teeth is a clinical reality, reflecting the growing adoption of revitalization procedures in young patients (Anna et al. 2024; Lee et al. 2018). Clinical evidence indicates that both mature and immature teeth can generally undergo orthodontic treatment shortly after completion of root canal treatment, with no delay in periapical healing or serious complications attributable to orthodontic forces (Alharbi et al. 2025; Chen et al. 2024; Keinan et al. 2022; Parashos 2023).

In immature vital teeth, orthodontic tooth movement does not appear to impede root development (Dalaie et al. 2021; Mavragani et al. 2002). By inference, continued root maturation after revitalization may be achievable under orthodontic treatment, provided the neurovascular supply and root-forming apparatus remain intact (Li, Parada, and Chai 2017). However, the reparative tissue formed after revitalization may have limited biological potential, and its response to orthodontic forces may differ from that of intact pulp tissue (Austah et al. 2018; Lei et al. 2015; Meschi et al. 2016). Consequently, while orthodontic movement of revitalized teeth is generally safe, these teeth remain biologically vulnerable.

Clinical reports suggest that orthodontic movement of revitalized teeth is safe when light forces are applied, periapical healing has been confirmed, and regular follow-up is maintained (Asgary and Talebzadeh 2023; Chaniotis 2018; Jawad et al. 2018; Natera and Mukherjee 2018; Stefopoulos et al. 2023; Yoshpe et al. 2025). Healing and continued root development have also been observed when revitalization occurs during ongoing orthodontic treatment, provided the affected tooth is temporarily excluded from active loading (Al-Tammami and Al-Nazhan 2016; Rai et al. 2016). Nevertheless, complications such as recurrent apical periodontitis and root resorption have been reported following orthodontic loading of revitalized teeth, highlighting the need for caution (Chaniotis and Chanioti 2022).

Since revitalization often targets immature permanent teeth following traumatic dental injuries (Kahler et al. 2024), orthodontic planning should follow established trauma management recommendations, including extended observation periods before applying forces, scaled to injury severity (Sandler et al. 2020). Teeth previously affected by trauma are presumed to have an increased susceptibility to pathological root resorption under orthodontic loading, though reported cases may often reflect trauma sequelae rather than direct effects of revitalization (Beck et al. 2013; Drysdale et al. 2016; Kindelan et al. 2008; Linge and Linge 1983; Morris et al. 2022; Sandler et al. 2020).

Precautionary strategies are recommended to minimize mechanical stress during orthodontic movement of revitalized

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teeth. These include applying light, intermittent forces, avoiding excessive intrusion and uncontrolled tipping, and limiting active loading phases (Acar et al. 1999; Ballard et al. 2009; Barbagallo et al. 2008; Gonzales et al. 2008; Paetyangkul et al. 2009; Segal et al. 2004). The timing of orthodontic loading should be guided by the extent of post-revitalization healing and any predisposing factors, such as prior trauma. A general observation period of about 12 months is recommended to confirm adequate periapical healing, which may be extended in cases with higher risk to monitor latent complications and continued root maturation (Maree et al. 2025; Sandler et al. 2020). Orthodontic movement should only proceed once clinical and radiographic assessments confirm periapical healing and reconstitution of a continuous apical periodontal ligament (Stefopoulos et al. 2023).

Finally, enhanced monitoring during orthodontic treatment is recommended to ensure patient safety and allow early detection of complications. Periodic follow-ups every 3–6 months are advised during both active tooth movement and early retention, with careful evaluation of clinical and radiographic findings.

7 | Complications and Failure Management

Although revitalization treatment has rapidly evolved over the past decade from an experimental approach to an accepted treatment option for immature permanent teeth in clinical practice, procedure-related complications remain a relevant clinical concern. Several potential etiologic sequelae have been addressed previously; however, the following section focuses on complications specifically associated with revitalization treatment, with particular emphasis on practical strategies for prevention and management.

7.1 | REP-Related Intracanal Mineralization (RIM)

RIM is a healing outcome characterized by non-physiologic, reparative mineralized tissue formation within the root canal system following revitalization or other REPs, previously referred to as revitalization-associated intracanal calcification (RAIC). It is observed radiographically and manifests as a calcified bridge (Figure 11) or partial to complete narrowing of the root canal lumen (Figure 12; Almutairi et al. 2019; Kahler et al. 2018; Song, Cao, et al. 2017; Song et al. 2025). Histologically, the narrowed canal lumen may be filled with bone-, cementum-, or periodontal ligament-related tissue (Kahler et al. 2018; Song, Cao, et al. 2017). It is important to distinguish RIM from primarily apical ingrowth of bone or cementum, which can lead to internal ankylosis by fusing with the apical bone or internal PDL, respectively (Chen et al. 2012; Gorp and Declerck 2023; Hu et al. 2023; Song et al. 2025).

RIM is frequently documented after revitalization, especially after traumatic events, and typically shows a progressive nature (Lu et al. 2023; Chen et al. 2012; Kahler et al. 2018; Song, Cao, et al. 2017). Incidence rates vary widely, from about one-third of treated cases to more than two-thirds (Almutairi et al. 2019; Al-Qudah et al. 2023; Jiang et al. 2023; Song et al. 2025), with cervical mineralization appearing to be particularly frequent (Chaniotis and Petridis 2019; Maree et al. 2025). Among the risk factors, calcium hydroxide placement and long-term intracanal dressing have been discussed (Almutairi et al. 2019; Al-Qudah et al. 2023; Jiang et al. 2023; Song, Cao, et al. 2017; Song et al. 2025).

Although RIM is recognized as an adverse outcome (Cushley et al. 2022; Zanjir et al. 2025), it represents a form of reparative healing. Based on the available data, it does not seem to compromise outcome after revitalization, and resolution of apical periodontitis is routinely observed. Continued root development can occur alongside RIM, even though sensibility is typically absent (Almutairi et al. 2019; Jiang et al. 2023, 2017; Kahler et al. 2018; Maree et al. 2025; Song, Cao, et al. 2017; Song et al. 2025). As RIM does not constitute a disease state, its management is primarily preventive and observational, with long-term follow-up recommended to monitor progression. Prophylactic endodontic intervention in revitalized teeth with RIM is not indicated. Intervention is warranted only for the development or recurrence of apical periodontitis, with nonsurgical or surgical treatment options aimed at tooth retention.

7.2 | REP-Related Intracanal Resorption (RIR)

Internal root resorption of inflammatory type can occur following revitalization treatment or other REPs (Chaniotis and Chanioti 2022). RIR is likely associated with persistent or secondary infection and may arise despite ongoing root development or mineralization. These lesions often appear delayed and unexpectedly, highlighting the importance of regular clinical and radiographic follow-up for early detection (Figure 13). Given the risk of rapid root structure loss, immediate re-entry and thorough disinfection of the canal are strongly recommended upon diagnosis to preserve the tooth.

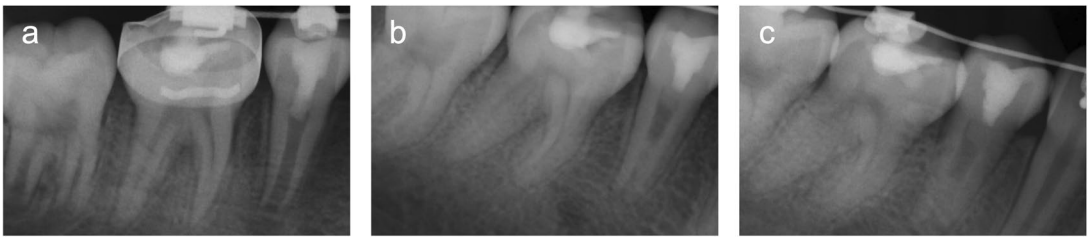


FIGURE 11 | Calcified bridge in a mandibular right second premolar following revitalization (RIM). (a) Preoperative radiograph of the tooth with clinically diagnosed pulp necrosis following orthodontic movement. (b) Radiograph at the 2-year follow-up demonstrating mineralization in the middle third and no periapical lesion. (c) Radiograph at the 3-year follow-up showing mineralization of the middle and apical thirds.

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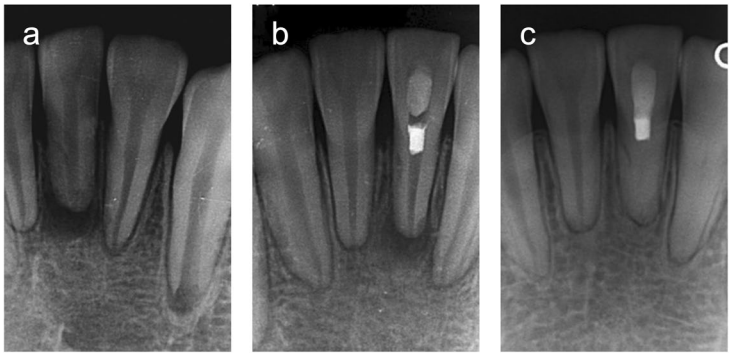


FIGURE 12 | Complete intracanal mineralization in a mandibular left central incisor following revitalization (RIM). (a) Preoperative radiograph after avulsion (2 h stored in milk) showing external inflammatory resorption and apical periodontitis. (b) Postoperative radiograph after revitalization. (c) Radiograph at the 54-month follow-up demonstrating complete mineralization and absence of periapical pathology. Courtesy of Dr. Jing Lu (Lu et al. 2023).

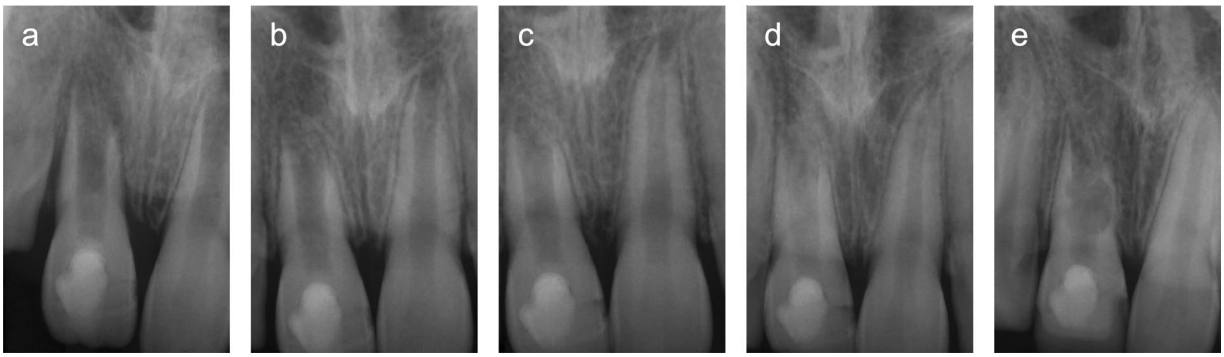


FIGURE 13 | Internal root resorption (RIR) in a maxillary right central incisor following revitalization after pulp necrosis due to avulsion (1 h physiological storage). (a) Postoperative radiograph after revitalization. (b) Radiograph at the 7-month follow-up showing no periapical lesion. (c, d) Radiographs at the 14- and 26-month follow-up. (e) Radiograph at the 42-month follow-up showing extensive inflammatory resorption without periapical pathology.

7.3 | Discolouration

The aesthetic appearance of anterior teeth is a patient-centred outcome for teeth treated with revitalization procedures. Tooth discoloration after revitalization has been reported in approximately half of cases, primarily due to intracanal medicaments, blood contamination, or the coronal barrier (Chrepa et al. 2020; Kahler et al. 2014; Kahler and Rossi-Fedele 2016). This underlines the importance of prevention through correct material selection and careful application, as described above.

To manage discoloration after revitalization, bleaching techniques can be considered. External bleaching, either dentist-supervised at-home bleaching or in-office procedures, may be attempted. However, if the discoloration is primarily caused by an inappropriate intracanal barrier material, these approaches are unlikely to provide satisfactory results (Kahler et al. 2024). In such situations, an internal approach is recommended, requiring gentle removal of the intracanal barrier down to the CEJ, which can result in a significant improvement in tooth colour (Figure 14; Kahler 2022; Timmerman and Parashos 2018). It is essential that at least 2 mm of barrier material be left in place and that an additional protective cervical seal, such as glass ionomer or composite, is applied to prevent diffusion of potentially harmful substances into the restored intracanal tissue. Internal bleaching can then be carried out using the walking bleach technique with peroxide-based or alternative intracoronal bleaching agents (Oliveira et al. 2003; Rotstein et al. 1992).

When the coronal pulp space is sealed off from the restored vital tissue in the root canal by the cervical base, an intracanal barrier, and often by newly formed hard tissue, the internal application of bleaching agents can be performed in a potentially safe manner (Antov et al. 2019; D'Mello and Moloney 2017; Kahler 2022; Kim et al. 2010; Timmerman and Parashos 2018). Despite these strategies, systematic analyses of revitalization cases that underwent external, internal, or combined bleaching report a moderate reliability and durability of results (Fagogeni et al. 2021; Kahler and Rossi-Fedele 2016).

7.4 | Failure

Clinical failure is defined as the inability to achieve the primary treatment aim, as outlined above, and is characterized by the persistence or recurrence of clinical signs or symptoms (e.g., pain, swelling, sinus tract formation, tenderness to percussion or palpation) and/or radiographic evidence of apical

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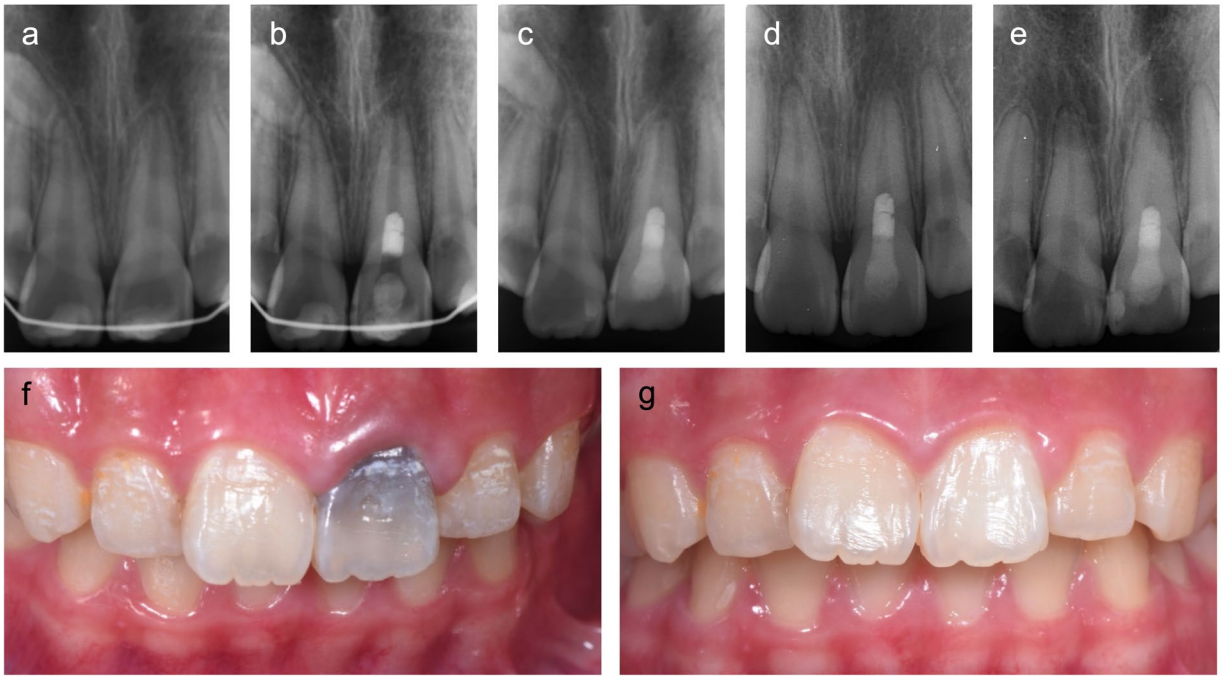


FIGURE 14 | Crown discoloration following revitalization of a maxillary left central incisor after avulsion. (a) Preoperative radiograph after replantation (1 h extra-oral dry time). (b) Postoperative radiograph following revitalization. (c) Radiograph at the 6-month follow-up showing normal periapical tissues. (d) Radiograph at the 1-year follow-up demonstrating thickening of canal walls in the apical third. (e) Radiograph at the 2-year follow-up showing complete mineralization of the canal space. (f) Clinical photograph showing crown discoloration due to use of HCS-based cement. (g) Clinical photograph after bleaching demonstrating improved aesthetics. Courtesy of Dr. Jing Lu (Kahler et al. 2024).

periodontitis, manifested as an unchanged or increased size of periapical radiolucency, or by other adverse events or complications necessitating additional clinical intervention (Kahler et al. 2018).

In general, treatment failure most commonly reflects inadequate control of the primary root canal infection or re-infection of the root canal system due to coronal leakage (Keinan et al. 2024; Lin, Shimizu, et al. 2014). Failure may present as an early (< 2 years), medium-term (2–5 years), or long-term (> 5 years) outcome (Doğramacı and Rossi-Fedele 2023; Nieuwenhuysen et al. 2023), and may be accompanied by radiographic evidence of no, partial, or complete continued root development (Almutairi et al. 2019; Lee and Song 2022).

When clinical failure occurs with the emergence of symptoms and/or signs indicative of persistent or secondary infection, the affected tooth can often still be successfully preserved. A second attempt at revitalization treatment may be considered, particularly in teeth with very thin root walls, where further root development could be advantageous (Almutairi et al. 2019; Chaniotis 2017; Keinan et al. 2024; Lee and Song 2022).

Alternatively, apexification approaches, such as apical barrier techniques or long-term calcium hydroxide placement, may be performed, or conventional root canal treatment may be initiated once sufficient root maturation has occurred (Figure 15; Almutairi et al. 2019; Chaniotis 2017; Keinan et al. 2024; Lee and Song 2022; Wikström et al. 2022). In cases where orthograde root canal access is difficult or associated with an increased risk of complications, surgical intervention may be considered (Keinan et al. 2024; Lee and Song 2022).

In cases where cyst-like lesions develop that are not consistent with infection-related apical periodontitis and may lead to extensive osseous defects, conventional nonsurgical endodontic treatment should remain the primary management approach. Adjunctive surgical intervention may be considered in the presence of large, long-standing, or symptomatic lesions, particularly when healing is incomplete after adequate nonsurgical treatment (Figure 16).

Lastly, when preservation of the revitalized tooth is no longer feasible, extraction followed by multidisciplinary management may be indicated. Depending on the clinical scenario, this may include orthodontic space management or mesialisation, autotransplantation, or temporization using removable appliances (e.g., Essix retainers) to maintain function and aesthetics until definitive rehabilitation can be achieved (Gorp and EzEldeen 2025; Kaán et al. 2025; Meschi et al. 2019; Plotino et al. 2021).

In selected cases without signs of persistent infection, alternative tooth-preserving strategies such as decoronation with root submergence may be considered to maintain alveolar bone volume and soft tissue architecture, particularly in growing patients or when future implant placement is anticipated (Figure 10; Gorp and EzEldeen 2025; Meschi et al. 2019).

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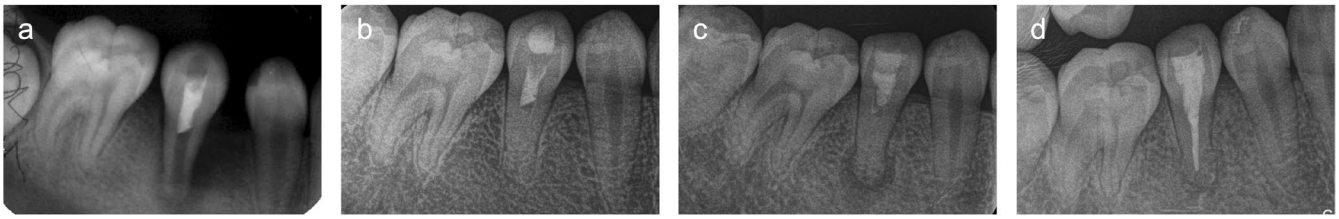


FIGURE 15 | Recurrence of apical periodontitis in a mandibular right second premolar following revitalization. (a) Postoperative radiograph after revitalization. (b) Radiograph at the 8-year follow-up showing intracanal mineralization without periapical pathology. (c) Radiograph at the 12-year follow-up with cusp fracture demonstrating recurrence of apical periodontitis requiring retreatment. (d) Radiograph at the 6-month follow-up after retreatment showing apical healing (Kahler et al. 2018).



FIGURE 16 | Cyst-like lesion associated with a tooth following revitalization. (a) Preoperative radiograph showing apical radiolucency. (b) Postoperative radiograph after revitalization. (c) Radiograph at the 2-year follow-up with no clinical symptoms (positive sensibility) or signs of infection. (d) Sagittal section of the cyst-like lesion. (e) Horizontal section. (f) Radiograph at the 1-year follow-up after cystectomy confirming a radicular cyst histopathologically.

8 | Future Perspectives

The revitalization protocol outlined in this document represents a cell-free, autologous therapeutic concept, relying on the formation of a blood clot scaffold within the root canal following induced bleeding from periapical tissues. This approach has been shown to reproducibly achieve the primary, secondary, and tertiary treatment aims, including resolution of symptoms, healing of apical pathology, improved patient-reported quality of life, and restoration of functional tissue responses (Lin et al. 2021).

As revitalization predominantly results in endodontic tissue repair, substantial efforts are currently directed toward achieving endodontic tissue regeneration, defined as the restoration of the original structure and function of the pulp-dentine complex, including the formation of pulp-analogous tissue with odontoblastic cells capable of depositing tubular dentine.

Within the framework of ETE, cell-based strategies aim to deliver stem cells into the disinfected root canal space, typically encapsulated within tailored scaffold materials and supplemented with targeted growth factors and signalling molecules (Widbiller, Knüttel, et al. 2023; Widbiller and Schmalz 2021). Several of these approaches have progressed to early clinical trial phases and have demonstrated promising biological outcomes (Brizuela et al. 2020; Gomez-Sosa et al. 2022; Nakashima et al. 2022; Nakashima and Tanaka 2024; Ulusoy et al. 2019; Xuan et al. 2018; Zhang and Sheng 2024). Nevertheless, their translation into routine clinical practice remains limited by regulatory challenges, logistical complexity, and the costs associated with standardized cell processing.

In parallel, cell-free tissue engineering approaches have gained increasing attention as potentially more translatable alternatives. These strategies are based on blood-derived matrices or bioengineered materials functionalized with signalling molecules, aiming to recruit endogenous cells and modulate the local regenerative microenvironment without exogenous cell delivery (Alshahhoud et al. 2024; Galler and Widbiller 2020; Ulusoy et al. 2019; Zhang and Sheng 2024; Zhujiang and Kim 2016). Owing to lower regulatory hurdles and reduced costs, such approaches may offer improved clinical feasibility.

Despite these advances, it is important to acknowledge that most current tissue engineering strategies primarily target biological outcome parameters. At present, there is limited evidence that these emerging approaches outperform established revitalization protocols in achieving primary, secondary, or tertiary aims. Future research should therefore focus not only on enhancing biological regeneration but also on demonstrating clear clinical and patient-related benefits to justify the implementation of more complex regenerative strategies in daily practice.

9 | Conclusion

Revitalization treatment has become a valuable biological approach in modern endodontics, offering new possibilities for the management of immature permanent teeth following loss of pulp vitality. Over the past decade, an expanding body of preclinical studies together with clinical observations has enhanced our understanding of the biological principles, procedural nuances, and factors that influence treatment outcomes.

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Our growing experience continues to clarify the critical aspects of case selection, procedural protocols, extended treatment applications, and the early detection and management of complications and failures. This evolving knowledge will guide a refined update of the ESE Position Statement, translating scientific insights into practical guidance for clinicians. Looking ahead, well-designed clinical studies, including qualitative and standardized trials, will be essential to further optimize outcomes and make revitalization—and potentially other regenerative and reparative endodontic procedures—widely accessible and truly beneficial for patients.

Author Contributions

Conceptualization: M. Widbiller, B. Kahler; Writing – Original Draft: M. Widbiller, X. Petridis, G. Krastl, N. Meschi, J. Camilleri, H.F. Duncan, M.T. Arias-Moliz, J.G. Leprince, G. Van Gorp, M. Arnold, K.M. Galler, S. Simon; Supervision: M. Widbiller, B. Kahler.

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Consent

The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The authors have nothing to report.

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