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Evaluation of changes in alveolar bone remodeling after orthodontic treatment using fractal analysis: A retrospective study

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Abstract

Aim: The aim of this retrospective study was to analyze trabecular changes in alveolar bone remodeling after orthodontic treatment by evaluating dental panoramic radiographs using the fractal dimension (FD) analysis method.
Methodology: This study included 146 individuals with dental class II malocclusion who had undergone fixed orthodontic treatment. The mean age of the patients was 14.88±2.11 years. Patients were divided into three groups: nonextraction control group (Group 1, n=45), moderate anchorage group with extraction (Group 2, n=53), and maximum anchorage group with extraction (Group 3, n=48). The region of interest in the maxillary first premolar apical area was determined using pre- and post-treatment (T0 and T1) panoramic radiographs obtained from archival records. FD analysis was conducted using ImageJ software (version 1.53, NIH). For intragroup data comparison, the paired sample t-test and Wilcoxon test were used. For intergroup data comparison, the Kruskal–Wallis and Mann-Whitney U tests were used. Statistical significance was set at $p<0.05$.
Results: No significant difference in FD values was found between the groups at T0 ($p>0.05$). At T1, compared to T0, FD values showed a significant decrease in Groups 2 and 3 ($p<0.05$) and no significant change in Group 1 ($p>0.05$). At T1, FD values of Groups 2 and 3 were significantly lower than those for Group 1 ($p<0.05$); no significant difference was found within Groups 2 and 3 ($p>0.05$). T0/T1 FD change was significantly more in Groups 2 and 3 compared to Group 1 ($p<0.05$).
Conclusion: Although fixed orthodontic treatments with extraction caused significant changes in the fractal dimensions of alveolar trabecular structures when compared to nonextraction, they did not cause destructive changes.

Keywords: Fractal analysis, bone remodeling, fixed orthodontic treatment, tooth extraction, trabecular structure

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Introduction

Dental panoramic radiographs are part of the patient records. They are taken during orthodontic treatments and are used to assess trabecular bone structural alterations and changes in teeth (1). Fractal dimension (FD) analysis is a mathematical technique used to measure and evaluate complex structures on dental panoramic radiographs, such as trabecular bone (2, 3).

Benoit Mandelbrot, a famous mathematician, introduced the idea of fractal shapes in the 1960s and 1970s (4). The word "fractal" originates from the Latin word fractus, which means broken or fragmented (5). Intricate structures whose dimensions and morphology cannot be determined or described by standard geometric shapes, such as a square, circle, or round, are referred to as fractals (6). This type of morphology is considered complex, is a measure of self-similarity, and defines the fractal geometry of the object (7). FD analysis is the simplification of such a complex structure and its transformation into a value, followed by the evaluation of the fractal properties and dimensions of an object using a box-counting algorithm (8). Because of its benefits—such as not being an invasive procedure, being easily accessible, and not being affected by projection geometry—fractal analysis has been applied in the medical field to assess the course, severity, and progression of a disease or to detect one that has not yet developed (6). According to published studies, FD analysis can reveal alterations in bone mineral density (6). Greater densities and complexity are indicated by higher FD values, whereas porous and less mineralized bones are indicated by lower FD values (6, 9).

Fractal analysis has been used in dentistry studies to meet a variety of objectives because of its capacity to identify trabecular bone changes, including the assessment of periodontal changes in the alveolar bone (6), examination of bone tissue in the implant surgery area (10), examination of joint status in patients with temporomandibular joint dysfunction (11), and assessment of bone healing in teeth with periapical lesions prior to and following root canal therapy (12). Recent orthodontic research has also made extensive use of the fractal analysis method. Fractal dimension (FD) analysis, a mathematical method of information processing, can be employed to assess the effects of orthodontic treatment on alveolar bone. The input data is represented as an image, and the derived information is presented as numerical values. The information that is produced is stored as numerical values. The processing of this submitted photograph necessitates a computer system. The quality of standardized photographs is a crucial consideration, since a significant compression ratio influences successful image compression (1, 6-8, 13, 14).

Comprehensive orthodontic treatment with fixed mechanics can be divided into extraction and nonextraction treatments. Extraction treatments typically involve tooth extraction to relieve dental or dentoalveolar protrusion and correct moderate to severe crowding. Nonextraction treatments are preferred in cases of mild skeletal and moderate dental disorders (15). A key component of extraction treatments is orthodontic anchorage, which is resistance against undesired tooth movement (16). Mini screws are temporary anchorage devices used for anchorage control and resistance against unwanted forces. They are used for anchorage support in extraction orthodontic treatments. Mini screws can be placed in the maxilla between the first and second premolar teeth—the most typical placement location in the buccal interproximal area—for cases involving maxillary first premolar extraction (17).

In addition to evaluating trabecular changes in bone structure (18), FD analysis is often used to assess bone mineral density, which has been shown to correlate well with the trabecular pattern, using panoramic radiographs (19). Pre- and post-treatment radiographs are commonly taken in orthodontic practice. Therefore, it is simple to apply FD analysis—a noninvasive technique—to these radiographic records to demonstrate the impact of orthodontic treatments on the bone structure of jaws (19).

To the best of our knowledge, no study has investigated the trabeculation of alveolar bone after orthodontic treatment involving extraction using the fractal analysis method.

Therefore, in this retrospective study, trabecular changes in alveolar bone remodeling after nonextraction fixed orthodontic treatment and treatment with extraction of both the upper left and right first premolars were analyzed by applying the fractal analysis technique to dental panoramic radiographs. The null hypothesis of the study was that there would be no change in the FD values of the groups following orthodontic treatment.

Materials and Methods

Ethics committee approval was received for this study from the Zonguldak Bulent Ecevit University, Noninterventional Clinical Research Ethics Committee, in accordance the World Medical Association Declaration of Helsinki, with the approval number: 2020/23-13.

The G*Power application (version 3.1.9.7; Heinrich Heine University, Dusseldorf, Germany) was used to determine the study's sample size. Accordingly, if the α error probability is fixed at 0.05 and the study's power (1 − β error probability) is 0.90, these results estimate the study's true power and total sample size to be 90% and 129, respectively. This retrospective analysis included 146 individuals (100 females and 46 males) whose orthodontic treatment was completed at Zonguldak Bulent Ecevit University Faculty of Dentistry, Department of Orthodontics.

A total of 146 patients participated in this study, of whom 45 comprised the control group (Group 1) and 101 belonged to the study group. The study group was further divided into two groups: patients treated with moderate anchorage (n = 53, Group 2) and patients treated with maximum anchorage (n = 48, Group 3).

This retrospective study analyzed intraoral photographs and dental panoramic radiographs obtained from clinical archival data. Measurements were made in a defined region on panoramic radiographs (Veraview IC5 HD, J Morita Mfg. Corp., Kyoto, Japan) taken at the start of treatment (T0) and after the treatment ended (T1). To ensure consistency, panoramic radiographs were taken in such a way that the Frankfurt horizontal plane was parallel to the surface and the bite bar was being bit in the right position.

The inclusion criteria were as follows: absence of congenital anomaly, history of trauma, and previous orthodontic treatment; fixed orthodontic treatment should have been conducted with 0.022 inch MBT prescription; presence of only mild crowding/diastema in nonextraction cases; presence of Angle class II molar relationship in extraction cases; removal of the upper first premolars on the right and left during orthodontic therapy for extraction cases; and the availability of good quality radiographic images with high resolution. Patients who did not meet at least one of these criteria were excluded from the study.

All 53 individuals in Group 2 were treated with moderate anchorage, and 48 individuals in Group 3 were treated with maximum anchorage. The treatment of 45 patients in Group 1 was completed with no extractions. The straight wire orthodontic technique was applied to patients in accordance with the MBTTM prescription by utilizing 0.022 × 0.028 inch Mini Master series stainless steel brackets (American Orthodontics, USA) (20). In nonextraction cases, after the placement of 0.014 inch and 0.016 inch round heat-activated nitinol archwires from American Orthodontics (AO), a 0.016 inch round stainless steel archwire was placed in the mouth. Subsequently, the prescribed order was followed when applying 0.019 × 0.025 inch rectangular stainless steel archwire and 0.019 × 0.025 inch rectangular nitinol heat-activated archwire (AO) (21). Extraction cases followed an identical protocol for using the archwires as the nonextraction cases, with the exception of placing a rectangular brass-posted stainless steel archwire (AO), which measured 0.019 × 0.025 inches, during space closure. For a duration of one month, the archwire was passive prior to space closure to provide the necessary torque adjustments and eventual leveling (21). When maximum anchorage was needed, local anesthesia was used to place mini screws of 1.5 mm diameter and 8 mm length (Tomas®-pins, Dentaurum GmbH & Co. KG Germany) between the roots of the second premolar and first molar teeth in the bone of the alveolar region (22). To ensure space closure with active tie-back activation at a force of about 200–250 grams, an elastic ligature was stretched at approximately twice its typical size. During space closure, tie-backs were activated from the first molar tube in Group 2 and from the mini screw to the hook of the brass-posted archwire in Group 3, and sessions were performed at 4-week intervals until orthodontic treatment was completed.

Fractal Analysis

For each patient, a 20 × 20 pixel trabecular bone region of interest (ROI) in the apical part of the maxillary first premolars, 20-25 mm distal and 2-3 mm inferior to the spina nasalis anterior, was determined in the panoramic radiographs using the ImageJ program (National Institutes of Health, version 1.53). White and Rudolph's box-counting approach (23) was used to perform FD analysis (Fig. 1).

The procedures required for fractal dimension analysis were performed separately at T0 and T1 by the same person on the same computer and screen. Care was taken to ensure that the regions selected for FD analysis were free of any pathology and the surrounding anatomical structures, such as the lamina dura, maxillary sinus, and tooth root.

The right side of the jaw was chosen as the ROI for every patient. For the fractal dimension analysis, the following procedures were performed: The ROI in the image was determined and duplicated. A Gaussian filter was used to blur the duplicate image. As a result, only significant intensity differences were left in the image, thus eliminating small- and medium-sized variations in brightness. Using the "Subtract" process, the original image was subtracted from the blurred version created using the Gaussian filter. To distinguish between trabeculae and bone marrow spaces, 128 gray values were added to each pixel. After conversion, the final image became "Binary." The "Erode" and "Dilate" processes were used to eliminate noise in the image, and the structure of the image became clearer. White areas were altered to black and black regions to white using the "Invert" option. Then, the "Skeletonize" procedure was used.

Thus, the produced image revealed the skeletal trabecular structure's contour. After completing these steps, the FD value of the final image was determined using the "Fractal Box Count" option in the "Analyze" tab. Figure 2 displays the steps involved in this process.

Statistical analysis

Statistical analysis of the study was performed using IBM SPSS Statistics (version 26; IBM Inc., Armonk, NY, USA).

The normality distribution of the data was assessed using the Kolmogorov-Smirnov test. For intra-group comparisons based on normality distribution, Wilcoxon and Paired Sample t-tests were used.

The Mann-Whitney U and Kruskal-Wallis tests were used for pairwise and intergroup comparisons, respectively.

Cronbach's α and two-way random effect interclass correlation coefficients between measurements done four weeks apart were used to assess reliability test. $p<0.05$ was considered statistically significant.

Results

High intraobserver reliability was noted in the remeasurements of 15 randomly selected patients after 4 weeks (91%). The mean FD values at T0 were 0.54 ± 0.08, 1.54 ± 0.16, and 1.57 ± 0.19 for Groups 1, 2, and 3, respectively. At T1, the mean FD values of Groups 1, 2, and 3 were 1.53 ± 0.08, 1.36 ± 0.19, and 1.36 ± 0.18, respectively.

Intergroup differences were not significantly different at T0 ($p>0.05$). Groups 2 and 3 showed a statistically significant decrease in FD values ($p<0.05$). However, Group 1 showed no significant difference in FD values at T1 compared to T0 ($p>0.05$). Intergroup differences were found to be statistically significant at T1 ($p<0.05$). Groups 2 and 3 had FD values that were statistically significantly lower compared to Group 1 ($p<0.05$). Groups 2 and 3 did not differ statistically significantly from one another ($p>0.05$). In comparison to Group 1, the T0/T1 difference was statistically significantly higher in Groups 2 and 3 ($p<0.05$). Table 1 shows the results of the intragroup and intergroup statistical analyses.

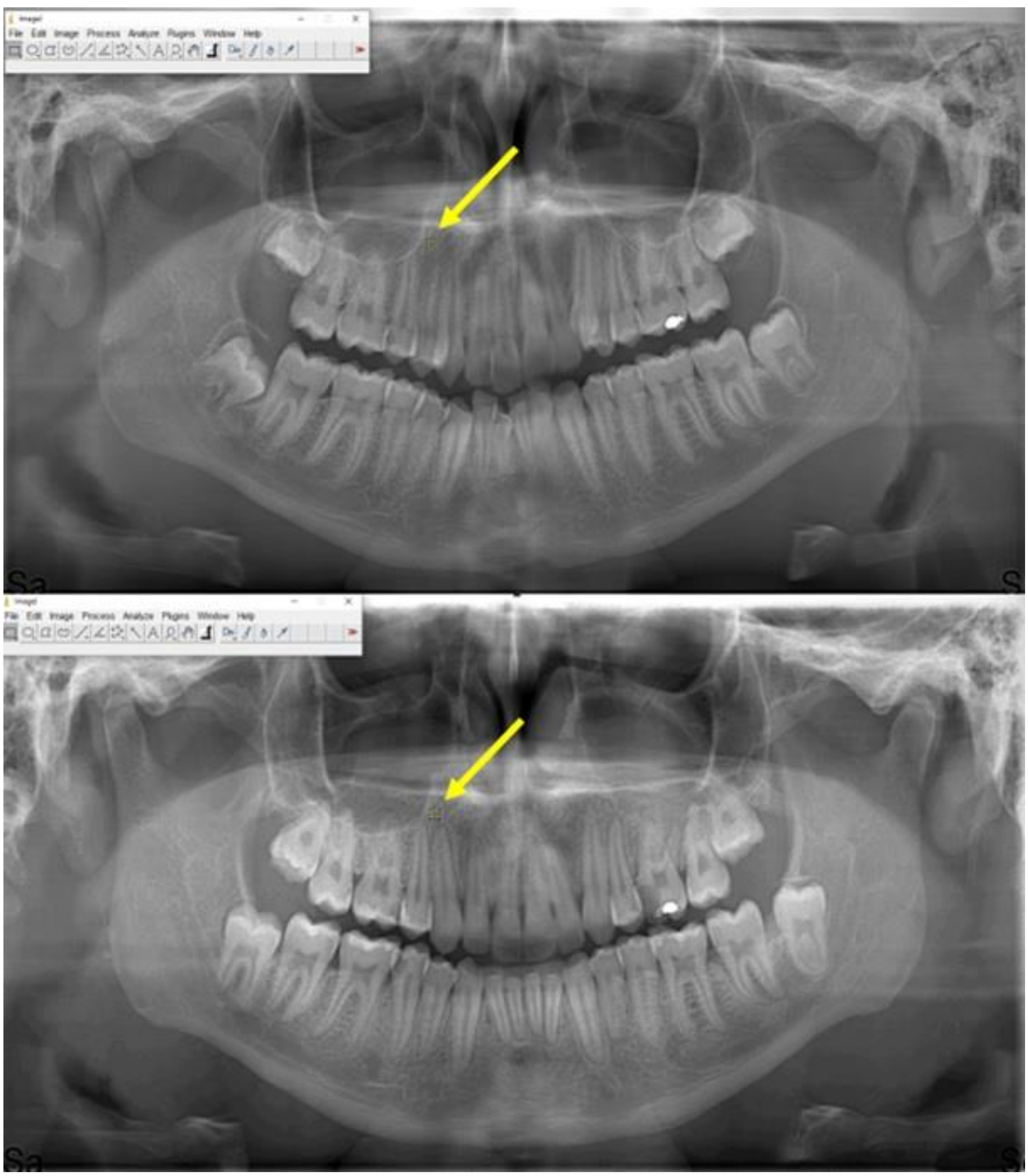

Figure 1. Determining a 20 x 20 pixel region of interest in panoramic radiography before and after extraction

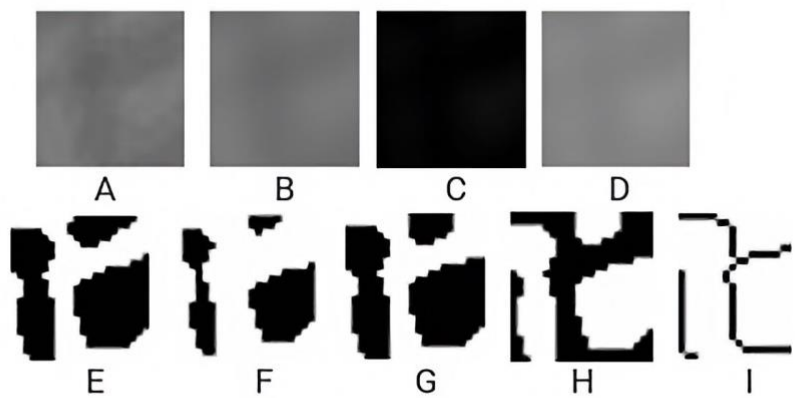

Figure 2. Process steps for Fractal Dimension analysis. (A) Duplication, (B) Image blurred with Gaussian filter, (C) Subtracting the blurred image from the original, (D) Adding 128 grays, (E) Binarization, (F) Erosde, (G) Dilate, (H) Invert, (I) Skeletonize

Table 1. Statistical analysis results intra- and inter-groups

		Group 1[a]	Group 2[b]	Group 3[c]	p
T0	Mean ± SD	1.54 ± 0.08	1.54 ± 0.16	1.57 ± 0.19	0.129 [K]
	Median	1.54	1.62	1.61	
T1	Mean ± SD	1.53 ± 0.08	1.36 ± 0.19	1.36 ± 0.18	**<0.001 * [K]**
	Median	1.53[b,c]	1.31[a]	1.35[a]	
T0/T1 difference	Mean ± SD	0.01 ± 0.05	0.18 ± 0.19	0.21 ± 0.18	**<0.001 * [K]**
	Median	0.01[b,c]	0.09[a]	0.16[a]	
Intra-group difference (p)		0.080 [P]	**<0.001 * [W]**	**<0.001 * [W]**	

[K]: Kruskal-wallis (Mann-Whitney U test) / [W]: Wilcoxon test / [P]: Paired t test
[a]: Difference with Group 1 $p< 0.05$ / [b]: Difference with Group 2 $p< 0.05$ / [c]: Difference with Group 3 $p< 0.05$
T0: Before treatment, T1: After treatment, SD: Standart Deviation

Discussion

The present study investigated alterations of bone trabeculation in the apical area of the maxillary first premolar teeth following orthodontic treatment in various patient groups. The mathematical technique known as FD analysis, which measures complex features such as trabecular bone, has long been used to assess how bone changes occur in various systemic disorders, and it can also be used in dental panoramic radiographs. It is possible to quantify the size and shape of structures by using fractal analysis. Upon reviewing the orthodontic literature, FD analysis has been applied in several studies to evaluate bone structure thus far (24). FD analysis was utilized in this study to assess trabecular alterations in the same location following non-extraction fixed orthodontic treatment and maxillary first premolars' extraction treatment due to its previously established validity.

Using panoramic radiographs taken at the beginning and end of the treatment, Ertuğrul et al. (13) evaluated the density of mandibular condyle bone using the fractal analysis method to assess the effects of fixed orthodontic treatment on the quality of the mandibular condyle bone across various malocclusion groups. They hypothesized that mandibular condyle head bone development and orthodontic treatment could be related. In the current study, FD analysis was conducted on panoramic radiographs acquired at T0 and T1 at the apical area of the upper first premolar. The alveolar bone fractal dimensions of the non-extraction and maxillary first premolar extraction groups differed significantly following fixed orthodontic treatment.

Functional appliances are used in functional jaw orthopedics to treat malpositions and structural jaw bone disorders (25). Functional appliances' influence on the trabecular bone has also been studied using fractal analysis (1, 6, 14). In a separate study, Ertuğrul (14), examined the effects of removable functional appliances on the mandibular condyle's bone quality. The results showed that certain functional orthodontic appliances—such as monoblock/twin block appliances and maxillary expansion appliances—increased the bone density at the mandibular condyle, whereas other appliances—such as face masks and chin-cups—decreased it. In this study, the moderate and maximum anchorage groups showed significant decreases at the end of the treatment, whereas the control group's FD values exhibited no significant change.

Four distinct ROIs (angulus of mandible, mental foramen, condylar process, and mandibular corpus) were assessed using pre- and post-treatment panoramic radiograph archives of individuals with class II malocclusions treated with monoblock or twin block appliances by Gümüş et al. (6), who used fractal analysis to investigate the effect of functional orthopedic therapy on the patients' mandibular trabecular bone. In their findings, functional orthodontic therapy had no effect on the mandibular condyle's FD values, and the mandibular corpus region's FD values were greatest prior to treatment and significantly decreased after treatment. A fractal analysis of the ROI in the current study, which was established using the spina nasalis anterior point as a reference, showed no significant differences between the non-extraction control group's fractal values before and after treatment. However, following extraction treatments, significant decreases in the alveolar bone's fractal values were observed.

To assess the effect of functional orthodontic treatment on the mandibular bone structure, Cesur et al. (1) evaluated FD values before and after orthodontic treatment. The study's findings showed that the treatment group's condylar process in the mandible on both the right and left sides, as well as the right mandibular corpus, had significantly higher FD values than the right condylar process in the control group. They observed significant differences between the control and treatment groups in the trabeculation of the mandibular corpus and the condyle of the mandible. Similarly, in our study, a T0/T1 difference was statistically significantly greater in the premolar extraction group than in the non-extraction group.

Fractal analysis is used for various purposes in the maxilla. Published studies have demonstrated that fractal analysis of the midpalatal suture may be used to objectively and quantitatively evaluate the consequences of rapid maxillary expansion (RME) on the teeth and skeleton (26). A prior study observed a high correlation between FD values and midpalatal suture maturation (24), indicating that fractal analysis may be an effective method for the objective quantitative assessment of midpalatal suture maturation. Arslan et al. (7) assessed reverse headgear (RHG) treatment with RME using FD analysis to investigate its effects on the mandibular trabecular structure. Between the untreated control group and the patients treated using RME + RHG for skeletal Class III malocclusions, the study found no statistically significant change in FD in any of the measured locations. They found that there was no significant trabecular alteration in the mandible resulting from RME + RHG therapy when compared to the control group. There were significant decreases in pre- and post-treatment FD values in the extraction groups undergoing fixed orthodontic treatment compared to the non-extraction control group in the current study. This difference in the extraction groups is thought to be due to alveolar remodeling after tooth extraction.

Determining the stage of an individual's growth potential is one of the basic elements of orthodontic diagnosis and treatment planning (27). In hand-wrist radiographs, Akbulut et al. (8) examined the efficacy of RME using fractal analysis. The following four locations were analyzed using FD analysis: the radius bone's epiphysis-diaphysis line and the middle finger's medial, distal, and proximal phalanges. They stated that the unsuccessful conventional RME group had significantly greater FD values for the medial phalanges, distal phalanges, and radius. As a result, they claimed that one useful tool for predicting the success of RMEs is the application of the fractal analysis method to hand-wrist radiographs. In the current study, the FD values of the remodeled alveolar bone were lower in the tooth-extraction region than in the non-extraction region. However, FD values revealed that there were no destructive effects on the trabecular structures in extraction-based orthodontic treatments, and it was thought that evaluating the trabecular fractal dimensions may be useful to understand whether the alveolar structure is healthy before orthodontic tooth movement.

Assessment of the trabecular microstructure of alveolar bone has also been conducted using fractal analysis. After investigating the possibility of a relationship between FD values and orthodontic treatment durations, Köse et al. (28) concluded that orthodontic treatment duration was negatively correlated with FD values in the mandibular mental foramen area. Accordingly, they reported that FD analysis may be used to predict orthodontic tooth movement and understand the alveolar bone's biological characteristics. This study showed that the alveolar bone's physiologic properties may vary depending on whether the treatment is extraction or non-extraction, whereas the anchorage method used has no effect on the alveolar bone's remodeling properties when extraction treatments are performed.

Since selecting a large area of interest in the fractal analysis method offers more information about trabecular structure (28), this study's limitations are that the size of the ROI chosen should be 20 × 20 pixels at most to avoid including the surrounding anatomical structures and that the fractal analysis of three-dimensional alveolar structures is performed on two-dimensional dental panoramic radiographs. However, many studies have reported that FD analysis findings on two-dimensional dental panoramic radiographs routinely taken during orthodontic diagnosis are reliable and reproducible (1, 7, 8, 14).

Conclusion

The null hypothesis of this study was rejected. After fixed, non-extraction orthodontic treatments, there were no significant changes in the alveolar bone's trabeculation, whereas significant decreases were found after extraction treatments.

It was concluded that although fixed orthodontic treatments with extraction caused significant decreases in the FD values of alveolar trabecular structures when compared with nonextraction but did not cause destructive changes. It is thought that FD analysis can be an important diagnostic material in understanding whether the alveolar trabecular structures are healthy or not.

Disclosures

Ethical Approval: Ethics committee approval was received for this study from the Zonguldak Bulent Ecevit University, Noninterventional Clinical Research Ethics Committee, in accordance the World Medical Association Declaration of Helsinki, with the approval number: 2020/23-13.

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