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Comparison of trabecular bone structure on periapical radiographs one year after apexification with MTA and regenerative endodontic treatment: a retrospective cohort study

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Abstract

Background This study aimed to evaluate and compare periapical healing by analyzing the architecture of post-treatment trabecular bone using fractal analysis (FA) following mineral trioxide aggregate (MTA) apexification and regenerative endodontic treatment (RET), as well as to investigate the correlation between FA findings and Periapical Index (PAI).

Methods A total of 37 patients (20 treated with apexification and 17 with RET) were included in the study. All selected teeth were single-rooted maxillary anterior incisors. Patients were divided into two groups based on the treatment received: either apexification or RET. At 12-month follow-up, periapical radiographs were obtained. From the designated regions of interest (ROI) on these radiographs, fractal dimension (FD) values were calculated, and PAI assessed by two observers were recorded. The Wilcoxon test was used to assess differences in time changes between measurements. Differences between groups were evaluated using the Mann-Whitney U test. Statistical significance was set at $p < 0.05$.

Results There was a statistically significant difference between the FD of the ROI post-operatively and at follow-up in both, the apexification and the RET treatment groups ($p < 0.001$). No statistically significant difference was observed in the changes in FD at the 12-month follow-up between the apexification and the RET group ($p > 0.05$). In the apexification treatment group, a moderate negative correlation was observed between the changes in PAI and the changes in FD values (Spearman's rho = −0.444, $p = 0.049$), indicating that increases in trabecular bone complexity (higher FD values) were associated with lower PAI. In contrast, in the RET group no statistically significant correlation was found between the changes in PAI and the changes in FD values ($p > 0.05$).

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Conclusion Both MTA apexification and RET support structural bone healing in the periapical region. FA offers an objective approach for quantifying changes in trabecular bone architecture and may enhance the radiographic assessment of periapical healing when used alongside conventional methods.

Clinical trial number Not applicable – retrospective analysis.

Keywords Apexification, Endodontic, Fractal analysis, Fractal dimension, Regenerative endodontic treatment

Introduction

The primary objective of root canal treatment is to clean and shape the canal system and achieve a three-dimensional obturation to prevent or heal apical periodontitis [1]. In immature permanent teeth with pulp necrosis, however, treatment is particularly challenging due to the wide apical foramen and thin dentinal walls, which make canal disinfection and apical sealing difficult using conventional methods [2].

In the past, immature permanent teeth with open apices were treated using multi-step calcium hydroxide dressings [3]. With the introduction of materials such as mineral trioxide aggregate (MTA), treatment strategies have evolved, and currently two main options are considered: apexification and regenerative endodontic treatment (RET) [4]. While apexification aims at inducing the formation of an artificial apical barrier to allow adequate obturation and resolution of apical pathology, the main objectives of RET include: (1) resolution of clinical symptoms and healing of apical periodontitis, (2) continued root development through apical closure and dentinal wall thickening, and (3) regeneration of pulp-like tissue that may contribute to a positive response to vitality testing [4]. The main limitation of apexification is the absence of further root maturation, which increases the long-term risk of cervical fracture [5]. Whereas for RET, outcomes remain variable, complete histological regeneration is rarely achieved and the need for longer treatment times [6].

Both apexification and RET have demonstrated favorable outcomes, with reported healing rates ranging from approximately 74% to 100% for apexification [7], and from 78% to 96% for RET [8]. However, rather than being interchangeable, apexification and RET represent distinct therapeutic strategies, each with specific indications determined by the clinical and biological characteristics of the individual case [9]. Although both treatments demonstrate high short-term success rates, their biological goals and healing mechanisms differ; therefore, a direct comparison provides insights into distinct patterns of periapical repair and root development. Factors including the patient's age, the stage of root development, or the presence of extensive periapical pathology should be taken into account during the decision-making process as these variables will have an impact on the success of each treatment option [10].

Periapical radiographs are widely used in endodontics, for diagnostic, treatment and follow-up purposes due to their accessibility, sufficient image resolution for detecting periapical pathology, and relatively low radiation dose compared to three-dimensional imaging modalities such as cone-beam computed tomography (CBCT) [11]. In most endodontic cases, a 12-month follow-up period is considered sufficient to evaluate treatment outcomes, as radiographic signs of healing typically become apparent within this timeframe [11]. In the literature, the degree of radiographic healing is commonly assessed using the periapical index (PAI), a widely used semi-quantitative method. However, this method as known limitations such as subjectivity in interpretation and reliance on two-dimensional radiographic images [12, 13].

Fractal analysis (FA) quantifies the structural complexity of trabecular bone within a region of interest (ROI) by assigning it a numerical value. Higher fractal dimension (FD) values indicate greater trabecular complexity, which reflects ongoing angiogenesis and bone remodeling [12, 14]. Previous studies have confirmed significant correlations between FD and the physical properties of bone, supporting its reliability as a tool for evaluating structural changes during healing [12, 15].

Hence, this study aimed to evaluate and compare periapical healing by analyzing the architecture of newly formed trabecular bone using FA following apexification and RET. Additionally, the study investigates the relationship between FA findings and the PAI. The null hypothesis is that there is no statistically significant difference in the periapical bone characteristics of healed lesions between the apexification and RET approaches.

Materials and methods

Sample selection

This retrospective study received ethical approval from the Local Ethics Committee (Date: 19.02.2025/Approval ID: 2025/86). The study protocol was designed in accordance with the principles of the Declaration of Helsinki. The required sample size was determined through a power analysis (G*Power, ver. 3.1.9.2, Franz Faul; Universitat Kiel, Germany) based on preliminary data, indicating that a minimum of 28 samples would be necessary to achieve a statistical power of 0.95, with an alpha level of 0.05 and an effect size of 1.34 [2, 12, 16]. The study

population consisted of 37 patients (12 males, 25 females) with a median age of 19 years.

Inclusion criteria –RET group

- Immature permanent teeth with an apical foramen diameter greater than 1.1 mm [9].
- Presence of a permanent tooth with an open apex and clinically confirmed pulp necrosis (i.e., no response to cold or electric pulp testing), along with radiographic evidence of apical pathology.
- Evidence of periapical pathology demonstrated as a periapical radiolucency measuring ≤ 5 mm in diameter.
- Absence of spontaneous pain, swelling, or the presence of an active sinus tract at the time of treatment.
- No history of systemic conditions (e.g. diabetes mellitus, osteoporosis, chronic kidney disease, immunodeficiencies, or the use of corticosteroids, bisphosphonates, or chemotherapeutic agents) known to interfere with periapical tissue healing or regenerative outcomes.
- Adequate remaining coronal tooth structure sufficient to enable proper rubber dam isolation and coronal sealing.

Inclusion criteria – Apexification (MTA barrier Technique) group

- Immature permanent teeth with clinically confirmed pulp necrosis (i.e., no response to cold or electric pulp testing) and radiographically confirmed apical periodontitis (i.e., presence of periapical radiolucency), deemed unsuitable for RET due to factors such as history of repeated dental trauma, radiographic signs of root canal calcification or obliteration, or previous failed RET attempts.
- Clinical scenarios necessitating rapid formation of an apical barrier to facilitate timely placement of definitive coronal restorations (e.g., for prosthetic or orthodontic treatment planning).
- Absence of systemic conditions or medications known to adversely affect periapical healing or hard tissue regeneration, such as diabetes mellitus, osteoporosis, chronic kidney disease, immunodeficiencies, or the use of corticosteroids, bisphosphonates, or chemotherapeutic agents.

Exclusion criteria

- Patients with systemic diseases or bone metabolism disorders (e.g., diabetes, osteoporosis, hypo/hyperparathyroidism), or those taking medications that could affect bone healing.
- Teeth with periodontal pockets > 3 mm or a diagnosis of generalized chronic periodontitis.
- Presence of clinical signs and symptoms such as sinus tract.
- Teeth with multiple roots or canals, internal or external root resorption, root fractures, or teeth that had undergone apical surgery.
- Cases with a follow-up period shorter than 12 months.
- Teeth requiring corono-radicular restorations due to extensive coronal tissue loss were excluded.

Treatment procedure

RET procedure

All RET procedures were performed by a single experienced endodontist (S.D.) with over 10 years of clinical experience and were completed in two appointments, under aseptic conditions.

First appointment

Infiltrative local anesthesia was administered using Ultracain® (Sanofi Aventis, Levent, Istanbul). The tooth was isolated with a rubber dam and the access cavity prepared using a sterile diamond round bur (Dentsply Sirona, Ballaigues, Switzerland). The working length was determined with an apex locator (ProPex Pixi, Dentsply Sirona, Ballaigues, Switzerland) and confirmed radiographically.

Minimal mechanical debridement was performed gently using H-type stainless steel hand files (Dentsply Sirona, Ballaigues, Switzerland) to remove necrotic tissue. The root canal was irrigated with 20 mL of 1.5% sodium hypochlorite (NaOCl) followed by 20 mL of 17% ethylenediaminetetraacetic acid (EDTA) (Coltène/Whaledent AG, Altstätten, Switzerland) using a 30-gauge side-vented needle placed 1 mm short of the working length.

After drying the canal with sterile paper points, calcium hydroxide paste (Ultradent Products, South Jordan, UT, USA) was placed as an intracanal medicament for 1 week. The access cavity was temporarily sealed with Cavit™ (3 M ESPE, St Paul, MN, USA), and the patient was recalled after one week.

Second appointment

Infiltrative local anesthesia without vasoconstrictor (Sefacain®, Sanofi Aventis) was administered. After rubber dam isolation, the the temporary filling was removed. Calcium hydroxide was removed using 17% EDTA (20 mL), activated ultrasonically with an Ultra X device (Changzhou, China) coupled with a flexible X Silvertip (25.02), following the manufacturer's protocol. Activation

was performed in three cycles of 20 s each (1 mm short of the working length).

After drying, bleeding was induced using a pre-curved K-file size #10 and #15 (Dentsply Sirona, Ballaigues, Switzerland) 2 mm beyond the apex. The canal was allowed to fill with blood up to the cementoenamel junction (CEJ). Bleeding was successfully induced in the majority of cases; however, in two cases ($n = 2$), adequate intracanal bleeding could not be achieved despite repeated attempts. These cases were therefore excluded from the RET group and subsequently treated using the MTA apexification protocol. A blood clot was stabilized at approximately 3 mm below the CEJ using sterile cotton pellets. A 3 mm layer of MTA (Cerkamed, Poland) was placed over the clot, followed by a 2–3 mm layer of glass ionomer cement (Fuji IX™, Japan), which was light-cured for 40 s. The final restoration was completed using composite resin (3 M ESPE, St Paul, MN, USA).

MTA apexification procedure

All apexification procedures using MTA (Cerkamed, Poland) were carried out over two appointments by a single experienced endodontist (S.D) under aseptic conditions.

First appointment

A similar protocol to the one described for the RET group was followed.

Second appointment

Following administration of local anesthesia and rubber dam isolation, the temporary restoration was removed. Calcium hydroxide was removed using 10 mL of 2.5% NaOCl and 10 mL of 17% EDTA (Coltène/Whaledent AG, Altstätten, Switzerland) which was activated ultrasonically using an Ultra X device (Changzhou, China) using a flexible X Silvertip file (25.02), positioned 1 mm short of the working length. Ultrasonic activation was performed in three cycles of 20 s each.

After drying the canal with paper points, MTA (Cerkamed, Poland) was mixed and delivered into the apical portion of the canal using an MTA-carrier (MAP System, Produits Dentaires SA, Switzerland), and gently condensed using a micro-plugger until a 3–4 mm apical plug was formed. A moist cotton pellet was placed to facilitate the setting of MTA, and the cavity was sealed temporarily with Cavit™ (3 M ESPE, St Paul, MN, USA). After 72 h, the setting of the MTA was confirmed clinically, the coronal third of root canal filled with warm gutta-percha (Eighteeth, China) and AH plus sealer (Dentsply Sirona, Ballaigues, Switzerland). Then, the tooth was restored definitively using composite resin (3 M ESPE, St Paul, MN, USA).

Treatment success and failure criteria

Treatment outcomes were evaluated based on the clinical and radiographic success criteria defined by the American Association of Endodontists (AAE, 2021) for immature necrotic permanent teeth [17]. The treatment was considered *successful* if all of the following criteria were satisfied:

- Absence of clinical signs and symptoms, such as pain, swelling, and sinus tract formation.
- Radiographic evidence of healing, defined as resolution or reduction of the preoperative periapical radiolucency.
- In cases treated with RET, additional signs of continued root development such as apical closure and/or increased dentinal wall thickness.

In contrast, treatment was considered unsuccessful if one or more of the following criteria were observed:

- Persistence or recurrence of clinical symptoms (e.g., pain, swelling, or sinus tract).
- Lack of radiographic healing or progression of periapical pathology.
- Absence of continued root development in RET cases.
- Tooth loss resulting from endodontic failure, structural compromise, or extraction.

These criteria facilitated standardized outcome evaluation in accordance with current AAE clinical considerations.

Periapical radiographs

All digital periapical radiographs of the anterior maxillary region were acquired using a standardized periapical radiographic unit (Gendex Expert DC; Hatfield, USA), equipped with size #2 photo-stimulable phosphor (PSP) plates and consistent exposure parameters (65 kV, 7 mA, 0.32 s). To ensure standardized projection geometry, an extension cone paralleling film holder specifically designed for anterior teeth was employed, and all images were obtained using a parallel technique. The images were scanned and digitized using a high-resolution scanner (Express; Instrumentarium, Tuusula, Finland), and saved as Tagged Image File Format (TIFF) files for further analysis. A blinded dentomaxillofacial radiologist (S.Y.), selected the post-treatment and 12-month follow-up radiographs. Prior to evaluation, all periapical radiographs were anonymized.

Fractal analysis

FA was conducted on standardized periapical radiographs using ImageJ software (version 1.53; National

Institutes of Health, Bethesda, MD, USA), a 64-bit, Java-based open-source platform. All radiographs were analyzed on a Dell Precision T5400 workstation (Dell, Round Rock, TX, USA) with a 19-inch monitor at a resolution of 1920 × 1080 pixels (Dell E190S, China). To maintain consistency across analyses, all images were resized to 878 × 1144 pixels prior to evaluation.

All measurements were performed by a blinded dentomaxillofacial radiologist (S.Y.). For each image, the ROI was selected from the apical area of maxillary anterior teeth exhibiting periapical lesions, as shown in Fig. 1. A

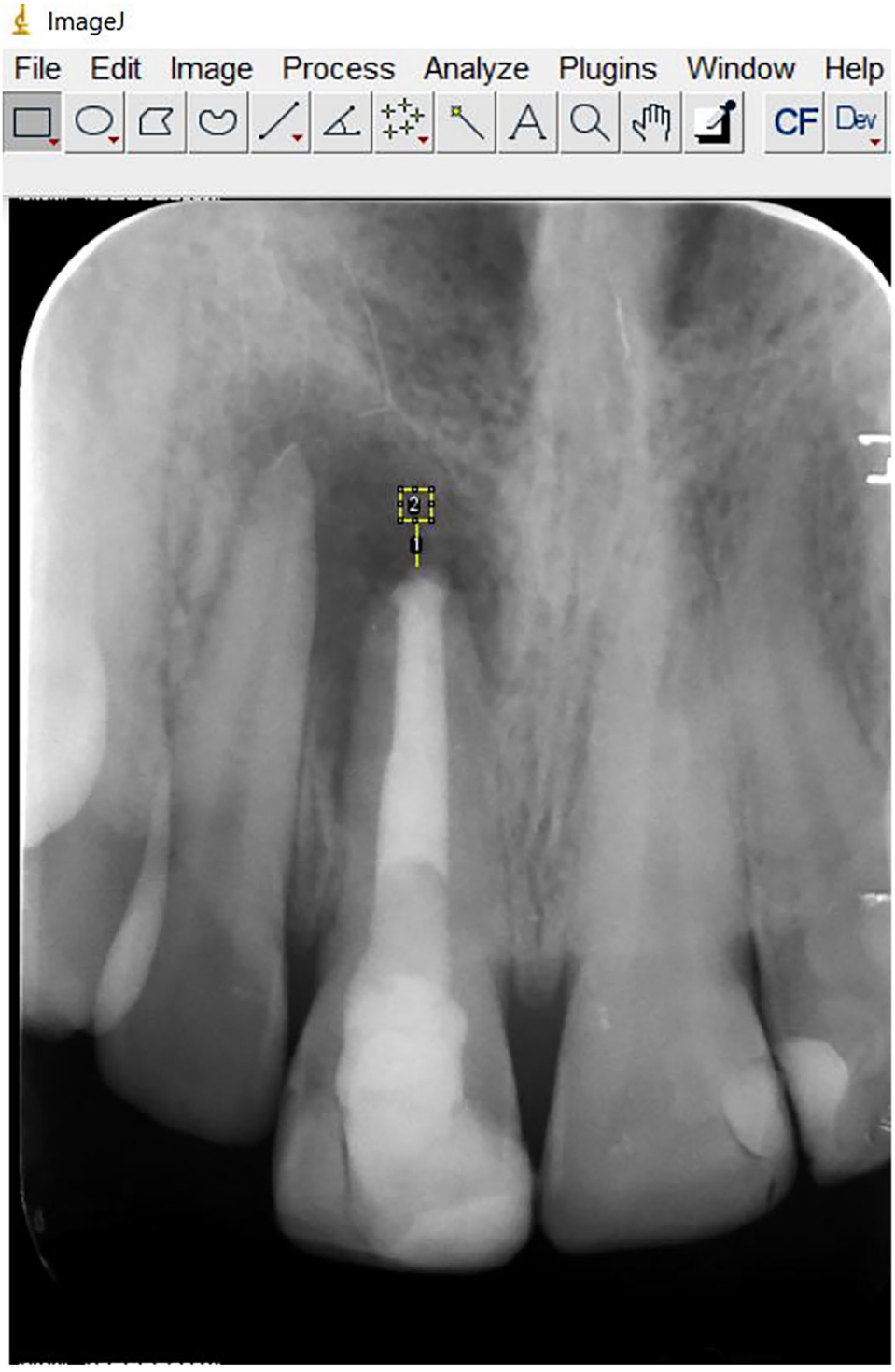


Fig. 1 Illustration of region of interest (ROI) selection for fractal analysis on a standardized periapical radiograph

standardized square ROI measuring 30 × 30 pixels was placed 1 mm apical to the root apex and centered within the lesion, avoiding contact with the lamina dura to prevent cortical bone interference. To standardize brightness and contrast, the ROI was cropped and duplicated. The duplicate image was subtracted from the original, followed by the addition of a gray value of 128. Binarization was applied using a fixed threshold value of 128. The image then underwent a series of processing steps, including erosion, dilation, inversion, and skeletonization (Supplementary Figure). FD of the resulting skeletonized image was calculated using the box-counting method through custom software developed by White and Rudolph [18].

In order to evaluate measurement reproducibility, 15 radiographs were randomly selected and re-analyzed by the same radiologist 14 days after the initial evaluation, under identical conditions and blinded to the initial results. The intraclass correlation coefficient (ICC) was calculated and found to be 0.914 indicating excellent measurement repeatability.

12-month follow-up evaluation

The initial assessment of 12-month follow up post-treatment outcomes was conducted using the PAI, a well-established five-point radiographic classification method [13]. Radiographs were independently assessed by two experienced endodontists (A.T.E.A. and I.E.A.), who were blinded to treatment allocation and timepoint. Prior to formal scoring, the observers underwent a calibration session involving 20 anonymized periapical radiographs representing the full range of PAI categories (PAI 1–5). The observers achieved consensus on these sample images based on the original criteria by Ørstavik et al. [13], ensuring standardization of interpretation.

Following calibration, each evaluator independently scored the radiographs. In cases of disagreement, a final consensus score was determined. To assess intra- and inter-observer reliability for PAI, Cronbach's alpha values were calculated. The intra-observer alpha values were (0.921 for A.T.E.A. and 0.914 for I.E.A.), and the inter-observer alpha was (0.928 for T0 measurement, 0.923 for T1 measurement), indicating high internal consistency.

Statistical analysis

All statistical analyses were performed using IBM SPSS Statistics software (version 23.0; IBM Corp., Armonk, NY, USA). Descriptive statistics for continuous variables were presented as median (minimum–maximum) due to non-normal data distribution, while categorical variables were reported as frequencies and percentages. The normality of continuous variables was assessed using the Kolmogorov–Smirnov test. Since the assumptions for parametric testing were not satisfied, non-parametric tests were employed for inferential analysis. The Wilcoxon signed-rank test was used to evaluate intra-group differences over time, while the Mann–Whitney U test was applied for comparisons between independent groups. The Spearman rank correlation coefficient was calculated to assess potential associations between continuous variables. Intra-observer reliability for repeated FD measurements was assessed using the ICC. ICC values were interpreted as follows: <0.5 = poor, 0.5–0.75 = moderate, 0.75–0.9 = good, and >0.9 = excellent reliability [19]. A p-value < 0.05 was considered statistically significant.

Results

Among the 37 patients included in the study, 12 (32.4%) were male and 25 (67.6%) were female, with a median age of 19 years (range: 10–46). Twenty (54.1%) subjects were in the apexification group and 17 (45.9%) in the RET group. The median age in the apexification and RET group was 19 years (range: 15–46) and 18 years (range: 10–33), respectively. In the RET group, apical closure was observed in 82.36% of cases, root lengthening in 94.12%, and dentinal wall thickening in 100%. These parameters were evaluated radiographically using standardized measurements at 12-month follow-up. Overall success based on AAE criteria was achieved in 88,2% of cases in the RET group and 95% in the apexification group (Table 1) (Fig. 2).

No statistically significant difference in FD value changes between sexes within both groups were observed ($p > 0.05$) (Table 2).

A statistically significant increase was found in the FD values of the ROI from baseline to the 12-month follow-up in the apexification ($p < 0.001$) and RET group ($p < 0.001$) (Table 3). A comparison of FD values at baseline and at 12-month follow-up between the two groups is shown in Fig. 3.

However, no statistically significant difference was found in the magnitude of FD changes between the apexification and RET groups at the 12-month follow-up ($p = 0.976$) (Table 3).

As shown in Fig. 4, a statistically significant negative correlation was observed between changes in PAI and FD values in the apexification group ($r = -0.444$, $p = 0.049$), indicating that greater improvements in bone architecture (higher FD values) were associated with lower PAI. In contrast, no statistically significant correlation was found in the RET group ($p = 0.235$).

Discussion

In the present study, both apexification and RET promoted periapical healing, as evidenced by significant reductions in PAI and concomitant increases in FD values after 12 months. Apexification achieved a slightly

Table 1 Individual treatment outcomes for apexification and RET: clinical success and radiographic parameters

Apexification Cases	Treatment Success	RET cases	Root lengthening	Dentinal wall thickening	Apical closure	Treatment success
1	+	1	-	+	-	-
2	+	2	+	+	+	+
3	+	3	+	+	-	-
4	+	4	+	+	+	+
5	+	5	+	+	-	+
6	+	6	+	+	+	+
7	+	7	+	+	+	+
8	+	8	+	+	+	+
9	-	9	+	+	+	+
10	+	10	+	+	+	+
11	+	11	+	+	+	+
12	+	12	+	+	+	+
13	+	13	+	+	+	+
14	+	14	+	+	+	+
15	+	15	+	+	+	+
16	+	16	+	+	+	+
17	+	17	+	+	+	+
18	+					
19	+					
20	+					

RET Regenerative Endodontic Treatment



Fig. 2 Representative periapical radiographs of immature permanent teeth treated with apexification and RET Apexification: (**A**) Baseline radiograph of tooth #21 presenting with an open apex and a distinct periapical radiolucency. (**B**) Radiograph at 12-month follow-up showing radiographic healing, with formation of a dense apical barrier and resolution of the periapical radiolucency RET: (**A**) Baseline radiograph of tooth #11 demonstrating an open apex and periapical radiolucency. (**B**) Radiograph at 12-month follow-up showing progressive apical closure, thickening of the canal walls, and resolution of the periapical radiolucency following regenerative treatment

higher overall success rate (95%) compared to RET (88.2%) when success was defined as radiographic resolution of apical periodontitis. This is consistent with the more predictable short-term outcomes of apexification, where apical barrier formation stabilizes the periapical environment and supports bone repair [20]. In contrast, RET demonstrated promising radiographic outcomes, with root lengthening observed in 94.1%, dentinal wall thickening in 100%, and apical closure in 82.4% of the cases. These findings align with previous reports highlighting the potential of RET to promote continued root development in immature teeth with necrotic pulps [21, 22]. Beyond these structural changes, RET also provided additional benefits, including the establishment of

Table 2 FD comparison by gender in treatment groups

GROUP	GENDER	*N*	FD MEDIAN (MIN-MAX)	*P*
RET	Male	7	1,22 (1,12 – 1,33)	0.669[a]
	Female	10	1,28 (1,11 – 1,38)	
Apexification	Male	5	1,26 (1,19 – 1,37)	0.445[a]
	Female	15	1,25 (1,11 – 1,37)	

FD Fractal Dimension, *RET* Regerative Endodontic Treatment

a: Mann-Whitney U test; median(minimum-maximum)

Table 3 Comparison of FD values at diagnosis (T0) and 12-Month Follow-up (T1) between apexification and RET groups

GROUP	TREATMENT STAGE	FD MEDIAN (MIN-MAX)	*p*
Apexification	T0	1.12 (1.00–1.26)	< 0.001 [a]
	T1	1.25 (1.10–1.37)	
RET	T0	1.08 (1.00–1.28)	< 0.001 [a]
	T1	1.27 (1.10–1.38)	
Apexification - RET	T1	Apexification: 1.25 (1.10–1.37)	0.976 [b]
		RET: 1.27 (1.10–1.38)	

FD Fractal Dimension, *RET* Regerative Endodontic Treatment

a: Wilxocon test; median (minimum-maximum) b: Mann-Whitney U test; median (minimum-maximum)

T0: diagnosis stage; T1: 12-month follow-up after treatment

a functional pulp–dentin complex through physiological and immune-mediated repair mechanisms [20]. Such advantages are clinically relevant because they may contribute to long-term tooth strength, enhanced functionality, and improved prognosis compared to apexification. The radiographically detectable physiological changes observed, although not histologically confirmed in the present study, are consistent with prior reports [23]. Importantly, the significant increase in FD values reflects remodeling of the trabecular bone architecture, confirming that FA can capture structural healing differences between apexification and RET [2, 16].

The combined use of PAI and FA, a semi-quantitative radiographic tool, allowed complementary assessment of periapical healing [12]. In the apexification group, a moderate negative correlation was observed between changes in FD and PAI (Spearman's rho = – 0.444, $p = 0.049$), suggesting that as trabecular bone complexity increased, signs of periapical pathology diminished. This may reflect the more predictable healing pattern achieved through apical barrier formation, which stabilizes the environment and promotes orderly bone regeneration. In contrast, the RET group did not show a statistically significant correlation ($p = 0.235$), potentially due to variable tissue responses and the inconsistent deposition of

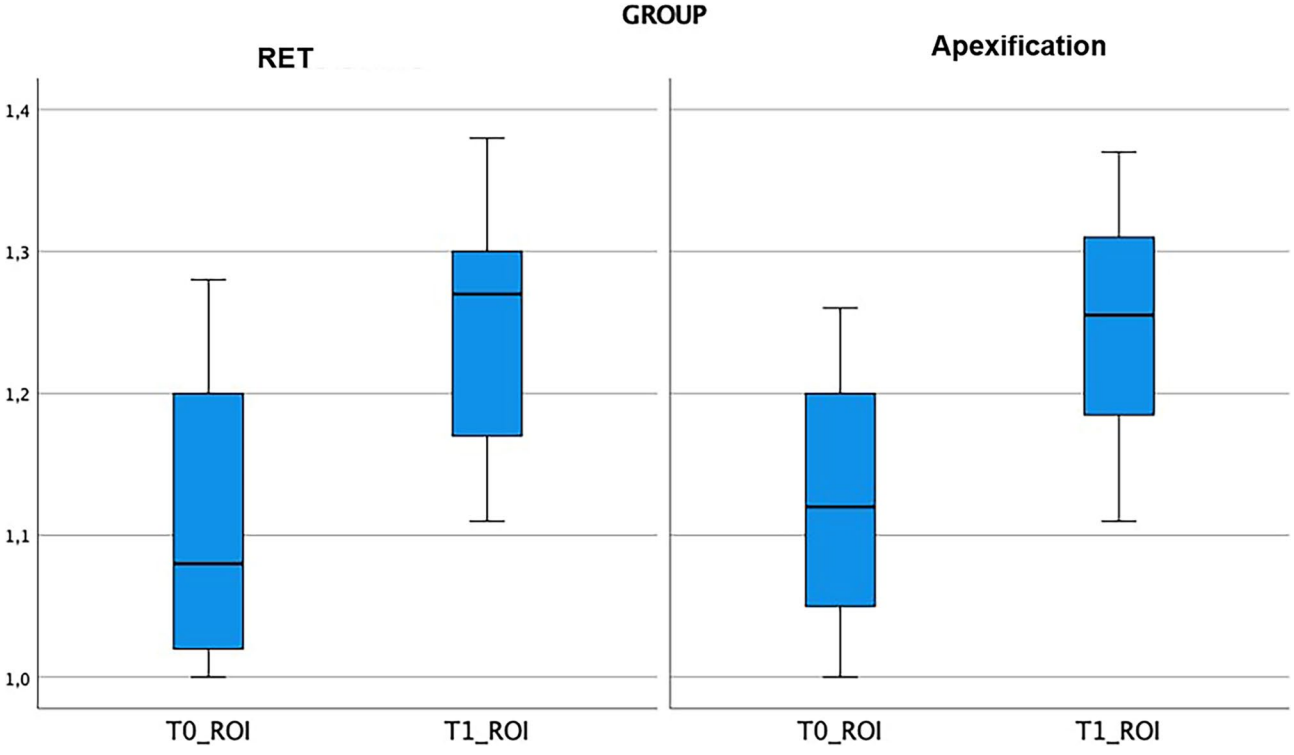


Fig. 3 Comparison of FD values at baseline (T0) and at 12-month follow-up (T1) in teeth treated with RET and apexification Box plots represent the distribution of FD values within each group. Both treatment approaches demonstrated a statistically significant increase in FD from baseline to follow-up ($p < 0.001$ within groups), indicating enhanced trabecular bone complexity over time. No statistically significant difference was observed between apexification and RET in the magnitude of FD changes ($p = 0.976$)

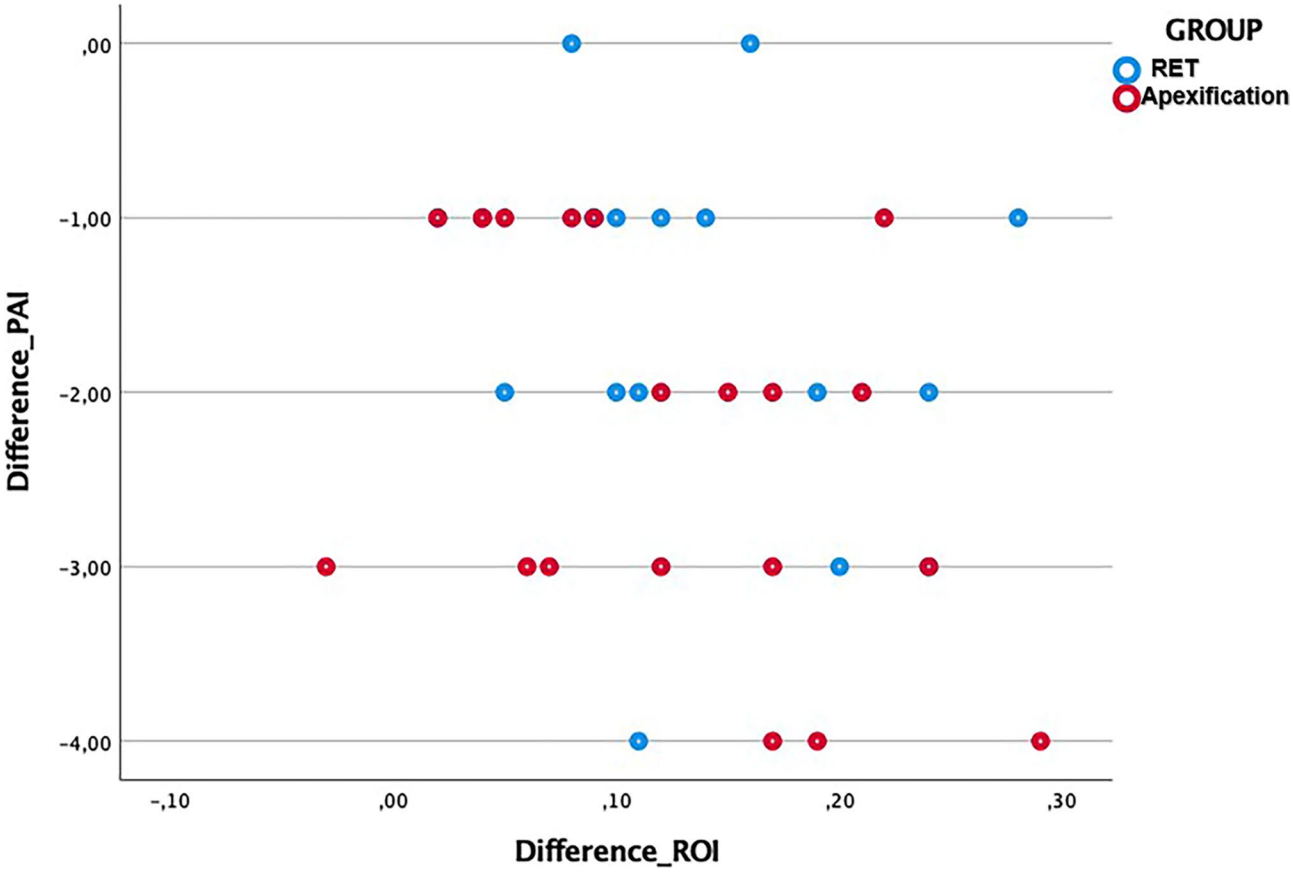


Fig. 4 Correlation between changes in PAI and FD values in teeth treated with apexification and RET Each point represents an individual case: red circles = apexification group; blue circles = RET group. The x-axis shows changes in FD values (ΔFD), and the y-axis shows changes in PAI (ΔPAI) between baseline and 12-month follow-up. A negative correlation was observed in the apexification group (Spearman's rho = −0.444, $p = 0.049$), indicating that greater increases in trabecular bone complexity were associated with larger reductions in PAI. No statistically significant correlation was found in the RET group ($p = 0.235$)

mineralized tissue in immature roots undergoing regenerative procedures. The persistence of pulp-like tissue within the apical region during the first year may further attenuate the correlation between FD and PAI [24]. These findings suggest that while FA can be a valuable adjunct for monitoring healing in apexification, its reliability in the context of RET may be limited or require longer follow-up periods. Although FA provides quantitative information, it remains semi-quantitative in nature and not entirely free of methodological variability, which may also have contributed to the observed results [12]. Overall, these findings directly address our second research question by demonstrating a significant negative correlation between FD and PAI in apexification, but not in RET.

In addition, no statistically significant differences in FD changes were observed between sexes within either treatment group, suggesting that gender did not influence the outcomes in this cohort. The median age was comparable between groups, indicating that the observed differences were not attributable to baseline demographic variations. These findings are consistent with previous reports indicating that demographic variables have limited influence on FD measurements in periapical healing [2, 16].

FA has been widely applied to evaluate trabecular bone complexity and has consistently been shown to reflect periapical healing after endodontic treatment [2, 12, 16, 25, 26]. This background supports our rationale to test FD not only in conventional endodontic cases but also in apexification and RET, where biological healing pathways differ. Importantly, the concurrent use of PAI provided internal validation, reinforcing that increases in FD paralleled clinical and radiographic signs of healing. These observations support the use of FA as a valuable adjunct for objectively monitoring periapical changes, provided that its methodological limitations are acknowledged.

A strength of this study is the integration of FA with PAI, enabling a complementary evaluation of healing through both quantitative and semi-quantitative approaches. Rigorous standardization of ROI placement and radiographic acquisition minimized technical variability, and high intra and inter-observer agreement confirmed the reproducibility of the measurements. Another

strength of this study is that it provides one of the first comparative insights into the applicability of FA in RET cases. Although the correlation with PAI was not significant in RET, identifying these limitations highlights important biological differences in healing patterns and underscores the need for longer follow-up and refined imaging approaches. This contributes to clarifying the potential and boundaries of FD as a monitoring tool in regenerative endodontics.

Several limitations must be considered. The relatively small sample size and inclusion of only single-rooted maxillary anterior teeth restrict the generalizability of the findings. The retrospective design limited the availability of clinical data and precluded histological validation. Moreover, although standardized periapical radiographs were used, reliance on two-dimensional imaging may have under- or overestimated trabecular changes. FA, while informative, remains dependent on ROI selection, operator technique, and the inherent constraints of 2D radiographs, which may have influenced variability, particularly in the RET group. Additionally, morphometric changes such as root lengthening and dentinal wall thickening were not quantified.

Future prospective studies with larger and more diverse populations, extended follow-up periods, and the use of three-dimensional imaging modalities such as CBCT are recommended. Combining these advanced imaging techniques with quantitative morphometric analyses may provide a more comprehensive understanding of trabecular remodeling and root maturation. Such approaches will be essential to fully validate FD as a reliable adjunctive tool for assessing periapical healing.

Conclusion

Within the limitations of this study, no statistically significant differences in FD values were observed between apexification and RET, indicating comparable periapical healing outcomes. Both treatments demonstrated significant increases in FD values after 12 months, consistent with decreases in PAI. A negative correlation between FD and PAI was observed in the apexification group, whereas no correlation was found in the RET group. These findings suggest that FA can serve as a reproducible method for monitoring periapical healing, with particular reliability in apexification cases.

Abbreviations

MTA	Mineral Trioxide Aggregate
ICC	Intraclass Correlation Coefficient
RET	Regenerative Endodontic Treatment
FA	Fractal Analysis
ROI	Region Of Interest
TIF	Tagged Image File
PAI	Periapical Index
FD	Fractal Dimension

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12903-025-07037-4.

Supplementary Material 1: Supplemental Figure 1. Stages of fractal dimension analysis, (a) cropped region of interest, (b)blurred image of duplicated region of interest, (c) subtraction of blurred image from the original image, (d) grey value of 128 to each pixel was added, (e) threshold, (f) binary, (g) erode, (h) dilate, (i) invert, and (j) skeletonize.

Authors' contributions

S.Y: Conceptualization, methodology, investigation, resource, formal analysis and writing - original draft, writing - review & editing.S.D: Data curation, resources, validation, writing - original draft, writing - review & editing.A.T.E.A: Validation, investigation, writing - original draft, writing - review & editing.I.E.A: Validation, investigation, writing - original draft, writing - review & editing.

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Data availability

No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate

To declare that this retrospective study conducted in Erciyes University, Faculty of Dentistry, Department of Endodontics was conducted by the applicable ethical principles, including the 1964 World Medical Association Declaration of Helsinki and its later versions. It was also reviewed and approved (Date: 19.02.2025/Approval ID: 2025/86) by the Erciyes University Clinical Research Ethics Committee. In addition, informed consent forms were obtained from all patients before the treatments.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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