ORIGINAL ARTICLE

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Evaluation of periapical lesion healing in mandibular molars with chronic apical periodontitis after initial root canal treatment and retreatment at 2-year follow-up using fractal analysis: A retrospective study

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Purpose: The aim of this retrospective study was to evaluate the degree of healing in the periapical region of teeth with chronic apical periodontitis (CAP) following initial root canal treatment (RCT) and retreatment using fractal analysis (FA) of panoramic radiographs after 2-year follow-up.

Methods: This study included a total of 136 mandibular molars, 71 initial RCTs and 65 retreatments. Teeth that were diagnosed with CAP and presented with a well-defined radiolucent periapical lesion were included in the study. Both preoperative and 2-year follow-up radiographs of ideal quality were chosen for the analysis. FA was performed using the box-counting method proposed by White and Rudolph using ImageJ 1.3 software (NIH, Bethesda, MD, USA). The data were analyzed using the Kolmogorov–Smirnov, Wilcoxon, and Chi–square tests and Spearman's correlation coefficient.

Results: No statistically significant difference was found between the healing rates of the initial RCT and retreatment procedures ($p>0.05$). There was a statistically significant difference between the fractal dimension values measured before treatment and 2 years after treatment in patients who underwent initial RCT and retreatment procedures ($p<0.05$).

Conclusion: According to the FA results, the healing rate in the periapical region was similar between the initial RCT and retreatment procedures.

Keywords: Apical periodontitis; fractal analysis; initial root canal treatment; periapical healing; retreatment.

Introduction

Apical periodontitis (AP) is an inflammatory disease of periapical tissues characterized by bone destruction in the periradicular region resulting from microbial infection within the pulp (1). Depending on the condition of the infection within the root canal, the inflammatory reaction may be either acute or chronic (2). In chronic apical periodontitis (CAP), the affected tooth is asymptomatic, and if this inflammation in the periapical tissues remains untreat-

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ed, bone destruction typically progresses gradually (3).

The etiological spectrum and treatment options for CAP differ between teeth that have not undergone root canal treatment (RCT) and those that have been previously treated with RCT (4). In teeth without prior RCT, potential causes of CAP include the progression of caries into the pulp, leading to microbial invasion, pulp necrosis, and the spread of inflammation to periapical tissues; the colonization of pulp tissue by microorganisms in cases where the pulp loses its blood supply due to trauma; and the development of pulp necrosis and subsequent periradicular pathology in situations where the pulp tissue is exposed due to dental wear (5).

The fundamental treatment steps for CAP involve the removal of intraradicular microorganisms through chemomechanical preparation to significantly reduce the microbial load and prevent reinfection with well-sealed root canal filling (6). Periapical lesion healing following RCT typically occurs through hard tissue regeneration, which is a reduction in radiolucency in the periapical region on follow-up radiographs (7). Although initial RCT has a high success rate reaching 89%, failure may occur over time following treatment. In teeth that have undergone RCT, reinfection can occur due to inadequate aseptic control, missed canals, insufficient instrumentation, inefficient irrigation, or leakage of temporary or permanent restorations, which can similarly trigger a periapical immune response (8). In cases where the initial RCT fails, retreatment is considered the first option, as it is cost-effective and provides satisfactory outcomes (9,10). The success rate of retreatment ranges between 64% and 91% (11).

To evaluate AP healing, clinical and radiographic follow-up at regular intervals is needed over a minimum observation period of 1 year following RCT (12). Dental radiographs are routinely employed to assess root canal treatment outcomes, track postoperative healing, and detect changes in bone density (13). The Brynolf criteria, Rud method, and periapical index (PAI) are subjective assessments used to evaluate radiographic changes in periapical tissues (14-16). Quantitative approaches, such as measuring bone density and analyzing it using Hounsfield units (HUs), have been developed to address the issue of subjectivity in evaluating radiopacity changes in visually assessed apical lesion healing (17). Recent studies in the literature have shown that the trabecular microstructure of the bone should also be considered when evaluating bone density (17,18). The branched structure and self-similarity of trabecular bone, which are fractal properties, enable the use of fractal analysis (FA) to quantitatively evaluate the complex structure of trabecular bone (19) . FA is an analysis capable of quantitatively evaluating changes occurring in bone tissue. FA has been reported to be an adequate technique for identifying osteoporotic conditions in the jaw (20). Additionally, FA is widely used in radiographs to detect and evaluate changes in bone, apical healing, the periapical bone, and systemic conditions affecting the bone (21).

The aim of this retrospective study was to evaluate the degree of healing in the periapical region of teeth with CAP following initial RCT and retreatment procedures using FA on panoramic radiographs after 2-year follow-up. The null hypothesis (H_0) of this study is that there is no significant difference in periapical healing, as measured by fractal dimension (FD) values obtained through fractal analysis of panoramic radiographs, between initial RCT and retreatment in cases of CAP.

Materials and Methods

Sample Selection

Ethical approval for this retrospective study was obtained from the Cukurova University Research Ethics Committee (Meeting no: 144, Decision no: 30, Date: May 10, 2024) and the study was conducted according to the Helsinki Declaration. The medical, clinical, and radiographic data of patients who underwent initial RCT or retreatment between 2020 and 2022 at the Department of Endodontics, Faculty of Dentistry, Cukurova University, were evaluated. A total of 276 patient records were initially screened from the institutional archive. After applying the inclusion and exclusion criteria, 140 cases were excluded due to missing or poor-quality preoperative or 2-year follow-up panoramic radiographs, systemic conditions affecting bone metabolism, periodontal involvement, or incomplete documentation. Ultimately, 136 mandibular molars from patients who met all inclusion criteria and had complete radiographic records of diagnostic quality were included in the final analysis (Fig. 1).

Inclusion Criteria

- Patients aged 18–65 years without any systemic diseases or periodontal problems affecting bone metabolism.

- Mandibular molars diagnosed with CAP, presenting with a well-defined radiolucent periapical lesion of at least 2×2 mm in size and radiographically exhibiting intact marginal adaptation of the coronal restoration (Fig. 1)

Patients included in the study were selected from those whose initial RCTs or retreatments were completed by a single endodontist (K.G.).

Exclusion Criteria

- Teeth with open apices and requiring root canal filling with MTA

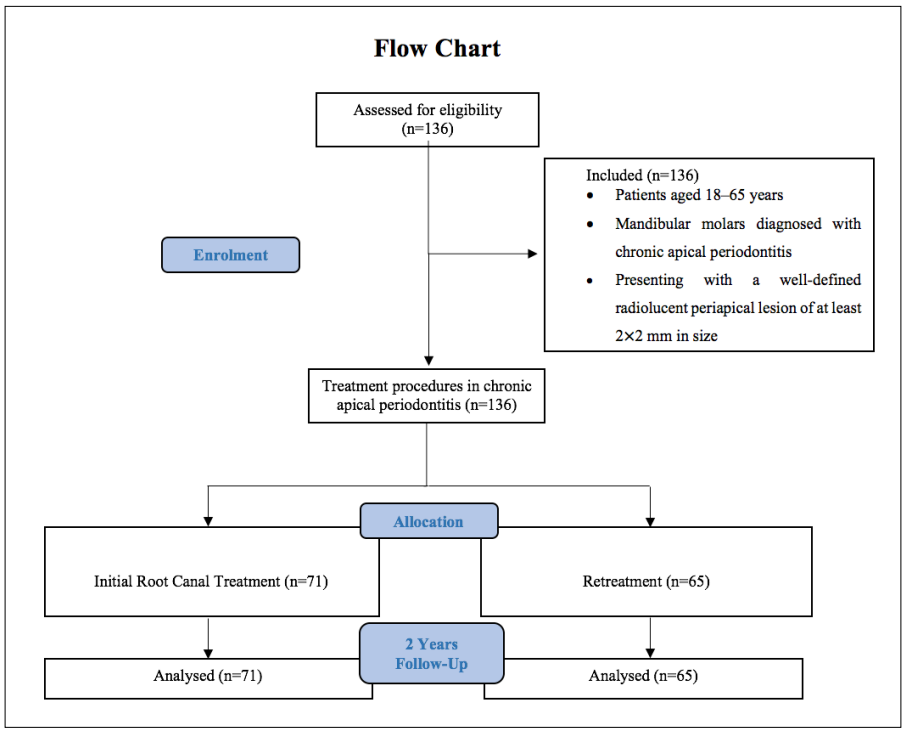

Fig. 1. The flowchartof participants throughout the trial.

- Teeth that have undergone surgical retreatment
- Patients with systemic diseases affecting bone metabolism or using medications related to bone metabolism
- Missing or poor-quality preoperative or 2-year follow-up panoramic radiographs
- Incomplete clinical or radiographic documentation

Sample Size Calculation

The sample size was calculated using power analysis (G*Power, ver. 3.1.9.2, Franz Faul; University of Kiel, Germany) on based a previous study (22), with 80% power, a 5% α error, and an effect size of 0.5. The minimum sample size was determined to be 50 teeth per group. The study was completed with a total of 136 teeth, including 71 initial RCTs and 65 retreatments, who had preoperative panoramic radiographs and 2-year follow-up radiographs and met the standards required for FA evaluation.

Initial RCT Procedures

All initial RCT procedures were performed at a single visit under magnification (3x loupe) and illumination. Local anesthesia was administered in both treatment modalities to ensure patient comfort during the placement of the rubber dam. The anesthesia technique utilized was the inferior alveolar nerve block. After the relevant tooth was anesthetized with 4% articaine hydrochloride with 1:100,000 epinephrine (Ultracain D-S; Sanofi, Paris, France), the tooth was isolated with a rubber dam. Any caries or coronal restorations present on the tooth were completely removed. An endodontic access cavity was prepared under water cooling using diamond round and fissure burs. The working length (WL) of the teeth was determined using a #10 K-type hand file and an electronic apex locator (VDW Gold; VDW, Munich, Germany), and periapical radiographs were taken to confirm the WL. After the WL was established, the root canals were irrigated with 2 ml of 2.5% sodium hypochlorite (NaOCl). A reproducible glide path was created using a #15 K-type hand file. The root canal shaping procedures were completed using the Reciproc Blue R25 file (25/.08) (RB, VDW, Munich, Germany). As the final irrigation solution, the root canals were irrigated sequentially with 2 ml of 2.5% NaOCl, 2 ml of 17% ethylenediaminetetraacetic acid (EDTA), and 2 ml of saline solution. After the root canals were dried with paper points, root canal obturation was performed using cold lateral condensation technique with gutta-percha and a root canal sealer (Adseal, Meta Biomed, Korea). The permanent restoration of the teeth was completed using composite resin (Clearfil Majesty Posterior, Kuraray Medical, Inc., Tokyo, Japan).

Retreatment Procedures

All retreatment procedures were performed at a single visit under magnification (3x loupe) and illumination. After the relevant tooth was anesthetized with 4% articaine hy-

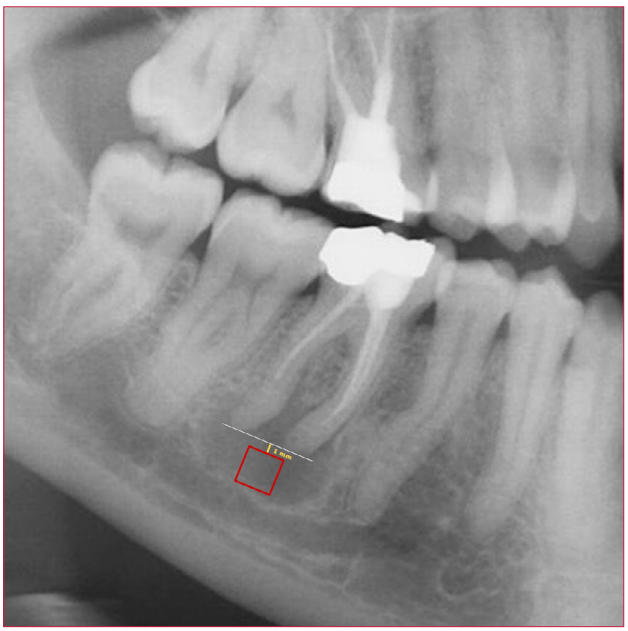

Fig. 2. Selection of the regions of interest (ROI) on the panoramic radiograph. The red square shows the ROI, the white line shows the root apex plane, and the yellow line indicates the distance between the ROI and the root apex plane.

drochloride with 1:100,000 epinephrine (Ultracain D-S; Sanofi, Paris, France), the tooth was isolated with a rubber dam. Any caries or coronal restorations present on the tooth were completely removed. An endodontic access cavity was prepared under water cooling using diamond round and fissure burs. Initial root canal fillings were removed using MicroMega Remover retreatment files (30/.07) (Coltene-Whaledent, Altstätten, Switzerland). The WL was determined using an electronic apex locator (VDW Gold; VDW, Munich, Germany), and periapical radiographs were taken to confirm the WL after the complete removal of the root canal filling. After the WL was established, the root canals were irrigated with 2 ml of 2.5% NaOCl. A reproducible glide path was created using a #15 K-type hand file. Root canal shaping was subsequently completed using Reciproc Blue R25 (25/.08) (RB, VDW, Munich, Germany) files for the mesial canals and Reciproc Blue R40 (40/.08) (RB, VDW, Munich, Germany) files for the distal canals. As the final irrigation solution, the root canals were irrigated sequentially with 2 ml of 2.5% NaOCl, 2 ml of 17% EDTA, and 2 ml of saline solution. After the root canals were dried with paper points, root canal obturation was performed using cold lateral condensation technique with gutta-percha and a root canal sealer (Adseal, Meta Biomed, Korea). Permanent restoration of the teeth was completed using composite resin (Clearfil Majesty Posterior, Kuraray Medical, Inc., Tokyo, Japan).

Radiography Protocol

Patients who had completed the initial RCT or retreatment procedures returned to the dental faculty hospital after 2 years for endodontic or other reasons and who had panoramic radiographs taken were selected for the study. Both preoperative and 2-year follow-up radiographs of ideal quality were chosen for image analysis. The actual follow-up duration was calculated individually based on the dates of the initial treatment and the follow-up panoramic radiograph. The mean follow-up time was 24.3±1.7 months, with a minimum of 22 months and a maximum of 28 months.

Coronal restorations were evaluated on panoramic radiographs to exclude teeth with gross defects. Only teeth with clearly intact proximal margins, without evidence of radiolucency, overhang, or marginal breakdown exceeding 0.5 mm, were included. All assessments were performed by a calibrated dentomaxillofacial radiologist under standardized conditions (high-resolution diagnostic monitor, consistent ambient lighting) to ensure reproducibility and minimize interobserver variability. The evaluation focused on the mesial and distal aspects of the restoration margins, where visibility is optimal in panoramic imaging.

Although periapical radiographs are generally preferred for the evaluation of periapical lesions and fractal analysis, this retrospective study included only patients who had returned to the faculty of dentistry for routine care, endodontic or other reasons and had panoramic radiographs of sufficient diagnostic quality. Standardized periapical images were not consistently available for all cases. Therefore, to maintain methodological consistency and reproducibility, only panoramic radiographs taken from the same digital unit under identical exposure parameters were used for FA.

Panoramic radiographs were obtained using a Planmeca ProMax (Helsinki, Finland) device with exposure parameters of 84 kilovolts (kVp), 16 milliamperes (mA), and a 14-second exposure duration.

Fractal Analysis

A dentomaxillofacial radiologist calculated the fractal dimension (FD) on each panoramic image. For both the pre- and postoperative radiographs, a 32×32-pixel region of interest (ROI) was placed 1 mm coronal to the radiographic apex (Fig. 2). The ROI was positioned at the same site on both images for each tooth to ensure standardization and reproducibility.

FA was performed using the box-counting method proposed by White and Rudolph (23) using ImageJ 1.3 software (NIH, Bethesda, MD, USA). First, the ROI was selected and copied (Fig. 3a). A Gaussian filter was applied to the image to create a blurred version (Fig. 3b). After

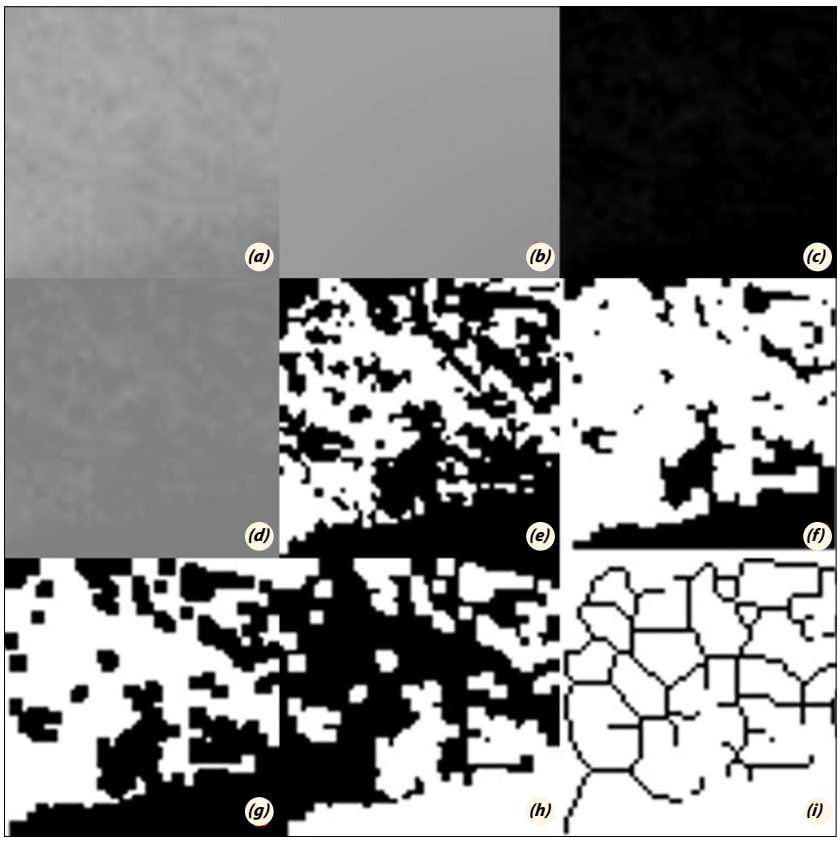

Fig. 3. Fractal analysis steps (a-i). **a)** Cropped and dublicated ROI **b)** Blurring of the duplicated image by applying the Gaussian blur filter **c)** Subtraction of the blurred image from the original image **d)** Addition of 128 gray values to each pixel location. **e)** Threshold. **f)** Erosion. **g)** Dilatation. **h)** Applied inversion processes to the image. **i)** Skeletonization.

generating a blurred version, we subtracted it from the original (Fig. 3c). A constant gray level of 128 was added to highlight marrow spaces and trabecular bone (Fig. 3d). The image was converted to black–white using a brightness threshold of 128 (Fig. 3e), and then processed with erosion, dilation, and inversion (Fig. 3f–h). As a final step, the image underwent skeletonization (Fig. 3i).

The tooth was considered to have successful healing if it was still present in the mouth, no disruption in the marginal adaptation of the tooth's coronal restoration was observed radiographically, and the FA results showed an increase in fractal dimension (FD) values in the periapical region. No change in FD values was considered uncertain, whereas a decrease in FD values was considered unsuccessful healing or no healing. Teeth classified as uncertain were scheduled for reevaluation after completing the 4-year follow-up period recommended by the ESE.

In the present dataset, no cases fell within the predefined "uncertain" range, which was defined as a change in FD values within ±0.01. All analyzed cases showed either an increase or a decrease exceeding this threshold. This may be attributed to the relatively long follow-up period (mean 24.3 months), which allowed sufficient time for bone remodeling processes to manifest as detectable changes in FD. Therefore, all included teeth could be objectively classified as healed or not healed based on the FD trend.

Statistical Analysis

Statistical analysis was performed using SPSS 26 software (IBM Corp., Armonk, NY, USA). The Kolmogorov–Smirnov test indicated that the quantitative FA data did not follow a normal distribution. The Wilcoxon test was used to compare the FD values before the initial RCT and retreatment with those obtained 2 years after the procedures. Spearman's correlation coefficient was used to analyze the changes in FD values before and after the procedures. The Chi-square test was used to compare the proportions of patients with and without healing between the two groups and between the genders and between the age groups (18–35, 36–50, and 51–65 years). The significance level was determined as 0.05.

Results

In this retrospective study, FA was used to calculate the changes in FD values from panoramic radiographs taken before treatment and 2 years after treatment. The radiographs of a total of 56 male and 80 female patients, including 71 initial RCTs and 65 retreatments, were evaluated.

No statistically significant difference was found between the healing rates of the initial RCT and retreatment procedures ($p>0.05$). The healing rate was 85.9% for the initial RCT, whereas it was 81.5% for retreatment procedure (Table 1).

The healing rates after the initial RCT and retreatment did not significantly differ between the genders ($p>0.05$). The healing rate following the initial RCT was 89.7% in females and 83.3% in males. For retreatment, the healing rate was 84.3% in females and 71.4% in males. When patients were categorized into three age groups (18–35, 36–50, and 51–65 years), healing and non-healing outcomes were analyzed within each group based on treatment type. Although slight differences in healing rates were observed across the groups, no statistically significant association was found between age group or treatment procedure and healing outcomes ($p>0.05$) (Table 1).

There was a statistically significant difference between the FD values measured before treatment and 2 years after treatment in patients who underwent initial RCT and retreatment procedures ($p<0.05$) (Table 2).

Discussion

In teeth with CAP, a successful RCT is expected to eliminate microorganisms and necrotic tissues, halt periradicular tissue destruction, and observe new bone formation in

Table 1. Distribution of healed and unhealed outcomes by treatment procedure, gender and age groups

	Healed (n=114)	Unhealed (n=22)	Total (n=136)	*p* Value*
Treatment Procedure				
Initial Root Canal Treatment	61 (85.9)	10 (14.1)	71 (52.2)	0.646
Retreatment	53 (81.5)	12 (18.5)	65 (100)	
Gender				
Female	69 (60.5)	11 (50)	80 (58.8)	0.495
Male	45 (39.5)	11 (50)	56 (41.2)	
	Initial Root Canal Treatment		**Retreatment**	
	Healed (n=61)	Unhealed (n=10)	Healed (n=53)	Unhealed (n=12)
Gender				
Female	26 (89.7)	3 (10.3)	43 (84.3)	8 (15.7)
Male	35 (83.3)	7 (16.7)	10 (71.4)	4 (28.6)
p Value*	0.511	0.271		
Age Group (years)				
18-35	21 (87.5)	3 (12.5)	18 (85.7)	3 (14.3)
36-50	22 (88)	3 (12)	20 (83.3)	4 (16.7)
51-65	18 (81.8)	4 (18.2)	15 (75)	5 (25)
p Value*	0.801	0.650		

The data are presented as the number of frequencies (%). *χ^2 Test.

Table 2. Comparison of changes in fractal dimension (FD) values between baseline and 2-year follow-up radiographs for the initial root canal treatment and retreatment groups

	FD Value			
	Baseline median(min-max)	2-year follow-up median(min-max)	r	*p* Value*
Initial Root Canal Treatment	1.2 (1 – 1.4)	1.3 (1.1 – 1.7)	0.238	<0.01
Retreatment	1.2 (0.9 – 1.5)	1.3 (1.1 – 2.3)	0.431	<0.01

*Wilcoxon Test, r: Correlation Coefficient.

follow-up radiographs (24,25). The European Society of Endodontology (ESE) (2006) recommends at least 4-year of clinical and radiographic follow-up to confirm the complete healing of AP (12). According to ESE's most recent clinical practice guidelines, when RCT is evaluated at least 1 year postoperative, the absence of symptoms such as pain, tenderness, or swelling; the absence of a sinus tract or functional loss; and radiographic reduction in the size of the periapical lesion indicate a positive healing outcome (26). However, Huumonen and Ørstavik reported that the healing of preexisting periapical lesions can be radiographically evident within 3 months to 2 years (27). The present study aimed to compare the changes in the size of periapical lesions in teeth between the initial RCT and retreatment procedures using FA on panoramic radiographs after 2 years of follow-up.

Previous studies examining the factors affecting the success of initial RCT and retreatment procedures have employed various clinical and radiographic evaluation methods (28). PAI is a subjective method used to assess periapical health radiographically and is frequently utilized in the endodontic literature (29). Another radiological examination method used for the quantitative evaluation of changes in periapical trabecular bone is FA (14). FA is a technique that allows for the quantitative assessment of changes in trabecular bone structure on based pixel density in a radiographic image (30). It is a simple, cost-effective, noninvasive, objective, and quantitative analysis method (16,31). One of its advantages is that it is not affected by minor changes in the projection angle or radiodensity (13,32). Additionally, this analysis can detect even very early changes in bone trabeculae within a small area (14). Higher FD values indicate less void space within the bone and increased complexity in bone trabeculation, whereas lower FD values suggest more void space within the bone and less bone trabeculation (33).

FA is used to evaluate bone changes associated with periodontal disease (34), alveolar bone surgery (35), systemic diseases (36), and early changes in the periapical bone following RCT (14). In previous studies by Tosun et al. (37), changes in the mean FD values of periapical lesion areas on 1-year follow-up radiographs after retreatment were similar to changes in the PAI scores (22). Similarly, in a study by Yilmaz et al. (38), which compared the healing of apical lesion after retreatment, FD values in the relevant areas significantly increased in the 1-year follow-up radiographs, and this result was consistent with changes in the PAI scores.

FA is not affected by minor changes in radiographic settings such as kVp, mA, or X-ray angulation (39,40). However, some studies have reported that FA results can be influenced by the location, size, and shape of the ROI (41,42). Another study reported no such effect (43). To ensure consistency in this study, preoperative and postoperative radiographs taken with a panoramic radiograph device using the same exposure settings were utilized. Additionally, the ROI was selected by a single observer in a manner that excluded surrounding anatomical structures such as tooth roots, lamina dura, and the mandibular canal, and it was placed in the same size and position on both preoperative and follow-up radiographs. This ensured that only changes in the area of the lesion were evaluated.

Periapical radiography, panoramic radiography, and cone-beam computed tomography (CBCT) are radiographic methods used for monitoring periapical lesions in endodontics. CBCT provides three-dimensional imaging of the periapical lesion area (44). However, due to its higher cost and exposure to ionizing radiation than two-dimensional radiographs do, its routine use in monitoring periapical lesions is limited. Instead, periapical radiography is used for lesion monitoring, as it allows for a more detailed evaluation of the affected area while utilizing less ionizing radiation than panoramic radiography does (30). However, due to the retrospective nature of the present study, routine panoramic radiographs taken from patients who returned to the dental faculty hospital 2 years later for endodontic or other reasons were used.

In clinical studies, numerous factors can influence the outcome of RCT (45). The preoperative conditions of the teeth (pulp and periapical status, size of the periapical lesion, history of trauma, resorption, fracture, cracks, swelling, and presence of a sinus tract) can potentially affect the treatment outcome. In the literature, many studies have demonstrated that the preoperative condition of the periapical lesion is a significant factor influencing the prognosis of RCT (46,47). In studies conducted by Friedman et al. (4) and Farzaneh et al. (48), the rate of periapical healing 4–6 years after initial RCT was significantly better in teeth without preoperative CAP than in those with CAP. Additionally, in retreatment cases, the success rate was significantly lower in the presence of a periapical lesion than in cases without lesions (49,50). Farzaneh et al. (51) compared the periapical healing rate of root canal-treated teeth without AP to those with AP 4–6 years after retreatment. The healing rate after retreatment was 97% in teeth without AP, whereas this rate decreased to 78% in teeth with AP. These studies in the literature confirm the negative impact of preoperative AP on periapical healing.

Primary treatment and nonsurgical retreatment differ markedly in prognosis. In retreatment cases, outcomes are affected by tooth type, presence/size of any preoperative radiolucency, presenting symptoms, periodontal

status, the integrity of the coronal restoration and prior endodontic work, and whether an intracanal post is present (52). Because retreatment follows failure of the initial RCT, its prognosis may be diminished by a microflora that is harder to eradicate (49), often dominated by gram-positive monoinfections, most notably Enterococcus faecalis (49,53). Consistent with these challenges, healing rates are generally higher after primary RCT than after retreatment, as reported by Sjögren et al. (46) and Friedman et al. (54).

In the present study, we aimed to evaluate how FA, as a quantitative method, can be used to assess the outcomes of the healing of apical lesion areas following RCT and retreatment of teeth. This study is the first to use FA as the sole method to comparatively evaluate the outcomes of initial RCT and retreatment procedures. Our results demonstrated that FD values significantly increased in both treatment groups 2 years after treatment compared with the preoperative values. This increase in FD values indicates new bone formation in the apical region along with an increase in trabeculation. These findings are consistent with those of previous studies (22,37,38,55). The results of the study revealed no statistically significant difference in periapical healing, as determined by changes in FD values, between initial RCT and retreatment groups ($p>0.05$), thereby supporting the acceptance of the null hypothesis (H_0).

Although gender-based biological differences, including hormonal influences on bone metabolism, may theoretically affect healing dynamics, the current evidence suggests that gender alone is not a significant determinant of periapical healing. Previous studies have similarly reported no statistically significant gender-related differences in healing outcomes when using either clinical or fractal analysis parameters (46,55,56). Similarly, in the present study, no significant difference was found between genders in terms of healing rates following initial RCT and retreatment procedures. Therefore, our findings are consistent with existing literature, supporting the notion that treatment-related and lesion-specific factors are likely to play a more decisive role than sex-based biological variation.

In addition to the overall analysis, patients were stratified into three clinically relevant age groups (18–35, 36–50, and 51–65 years) to evaluate the potential influence of age on periapical healing. Healing rates across these subgroups were slightly different numerically but did not demonstrate statistically significant differences between age groups or treatment modalities. These findings suggest that, within a healthy population aged 18 to 65 years, age alone may not be a determining factor in periapical healing outcomes following either initial treatment or retreatment. Nonetheless, the biological variability associated with age—such as changes in bone metabolism or hormonal status —may not be fully captured in this retrospective design. Therefore, future prospective studies with stratified and adequately powered samples are needed to further explore age-related differences in healing dynamics.

The present study has several limitations. First, due to its retrospective design, the evaluation of treatment success was based solely on radiographic parameters, without the inclusion of clinical signs and symptoms such as pain, swelling, or sinus tract presence. Additionally, functional status and standardized indices like the PAI, which are commonly used in conjunction with radiographic evaluations, were not assessed owing to the lack of uniform clinical documentation. Instead, periapical healing was determined solely through changes in FD values obtained from panoramic radiographs. Although FA offers a quantitative and objective measure, relying exclusively on this method may not fully capture the complexity of biological healing. Furthermore, although PAI scoring was excluded due to projection variability and anatomical superimposition on panoramic images, the same radiographs were used for FA. However, unlike PAI, fractal analysis has been shown to be less sensitive to variations in angulation and projection geometry, particularly when the ROI is standardized in size and location (13,39). In the present study, all radiographs were obtained using the same panoramic unit under consistent exposure parameters, and ROI placement was performed by a calibrated observer. Moreover, the use of panoramic radiographs—despite their practicality and standardization—comes with inherent limitations in spatial resolution compared to periapical imaging. Specifically, only gross defects in coronal restorations that were clearly visible on panoramic radiographs—such as pronounced marginal gaps, overhangs, or recurrent caries—were used as exclusion criteria. However, panoramic imaging may not reliably detect minor marginal discrepancies, which can still compromise the integrity of the coronal seal and negatively influence periapical healing. Additionally, the relatively short follow-up period (approximately 24 months), although sufficient for initial bone remodeling, does not meet the 4-year follow-up interval recommended by the ESE for definitive confirmation of healing.

Conclusion

FA, which is based on objective and quantitative criteria, is a reliable method for monitoring the healing of periapical lesions following initial RCT and retreatment. According to the FA results, the healing rate in the periapical region was similar between the two treatment procedures.

Authorship Contributions: Concept: K.G., B.T.U., K.Y.; Design: K.G., K.Y.; Supervision: K.G., K.Y.; Materials: K.G.; Data: K.G., B.T.U.; Analysis: B.T.U.; Literature Search: K.G., B.T.U.; Writing: K.G., B.T.U.; Critical Revision: K.Y.

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Informed consent: Not applicable.

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