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Optimising Outcomes in Endodontic Microsurgery: Evidence, Uncertainties and Future Directions

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ABSTRACT

Endodontic microsurgery (EMS) is a reliable treatment modality for managing persistent or recurrent periapical pathologies, particularly when conventional nonsurgical retreatment is infeasible or has failed. Various factors influence EMS outcomes, among which the lesion type is a key determinant. Isolated endodontic lesions generally exhibit favourable outcomes, whereas combined endodontic–periodontal lesions and through-and-through defects are clinically challenging and associated with less predictable outcomes. The adjunctive use of regenerative procedures, such as bone grafts, barrier membranes and biologically active agents, aims to enhance periapical healing; however, current evidence remains inconclusive, and further studies with clear lesion-type classification are required to determine their true benefits. Guided surgical approaches, including static, dynamic and robot-assisted systems, have been introduced in EMS to enhance surgical precision and predictability. These technologies appear particularly beneficial in small isolated lesions or when critical anatomical structures must be protected, but further studies are required to validate their clinical effectiveness. This review encourages clinicians to approach EMS with a clear understanding of the effect of lesion type on the prognosis, and to critically assess the usefulness of adjunctive regenerative procedures and advanced technologies based on lesion-specific considerations. Although predictable outcomes are mostly dependent on sound diagnosis, thoughtful case selection, and meticulous surgical techniques, accumulating evidence and technical progress suggest that the indications for EMS may be reasonably expanded in well-selected cases.

1 | Introduction

Endodontic microsurgery (EMS) has become an increasingly reliable option for managing persistent periapical lesions when conventional nonsurgical root canal treatment or retreatment alone does not achieve adequate resolution. Nonsurgical root canal treatment remains the standard of care for apical periodontitis and has shown high survival rates in large-cohort and population-based studies (Kwak et al. 2019; Ng et al. 2010, 2011). When the initial treatment fails because of factors such as missed canals or persistent infection, nonsurgical retreatment generally yields good outcomes, with success rates of approximately 80%–90% (Kang et al. 2015; Kwak et al. 2019; Ng et al. 2011). This implies that persistent disease occurs in 10%–20% of cases. When nonsurgical retreatment is infeasible because of complex canal anatomy, obstructions, or procedural limitations or when retreatment fails to resolve the pathology (Siqueira Jr. and Rôças 2008), EMS serves as a predictable and effective surgical alternative to preserve the natural tooth (Kim and Kratchman 2006; Torabinejad and White 2016). Advances in microsurgical techniques, including the use of operating microscopes, ultrasonic retrograde preparation, and biocompatible calcium silicate cements, have markedly improved clinical outcomes, and recent clinical studies and meta-analyses have consistently reported success rates ≥ 90%

(Azim et al. 2021; Setzer et al. 2010; Tsesis et al. 2009, 2013; Yang et al. 2024; Zhang et al. 2023).

The growing popularity of dental implants often shifts treatment preferences away from the preservation of natural teeth (Lee, Kang, et al. 2020). However, when evaluated using the same rigorous success criteria as for EMS, such as the absence of clinical symptoms, radiographic pathology, and complications, the long-term outcomes of implants are not necessarily superior (Setzer and Kim 2014; Torabinejad et al. 2015). Furthermore, several studies with broader definitions of success have shown that EMS and implants yield comparable outcomes (Chércoles-Ruiz et al. 2017). These findings challenge the widely held assumption that implants are inherently more predictable and highlight the need to reassess the role of EMS as a reliable and conservative treatment option.

EMS maintains the natural dentition, which offers unique biological and long-term functional benefits, including maintenance of the periodontal ligament, proprioceptive feedback and minimal biological alteration of surrounding tissues. A salvageable natural tooth is biomechanically and biologically superior to any prosthetic replacement. Thus, EMS should be recognised as a critical intervention that often represents the final opportunity to retain a compromised tooth. Therefore, clinicians must be equipped with a clear understanding of the indications, technical considerations, and prognostic factors associated with EMS to make responsible and patient-centred decisions.

This narrative review aimed to provide a focused overview of the current evidence on EMS, with particular emphasis on the effect of the lesion type on clinical outcomes. In addition, we examined the efficacy of adjunctive regenerative procedures, reviewed the latest technological advancements in guided surgical techniques, including static, dynamic, and robot-assisted navigation systems, and evaluated their potential impact on prognosis according to the lesion type. This article integrates insights from recent scientific and clinical studies, highlights the limitations of current approaches and unresolved questions, and aims to support clinicians in optimising treatment planning and achieving predictable clinical outcomes in modern endodontic practice.

2 | Lesion Type Based Outcomes

Before reviewing clinical outcomes, the definition of the lesion types commonly encountered in EMS is important. Kim and Kratchman (2006) proposed a classification system (Classes A–F) for surgically treated periradicular lesions. Briefly, Classes A–C represent isolated endodontic lesions confined to the apical region without periodontal involvement, whereas Classes D–F correspond to combined endodontic–periodontal lesions characterised by periodontal pocket formation, endodontic–periodontal communications, or loss of the buccal plate. Therefore, this review considered outcomes and prognostic factors separately for isolated endodontic and combined endodontic-periodontal lesions.

Radiographic assessment of surgical outcomes has conventionally relied on two-dimensional periapical radiographs, most commonly using the criteria of Rud et al. (1972) and Molven et al. (1987), which classify healing as complete, incomplete, uncertain, or unsatisfactory. More recently, three-dimensional (3D) cone-beam computed tomography (CBCT)–based evaluation criteria have been introduced to overcome the limitations of two-dimensional imaging. The modified PENN 3D criteria classify healing into four categories: complete, limited, uncertain and unsatisfactory, based on CBCT findings such as regeneration of the periodontal ligament space and lamina dura, bone repair at the resection site and osteotomy, and the presence of residual radiolucency (Schloss et al. 2017). Similarly, von Arx et al. (2016) proposed the RAC/B system, which scores four independent CBCT parameters: R (resection plane), A (apical area), C (cortical plate) and B (overall bone healing), to provide a structured, multiparameter assessment with good repeatability and reproducibility.

With these definitions and outcome criteria established, the following sections separately examine the prognostic factors and clinical outcomes associated with isolated endodontic lesions and endodontic–periodontal combined lesions.

2.1 | Isolated Endodontic Lesions

Isolated endodontic lesions, characterised by the absence of periodontal involvement, are consistently associated with favourable outcomes after EMS. Reported success rates typically approach or exceed 90%, with both retrospective and prospective studies confirming the stability of healing over time (Kim, Ku, et al. 2016; Song et al. 2011; Song, Kim, Lee, et al. 2013). Recent CBCT-based studies using the modified PENN 3D criteria have reported EMS success rates of approximately 88%–89% (Bieszczad et al. 2022; Zhang et al. 2023).

In a long-term follow-up study, Yoo et al. (2024) reported a 10-year survival rate > 80% for teeth treated with EMS. Similarly, Pallarés-Serrano et al. (2021) reported a mean healing rate of 81% after 5–9 years of follow-up, and von Arx et al. (2019) reported a 10-year healing rate of 81.5% after apical surgeries performed with endoscopic assistance and root-end filling using mineral trioxide aggregate. Overall, these findings support the long-term reliability of EMS as a treatment option.

Although isolated endodontic lesions are generally associated with favourable outcomes, caution is warranted in the molars, particularly because of the presence of canal isthmuses. Tooth type is a significant prognostic factor in EMS, with consistently lower success rates in the molars than in the anterior teeth (Bieszczad et al. 2022; Pallarés-Serrano et al. 2021; Song et al. 2018; Song, Kim, Lee, et al. 2013). Kim, Jung, et al. (2016) reported that the presence of an isthmus was a significant negative prognostic factor, particularly in the long term. Therefore, thorough inspection and identification of the isthmuses, particularly in the mesial roots of the mandibular molars, is essential. These roots typically contain two canals frequently connected by an isthmus. Previous studies have consistently reported a high prevalence (83%–100%) of isthmuses 3–4 mm from the apex in these roots (Kang et al. 2020; Karunakaran et al. 2019; von Arx 2005). When present, the isthmus should be included in the retrograde cavity preparation. Ideally, the preparation should

achieve sufficient depth and consistency to allow proper isthmus management while avoiding unnecessary dentine removal. However, this can be technically challenging because of the limited access and narrow shape of the isthmus. Extending the preparation may thin the surrounding dentine, which can compromise the structural integrity and increase the risk of vertical root fracture (Kim, Jung, et al. 2016; von Arx et al. 2019). This is consistent with the findings of finite-element analysis that thinning may result in increased stress concentration, potentially leading to crack initiation and root fracture (Kim, Chen, et al. 2020; Kim et al. 2019). These considerations highlight the importance of balancing surgical thoroughness with preservation of the root structure during EMS. The anatomical and technical challenges associated with the molars suggest the need for continued refinement of retrograde preparation techniques and the development of instruments that support effective conservative management.

2.2 | Combined Endodontic-Periodontal Lesions

The prognosis of EMS is considerably more variable in cases involving both endodontic and periodontal components. Combined endodontic–periodontal lesions pose significant challenges for long-term healing. Unlike isolated endodontic lesions, which typically demonstrate consistent and favourable healing patterns, combined endodontic-periodontal lesions often exhibit delayed or incomplete healing and are more susceptible to relapse over time (Song et al. 2018; Song, Kim, Shin, et al. 2013; von Arx et al. 2012).

Several clinical studies have consistently demonstrated the prognostic impact of lesion type. A prospective cohort study by Kim et al. (2008) reported that the success rate in combined endodontic–periodontal lesions was markedly lower (77.5%) than that in isolated endodontic lesions (95.2%). Similarly, Song, Kim, Shin, et al. (2013) reported that the presence of a buccal bone plate > 3 mm significantly improved healing outcomes (94.3% vs. 68.8%), underscoring the importance of local bone support. Moreover, in a propensity score–matched survival analysis, endodontic–periodontal lesions were associated with a significantly lower cumulative success rate (72.3%) than isolated lesions (87.3%) (Song et al. 2018). The prognostic relevance of lesion type has been validated in CBCT-based studies, which showed that periodontal involvement negatively influences 3D healing outcomes (Bieszczad et al. 2022; Zhang et al. 2023). This distinction was further validated in a systematic review and meta-analysis by Sabeti et al. (2023) in which lesions involving both endodontic and periodontal components consistently demonstrated inferior treatment outcomes compared with isolated endodontic lesions. Notably, some studies reporting higher overall success rates, such as Kim, Ku, et al. (2016) and Yoo et al. (2024), explicitly excluded cases with endodontic–periodontal communications extending to the apex, which are defined as apicomarginal bone defects, to control for this confounding variable.

Considering the consistently lower success rates in combined endodontic–periodontal lesions, examining the factors that may influence periodontal tissue healing is important. Unlike isolated endodontic lesions, combined endodontic–periodontal lesions are biologically complex, because the healing process depends not only on resolution of periapical infection, but also on regeneration of the supporting periodontal structures. Among the systemic and behavioural variables that affect periodontal health, tobacco smoking is a well-known factor that impairs soft-tissue healing and promotes periodontal breakdown (Ng et al. 2015). Truschnegg et al. (2020) reported higher failure rates after 10–13 years in smokers and attributed these outcomes to the development of apicomarginal or furcation involvement. These findings suggest that in combined endodontic–periodontal lesions, attention should be paid to risk factors that may indirectly compromise long-term healing through their detrimental effects on periodontal stability. In addition, a longer follow-up may be necessary to monitor potential late-stage failures related to progressive periodontal breakdown.

Other systemic conditions may also influence healing in combined endodontic–periodontal lesions. Evidence from nonsurgical endodontic treatment indicates that systemic diseases such as diabetes mellitus, cardiovascular disease, and hypertension can negatively affect endodontic outcomes (Aminoshariae et al. 2017; Segura-Egea et al. 2023). Likewise, consensus reports in periodontology have identified diabetes, obesity, osteoporosis, rheumatoid arthritis and other systemic inflammatory conditions as important modifiers of periodontal health and regeneration (Albandar et al. 2018; Jepsen et al. 2018). Considering that healing in combined endodontic–periodontal lesions requires both periapical resolution and periodontal regeneration, these systemic factors are highly relevant to prognosis. Nevertheless, most EMS outcome studies included systemically healthy cohorts. Therefore, future studies should investigate the effects of systemic conditions on both endodontic and periodontal healing to better inform the management of combined lesions.

3 | Unresolved Issues and Innovations in Optimising EMS Outcomes

3.1 | Adjunctive Regenerative Procedures

Adjunctive regenerative procedures in EMS generally refer to additional interventions designed to enhance bone fill and facilitate predictable periapical healing (Bashutski and Wang 2009). These include the use of bone-graft materials, collagen-based scaffolds, barrier membranes and biologically active agents such as platelet concentrates (platelet-rich fibrin [PRF], concentrated growth factor, platelet-rich plasma [PRP] and their variants) that promote osteogenesis and soft-tissue repair. Over the past few decades, the incorporation of these regenerative approaches into EMS has been a subject of continued scholarly interest, as reflected in multiple systematic reviews (Flynn et al. 2024; Liu et al. 2021; Rosen et al. 2023). Various strategies have been explored, including resorbable membranes without graft material (Garrett et al. 2002; Parmar et al. 2019), combinations of bone grafts with resorbable (Baruwa et al. 2023; Taschieri et al. 2011, 2008, 2007) or non-resorbable membranes (Pecora et al. 1995), and the use of biologically active agents such as PRF (Arpitha et al. 2023; Dhiman et al. 2015; Meschi et al. 2020), PRP (Dhamija et al. 2024, 2020) and concentrated growth factor (Yahata et al. 2023; Yan et al. 2023; You et al. 2023). Despite their biological plausibility and increased clinical use, the precise indications and clinical effectiveness of regenerative interventions

remain unclear. Furthermore, the radiopacity of some graft materials may lead to an overestimation of healing on follow-up imaging, complicating the evaluation of the true regenerative outcomes.

Previous studies have reported conflicting findings regarding the effectiveness of adjunctive regenerative procedures in EMS; while some reported improved healing, others showed no significant additional benefit. However, a considerable portion of the current evidence is derived from studies providing relatively low levels of evidence, such as uncontrolled case series or small clinical trials (Baruwa et al. 2023; Dietrich et al. 2003; Goyal et al. 2011), which have limited ability to demonstrate a true treatment effect. Methodological issues such as nonrandomized study designs (Dominiak et al. 2009), insufficient randomization and unequal group allocation (Taschieri et al. 2007), small sample sizes (Garrett et al. 2002; Goyal et al. 2011; Meschi et al. 2020; You et al. 2023), or high loss to follow-up (Garrett et al. 2002) further compromise the reliability of the available data. In addition, several reports do not clearly differentiate lesion types (Alkandari et al. 2024; Azim et al. 2021; Meschi et al. 2018, 2020; Pantchev et al. 2009; Yan et al. 2023), making it difficult to determine whether regenerative interventions exert consistent benefits across distinct anatomical conditions. Considering that the biological and structural characteristics of each lesion type may substantially influence healing dynamics, the evidence should be interpreted within the context of lesion classification. Table 1 summarises the current clinical studies on adjunctive regenerative procedures with EMS, categorised by lesion type.

Regarding isolated endodontic lesions, only a few studies have directly examined the effect of adjunctive regenerative procedures on EMS outcomes, when excluding those that focused solely on postoperative pain or patient-reported outcomes without assessing periapical healing (Soto-Peñaloza et al. 2020; Taschieri et al. 2014). This is likely because the baseline success rate of EMS in this lesion type is already high, and the limited extent of bone defects generally provides favourable conditions for healing. Although lesion size may influence the healing potential, adjunctive regenerative procedures mainly appear to accelerate the initial bone formation without a significant difference in the overall healing outcome (Garrett et al. 2002; Taschieri et al. 2007; Yahata et al. 2023; You et al. 2023).

Case series such as those by Baruwa et al. (2023) and Dietrich et al. (2003) have reported favourable outcomes in combined endodontic–periodontal lesions treated with adjunctive regenerative procedures. However, high-quality randomised controlled trials directly comparing cases treated with and without adjunctive regenerative procedures are scarce (Rosen et al. 2023). This scarcity is likely attributable to the difficulty in recruiting eligible patients, owing to challenges in establishing strict and appropriate inclusion criteria because of the diverse progression patterns of these lesions and the uncertainty in distinguishing their primary etiologies. A recent randomised controlled trial investigated EMS in apicomarginal bone defects, the most severe form of combined endodontic-periodontal lesions, and reported an identical overall success rate of 80% in both groups with and without adjunctive regenerative procedures based on the modified PENN 3D criteria. However, the intervention group demonstrated a high proportion of complete healing and showed improved labial alveolar bone regeneration compared with the control group (Sharma et al. 2025). This result is noteworthy considering the limited high-quality evidence available for this lesion type. Previous research has shown that the success rate of EMS is significantly lower when the residual marginal bone height is less than 3 mm, and cases with complete loss of the buccal bone plate exhibit similarly compromised outcomes (Song, Kim, Shin, et al. 2013). When considering that surgical flap elevation and closure inevitably result in a certain degree of marginal bone loss (Fickl et al. 2011), residual marginal bone below a critical threshold may functionally resemble an apicomarginal bone defect in terms of healing potential. Based on these observations, a clinical study is currently underway at our institution to evaluate the long-term impact of adjunctive regenerative procedures in combined endodontic-periodontal lesions and to establish evidence-based indications for their clinical use.

Through-and-through lesions, characterised by the loss of both buccal and lingual (or palatal) cortical plates, are prone to delayed or incomplete healing, likely due to altered osseous healing dynamics (Baek and Kim 2001). Consequently, the use of adjunctive regenerative procedures in this lesion type has been of clinical interest for long. With the advent of CBCT-based 3D assessment, which allows more precise evaluation of bone defects and healing dynamics, studies on through-and-through lesions have been increasingly conducted in recent years, providing relatively more evidence of higher methodological quality compared with that for other lesion types discussed earlier. Nonetheless, the findings are inconclusive. In randomised controlled trials with longitudinal follow-ups and CBCT evaluation, Dhamija et al. (2020, 2024) reported that the adjunctive use of PRP significantly improved healing in through-and-through lesions compared with that in controls. In contrast, Bieszczad et al. (2022) reported no significant improvement, and Arpitha et al. (2023) reported that the adjunctive use of injectable PRF combined with type I collagen particles did not enhance healing outcomes. Similarly, Parmar et al. (2019) found no advantage in using collagen membranes. These discrepancies were further reflected in a recent systematic review and meta-analysis by Fatima et al. (2025), which showed that adjunctive regenerative procedures did not significantly improve periapical healing in through-and-through lesions. These discrepancies may partly be explained by differences in the regenerative materials and protocols used across studies. A recently published retrospective study (Kim et al. 2025) demonstrated that the 1-year success rate was significantly lower in through-and-through lesions (77.3% vs. 88.0%), although the difference was no longer evident at 3 years. In addition, preliminary data from an ongoing institutional study (manuscript in preparation) suggest that adjunctive regenerative procedures did not substantially improve outcomes in through-and-through lesions. These findings suggest that although the initial healing may be less favourable in extensive defects, long-term outcomes may equalise over time, regardless of the use of regenerative materials in through-and-through lesions.

Lesion dimension is another important factor influencing healing potential in EMS and may determine the need for adjunctive regenerative procedures used in this context. A recent systematic review and meta-analysis (Sabeti et al. 2023) reported that

TABLE 1 | Clinical studies on adjunctive regenerative procedures in EMS.

Lesion type	Author (year)	Study design	OCEBM level	Number of subjects/teeth			Regenerative technique/ material	Evaluation tool	Follow-up period	Key findings	Notes/ limitations
				Total	Intervention	Control					
Isolated endodontic lesions	Yahata et al. (2023)	Multicentre RCT	2	24 teeth	12 teeth	12 teeth	Autologous CGF	Periapical; CBCT (modified PENN 3D)	1 year	No significant difference in success; CGF group showed faster lesion reduction	—
Isolated endodontic lesions	You et al. (2023)	RCT†	3	18 teeth	6/6 teeth	6 teeth	PRF membrane; CGF membrane	CBCT (bone-defect volume)	3, 6 months	PRF and CGF promote early (3 months) bone healing; no differences at 6 months	Anterior teeth only. †Small sample size.
Isolated endodontic lesions	Soto-Peñaloza et al. (2020)	RCT	2	50 subjects	25 subjects	25 subjects	A-PRF+	Visual analog scale; Likert scale-based questionnaire	1 week	No significant difference in pain perception	No evaluation of periapical healing. Maxillary teeth (second premolar to second premolar) only
Isolated endodontic lesions	Taschieri et al. (2014)	Retrospective cohort	3	20 subjects	8 subjects	12 subjects	Plasma rich in growth factors applied when Schneiderian membrane perforation occurred during EMS	Visual analog scale; Likert scale-based questionnaire	1 week	Significantly improved patients' quality of life	No evaluation of periapical healing. Only maxillary molars were included. Retrospective nature of study
Isolated endodontic lesions	Dominiak et al. (2009)	Non-randomised controlled cohort study	3	106 subjects/167 teeth	26/30/25 subjects	25 subjects	Resorbable collagen membrane (Bio-Gide); xenogenic collagen material (Bio-Oss Collagen material); xenogenic collagen material + PRP	Periapical	1 year	Superior efficacy of three GTR methods versus control	Retrograde filling with glass ionomer cement

(Continues)

TABLE 1 | (Continued)

Lesion type	Author (year)	Study design	OCEBM level	Number of subjects/teeth			Regenerative technique/ material	Evaluation tool	Follow-up period	Key findings	Notes/ limitations
				Total	Intervention	Control					
Isolated endodontic lesions	Garrett et al. (2002)	RCT†	3	25 teeth	16 teeth	9 teeth	Bioresorbable polylactic acid membrane (Guidor)	Periapical	1 year	No difference in healing rate	Detailed description of root resection and retrograde preparation and filling procedures lacking. †Small sample size. †High loss to follow-up
Combined endodontic-periodontal lesions	Sharma et al. (2025)	RCT	2	30 subjects	15 subjects	15 subjects	Demineralized freeze-dried bone allograft with a collagen membrane (PerioCol-GTR)	Periapical; CBCT (modified PENN 3D, labial alveolar bone height)	1 year	Both groups showed favourable outcomes; GTR (allograft + collagen) improved labial alveolar bone regeneration	—
Combined endodontic-periodontal lesions	Baruwa et al. (2023)	Case series	4	12 subjects/13 teeth	12 subjects/13 teeth	—	Resorbable membrane (Bio-Gide) ± bone graft (xenograft: Bio-Oss/ autogenous)	Periapical	2 to 9 years	Favourable long-term outcomes	—
Combined endodontic-periodontal lesions	Dhiman et al. (2015)	RCT	2	30 teeth	15 teeth	15 teeth	PRF	Periapical	1 year	No benefit of PRF	—
Combined endodontic-periodontal lesions	Goyal et al. (2011)	RCT†	3	25 teeth	10 teeth; 6 teeth; 9 teeth	—	Collagen membrane (Healiguide); PRP; PRP with collagen sponge (Collacote)	Periapical	1 year	PRP or PRP + collagen sponge showed similar outcomes to collagen membrane in apico-marginal defects; PRP may substitute GTR membrane	†Small sample size. †Active-controlled (no negative control). †High loss to follow-up

(Continues)

TABLE 1 | (Continued)

Lesion type	Author (year)	Study design	OCEBM level	Number of subjects/teeth			Regenerative technique/ material	Evaluation tool	Follow-up period	Key findings	Notes/ limitations
				Total	Intervention	Control					
Combined endodontic-periodontal lesions	Dietrich et al. (2003)	Case series	4	22 subjects/23 teeth	22 subjects/23 teeth	—	Inorganic bovine bone mineral (Bio-Oss) with collagen membrane (Bio-Gide)	Periapical	1 year	Favourable periapical and periodontal healing	Mainly evaluated about periodontal attachment
Through and through lesions	Dhamija et al. (2024)	RCT†	3	24 subjects/44 teeth	13 subjects/26 teeth	11 subjects/18 teeth	PRP	Periapical; CBCT (modified PENN 3D, RAC/B, volume of lesion)	5 years	PRP group showed significantly better 3D healing than control	Anterior teeth only. †Dropout rate of 25%
Through and through lesions	Arpitha et al. (2023)	RCT	2	34 subjects/68 teeth	18 subjects/32 teeth	16 subjects/36 teeth	i-PRF + Type I collagen	Periapical; CBCT (modified PENN 3D, volume of lesion, cortical window area)	1 year	No significant clinical or radiographic healing difference	Anterior teeth only
Through and through lesions; Isolated endodontic lesions	Bieszczad et al. (2023)	Retrospective cohort	3	15 teeth (through and through); 84 teeth (destruction of one plate); 62 teeth (isolated endodontic)	12 teeth (through and through); 46 teeth (destruction of one plate); 31 teeth (isolated endodontic)	3 teeth (through and through); 38 teeth (destruction of one plate); 31 teeth (isolated endodontic)	Not reported	CBCT (modified PENN 3D)	over 1 year	Effective in lesions $\geq 100\,mm^3$ and those with preoperative cortical plate destruction (one-sided or through-and-through)	Retrospective nature of study
Through and through lesions; Combined endodontic-periodontal lesions	Bieszczad et al. (2022)	Retrospective cohort	3	8 teeth (through and through); 23 teeth (lesions of volume $>475.5\,mm^3$); 21 teeth (combined endodontic-periodontal)	5 teeth (through and through); 13 teeth (lesions of volume $>475.5\,mm^3$); 7 teeth (combined endodontic-periodontal)	3 teeth (through and through); 10 teeth (lesions of volume $>475.5\,mm^3$); 14 teeth (combined endodontic-periodontal)	Not reported	CBCT (modified PENN 3D)	over 1 year	No significant impact was demonstrated	Retrospective nature of study

(Continues)

TABLE 1 | (Continued)

Lesion type	Author (year)	Study design	OCEBM level	Number of subjects/teeth			Regenerative technique/ material	Evaluation tool	Follow-up period	Key findings	Notes/ limitations
				Total	Intervention	Control					
Through and through lesions	Dhamija et al. (2020)	RCT	2	32 subjects/59 teeth	16 subjects/31 teeth	16 subjects/28 teeth	PRP	Periapical; CBCT (modified PENN 3D, RAC/B, volume of lesion)	1 year	PRP improves the healing outcome in through-and-through lesions	Anterior teeth only
Through and through lesions	Parmar et al. (2019)	RCT	2	30 subjects/49 teeth	15 subjects/29 teeth	15 subjects/20 teeth	Resorbable collagen membrane (Healiguide)	Periapical; CBCT (modified PENN 3D, RAC/B, volume of lesion)	1 year	Collagen membrane provided no additional benefit	—
Through and through lesions	Taschieri et al. (2012)	Case report	4	1 subject	1 subject	—	Plasma rich in growth factors + bovine bone (Bio-Oss spongiosa) with collagen membrane (Bio-Gide)	Periapical; CT scan	1 year	Growth factor concentrate + GTR may enhance hard and soft tissue healing	Retrograde filling with a zinc-oxide EBA-reinforced cement
Through and through lesions	Taschieri et al. (2011)	Retrospective cohort†	4	33 subjects/43 teeth	33 subjects/43 teeth	—	Bovine bone with a resorbable membrane	Periapical	4 years	EMS with GTR achieved excellent outcomes	†No control. Retrograde filling with a zinc-oxide EBA-reinforced cement. Retrospective nature of study
Through and through lesions	Taschieri et al. (2008)	RCT	2	25 subjects/31 teeth	17 teeth	14 teeth	Bovine bone (Bio-Oss spongiosa) with collagen membrane (Bio-Gide)	Periapical	1 year	GTR with anorganic bovine bone may enhance healing	Two-clinic setup with two operators. Retrograde filling with a zinc-oxide EBA-reinforced cement

(Continues)

TABLE 1 | (Continued)

Lesion type	Author (year)	Study design	OCEBM level	Number of subjects/teeth			Regenerative technique/ material	Evaluation tool	Follow-up period	Key findings	Notes/ limitations
				Total	Intervention	Control					
Isolated endodontic lesions; Through and through lesions	Taschieri et al. (2007)	RCT†	3	41 subjects/59 teeth	16 teeth (isolated endodontic); 8 teeth (through and through)	22 teeth (isolated endodontic); 13 teeth (through and through)	Bovine bone (Bio-Oss spongiosa) with collagen membrane (Bio-Gide)	Periapical	1 year	No added benefit of GTR with anorganic bovine bone	†Lesion type-specific randomization absent. †Unequal allocation ratio. Two-clinic setup with two operators. Retrograde filling with a zinc-oxide EBA-reinforced cement
Through and through lesions	Pecora et al. (2001)	RCT	2	20 subjects	10 subjects	10 subjects	Calcium sulphate (Surgiplaster)	Periapical	1 year	Calcium sulphate bone graft improved clinical outcome	Retrograde filling with super EBA
Lesion type not specified	Alkandari et al. (2024)	Retrospective cohort	3	33 subjects/53 teeth	19 teeth	34 teeth	Collagen membrane with or without allograft	CBCT (study specific criteria)	> 6 months	Performing the regenerative approach in EMS resulted in better healing rates	Retrospective nature of study
Lesion type not specified	Yan et al. (2023)	Prospective comparative cohort	3	54 subjects/67 teeth	31 subjects/41 teeth	23 subjects/26 teeth	CGF (alone or mixed with bone graft depending on defect size)	Periapical; CBCT (lesion diameter, presence of cortical bone perforation)	6,12,18 months	CGF group showed significantly higher success at all follow-ups	—
Lesion type not specified	Azim et al. (2021)	Retrospective cohort	3	68 subjects/83 teeth	56 teeth	27 teeth	Not reported	Periapical; CBCT (study specific scoring system)	1 to 3 years	GTR did not improve outcome but altered apical bone remodelling after EMS	Retrospective nature of study

(Continues)

TABLE 1 | (Continued)

Lesion type	Author (year)	Study design	OCEBM level	Number of subjects/teeth			Regenerative technique/ material	Evaluation tool	Follow-up period	Key findings	Notes/ limitations
				Total	Intervention	Control					
Lesion type not specified	Meschi et al. (2020)	RCT†	3	44 subjects	11 subjects; 11 subjects; 8 subjects	14 subjects	LPRF clots + LPRF membrane; LPRF clots + collagen membrane (Bio-Gide) + LPRF membrane; collagen membrane (Bio-Gide)	Ultrasound imaging; Periapical; CBCT (RAC/B, volume of lesion)	1 year	L-PRF showed no benefit; collagen membrane improved bone healing	†Small sample size
Lesion type not specified	Meschi et al. (2018)	RCT	2	50 subjects	12 subjects; 13 subjects; 10 subjects	15 subjects	LPRF clots + LPRF membrane; LPRF clots + collagen membrane (Bio-Gide) + LPRF membrane; collagen membrane (Bio-Gide)	Visual analog scale; Likert scale-based questionnaire	1 week	No significant evidence for improvement of patient's quality of life in patients with LPRF	No evaluation of periapical healing
Lesion type not specified	Pantchev et al. (2009)	Retrospective cohort	3	131 subjects/186 teeth	76 teeth	110 teeth	Bone graft substitute PerioGlas	Periapical	Short-term (9 months to 2 years) and long-term (33 months to more than 4 years)	PerioGlas showed no significant improvement in healing	Retrospective nature of study. Retrograde filling with super EBA

Note: Studies that did not perform root resection or used traditional techniques such as bur-based retrograde preparation were excluded. Levels of evidence were classified according to the OCEBM criteria (Howick et al. 2011) for therapy (Treatment Benefits). Level 1 = systematic review or meta-analysis of randomised trials or n-of-1 trials; Level 2 = individual randomised controlled trial (or observational study with dramatic effect); Level 3 = nonrandomized controlled cohort or follow-up study; Level 4 = case series or case–control study. Levels were downgraded one step (indicated with †) when major methodological limitations were identified, such as small sample size, nonrandomized design, inadequate control, high loss to follow-up, or other factors affecting study quality or internal validity. The specific reason for downgrading is noted in the 'Notes/limitations' column. Daggers (†) indicate the reason for downgrading, while other comments in this column denote general study limitations or notable characteristics.

Abbreviations: A-PRF+, advanced platelet-rich fibrin; CGF, concentrated growth factor; GTR, guided tissue regeneration; i-PRF, injectable platelet rich fibrin; LPRF, leukocyte and platelet rich fibrin; OCEBM, 2011 Oxford Centre for Evidence-Based Medicine criteria; PRF, platelet-rich fibrin; PRP, platelet rich plasma; RCT, randomised controlled trial.

smaller lesions tend to demonstrate more favourable healing, underscoring the prognostic relevance of lesion size. Recent CBCT-based investigations by Alkandari et al. (2024) and Bieszczad et al. (2022, 2023) further examined the relationship between lesion dimension and the effectiveness of adjunctive regenerative procedures in EMS, providing meaningful insights toward identifying a potential critical threshold at which these procedures may begin to confer additional benefit. Taken together, both lesion type and lesion dimension should be considered when determining the indication for adjunctive regenerative procedures in EMS. Future research should adopt rigorous, standardised designs that account for both parameters to establish evidence-based clinical guidelines. Well-controlled prospective studies and randomised clinical trials with long-term follow-up are particularly needed to clarify the specific conditions under which adjunctive regenerative procedures truly enhance healing and prognosis in EMS.

3.2 | Guided/Navigation Surgery and Robotic Technologies

The integration of digital technologies has enabled the emergence of guided EMS for improving surgical precision and predictability in anatomically complex situations (Setzer and Kratchman 2022). Although the added value may be limited in cases with severe bone loss, such as combined endodontic–periodontal or through-and-through lesions, where apical access is straightforward, guided EMS can provide substantial benefit in cases of isolated endodontic lesions with smaller defect sizes, where residual bone is preserved. When thick buccal cortical bone is present, locating the root apex becomes technically challenging and increases the overall surgical difficulty. In such situations, guided EMS may help improve outcomes by providing more accurate access and minimising procedural errors.

Static navigation using 3D-printed guides fabricated using CBCT and intraoral-scan data for osteotomy and root-end resection was the first guided approach to be clinically applied. These guides help surgeons follow preplanned trajectories with improved accuracy and reduced variability (Ahn et al. 2018; Giacomino et al. 2018; Kim, Kim, and Kim 2020; Lee, Yu, et al. 2020; Strbac et al. 2017). Cadaveric studies have demonstrated high resection accuracy and shorter procedure times (Ha et al. 2025; Westbrook et al. 2023), and Buniag et al. (2021) reported a 1-year clinical success rate of 91.7% based on a combined clinical and CBCT-based 3D assessment. This outcome is particularly meaningful considering that the majority of treated cases were anatomically challenging, involving the second molars and roots with limited accessibility, such as the maxillary palatal and mandibular distal roots.

Dynamic navigation was introduced to address the limitations of static guides such as fabrication errors, interocclusal space restrictions and inflexibility (Kapoor et al. 2025). These systems provide real-time feedback by tracking surgical instruments and displaying their positions relative to the plan, thereby enabling intraoperative adjustments. Cadaveric studies have shown that dynamic navigation reduces linear and angular deviations compared to freehand methods and shortens the operating time (Dianat et al. 2021). Martinho et al. (2022) reported that dynamic navigation improved the performance of both novice and experienced endodontists. Furthermore, a prospective clinical study with CBCT-based 3D assessment reported that the 1-year success rate of EMS with dynamic navigation was 94.3% (Chen et al. 2023).

Technical refinements have expanded the application of dynamic navigation beyond osteotomy and root-end resection to include ultrasonic retrograde preparation, which has been shown to reduce deviations across all surgical steps in vitro (Martinho et al. 2025). Additionally, augmented-reality head-mounted displays have been integrated to improve visual ergonomics, leading to lower deviations and improved time efficiency (Martinho et al. 2023). Despite these advances, the precision of the EMS partly depends on the operator's skill. To reduce operator variability further, robot-assisted systems with haptic guidance have been developed to provide real-time feedback and limit deviations from planned paths (Isufi et al. 2024; Liu et al. 2024). Liu et al. (2025) demonstrated that robotic systems can outperform dynamic navigation in both linear and angular deviations in vitro, whereas Chen et al. (2024) reported higher accuracy across multiple parameters compared to static and dynamic systems.

Overall, guided surgical systems from static and dynamic navigation to emerging robotic platforms have demonstrated promising precision and reproducibility in EMS. The reported 1-year success rates for static and dynamic navigation are > 90% (Buniag et al. 2021; Chen et al. 2023), and patient-related outcomes are comparable (Chen et al. 2025). These technologies can help address anatomical complexity, case difficulty, and operator variability and contribute to improved precision and reduced operating time. However, broader implementation requires careful consideration of costs and feasibility, and further evidence is needed to clarify its actual impact on long-term treatment outcomes. A comparative summary of these guidance modalities is provided in Table 2.

4 | Conclusions

This narrative review explored the current evidence on EMS according to the lesion type and discussed recent advances aimed at improving treatment outcomes. Adjunctive regenerative procedures and guided surgical systems represent important developments. Although supporting evidence continues to accumulate, their benefits are not yet clearly defined. Further high-quality studies with rigorous designs and long-term follow-up that consider the lesion type are needed to establish evidence-based indications and clarify their true impact on prognosis.

The decision to perform EMS should be grounded in a clear understanding of the lesion-specific prognostic factors and supported by evidence-based strategies. As the field continues to evolve, combining biologically informed principles with advanced surgical techniques is essential for improving outcomes and preserving the natural dentition in contemporary endodontic practice. Considering the ongoing technological progress and accumulating evidence of high success rates, expanding the clinical indications for EMS may be justified in carefully selected cases.

TABLE 2 | Comparative considerations of static, dynamic and robotic guidance systems in endodontic microsurgery.

Aspect	Static navigation	Dynamic navigation	Robot-assisted surgery
Principle	Preoperative CBCT and intraoral-scan data are merged to design a 3D-printed surgical guide for osteotomy and root-end resection	Real-time stereoscopic tracking system displays the instrument's position relative to the surgical plan, allowing intraoperative adjustment	Robotic arm or haptic-feedback system executes preplanned trajectories semi-autonomously under real-time monitoring
Key components	CBCT, intraoral scanner, planning software, 3D-printed guide, surgical motor/piezosurgery unit	CBCT, tracking camera, computer platform, navigation software, jaw and handpiece attachments	Robotic platform with integrated navigation, haptic sensors and adaptive control algorithms
Accuracy	High, but affected by fabrication and registration errors; cannot be modified intraoperatively	Higher accuracy with reduced linear and angular deviations; operator-dependent variability remains	Highest accuracy; minimal angular, platform and apical deviation compared with dynamic navigation
Intraoperative flexibility	None—the plan cannot be changed after guide fabrication	High—real-time feedback allows plan modification during surgery	Moderate—movement constrained by preprogrammed trajectory; limited manual override
Learning curve	Relatively simple once guide is fabricated	Requires training in calibration and software handling	Requires extensive technical and calibration training
Advantages	Simple workflow, cost-effective, consistent osteotomy path, reduced risk to adjacent structures	Real-time adjustability, preserves tactile feedback, faster operation time, effective even in posterior regions	Eliminates hand tremor, highest reproducibility, standardised precision in complex anatomy, potential for automation
Limitations	Rigid, cannot adapt intraoperatively, guide design errors propagate, limited access in posterior areas, not reusable	Operator-dependent variability, high equipment cost, potential lag or registration error	Very high cost and setup time, reduced tactile control, complex calibration requirements
Representative outcomes	1-year success ≈91.7% (Buniag et al. 2021)	1-year success ≈94.3% (Chen et al. 2023)	In vitro accuracy superior to dynamic navigation; early clinical validation ongoing (Liu et al. 2025)
Future directions	Simplify design and printing workflow, improve material sterilisability	Integrate ultrasonic and augmented reality-based visualisation, standardise calibration protocols	Shorten setup time, improve user-friendliness, incorporate adaptive algorithms and in vivo cost-effectiveness validation

Author Contributions

E.K. conceived and designed the study. U.K. wrote and prepared the original draft. U.K. and E.K. revised and edited the manuscript. All authors critically reviewed and approved the final manuscript.

Ethics Statement

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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