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CASE REPORT

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Long-term follow-up of regenerative endodontic therapy in immature permanent molars: a report of three cases

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Abstract

Background: Regenerative endodontic therapy (RET) is a biologically based treatment for immature permanent teeth with necrotic pulp that promotes root development through intracanal disinfection and the use of calcium silicate-based materials; however, long-term clinical and radiographic data for immature permanent molars remain limited. The purpose of this case report was to present the long-term clinical and radiographic outcomes of RET in immature mandibular first molars and to assess its clinical applicability. **Cases**: RET was performed in three immature mandibular first molars of 9-year-old patients with follow-up periods ranging from 5 to 10 years. RET was applied under varying clinical conditions, including pulp necrosis and irreversible pulpitis, with treatment selection influenced by immature root morphology and patient cooperation. Throughout the follow-up period, all treated teeth remained asymptomatic and showed continued root development with apical closure. Root maturation progressed more slowly than expected, with apical closure occurring approximately two years later than the typical developmental timeframe. **Conclusions**: These case reports describe long-term clinical and radiographic outcomes following RET in immature mandibular first molars. In our cases, root maturation and apical closure occurred later than expected in all treated teeth. However, this gradual development was not associated with adverse clinical findings during follow-up. Although limited by the small number of cases, these observations may support the possibility that RET is a viable treatment approach for some immature permanent molars.

Keywords

Regenerative endodontic therapy; Immature permanent molars; Apical closure

1. Introduction

Pulp necrosis and irreversible pulpitis in immature permanent teeth interrupt normal root development, resulting in thin root walls and an increased risk of fracture. Conventional apexification using calcium hydroxide promotes apical closure; however, despite its long history of clinical success, this technique has several limitations, including the lack of reinforcement of the root canal walls, the need for multiple visits, and prolonged treatment duration, all of which may affect patient compliance [1, 2]. Recent trends in the management of immature permanent teeth have shifted from traditional apexification to biologically based regenerative endodontic therapy (RET), which not only achieves periapical healing but also promotes structural reinforcement by increasing root length and dentinal wall thickness [3]. RET is primarily based on chemical disinfection, intracanal medication, induction of apical bleeding, and placement of calcium silicate-based materials to facilitate root development and periapical healing. Recent systematic reviews have further supported the growing clinical application of regenerative endodontic procedures because of their favorable healing outcomes and biologically based treatment concept [4].

Conventional endodontic procedures for immature permanent molars are often difficult to perform in pediatric patients or those with special needs because of limited cooperation. RET, which minimizes mechanical instrumentation and relies primarily on intracanal disinfection, offers a simpler approach requiring fewer clinical visits [1, 5]. Although earlier studies have suggested more favorable outcomes in teeth with wider apical diameters, recent evidence indicates that treatment success is not significantly associated with the stage of root development, including in immature mandibular molars [6–8]. This potential for continued root maturation is particularly important in the mandibular first molars, which are subjected to high occlusal loads and require sufficient root length and dentinal wall thickness for long-term stability.

Although RET has demonstrated encouraging results in immature permanent teeth, most reports involving mandibular molars have been limited to short- or mid-term follow-up periods [8, 9]. Consequently, long-term clinical and radiographic observations of the stability of root development, apical clo-

sure, and periapical healing remain limited.

This case report describes the long-term clinical and radiographic outcomes of RET in immature permanent molars with open apices, with a specific focus on the timeline of apical closure and the clinical significance of canal changes.

2. Case presentations

This study was approved by the Kyungbook National University Dental Hospital Institutional Review Board (protocol number: KNUDH-2026-03-01-00). Written informed consent was obtained from all patients and/or their legal guardians for the publication of this case report and accompanying radiographs.

All regenerative endodontic procedures were performed in accordance with the guidelines of the American Association of Endodontists (AAE). Following local anesthesia, access cavities were prepared using rubber dam isolation. The root canals were gently irrigated with 1.5% sodium hypochlorite (NaOCl) and saline while minimizing mechanical instrumentation, and were subsequently dried with paper points. A triple-antibiotic paste composed of ciprofloxacin, metronidazole, and minocycline was placed in the canals. A sterile cotton pellet was positioned over the medication, and the access cavity was temporarily sealed with provisional restorative material. Three weeks later, all patients returned without clinical symptoms such as pain, swelling, or fistula. Under rubber dam isolation and local anesthesia, the canal was irrigated with 1.5% NaOCl, saline, and 17% ethylenediaminetetraacetic acid (EDTA) and dried using paper points. A sterile file was inserted beyond the apex to induce intentional bleeding, and a calcium silicate-based barrier material was placed over the blood clot.

2.1 Case 1

In September 2019, a 9-year-old boy presented with gingival swelling in the left mandibular molar region. Clinical and radiographic examinations revealed a periapical radiolucent lesion associated with the left mandibular first molar (Fig. 1A), and pulpal necrosis was diagnosed. Regenerative endodontic treatment was performed according to the general principles recommended by the American Association of Endodontists, using Endocem MTA (Maruchi, Korea), a mineral trioxide aggregate (MTA) material, as the coronal barrier.

At the 2-month follow-up, a radiographic reduction in the periapical radiolucency was observed (Fig. 1B), and the tooth was restored with a stainless-steel crown. The patient remained asymptomatic during follow-up. At the 4-year and 4-month follow-up, complete resolution of the periapical lesion and apical closure were observed, along with pulpal canal obliteration (PCO) (Fig. 1C). At the last follow-up in January 2026, the tooth remained asymptomatic with no radiographic evidence of periapical pathology. Radiographic findings were comparable to those at the previous follow-up, with no further root development (Fig. 1D).

2.2 Case 2

A 9-year-old boy presented to our hospital in January 2016 with spontaneous pain in the right mandibular molar region. The patient reported that the pain persisted until 1 week prior to presentation but resolved spontaneously. Intraoral examination revealed extensive occlusal caries on the right mandibular first molar that was sensitive to percussion but not to palpation. Radiographic examination revealed deep occlusal caries involving the pulp, with an open apex (Fig. 2A). Based on clinical and radiographic findings, irreversible pulpitis was diagnosed, and regenerative endodontic treatment was performed according to the general principles recommended by the American Association of Endodontists using ProRoot MTA (Dentsply) as the coronal barrier material.

At the 3-month follow-up, the patient was asymptomatic, and the tooth was restored with composite resin (Fig. 2B). The patient remained asymptomatic throughout the 5-year follow-up period, with no clinical or radiographic evidence of periapical pathology during periodic evaluations. At the 15-month follow-up visit, radiography revealed evidence of PCO (Fig. 2C). Radiographic examination at five years revealed complete apical closure, which occurred between the 2-year and 5-year follow-up evaluations (Fig. 2D,E). At the last follow-up, in August 2021, the tooth remained asymptomatic.

2.3 Case 3

A 9-year-old girl presented in April 2015 with dental caries in the right mandibular molar region. The patient had an intellectual disability, which limited reliable pain assessment. Intraoral examination revealed extensive occlusal caries in the right mandibular first molar. The tooth was sensitive to percussion but not to palpation. Radiographic examination revealed a mild periapical radiolucency associated with the distal root of the right mandibular first molar (Fig. 3A). Irreversible pulpitis was diagnosed based on the clinical and radiographic findings. Considering the patient's limited cooperation, RET was selected to minimize the treatment complexity, and Endocem MTA (Maruchi, Korea) was used as the coronal barrier material.

The patient was followed up clinically and radiographically for 10 years. The patient remained asymptomatic throughout the follow-up period, and no periapical radiolucency was observed. At the 14-month follow-up visit, radiography revealed early signs of PCO (Fig. 3B). Complete apical closure was observed at the 5-year follow-up, and the radiographic findings remained stable at the last follow-up in May 2025 (Fig. 3C–E).

The clinical characteristics and long-term clinical and radiographic outcomes of the three patients are summarized in Table 1.

3. Discussion

This case report describes the long-term clinical and radiographic prognoses of RET in three immature mandibular first molars with different initial diagnoses. As summarized in Table 1, all treated teeth remained asymptomatic during the 5–10-year follow-up period. They showed resolution of the apical pathology and achieved apical closure despite variations in the initial diagnosis and clinical conditions.

In recent years, the management of immature permanent teeth has increasingly emphasized biologically based

FIGURE 1. Serial periapical radiographs of Case 1. (A) Pre-treatment periapical radiograph of the left mandibular first molar. (B–D) Radiograph at the 2-month, 4-year 4-month, 6-year follow-ups, demonstrating continued root development and progressive canal narrowing.

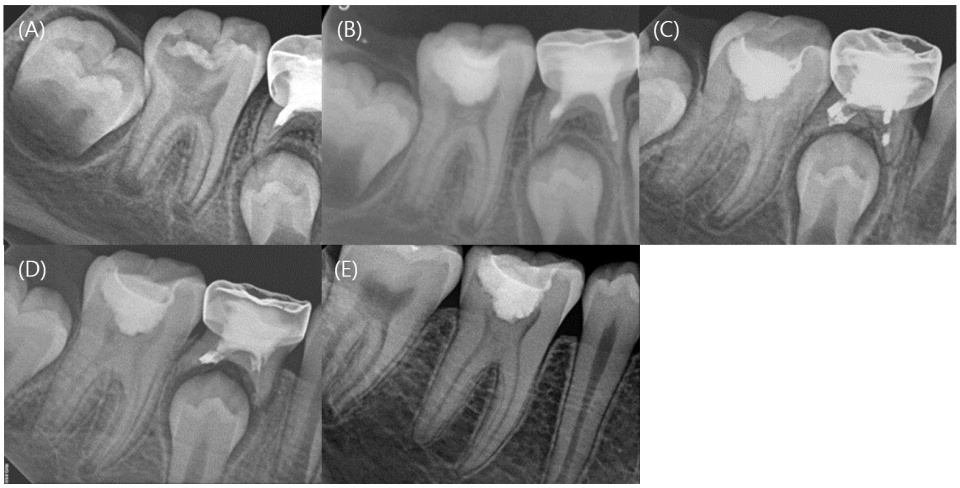

FIGURE 2. Serial periapical radiographs of Case 2. (A) Pretreatment periapical radiograph of the mandibular right first molar. (B–E) Radiographs at the 3-month, 15-month, 2-year, 5-year follow-ups demonstrating continued root development, apical closure, and progressive canal narrowing.

FIGURE 3. Serial periapical radiographs of Case 3. (A) Pretreatment periapical radiograph of the mandibular right first molar. (B–E) Radiographs at the 14-month, 3-year, 5-year, and 10-year follow-ups demonstrating continued root development, apical closure, and stable radiographic findings with progressive canal narrowing.

TABLE 1. Summary of clinical characteristics and outcomes of the three cases.

	Case 1	Case 2	Case 3
Diagnosis	Pulp necrosis	Irreversible pulpitis	Irreversible pulpitis
Follow-up period (yr)	6	5	10
Final restoration	SS crown	Composite resin	Composite resin
Clinical symptoms	Absent	Absent	Absent
Apical lesion	Absent	Absent	Absent
Root development	Present	Present	Present
Apical closure (yr)	2–4	2–5	2–5
Pulp canal obliteration	Present	Present	Present

SS: stainless steel.

approaches that minimize mechanical instrumentation and rely on chemical disinfection and intracanal medicaments to control infection and support healing. Recent evidence and systematic reviews suggest that regenerative endodontic therapy is increasingly recognized as a clinically favorable treatment approach in contemporary endodontic practice because of its potential to promote healing and preserve tooth structure [4]. This approach is particularly useful in view of the thin dentinal walls and increased susceptibility of the immature roots to structural weakening [10]. The biological potential of RET to support continued root maturation is particularly relevant in the mandibular first molars, which are subjected to substantial occlusal forces and require adequate root length and dentinal wall thickness for long-term stability [11]. In contrast to conventional apexification, which arrests root development, RET allows for the continued maturation and long-term functional preservation of teeth [1, 12]. Beyond these biological advantages, RET offers a pragmatic solution for specific patient populations, such as pediatric patients and those with intellectual disabilities. These patients often face challenges with behavioral management and may find it challenging to endure multiple prolonged appointments that are often required for traditional apexification. Given that conventional management of immature necrotic teeth often involves complex and prolonged procedures, RET may represent a clinically favorable alternative for patients with limited cooperation, as it can reduce treatment complexity [13]. RET can provide a more efficient and less invasive alternative, with a simplified clinical protocol that may help minimize chair time. In this report, all cases involved pediatric patients or patients with intellectual disabilities (Case 3). The simplified RET protocol facilitated successful treatment outcomes, whereas conventional methods may have been less feasible.

In these cases, RET was performed at approximately 9 years of age, when the mandibular first molars were near the completion of physiological root development [14]. Following RET, gradual root elongation was observed during the early post-treatment period with progressive increases in the root-to-crown ratio (Table 2). As follow-up continued, root development proceeded, and apical closure was radiographically confirmed at approximately 14 years of age in all cases. After apical closure, the root development remained stable during the extended follow-up period, particularly in Cases 1 and 3.

Physiological data indicate that apical closure of mandibular first molars typically occurs at 11–12 years of age [14, 15]. In comparison with previously reported physiologic root development timelines, apical closure in the present cases was radiographically observed at a relatively later age, approximately 2 years beyond the expected physiologic timeframe. However, long-term evidence regarding the timing of root maturation after RET remains limited, making direct comparison with physiologic root development difficult. In addition, prolonged root maturation after RET has been reported in long-term follow-up studies [16, 17]. Therefore, the relatively later timing of apical closure observed in the present cases should be interpreted with caution and may reflect the prolonged nature of post-treatment root maturation. Importantly, despite the delayed timing of apical closure, all treated teeth remained clinically asymptomatic and free of progressive periapical pathology throughout long-term follow-up, suggesting that a temporal lag in root development should not be interpreted as treatment failure.

All patients demonstrated radiographic evidence of PCO during the follow-up. Similar findings have frequently been reported following RET and are often interpreted as a reparative response rather than a true regeneration of the pulp–dentin complex [18, 19]. Histologic studies have suggested that the tissue formed within revascularized canals more closely resembles cementum-like, bone-like, or periodontal ligament-like tissue, rather than functional pulp tissue [20]. However, because histological examination and cone-beam computed tomography (CBCT) evaluation were not performed in the present cases, the exact nature of the obliterating tissue could not be confirmed. In the present cases, canal narrowing occurred predominantly during the early follow-up period and progressed slowly thereafter. Importantly, none of the treated teeth exhibited clinical symptoms or recurrent periapical disease, suggesting that radiographic PCO is not necessarily associated with unfavorable clinical outcomes [21]. Consistent with previous reports recommending a watchful-waiting approach for asymptomatic teeth with PCO, the present cases were followed conservatively, with periodic clinical and radiographic evaluations [22].

Current guidelines emphasize the importance of timely definitive coronal restoration, including full-coverage

TABLE 2. Apical closure status and root-to-crown ratio compared with physiologic reference values.

Parameter	9 yr	12 yr	14 yr	>14 yr
Physiologic apical closure (%)	41.2	92.2	100	100
Case 1 (root/crown ratio)	Open (1.40)	-	Closed (2.19)	Stable (2.20)
Case 2 (root/crown ratio)	Open (1.42)	Open (1.74)	Closed (2.07)	-
Case 3 (root/crown ratio)	Open (1.44)	Open (1.76)	Closed (1.79)	Stable (1.80)

Values in parentheses indicate root-to-crown ratios, which were descriptively assessed on serial periapical radiographs using consistent reference points between the cemento-enamel junction, cusp tip, and mesial root apex. Measurements were independently performed by two evaluators, demonstrating excellent inter-observer reliability (ICC = 0.918). "Stable" indicates no clinically meaningful change in root length during further follow-up, and all measurements should be interpreted within the limitations of longitudinal radiographic assessment.

restorations such as stainless-steel crowns, following RET to maintain an adequate coronal seal and provide structural protection. However, the present cases were retrospectively evaluated from routine clinical practice. Therefore, the timing of definitive restoration was influenced by clinical circumstances, including the patient's ability to tolerate additional procedures, treatment burden, and the clinician's judgment regarding the optimal timing for comprehensive treatment completion. Nevertheless, the treated teeth remained functional and asymptomatic throughout the long-term follow-up, and no restorative failures were observed. Although these patients showed favorable long-term survival, even when full-coverage restorations were delayed, the importance of definitive coronal protection should not be underestimated.

Although generalization of the findings from a limited number of cases is challenging, the long-term follow-up data presented here may offer preliminary insights into the clinical management of RET. First, the absence of clinical symptoms and evidence of progressive periapical healing should serve as the primary indicators of success. Second, clinicians should recognize that root maturation after RET may not coincide with the expected physiological timeframe, because definitive apical closure may be delayed by several years beyond the typical age of maturation. Third, the presence of PCO without associated symptoms should be considered clinically acceptable. This patient-centered approach to follow-up may help clinicians avoid unnecessary or premature interventions while biological healing and maturation are still ongoing.

The present report has several limitations. Owing to the small number of cases and the descriptive retrospective nature of this case report, the findings should be interpreted with caution and cannot be generalized. In addition, histological examinations and CBCT evaluations were not performed, and serial radiographic assessments were based on periapical radiographs obtained during routine clinical follow-up. Although root-to-crown ratios were assessed using consistent radiographic reference points and demonstrated excellent inter-observer reliability, the quantitative evaluation of root development and detailed characterization of tissues associated with pulp canal obliteration remain limited because of variations in radiographic angulation during long-term follow-up. A standardized assessment of coronal discoloration was not consistently available during follow-up because the present report primarily focused on the long-term functional and radiographic outcomes of regenerative endodontic therapy.

4. Conclusions

This case report describes the favorable long-term clinical and radiographic outcomes following RET in three immature mandibular first molars. In these cases, root maturation and apical closure were observed later than the expected physiological timeline; however, no adverse clinical findings were identified during follow-up. Given the limited number of cases and the retrospective nature of this report, these observations should be interpreted with caution. Nevertheless, the present cases suggest that a biologically based, minimally instrumented approach to RET may support favorable long-term outcomes in some immature permanent molars.

ABBREVIATIONS

RET, Regenerative endodontic therapy; PCO, Pulp canal obliteration; AAE, American Association of Endodontists; NaOCl, sodium hypochlorite; EDTA, ethylenediaminetetraacetic acid; MTA, mineral trioxide aggregate; SS, stainless steel; CBCT, cone-beam computed tomography.

AVAILABILITY OF DATA AND MATERIALS

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

AUTHOR CONTRIBUTIONS

NEK—wrote the first draft of the manuscript. SJL—contributed to manuscript revision and critical review of the manuscript. JSL—provided critical feedback and was responsible for the final approval of the manuscript. All authors contributed to this article and have commented on previous versions of the manuscript. All authors read and approved the final manuscript.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

The Institutional Review Board of the Kyungbook National University Dental Hospital approved this study (protocol no.

KNUDH-2026-03-01-00). Written informed consent was obtained from all patients and/or their legal guardians for the publication of this case report and accompanying radiographs.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest.

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