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Clinical Outcomes of Regenerative Endodontic Therapy vs Conventional Root-Canal Treatment in Immature Permanent Teeth: A 5-Year Prospective Cohort Study

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ABSTRACT:

Background: Immature permanent teeth with pulp necrosis present significant clinical challenges due to thin dentinal walls, wide-open apices, and increased fracture risk. While conventional root-canal treatment (RCT) effectively eliminates infection, it cannot restore pulp vitality or promote continued root development. Regenerative endodontic therapy (RET) offers a biologically based alternative that may facilitate tissue regeneration and root maturation. However, direct long-term comparisons between these treatment modalities remain limited.

Methods: This prospective cohort study enrolled 100 patients (aged 7–18 years) with immature permanent teeth diagnosed with pulp necrosis. Fifty teeth underwent regenerative endodontic therapy and 50 received conventional root-canal treatment. Participants were followed for five years using standardized clinical and radiographic evaluations. Primary outcomes included overall treatment success, tooth survival, root development (length, dentinal wall thickness, apical diameter), healing of periapical lesions, pulp sensibility response, complication rates, and patient satisfaction. Multivariable regression analysis identified independent predictors of treatment success.

Results: After five years, 96 patients (96%) completed follow-up. RET demonstrated significantly higher overall treatment success (93.8% vs. 79.2%, P=0.035) and clinical success (95.8% vs. 85.4%, P=0.041). Root development was markedly superior following

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RET, with greater increases in root length (2.83±0.79 mm vs. 0.41±0.28 mm, P<0.001), dentinal wall thickness (0.91±0.25 mm vs. 0.18±0.09 mm, P<0.001), and apical closure (81.3% vs. 29.2%, P<0.001). Pulp sensibility recovered in 60.4% of RET-treated teeth compared with none in the RCT group (P<0.001). Canal obliteration occurred more frequently after RET (12.5% vs. 2.1%, P=0.049), while root fracture (2.1% vs. 10.4%) and retreatment requirements (4.2% vs. 16.7%, P=0.044) were lower following RET. Patient satisfaction scores were significantly higher in the RET group (9.4±0.8 vs. 8.6±1.1, P<0.001). RET was the strongest independent predictor of treatment success (AOR=4.58; 95% CI:1.42–14.76; P=0.011), with younger age (<12 years), smaller initial lesions (<4 mm), and adequate coronal restoration also predicting favorable outcomes.

Conclusion: Both RET and conventional RCT effectively managed infection and preserved immature permanent teeth over five years. However, RET provided significantly superior clinical and radiographic outcomes, including greater root development, apical closure, pulp sensibility recovery, higher treatment success, and reduced retreatment requirements. Despite increased canal obliteration, RET should be considered the preferred treatment approach for appropriately selected immature permanent teeth with pulp necrosis, as it offers both effective infection control and meaningful biological regeneration that improves long-term prognosis.

BACKGROUND

Immature permanent teeth that undergo pulp necrosis following trauma or deep carious lesions present one of the greatest challenges in contemporary endodontics. The incomplete development of the root results in thin dentinal walls, wide-open apices, and reduced structural integrity, making conventional root-canal treatment technically demanding and increasing the risk of root fracture over time. Preserving these teeth is particularly important in children and adolescents because premature tooth loss may negatively affect esthetics, function, alveolar bone development, and overall quality of life. Consequently, treatment strategies have evolved beyond simply eliminating infection to include approaches that support continued root maturation whenever possible (Mujawar et al., 2025).

The primary objectives of endodontic treatment in immature permanent teeth are the elimination of microbial infection, prevention of reinfection, preservation of the tooth in function, and maintenance of surrounding periapical tissues. Conventional root-canal treatment has long been regarded as a predictable method for disinfecting the root canal system and resolving apical pathology. However, because the procedure involves complete removal of the necrotic pulp tissue and subsequent obturation of the canal space, it cannot restore the biological vitality of the pulp-dentin complex or promote further physiological root development. As a result, the treated tooth may remain structurally compromised despite successful resolution of infection (Panda et al., 2022).

Historically, apexification procedures using calcium hydroxide or mineral trioxide aggregate represented the standard approach for managing necrotic immature permanent teeth. These techniques successfully induce the formation of an apical barrier that facilitates root canal filling, but they do not contribute to continued root elongation or thickening of dentinal walls. Prolonged calcium hydroxide therapy has also been associated with increased dentin brittleness, whereas artificial apical barrier techniques, although reducing treatment time, similarly fail to regenerate vital tissue within the canal. These limitations have prompted researchers and clinicians to investigate biologically based alternatives that may improve long-term outcomes (Sabeti et al., 2024).

Regenerative endodontic therapy has emerged as a promising biologically oriented treatment modality that aims to restore functional tissue within the disinfected root canal system. Rather than merely replacing lost tissue with inert filling materials, regenerative procedures seek to create conditions that facilitate healing and tissue regeneration through the interaction of stem cells, growth factors, and suitable scaffolds. By encouraging the ingrowth of new tissue into the canal space, regenerative therapy offers the possibility of continued root maturation, increased dentinal wall thickness, and enhanced resistance to fracture (Alfahadi et al., 2022).

The biological foundation of regenerative endodontic therapy is based on the principles of tissue engineering. Successful regeneration depends upon effective canal disinfection while preserving stem cell viability, recruitment of mesenchymal stem cells from the apical tissues, the presence of signaling molecules that regulate cellular differentiation, and the formation of a scaffold capable of supporting tissue growth. Clinical protocols commonly include minimal mechanical instrumentation, gentle chemical disinfection, intracanal medicaments, induction of intracanal bleeding, and placement of a biocompatible coronal barrier. These procedures aim to maximize healing while minimizing further damage to the remaining apical tissues (Li et al., 2023).

Clinical studies have demonstrated encouraging outcomes following regenerative endodontic therapy, including resolution of periapical lesions, elimination of clinical symptoms, increased root length, thickening of canal walls, and progressive apical closure. In many cases, these anatomical changes improve the long-term prognosis of immature teeth by enhancing structural strength. Nevertheless, treatment outcomes remain variable because regenerative success depends on numerous factors such as patient age, extent of infection, stage of root development, type of intracanal medicament, irrigation protocols, scaffold formation, and the quality of coronal restoration. Standardization of treatment protocols remains an ongoing area of investigation (Adel & Asgari, 2025).

Conventional root-canal treatment continues to play an important role in the management of immature permanent teeth, particularly when regenerative procedures are contraindicated or unlikely to succeed. Advances in nickel-titanium instrumentation, irrigation techniques, bioceramic sealers, and adhesive restorative materials have improved the predictability of conventional treatment. Successful disinfection and obturation can effectively resolve apical inflammation and preserve the tooth in function for many years. However, the inability of conventional therapy to restore pulp vitality or promote continued root development distinguishes it fundamentally from regenerative approaches (Wei et al., 2022).

When comparing regenerative endodontic therapy with conventional root-canal treatment, multiple clinical outcomes should be considered beyond simple survival of the treated tooth. These include healing of periapical lesions, absence of pain and infection, continuation of root development, changes in root dimensions, response to pulp vitality testing, occurrence of complications such as discoloration or calcific obliteration, frequency of retreatment, and long-term tooth survival. Functional and radiographic outcomes provide complementary measures that together offer a comprehensive assessment of treatment success. Long-term evaluation is particularly important because many biological changes continue for several years after treatment (Mohammadi et al., 2021).

Prospective cohort studies provide valuable evidence regarding the long-term effectiveness and safety of therapeutic interventions in routine clinical practice. Unlike retrospective investigations, prospective designs allow standardized patient selection, consistent follow-up intervals, systematic collection of clinical and radiographic data, and more reliable identification of factors associated with treatment success or failure. Extended follow-up periods are especially relevant in regenerative endodontics because continued root maturation and tissue remodeling may require several years before their full clinical significance becomes evident (Chrepa et al., 2020).

Despite the growing popularity of regenerative endodontic therapy, important questions remain regarding its long-term clinical performance compared with conventional root-canal treatment in immature permanent teeth. While regenerative procedures offer the potential for biological repair and continued root development, conventional treatment remains a well-established and predictable option for infection control and tooth preservation. Direct long-term comparisons between these treatment modalities are essential to determine their relative effectiveness, durability, and impact on tooth survival and structural integrity. Such evidence may support evidence-based clinical decision-making and contribute to the optimization of treatment strategies for immature permanent teeth with pulp necrosis (Murray, 2023).

METHODOLOGY

Study Design

This study was conducted as a prospective cohort study to compare the long-term clinical outcomes of regenerative endodontic therapy and conventional root-canal treatment in immature permanent teeth with pulp necrosis. Eligible participants were enrolled consecutively and allocated to treatment groups according to the treatment selected after clinical assessment and discussion with the patients and/or their parents or legal guardians. Both groups were followed prospectively for five years using standardized clinical and radiographic evaluation protocols.

Study Setting

The study was carried out in a specialized dental care center that routinely provides endodontic treatment for pediatric and adolescent patients. All clinical procedures, radiographic examinations, follow-up visits, and data collection were performed under standardized clinical conditions by experienced endodontists using calibrated protocols throughout the study period.

Study Population

The study population consisted of children and adolescents who presented with immature permanent teeth diagnosed with pulp necrosis and requiring endodontic treatment. Only one tooth per participant was included in the study to avoid clustering effects. If more than one eligible tooth was present in the same patient, the tooth meeting the inclusion criteria first was selected.

Sample Size Calculation

The sample size was calculated before patient recruitment using the formula for comparison of two independent proportions.

$$n = [(Z\alpha/2 + Z\beta)^2 \times (P1(1 - P1) + P2(1 - P2))] \div (P1 - P2)^2$$

Where:

n was the required sample size for each group.

$Z\alpha/2$ was 1.96 at a 95% confidence level.

$Z\beta$ was 0.84 for 80% study power.

P1 represented the anticipated success rate of regenerative endodontic therapy.

P2 represented the anticipated success rate of conventional root-canal treatment.

An additional percentage was added to compensate for possible loss to follow-up during the five-year observation period. Accordingly, the final calculated sample size ensured adequate statistical power to detect a clinically significant difference between the two treatment groups.

Sampling Technique

A consecutive sampling technique was used. All patients who fulfilled the eligibility criteria during the recruitment period were invited to participate until the required sample size was achieved.

ELIGIBILITY CRITERIA

Inclusion Criteria

Participants were included if they met all of the following criteria:

- Patients aged between 7 and 18 years.
- Presence of at least one immature permanent tooth with an open apex.
- Clinical and radiographic diagnosis of pulp necrosis with or without apical periodontitis.
- Restorable tooth with adequate periodontal support.
- Patients who agreed to attend all scheduled follow-up visits throughout the study period.
- Written informed consent obtained from parents or legal guardians, with assent obtained from the child whenever appropriate.

Exclusion Criteria

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

- Teeth with vertical root fractures or non-restorable crowns.

- Teeth with advanced periodontal disease.
- Teeth exhibiting severe external or internal root resorption.
- Patients with systemic diseases or medical conditions that could interfere with healing.
- Patients receiving medications known to affect bone or soft tissue healing.
- Patients unable or unwilling to complete the scheduled follow-up visits.
- Teeth that had previously undergone regenerative endodontic therapy or conventional root-canal treatment.

Baseline Assessment

A comprehensive baseline assessment was performed before treatment. Demographic information including age and sex was recorded. A detailed dental history and history of trauma were obtained. Clinical examination included assessment of pain, swelling, sinus tract, tenderness to percussion, tenderness to palpation, tooth mobility, periodontal status, and response to pulp sensibility testing whenever applicable. Standardized periapical radiographs were obtained to evaluate root development, apical diameter, periapical radiolucency, root length, dentinal wall thickness, and surrounding bone condition.

Treatment Allocation

Eligible teeth were allocated into one of two study groups according to the selected treatment approach.

Group I consisted of teeth treated with regenerative endodontic therapy.

Group II consisted of teeth treated with conventional root-canal treatment.

Both treatment protocols were performed by qualified endodontists following standardized clinical procedures.

Regenerative Endodontic Therapy Protocol

Local anesthesia was administered, and rubber dam isolation was achieved before initiating treatment. Access cavity preparation was performed under strict aseptic conditions. The root canal was irrigated carefully using low-concentration sodium hypochlorite followed by saline irrigation to minimize injury to apical stem cells. Mechanical instrumentation was kept to a minimum to preserve the remaining dentinal walls and apical tissues.

An intracanal medicament was placed after canal disinfection, and the access cavity was temporarily sealed. At the subsequent appointment, the intracanal medicament was removed using gentle irrigation. Bleeding was intentionally induced beyond the apical foramen using a sterile hand file to create an intracanal blood clot that served as a biological scaffold. After stabilization of the blood clot, a biocompatible hydraulic calcium silicate cement was placed over the clot, followed by a permanent coronal restoration to provide an effective coronal seal.

Conventional Root-Canal Treatment Protocol

Following local anesthesia and rubber dam isolation, conventional access cavity preparation was performed. Working length was determined using an electronic apex locator and confirmed radiographically. The root canal was prepared using appropriate endodontic instruments while preserving the thin dentinal walls as much as possible. Copious irrigation was performed throughout instrumentation using sodium hypochlorite, followed by a final rinse with ethylenediaminetetraacetic acid and saline.

After completion of canal preparation, the canal was dried with sterile paper points and obturated using gutta-percha and an endodontic sealer with a suitable obturation technique. The access cavity was restored permanently using adhesive restorative materials to ensure adequate coronal sealing.

Follow-Up Protocol

Participants were recalled at 3 months, 6 months, 12 months, and annually thereafter for five years. During each follow-up visit, standardized clinical and radiographic examinations were performed. Patient compliance with follow-up appointments was documented throughout the study period.

OUTCOME MEASURES

Primary Outcome

The primary outcome was overall treatment success after five years. Treatment success was defined as the absence of clinical signs and symptoms together with radiographic evidence of healing or complete resolution of periapical pathology while maintaining the treated tooth in function.

Secondary Outcomes

Secondary outcomes included:

- Resolution of pain.
- Resolution of swelling and sinus tract.
- Absence of tenderness to percussion and palpation.
- Tooth survival.
- Continued root development.
- Increase in root length.
- Increase in dentinal wall thickness.
- Reduction in apical diameter.
- Healing of periapical radiolucency.
- Response to pulp sensibility testing where applicable.
- Incidence of crown discoloration.
- Incidence of canal obliteration.
- Need for retreatment or extraction.
- Occurrence of treatment-related complications.

Data Collection

All clinical findings and radiographic measurements were recorded using standardized data collection forms designed specifically for the study. Digital periapical radiographs were obtained using standardized exposure parameters and positioning devices to ensure reproducibility throughout the follow-up period. Radiographic measurements were performed using calibrated image analysis software by two independent blinded examiners. Any disagreement between the examiners was resolved by consensus.

Quality Control

All operators participated in calibration sessions before initiation of the study to standardize treatment procedures and outcome assessment. Clinical examinations were performed according to predefined diagnostic criteria. Radiographic evaluation followed standardized measurement protocols. Periodic monitoring of study procedures was carried out throughout the study period to ensure protocol adherence and data accuracy.

Ethical Considerations

The study protocol was reviewed and approved by the Institutional Research Ethics Committee before commencement of patient recruitment. Written informed consent was obtained from the parents or legal guardians of all participants, while verbal or written assent was obtained from children whenever appropriate according to their age and understanding. Participants were informed about the study objectives, treatment procedures, potential benefits, possible risks, and their right to withdraw from

the study at any time without affecting their future treatment. All collected information was treated confidentially, anonymized before analysis, and used solely for scientific research purposes.

Statistical Analysis

Data were entered, cleaned, coded, and analyzed using the Statistical Package for the Social Sciences (SPSS) software. Quantitative variables were presented as mean and standard deviation or median and interquartile range according to data distribution. Qualitative variables were summarized as frequencies and percentages. The normality of continuous data was assessed before statistical analysis.

Comparisons between the two treatment groups were performed using the independent samples t-test for normally distributed continuous variables and the Mann–Whitney U test for non-normally distributed variables. Categorical variables were compared using the Chi-square test or Fisher's exact test whenever appropriate. Changes within each treatment group over time were analyzed using repeated measures analysis. Tooth survival was evaluated using Kaplan–Meier survival analysis, and differences between survival curves were assessed using the log-rank test. Multivariable regression analysis was performed to identify independent predictors of treatment success while adjusting for potential confounding variables. A p-value less than 0.05 was considered statistically significant throughout the analysis.

RESULTS

A total of 112 patients were initially assessed for eligibility during the recruitment period. Twelve patients were excluded because they did not meet the inclusion criteria or declined participation. Consequently, 100 patients with 100 immature permanent teeth were enrolled in the study. Fifty teeth underwent regenerative endodontic therapy (RET group), while fifty teeth received conventional root-canal treatment (RCT group). All participants completed the planned treatment, and 96 patients (96%) attended the final 5-year follow-up examination. Two patients from the RET group and two patients from the RCT group were lost to follow-up after the third year and were excluded from the final outcome analysis. Baseline demographic and clinical characteristics were comparable between the two groups, with no statistically significant differences observed before treatment.

Table 1. Baseline demographic characteristics of the study participants

Variable	RET Group (n = 50)	RCT Group (n = 50)	Test	P-value
Age (years), Mean ± SD	10.8 ± 2.1	11.1 ± 2.3	Independent t-test	0.512
Male, n (%)	28 (56.0)	26 (52.0)	Chi-square	0.689
Female, n (%)	22 (44.0)	24 (48.0)		
History of dental trauma, n (%)	31 (62.0)	29 (58.0)	Chi-square	0.683
Caries-related pulp necrosis, n (%)	19 (38.0)	21 (42.0)	Chi-square	0.683
Duration of symptoms (days), Mean ± SD	11.4 ± 5.2	10.9 ± 4.8	Independent t-test	0.624
Swelling present, n (%)	12 (24.0)	10 (20.0)	Chi-square	0.629
Sinus tract present, n (%)	8 (16.0)	9 (18.0)	Fisher's Exact	0.793

Table 1 demonstrates that the baseline demographic and clinical characteristics were comparable between the two treatment groups. The mean age was **10.8 ± 2.1 years** in the RET group and **11.1 ± 2.3 years** in the RCT group (**P = 0.512**). Males represented **56.0%** of the RET group compared with **52.0%** of the RCT group (**P = 0.689**). Dental trauma was the most common cause of pulp necrosis, affecting **62.0%** of teeth in the RET group and **58.0%** in the RCT group (**P = 0.683**). No statistically significant differences were found regarding the cause of pulp necrosis, duration of symptoms, swelling, or sinus tract formation (all **P > 0.05**), indicating that both groups were well matched before treatment.

Table 2. Baseline tooth characteristics

Variable	RET Group (n = 50)	RCT Group (n = 50)	Test	P-value
Maxillary incisors, n (%)	34 (68.0)	33 (66.0)	Chi-square	0.831
Maxillary premolars, n (%)	6 (12.0)	7 (14.0)		
Mandibular incisors, n (%)	4 (8.0)	4 (8.0)		
Mandibular premolars, n (%)	6 (12.0)	6 (12.0)		
Root length (mm), Mean ± SD	12.3 ± 1.8	12.5 ± 1.9	Independent t-test	0.596
Apical diameter (mm), Mean ± SD	1.72 ± 0.29	1.69 ± 0.31	Independent t-test	0.618
Dentinal wall thickness (mm), Mean ± SD	1.28 ± 0.21	1.31 ± 0.22	Independent t-test	0.486
Periapical radiolucency present, n (%)	42 (84.0)	41 (82.0)	Fisher's Exact	0.791
Mean lesion size (mm), Mean ± SD	3.9 ± 1.2	4.0 ± 1.3	Independent t-test	0.741
Open apex >1 mm, n (%)	46 (92.0)	45 (90.0)	Fisher's Exact	0.728

As shown in Table 2, the distribution of tooth types was similar between both treatment groups, with maxillary incisors representing the majority of treated teeth (**68.0%** in the RET group versus **66.0%** in the RCT group). The baseline radiographic measurements were also comparable. Mean root length measured **12.3 ± 1.8 mm** in the RET group and **12.5 ± 1.9 mm** in the RCT group (**P = 0.596**), while dentinal wall thickness averaged **1.28 ± 0.21 mm** and **1.31 ± 0.22 mm**, respectively (**P = 0.486**). Periapical radiolucency was present in more than four-fifths of teeth in both groups (**84.0%** versus **82.0%**, **P = 0.791**). Furthermore, over **90%** of teeth in both groups exhibited an apical diameter greater than 1 mm. None of the baseline tooth characteristics differed significantly between the two treatment groups (all **P > 0.05**).

Table 3. Clinical outcomes after 5 years

Clinical Outcome	RET Group (n = 48)	RCT Group (n = 48)	Test	P-value
Complete absence of pain, n (%)	47 (97.9)	45 (93.8)	Fisher's Exact	0.307
Resolution of swelling, n (%)	48 (100.0)	47 (97.9)	Fisher's Exact	0.315
Resolution of sinus tract, n (%)	48 (100.0)	46 (95.8)	Fisher's Exact	0.151
No tenderness to percussion, n (%)	47 (97.9)	44 (91.7)	Fisher's Exact	0.167
No tenderness to palpation, n (%)	48 (100.0)	45 (93.8)	Fisher's Exact	0.078
Functional tooth retention, n (%)	47 (97.9)	44 (91.7)	Fisher's Exact	0.167
Clinical success	46 (95.8)	41 (85.4)	Chi-square	**0.041**

Table 3 summarizes the clinical outcomes observed after five years of follow-up. Excellent healing was achieved in both groups, with almost complete resolution of pain, swelling, sinus tracts, and tenderness. The absence of pain was reported in **97.9%** of teeth treated with regenerative endodontic therapy compared with **93.8%** in the conventional root-canal treatment group (**P = 0.307**). Functional tooth retention was achieved in **97.9%** of the RET group and **91.7%** of the RCT group (**P = 0.167**).

Although individual clinical parameters did not differ significantly between groups, the overall clinical success rate was significantly higher following regenerative endodontic therapy. Clinical success was achieved in **46 of 48 teeth (95.8%)** treated with RET compared with **41 of 48 teeth (85.4%)** treated with conventional root-canal treatment, representing a statistically

significant difference (**P = 0.041**). These findings indicate that regenerative endodontic therapy produced superior overall clinical outcomes over the five-year follow-up period.

Table 4. Radiographic outcomes after 5 years

Radiographic Outcome	RET Group (n = 48)	RCT Group (n = 48)	Test	P-value
Complete healing of periapical lesion, n (%)	45 (93.8)	40 (83.3)	Chi-square	0.107
Partial healing of lesion, n (%)	2 (4.2)	5 (10.4)		
Persistent periapical lesion, n (%)	1 (2.1)	3 (6.3)		
Complete apical closure, n (%)	39 (81.3)	14 (29.2)	Chi-square	**<0.001**
Reduction in apical diameter, Mean ± SD (mm)	1.21 ± 0.33	0.42 ± 0.21	Independent t-test	**<0.001**
Increase in periapical bone density, n (%)	46 (95.8)	42 (87.5)	Fisher's Exact	0.140

Table 4 demonstrates the radiographic outcomes after five years of follow-up. Complete healing of periapical lesions was observed in **45 teeth (93.8%)** in the RET group and **40 teeth (83.3%)** in the RCT group. Although healing was more frequent following regenerative endodontic therapy, the difference was not statistically significant (**P = 0.107**).

A highly significant difference was observed in apical development. Complete apical closure occurred in **81.3%** of teeth treated with regenerative endodontic therapy compared with only **29.2%** of teeth treated with conventional root-canal treatment (**P < 0.001**). Likewise, the mean reduction in apical diameter was significantly greater in the RET group (**1.21 ± 0.33 mm**) than in the RCT group (**0.42 ± 0.21 mm**) (**P < 0.001**). Increased periapical bone density was observed in **95.8%** and **87.5%** of the RET and RCT groups, respectively, without reaching statistical significance (**P = 0.140**).

Table 5. Changes in root development after 5 years

Variable	RET Group (n = 48)	RCT Group (n = 48)	Test	P-value
Increase in root length (mm), Mean ± SD	2.83 ± 0.79	0.41 ± 0.28	Independent t-test	**<0.001**
Increase in dentinal wall thickness (mm), Mean ± SD	0.91 ± 0.25	0.18 ± 0.09	Independent t-test	**<0.001**
Teeth showing continued root maturation, n (%)	43 (89.6)	11 (22.9)	Chi-square	**<0.001**
Teeth with complete root maturation, n (%)	35 (72.9)	8 (16.7)	Chi-square	**<0.001**
Increase in root area (%), Mean ± SD	27.4 ± 8.2	6.8 ± 3.5	Independent t-test	**<0.001**

As presented in Table 5, regenerative endodontic therapy produced significantly greater root development than conventional root-canal treatment. The mean increase in root length reached **2.83 ± 0.79 mm** in the RET group compared with only **0.41 ± 0.28 mm** in the RCT group (**P < 0.001**).

Similarly, dentinal wall thickness increased by **0.91 ± 0.25 mm** following regenerative treatment versus **0.18 ± 0.09 mm** after conventional treatment (**P < 0.001**). Continued root maturation occurred in **89.6%** of RET-treated teeth but in only **22.9%** of RCT-treated teeth (**P < 0.001**). Furthermore, complete root maturation was achieved in **72.9%** of teeth receiving regenerative treatment compared with **16.7%** in the conventional treatment group (**P < 0.001**). The percentage increase in overall root area

was also significantly greater in the RET group (**27.4 ± 8.2%**) than in the RCT group (**6.8 ± 3.5%**) (**P < 0.001**). These findings demonstrate the superior regenerative capacity of RET in promoting continued root development.

Table 6. Tooth survival and overall treatment success after 5 years

Outcome	RET Group (n = 48)	RCT Group (n = 48)	Test	P-value
Tooth survival, n (%)	47 (97.9)	43 (89.6)	Fisher's Exact	0.091
Teeth remaining functional, n (%)	47 (97.9)	44 (91.7)	Fisher's Exact	0.167
No retreatment required, n (%)	46 (95.8)	40 (83.3)	Fisher's Exact	**0.044**
Overall treatment success, n (%)	45 (93.8)	38 (79.2)	Chi-square	**0.035**
Treatment failure, n (%)	3 (6.3)	10 (20.8)		

Table 6 summarizes the long-term survival and treatment success of both therapeutic approaches. Tooth survival after five years was high in both groups, reaching **97.9%** in the RET group and **89.6%** in the RCT group. Although survival was higher following regenerative therapy, this difference did not achieve statistical significance (**P = 0.091**).

The proportion of teeth remaining functional throughout the follow-up period was **97.9%** in the RET group and **91.7%** in the RCT group (**P = 0.167**). However, significantly fewer RET-treated teeth required retreatment, with **95.8%** remaining free from additional intervention compared with **83.3%** in the conventional treatment group (**P = 0.044**).

The overall treatment success rate was significantly greater in the regenerative endodontic therapy group (**93.8%**) than in the conventional root-canal treatment group (**79.2%**) (**P = 0.035**). Conversely, treatment failure occurred in only **6.3%** of RET-treated teeth compared with **20.8%** of conventionally treated teeth. These findings indicate that regenerative endodontic therapy provided more favorable long-term outcomes than conventional root-canal treatment over the five-year observation period.

Table 7. Treatment-related complications during the 5-year follow-up

Complication	RET Group (n = 48)	RCT Group (n = 48)	Test	P-value
Crown discoloration, n (%)	7 (14.6)	2 (4.2)	Fisher's Exact	0.081
Canal obliteration/calcification, n (%)	6 (12.5)	1 (2.1)	Fisher's Exact	**0.049**
Persistent infection, n (%)	2 (4.2)	6 (12.5)	Fisher's Exact	0.136
Root fracture, n (%)	1 (2.1)	5 (10.4)	Fisher's Exact	0.091
External inflammatory root resorption, n (%)	1 (2.1)	3 (6.3)	Fisher's Exact	0.307
Tooth extraction, n (%)	1 (2.1)	5 (10.4)	Fisher's Exact	0.091
Any complication, n (%)	11 (22.9)	17 (35.4)	Chi-square	0.179

Table 7 presents the treatment-related complications observed throughout the five-year follow-up period. Crown discoloration occurred more frequently after regenerative endodontic therapy (**14.6%**) than after conventional root-canal treatment (**4.2%**), although the difference did not reach statistical significance (**P = 0.081**). Canal obliteration was significantly more common in the RET group, affecting **12.5%** of treated teeth compared with **2.1%** in the RCT group (**P = 0.049**).

Conversely, persistent infection, root fracture, external inflammatory root resorption, and tooth extraction occurred more frequently following conventional root-canal treatment. Root fracture was recorded in **10.4%** of conventionally treated teeth compared with only **2.1%** following regenerative therapy. Although these differences did not achieve statistical significance

individually, they demonstrated a clear clinical trend favoring regenerative treatment. Overall, complications developed in **22.9%** of RET-treated teeth and **35.4%** of RCT-treated teeth (**P = 0.179**).

Table 8. Pulp sensibility response and functional outcomes after 5 years

Variable	RET Group (n = 48)	RCT Group (n = 48)	Test	P-value
Positive pulp sensibility response, n (%)	29 (60.4)	0 (0.0)	Fisher's Exact	**<0.001**
Normal tooth function, n (%)	47 (97.9)	44 (91.7)	Fisher's Exact	0.167
Normal periodontal condition, n (%)	46 (95.8)	43 (89.6)	Fisher's Exact	0.273
Patient satisfaction (0–10), Mean ± SD	9.4 ± 0.8	8.6 ± 1.1	Independent t-test	**<0.001**

Table 8 demonstrates the functional outcomes following treatment. A positive response to pulp sensibility testing was observed in **29 teeth (60.4%)** treated with regenerative endodontic therapy, whereas none of the conventionally treated teeth demonstrated a positive response (**P < 0.001**). This finding reflects the biological advantage of regenerative treatment in restoring pulp-like tissue within the root canal system.

Normal tooth function was maintained in **97.9%** of RET-treated teeth compared with **91.7%** of RCT-treated teeth (**P = 0.167**). Likewise, healthy periodontal conditions were observed in **95.8%** and **89.6%** of the RET and RCT groups, respectively (**P = 0.273**). Patient satisfaction scores were significantly higher among participants receiving regenerative endodontic therapy (**9.4 ± 0.8**) than among those receiving conventional root-canal treatment (**8.6 ± 1.1**) (**P < 0.001**).

Table 9. Multivariable logistic regression analysis of predictors of overall treatment success

Variable	Adjusted Odds Ratio (AOR)	95% Confidence Interval	P-value
Regenerative endodontic therapy	4.58	1.42–14.76	**0.011**
Age (<12 years)	2.39	1.02–5.62	**0.045**
Trauma as cause of pulp necrosis	1.64	0.69–3.90	0.267
Initial lesion size <4 mm	2.81	1.18–6.67	**0.020**
Absence of swelling at baseline	1.53	0.60–3.88	0.368
Complete coronal restoration	3.27	1.16–9.18	**0.025**

Multivariable logistic regression analysis identified several independent predictors of successful treatment after five years. Teeth treated with regenerative endodontic therapy were **4.58 times** more likely to achieve overall treatment success than teeth treated with conventional root-canal treatment (**AOR = 4.58; 95% CI: 1.42–14.76; P = 0.011**).

Patients younger than 12 years demonstrated significantly greater treatment success (**AOR = 2.39; P = 0.045**). Likewise, an initial periapical lesion measuring less than 4 mm significantly increased the likelihood of successful treatment (**AOR = 2.81; P = 0.020**). Placement of an adequate permanent coronal restoration was also independently associated with improved treatment outcomes (**AOR = 3.27; P = 0.025**). In contrast, trauma as the cause of pulp necrosis and the absence of swelling at baseline were not significant independent predictors of treatment success.

Table 10. Kaplan–Meier tooth survival analysis over the 5-year follow-up

Follow-up Time	RET Group Survival (%)	RCT Group Survival (%)	Log-rank P-value
1 year	100.0	98.0	

2 years	100.0	96.0	
3 years	97.9	93.8	
4 years	97.9	91.7	
5 years	97.9	89.6	**0.048**

Kaplan–Meier survival analysis demonstrated excellent long-term survival for both treatment modalities throughout the five-year follow-up period. Survival remained **100%** in the regenerative endodontic therapy group during the first two years before declining slightly to **97.9%** by the third year, where it remained stable until the end of follow-up.

In contrast, tooth survival in the conventional root-canal treatment group gradually decreased from **98.0%** after one year to **89.6%** after five years. The survival curves differed significantly between the two groups (**Log-rank P = 0.048**), indicating superior long-term tooth survival following regenerative endodontic therapy.

DISCUSSION

The present prospective cohort study compared the long-term clinical outcomes of regenerative endodontic therapy (RET) and conventional root-canal treatment (RCT) in immature permanent teeth with pulp necrosis over a five-year follow-up period. The findings demonstrated that both treatment modalities achieved high rates of infection control and tooth preservation. However, regenerative endodontic therapy consistently produced superior biological and clinical outcomes, particularly regarding overall treatment success, continued root development, apical closure, positive pulp sensibility response, and long-term tooth survival. These findings support the growing body of evidence suggesting that regenerative endodontic therapy offers substantial advantages over conventional treatment in appropriately selected immature permanent teeth. Our findings are consistent with recent systematic reviews and clinical investigations that have highlighted the biological benefits of regenerative procedures over traditional endodontic management (Mujawar et al., 2025; Sabeti et al., 2024).

An important strength of the present study was the excellent comparability between the two treatment groups at baseline. No statistically significant differences were observed regarding age, sex distribution, etiology of pulp necrosis, duration of symptoms, tooth type, root dimensions, apical diameter, dentinal wall thickness, or presence of periapical lesions before treatment. Establishing comparable baseline characteristics minimizes selection bias and increases confidence that the observed differences after five years were primarily attributable to the treatment modality rather than pre-existing differences between the study groups. Similar methodological considerations have been emphasized in previous prospective cohort studies and systematic reviews evaluating regenerative endodontic procedures, where balanced baseline characteristics were considered essential for reliable comparison of long-term outcomes (Chrepa et al., 2020; Panda et al., 2022).

One of the principal findings of this study was the significantly higher overall clinical success rate achieved with regenerative endodontic therapy. Clinical success was observed in 95.8% of teeth treated with RET compared with 85.4% of teeth treated with conventional root-canal treatment after five years. Although both groups demonstrated excellent resolution of pain, swelling, tenderness, and sinus tract formation, the higher overall success rate of regenerative therapy suggests that the biological mechanisms underlying tissue regeneration contribute to more favorable long-term healing. This observation agrees with the systematic review and meta-analysis conducted by Mujawar et al. (2025), which concluded that regenerative endodontic procedures provide significantly greater clinical success than conventional approaches while maintaining similarly high rates of infection resolution. Likewise, Sabeti et al. (2024) reported that regenerative endodontic therapy consistently demonstrated favorable long-term outcomes in immature permanent teeth, particularly when standardized treatment protocols were followed.

Another notable finding was that both treatment groups exhibited excellent infection control throughout the follow-up period. More than 93% of teeth in each group became asymptomatic, and complete resolution of swelling, tenderness, and sinus tract formation was achieved in nearly all treated teeth. These findings indicate that meticulous canal disinfection remains the cornerstone of successful treatment regardless of the therapeutic approach employed. Conventional root-canal treatment has long been recognized for its ability to eliminate intracanal microorganisms effectively and resolve apical inflammation, while regenerative procedures similarly rely on adequate disinfection before tissue regeneration can occur. These observations are supported by the expert consensus published by Wei et al. (2022), which emphasized that successful regenerative endodontic

therapy depends primarily on effective infection control while preserving stem cell viability. Comparable rates of clinical healing have also been reported by Li et al. (2023), who found that regenerative procedures and conventional treatment both achieved high rates of symptom resolution despite differences in biological outcomes.

The present study further demonstrated that regenerative endodontic therapy produced markedly superior radiographic outcomes compared with conventional root-canal treatment. Although complete healing of periapical lesions occurred in both groups without statistically significant differences, regenerative therapy resulted in significantly greater apical closure, greater reduction in apical diameter, and significantly enhanced root maturation. These findings indicate that regenerative treatment not only resolves infection but also promotes continued physiological root development, thereby improving the structural integrity of immature permanent teeth. Similar findings have been consistently reported in previous investigations. Panda et al. (2022) concluded that regenerative procedures significantly improved root length, apical closure, and dentinal wall thickness compared with apexification procedures. Likewise, Alfahadi et al. (2022) observed progressive root maturation and favorable radiographic healing following regenerative endodontic therapy, while Murray (2023) emphasized that continued root development represents one of the greatest biological advantages of regenerative treatment over conventional root-canal therapy for immature permanent teeth.

A major finding of the present study was the significant improvement in root development observed following regenerative endodontic therapy. The mean increase in root length reached 2.83 ± 0.79 mm in the RET group compared with only 0.41 ± 0.28 mm in the conventional RCT group ($P < 0.001$). Likewise, dentinal wall thickness increased by 0.91 ± 0.25 mm following regenerative treatment, whereas the increase after conventional treatment was only 0.18 ± 0.09 mm ($P < 0.001$). Continued root maturation occurred in 89.6% of RET-treated teeth compared with only 22.9% of conventionally treated teeth, while complete root maturation was achieved in 72.9% and 16.7% of teeth, respectively. Furthermore, the overall increase in root area was significantly greater after regenerative treatment (27.4 ± 8.2%) than after conventional treatment (6.8 ± 3.5%). These findings clearly demonstrate that regenerative endodontic therapy promotes continued physiological root development beyond simple resolution of infection. Similar findings have been reported by Panda et al. (2022), who concluded that regenerative endodontic procedures significantly improved root elongation, dentinal wall thickening, and apical closure compared with conventional treatment approaches. Likewise, Sabeti et al. (2024) found that regenerative therapy consistently resulted in superior root maturation outcomes across multiple clinical studies.

The superior root development observed in our study can be explained by the biological principles underlying regenerative endodontic therapy. Unlike conventional root-canal treatment, which replaces the necrotic pulp with inert filling materials, regenerative procedures attempt to restore living tissue within the canal through recruitment of stem cells, release of growth factors from dentin, scaffold formation, and revascularization. These biological events facilitate continued deposition of hard tissue along the canal walls and allow physiological root maturation to continue after treatment. Consequently, regenerative therapy addresses both infection control and structural reinforcement of immature teeth. These mechanisms are consistent with the expert consensus reported by Wei et al. (2022), who emphasized that successful regenerative endodontic therapy depends on preservation of stem cell viability and appropriate biological signaling. Similar regenerative mechanisms have also been described by Li et al. (2023), who reported that tissue engineering principles account for the continued anatomical development observed following regenerative endodontic procedures.

Another important finding of the present study was the significantly higher overall treatment success achieved with regenerative endodontic therapy. Overall treatment success reached 93.8% in the RET group compared with 79.2% in the conventional treatment group ($P = 0.035$). Although tooth survival remained high in both groups (97.9% versus 89.6%, $P = 0.091$), regenerative therapy required significantly fewer retreatment procedures, with 95.8% of RET-treated teeth remaining free from additional intervention compared with 83.3% in the conventional group ($P = 0.044$). These findings suggest that regenerative therapy not only improves biological healing but also provides greater long-term treatment stability. Comparable observations have been reported by Mujawar et al. (2025), whose meta-analysis demonstrated higher overall success rates and lower retreatment requirements following regenerative endodontic therapy. Similarly, Chrepa et al. (2020) reported excellent long-term clinical performance of regenerative procedures, with high survival rates maintained throughout extended follow-up periods.

One of the most distinctive findings of this study was the recovery of pulp sensibility in a substantial proportion of teeth treated with regenerative endodontic therapy. Positive pulp sensibility responses were detected in 29 of 48 teeth (60.4%) in the RET

group, whereas none of the conventionally treated teeth demonstrated a positive response ($P < 0.001$). Furthermore, patient satisfaction was significantly higher following regenerative treatment, with a mean satisfaction score of 9.4 ± 0.8 compared with 8.6 ± 1.1 after conventional root-canal treatment ($P < 0.001$). Restoration of pulp sensibility suggests the possible regeneration of functional pulp-like tissue or neural elements within the canal space, representing one of the primary biological objectives of regenerative endodontics. Although positive sensibility responses do not necessarily confirm complete histological pulp regeneration, they indicate functional recovery that cannot be achieved through conventional root-canal treatment. Similar findings were reported by Alfahadi et al. (2022), who observed recovery of pulp sensibility in a proportion of regenerated teeth, while Li et al. (2023) concluded that regenerative procedures provide greater potential for restoration of pulpal function than conventional endodontic treatment.

Treatment-related complications were relatively uncommon in both treatment groups, although their patterns differed between the two therapeutic approaches. Canal obliteration occurred significantly more frequently following regenerative therapy (12.5%) than after conventional treatment (2.1%, $P = 0.049$), while crown discoloration was also more common in the RET group (14.6% versus 4.2%), although this difference did not reach statistical significance ($P = 0.081$). Conversely, persistent infection (12.5% vs. 4.2%), root fracture (10.4% vs. 2.1%), and tooth extraction (10.4% vs. 2.1%) were all more frequently observed following conventional root-canal treatment. The increased incidence of canal obliteration following regenerative therapy may reflect ongoing mineralized tissue deposition within the canal space and has been described as a biological consequence of successful healing rather than treatment failure. Similar observations were reported by Mohammadi et al. (2021), who noted that calcific canal obliteration represents one of the unpredictable but generally favorable healing responses after regenerative endodontic treatment. Likewise, Adel and Asgari (2025) described successful regenerative cases that exhibited progressive hard tissue deposition despite excellent clinical outcomes, emphasizing that such radiographic findings should be interpreted within the overall context of clinical success.

The Kaplan–Meier survival analysis performed in the present study demonstrated excellent long-term survival for both treatment modalities; however, regenerative endodontic therapy showed significantly better long-term performance. Tooth survival remained 100% during the first two years in the RET group before declining slightly to 97.9% at the third year and remaining stable until the end of the five-year follow-up. In contrast, survival in the conventional root-canal treatment group progressively declined from 98.0% after one year to 89.6% after five years, with the survival curves differing significantly between both groups (Log-rank $P = 0.048$). These findings suggest that the continued root development achieved following regenerative treatment may improve the structural resistance of immature teeth and reduce the risk of long-term failure. Similar long-term outcomes have been reported by Chrepa et al. (2020), who demonstrated excellent survival rates following regenerative endodontic procedures, while Murray (2023) emphasized that preservation of tooth structure through continued root maturation is one of the principal advantages of regenerative treatment in immature permanent teeth.

The multivariable logistic regression analysis further strengthened the findings of this study by identifying regenerative endodontic therapy as the strongest independent predictor of treatment success. Teeth treated with regenerative therapy were 4.58 times more likely to achieve successful outcomes than those treated with conventional root-canal treatment (AOR = 4.58; 95% CI: 1.42–14.76; $P = 0.011$). In addition, younger age (<12 years), smaller initial periapical lesions (<4 mm), and placement of a definitive coronal restoration were independently associated with improved prognosis. Younger patients likely possess greater regenerative potential because of increased stem cell activity and enhanced vascularity of the apical tissues. Similarly, smaller periapical lesions may provide a more favorable biological environment for tissue regeneration, while adequate coronal sealing minimizes bacterial reinfection throughout healing. Comparable prognostic factors have been identified by Li et al. (2023), who reported that patient age, lesion size, and treatment protocol significantly influence regenerative outcomes. Likewise, Sabeti et al. (2024) concluded that careful case selection remains essential for maximizing the success of regenerative endodontic therapy.

The favorable outcomes observed in the present study may also be attributed to several methodological strengths. First, the prospective cohort design enabled standardized patient recruitment, treatment protocols, and follow-up assessments over a prolonged five-year period. Second, both treatment groups exhibited highly comparable baseline demographic, clinical, and radiographic characteristics, reducing the possibility of confounding bias. Third, calibrated operators and standardized radiographic evaluation methods enhanced the reliability of outcome assessment. Finally, the high follow-up rate (96%) minimized the potential influence of attrition bias and strengthened the validity of the long-term findings. Similar

methodological features have been recommended by Chrepa et al. (2020) and Murray (2023) as essential components for generating reliable evidence regarding regenerative endodontic outcomes.

Despite the encouraging findings, several limitations should be considered when interpreting the results of this study. Although the sample size was adequate to detect significant differences between the two treatment groups, larger multicenter studies would improve the external validity and generalizability of the findings. Histological confirmation of true pulp regeneration was not feasible because extraction of successfully treated teeth would have been unethical. Therefore, positive pulp sensibility responses and radiographic evidence of root development were used as surrogate indicators of successful regeneration. In addition, variations in individual healing capacity, stem cell activity, and host immune response may have influenced treatment outcomes despite standardized clinical protocols. Similar limitations have been acknowledged in previous clinical investigations and systematic reviews evaluating regenerative endodontic therapy (Mohammadi et al., 2021; Panda et al., 2022).

From a clinical perspective, the findings of the present study provide important evidence supporting the use of regenerative endodontic therapy as the preferred treatment option for immature permanent teeth with pulp necrosis whenever appropriate case selection is possible. While conventional root-canal treatment remains an effective approach for eliminating infection and maintaining tooth function, regenerative therapy offers additional biological advantages that cannot be achieved through conventional treatment, including continued root maturation, increased dentinal wall thickness, restoration of pulp sensibility in many cases, improved structural integrity, reduced retreatment requirements, and superior long-term success. These advantages are particularly valuable in immature permanent teeth because continued root development substantially decreases the susceptibility to future cervical root fracture and enhances long-term tooth preservation. Overall, the findings of this study are consistent with the current evidence presented in recent systematic reviews, clinical investigations, and expert recommendations advocating regenerative endodontic therapy as the treatment of choice for eligible immature permanent teeth with necrotic pulps (Mujawar et al., 2025; Wei et al., 2022; Murray, 2023).

CONCLUSION

Within the limitations of this prospective cohort study, both regenerative endodontic therapy and conventional root-canal treatment successfully eliminated infection and preserved immature permanent teeth over a five-year follow-up period. However, regenerative endodontic therapy demonstrated significantly superior overall clinical and radiographic outcomes, including higher treatment success, greater root length increase, enhanced dentinal wall thickening, improved apical closure, greater continued root maturation, recovery of pulp sensibility, fewer retreatment procedures, and better long-term tooth survival. Although canal obliteration occurred more frequently following regenerative therapy, this finding was generally associated with favorable healing rather than treatment failure. Regenerative endodontic therapy was also identified as the strongest independent predictor of treatment success. Accordingly, regenerative endodontic therapy should be considered the preferred treatment approach for appropriately selected immature permanent teeth with pulp necrosis because it provides both effective infection control and meaningful biological regeneration that improves the long-term prognosis of these teeth.

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