BRAZILIAN JOURNAL OF IMPLANTOLOGY AND HEALTH SCIENCES

ISSN 2674-8169

Avaliação da dimensão fractal do tecido ósseo na região de incisivos com e sem reabsorção radicular apical

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https://doi.org/10.36557/2674-8169.2025v7n4p368-382
Artigo recebido em 28 de Fevereiro e publicado em 08 de Abril de 2025

ARTIGO ORIGINAL

RESUMO

Introdução: A reabsorção radicular apical (RRA) é uma consequência comum do tratamento ortodôntico e é caracterizada pelo arredondamento ou encurtamento da raiz dentária. A avaliação da qualidade do tecido ósseo adjacente à reabsorção radicular pode ser realizada por meio da tomografia computadorizada de feixe cônico (TCFC), através da análise da dimensão fractal (DF). **Objetivo:** O objetivo deste estudo observacional transversal foi avaliar a qualidade do osso adjacente ao terço apical da raiz de incisivos superiores com RRA em pacientes sob tratamento ortodôntico, determinando a DF na TCFC e comparando-as com as imagens dos dentes contralaterais correspondentes sem RRA no mesmo indivíduo. **Material e métodos:** A amostra do estudo foi composta por 20 pacientes em tratamento ortodôntico com aparelho edgewise, que apresentavam RRA em um incisivo superior (grupo experimental) e ausência de RRA no incisivo contralateral correspondente (grupo controle), identificados por meio de radiografias periapicais de rotina. A DF das quatro regiões do osso alveolar de incisivos com RRA e seus contralaterais sem RRA foi determinada e comparada. **Resultados:** Em todas as regiões ósseas avaliadas, os incisivos sem RRA apresentaram valores de DF mais altos do que os incisivos com RRA, mas não houve diferença significativa. **Conclusão:** Não foi encontrada diferença significativa entre a qualidade do tecido ósseo, avaliada por meio da análise da dimensão fractal, na região apical dos incisivos superiores com e sem reabsorção radicular apical do mesmo paciente ortodôntico.

Palavras-chave: Ortodontia; Movimento dentário; Reabsorção da raiz; Tomografia computadorizada de feixe cônico.

Fractal dimension assessment of bone tissue in the region of incisives with and without apical root resorption

ABSTRACT

Introduction: Apical root resorption (ARR) is a common consequence of orthodontic treatment, and is characterized by the rounding or shortening of the tooth root. The quality of the bone tissue adjacent to root resorption can be assessed using cone beam computed tomography (CBCT), by analyzing the fractal dimension (FD). **Objective:** The aim of this observational cross-sectional study was to assess the quality of the adjacent bone of the root apical third of maxillary incisors with ARR in patients under orthodontic treatment by determining the FD in CBCT and comparing them with the images of the corresponding contralateral teeth without ARR in the same individual. **Material and methods:** The study sample consisted of 20 patients under orthodontic treatment with edgewise appliance, who presented apical root resorption in a maxillary incisor (experimental group) and absence of root resorption in the corresponding contralateral incisor (control group), identified through routine periapical dental radiographs. The FD of four regions in the adjacent alveolar bone of incisors with ARR and their contralateral teeth without ARR was determined and compared. **Results:** In all bone regions evaluated, the incisors without ARR had higher FD values than incisors with ARR, but there was no significant difference. **Conclusion:** No statistical difference was found between the quality of the bone tissues, assessed through the analysis of the FD, in the apical region of the maxillary incisors with and without apical root resorption of the same orthodontic patient.

Keywords: Orthodontics; Tooth movement; Root resorption; Cone beam computed tomography.

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INTRODUCTION

Apical root resorption (ARR) is a common consequence that affects most orthodontically treated teeth and is characterized by root shortening or even apical rounding[1]. Despite its high prevalence, the severity of the resorption related to orthodontic treatment usually has minimal clinical significance[2], however, ARR is a concern for the orthodontist since it jeopardizes treatment success[3].

The factors responsible for ARR during orthodontic treatment have not yet been fully understood, and their origin is considered multifactorial[3]. The biological factor most likely to influence the susceptibility to resorption is genetics[3,4].

According to Goldie and King[5], Rygh and Reitan[6] the bone mineral density is a factor related to ARR. It has been suggested that greater mineral density requires the application of more intense forces to accomplishment dental movement[6,7], and consequently result in more root resorption[6]. However, there are still divergent results that do not find an association between the alveolar bone density around the roots and the amount of corresponding root resorption[3].

The CBCT (cone beam computed tomography) has been frequently used to determine the mineral density of craniofacial structures[8]. The main advantages of CBCT are the low radiation dose, shorter image acquisition time and reduced costs compared to conventional computed tomography (CT)[9,10]. In the CBCT occurs a non-uniform angular distribution of X-ray beam intensity leading to nonuniformity of Hounsfield Unit (HU), which has been used in conventional CT to measure bone mineral density[11].

Because of the fact that HU values are not valid in CBCT, the fractal dimension (FD) has been suggested as an alternative for evaluation of bone quality when this exam is undertaken[11,12]. Fractal analysis is a method used for quantitative evaluation of structures with complex geometry, which is represented by a single number, the FD[13,14]. Although quantitative, the FD represents a qualitative evaluation of the bone texture that is closely related to bone density[15].

The aim of this study was to assessed the quality of the adjacent bone of the root apical third of maxillary incisors with ARR in patients under orthodontic treatment by determining the FD in CBCT and comparing them with the images of the corresponding contralateral teeth without ARR in the same individual.

MATERIAL AND METHODS

The sample consisted of 20 individuals (9 males and 11 females) with the mean age of 20.3 years (14-28 years), under orthodontic treatment with edgewise appliance, who were not orthodontically treated before and presented apical root resorption in a maxillary incisor (experimental group) and absence of root resorption in the corresponding contralateral incisor (control group). Routine periapical dental radiographs of the maxillary incisors, at different phases of the orthodontic treatment, were used to identify these conditions.

The subjects presented absence of disturbance involving calcium metabolism or history of trauma in the maxillary incisors. Furthermore, their pre-treatment records showed symmetrical malocclusions, and selected incisors (with and without resorption) with no root resorption, no endodontic treatment, no morphological alteration, same root length and similar root structures.

This study has been approved by the Ethics Committee of the *** University and all individuals who voluntarily participated in this research signed the informed consent term after thorough explanation about the procedures.

After identification of the incisors with and without ARR, the subjects who met the inclusion criteria were submitted to CBCT, performed with an i-CAT scanner (Imaging Sciences International, Hatfield, PA-USA), operated at 120kV and 3-8mA, voxel size of 0.25mm, rotation time of 26.9s, and field of view (FOV) of 160mm in diameter and 100mm in height.

For image acquisition, each individual was positioned with the chin resting on the appropriate support, with the Frankfurt plane parallel to the ground and the median sagittal plane perpendicular to the ground and the mandible in maximum intercuspation position. The FOV was positioned so that the occlusal plane occupied its vertical center and the anterior nasal spine was 35 mm from its anterior border.

Determination of CBCT incisor images:

The 40 incisors (22 lateral and 18 central incisors) were evaluated by one calibrated examiner (orthodontist with more than 5 years of clinical experience in CBCT imaging). The selected incisors were initially analyzed with i-CAT Vision (Imaging

Sciences International Inc., Hatfield, USA) software in MPR (multiplanar reconstruction) mode, with 0.5mm thick slices. They were vertically positioned so that the intersection of the sagittal and coronal sections coincided with its long axis and the coronal section was parallel to the incisal border.

The sagittal slice was positioned at the mesiodistal center of the incisors, and in this sagittal image the root length was determined by the distance between the most apical point of the dental root and its orthogonal projection on a perpendicular line to the long axis of the tooth, which was positioned equidistant from the buccal and lingual cementum-enamel junctions (CEJ) (Figure 1). The extension of the root resorption was determined by the difference between the root length of the incisors without and with resorption, since both had the same length at the beginning of orthodontic treatment.

Figure 1 - Determination of the root length. (a) Horizontal line drawn through the CEJ of the buccal and lingual tooth surface. (b) Perpendicular line to the long axis of the tooth, equidistant from the buccal and lingual cementum-enamel junctions. (c) Line representing the root length.

In order to evaluate bone tissues in similar regions of the incisors with and without ARR from the same patient, the apical third of the teeth was calculated by dividing the root length of the incisors with ARR into three equal parts. This measure was applied from the most apical point of the root in the incisor with ARR, but in the incisors without ARR, the extension of the root resorption was discounted. The limits of the apical third were identified by two lines in the incisors with ARR (Figure 2a) and four lines in the incisors without ARR (Figure 2b), in order to allow the selection of the regions of interest (ROIs), and the image of the sagittal slice was saved in JPEG format (Joint Photographics Expert Groups) in standardized size (1444x900 pixels).

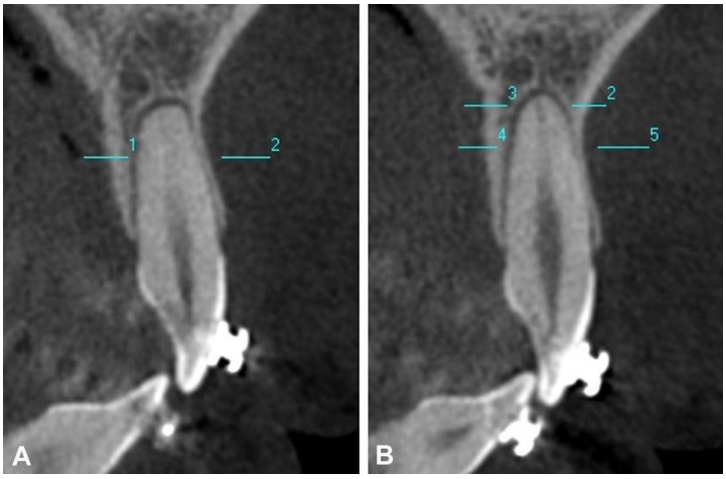

Figure 2 - Buccal and lingual lines in sagittal slice indicating the apical third of the incisors. (a) The limits of the apical third were identified by two lines in the incisors with ARR and (b) Four lines in the incisors without ARR, with the two upper lines indicating the limits of the resorption in the contralateral incisor.

ROIs of alveolar bone:

The images of the sagittal slices were analyzed with ImageJ (National Institutes of Health, USA) and three vertically distributed areas (upper, middle and lower) were selected along the lingual bone of the apical third of the root. Each area had one third of the length of the apical third of the root and 1mm in width. These areas were positioned as near as possible to the root, limited by the periodontal ligament, and had the same size in teeth with and without resorption from the same individual (Figure 3).

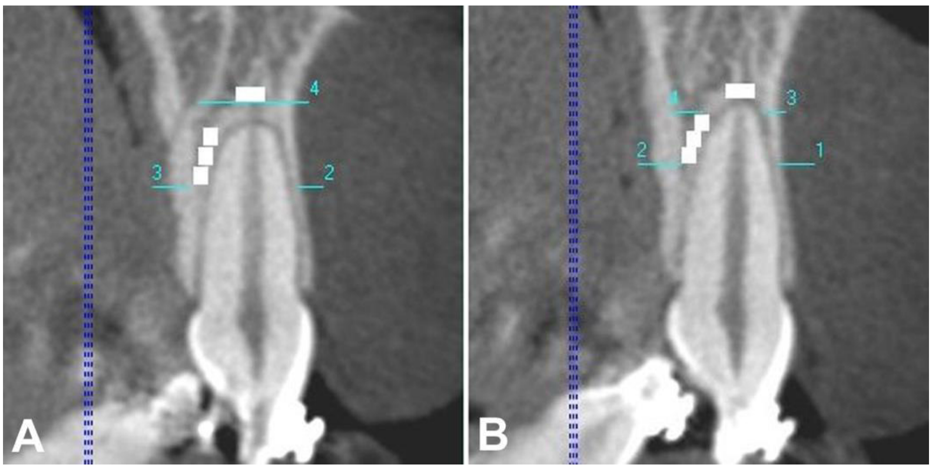

Figure 3 - Determination of the ROIs for the analysis of the fractal dimension of the alveolar bone in teeth with and without ARR.

The other area of bone evaluation, the supra-apical area, was 1mm in height and 2mm in width and positioned in the center of the root apex. In teeth without ARR, this area was positioned immediately above the root apex and in teeth with ARR it was positioned away from the apex at the same distance as the extent of the resorption (Figure 3).

Since ImageJ only measures in pixels, the lines that limit the apical third of the root served as a scale for the conversion of pixel to millimeters.

Determination of the fractal dimension:

The fractal dimension (FD) of four areas of alveolar bone were determined with ImageJ software. The digital images of each ROI were converted from RGB color to 8 bits (Figure 4a). Then the ROIs were duplicated and blurred through the use of a Gaussian filter with a diameter of 35 pixels (Figure 4b). What happens in this step is the removal of all fine and medium scale structure and maintenance of only large variations in density. The next step consisted in subtracting the resulting heavily blurred image from the original image (Figure 4c). Then, a constant grayscale value of 128 was added to the result at each pixel location (Figure 4d). The next step consisted of transforming the resulting image into a binary image (Figure 4e) for the erosion step to be performed. In order to dilate the image, each pixel is replaced with the maximum value of the neighboring pixels. In the inversion, the image of the previous result was inverted, and the trabeculae changed from white to black, making it easier to count. Then, there was a transformation into an outline image (Figure 4f). In this process, the pixels of the edges of the images were removed until the image was reduced to a single broad skeleton with the size of a pixel. In the outline images, analyzes were performed in box counting method, generating then, the values of the FD[16].

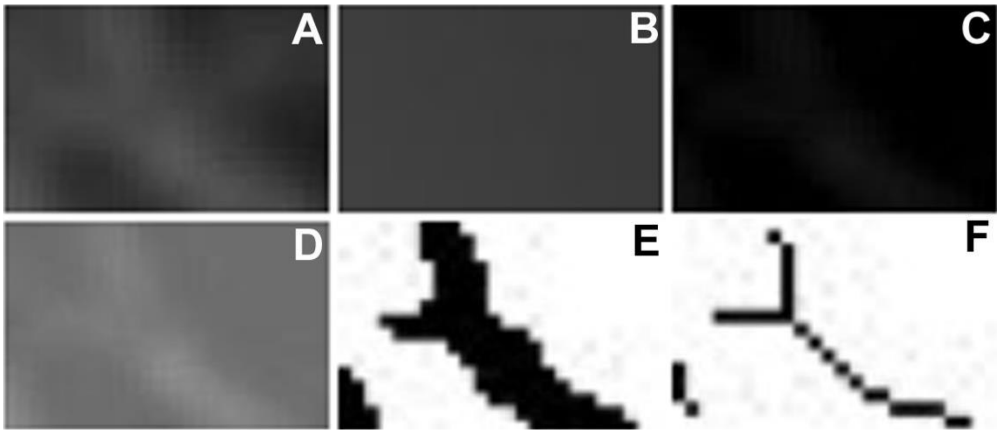

Figure 4 - Transformation of the ROI image prior to calculation of FD. (a) Original image of the supra-apical area with an 8 bit gray scale. (b) The result of blurring the image. (c) The result of subtracting the blurred image from the original image (d) and adding 128 pixels. (e) Transformation of the image into a binary image. (f) The trabecular pattern is outlined.

The sagittal FD values were used to determined the mean FD of the lingual alveolar bone was calculated based on the FD values of the lower, middle and upper areas of lingual alveolar bone. The FD values of supra-apical ROI and the means of the lingual alveolar bone (upper, middle and lower), in teeth with and without ARR, were compared.

Statistical analysis:

The intra-examiner reliability was analyzed by the determination of the intraclass correlation coefficient (ICC), which was calculated from the values of FD of alveolar bone of eight incisors randomly chosen, measured twice, with a 15-day interval between measurements.

The normality test (Shapiro-Wilk) was performed in order to evaluate the distribution pattern of the values obtained for each variable. To compare the values of bone FD between the groups, the Wilcoxon test was used. A significance level of 5% was adopted and the analysis was performed in SPSS 20.0.0 software (SPSS, Chicago, IL, USA).

RESULTS

The intra-examiner reliability test for the variables root length and FD of the supra-apical bone presented values above 0.9, indicating an excellent concordance.

The Shapiro-Wilk test (Table 1) showed that some variables did not present normal distribution and, therefore, the Wilcoxon test was used for comparisons between the groups.

Table 1 - Shapiro-Wilk normality test.

Variables	Incisors with ARR	Incisors without ARR
Root lenght	0.902	0.578
Supra apical alveolar bone	0.001*	0.350
Lower lingual alveolar bone	0.082	0.473
Middle lingual alveolar bone	0.110	0.035*
Upper lingual alveolar bone	0.334	0.051
Mean lingual alveolar bone	0.080	0.019*

* - significant difference.

The values of root length and fractal dimension of the alveolar bone in the supra-apical region and in the lingual region (lower, middle, upper and mean), are described in Table 2.

The incisors with ARR presented a statistically smaller root length than the incisors without ARR, with a mean difference of 1.29 mm or 9.91% (Table 2). The fractal dimensions of the alveolar bone of the incisors with and without ARR did not present a statistically significant difference, however, a lower value of FD could be observed in the teeth with ARR in all variables.

Table 2 - Mean values and standard deviations of the fractal dimension of each variable in incisors with and without ARR, and the comparisons between two groups.

	INCISORS WITH ARR			INCISORS WITHOUT ARR			P-VALUE*
	N	MEAN	SD	N	MEAN	SD	
Root lenght (mm)	20	11.725	1.133	20	13.012	1.663	0.000
Supra apical alveolar bone (FD)	20	0.727	0.245	20	0.786	0.117	0.117
Lower lingual alveolar bone (FD)	16	0.578	0.162	16	0.586	0.135	0.955
Middle lingual alveolar bone (FD)	17	0.627	0.185	17	0.669	0.117	0.868
Upper lingual alveolar bone (FD)	17	0.613	0.171	17	0.621	0.189	0.427
Mean lingual alveolar bone (FD)	17	0.606	0.111	17	0.629	0.654	0.795

ARR - apical root resorption; SD - standard deviation; FD - fractal dimension; * Wilcoxon test.

DISCUSSION

Apical root resorption is a common undesirable effect of orthodontic treatment[1,17,18] and the most involved teeth are the maxillary incisors[4,19,20], this could be explained by their highest percentages of abnormal root shapes and tendency to have more slender roots, especially the upper lateral incisors[4], and also by the greater movement they are subjected during orthodontic treatment[19]. In order to monitor the appearance and progression of these lesions during the orthodontic treatment, periapical radiographs are frequently requested and, therefore, these exams were used for the initial selection of patients for this study, when the presence of ARR in a superior incisor and the absence of this lesion in the contralateral incisor were identified during the orthodontic treatment. However, in two-dimensional radiographic methods, the extent of the ARR might be underestimated due to overlapping structures[21], therefore, CBCT provides the best images for the correct diagnosis of ARR[22] and it is used for the confirmation of the diagnosis of ARR and analysis of the images of the incisors.

Due to the multifactorial characteristic of ARR, in the studies that involve the assessment of this condition, a strict control of the variables is necessary to select the sample. In order to control some possible etiological factors related to individual susceptibility to ARR, such as genetic or systemic factors, gender and age[3,4], the comparison of the incisors with and without resorption was made from the same individual. Other possible etiological factors of ARR such as trauma[23], root morphology[4,24] and the application of orthodontic forces[25,26] were controlled by the inclusion criteria. The inclusion of individuals with only symmetric malocclusion creates the possibility of applying symmetric protocols of orthodontic forces on each maxillary incisor of the same orthodontic patient.

The most commonly procedure performed to measure bone quality through radiological techniques is the use of the Hounsfield scale to quantify the radiodensity in computed tomography images[27,28]. Although CBCT is an exam with a lower dose of effective radiation, its image present instability of the voxel values, which compromises the application of the Hounsfield scale[11,29,30]. As an alternative, the use of fractal analysis in conjunction with CBCT has been suggested for the assessment of bone quality[11,12,31]. This technique was chosen to evaluate the quality of the bone in this study, since it allows an analysis of the texture and complexity of the architecture of mineralized tissue[11,15,31].

The comparison between results addressing bone mineral radiodensity and FD is possible because, although fractal analysis is a quantitative measure[32] both methods are used to define the quality of mineralized tissues[11,12,33] and previous studies have stated that the density of the alveolar bone was positively correlated to the FD values on periapical radiographs[15] and CBCT images[34].

The box-counting method used in this study is a common, simple and accessible method to calculate the FD[14,35]. The image is covered by a grid of progressively reduced squares and the number of squares containing the structure is counted. A graph of the inverse of the size of the box versus the log of the number of elements containing the squares is obtained. The slope of the graph is the fractal dimension[36]. A limitation of this method is the impossibility of calculating the fractal dimension of an irregular ROI[37,38]. When an irregular structure is selected, it is automatically complemented by a black background, creating a rectangular image that is used for the application of the box counting method. This background interferes with the value of the FD, since the black pixels have value equal to zero[38]. Thus, in this study, the ROIs in the lingual and supra-apical regions of the alveolar bone respected the rectangular shape so that the FD could be correctly calculated. Additionally, the fact that the images of ROIs were binarized using the method described by White and Rudolph[16], which even though it was developed to be applied to periapical radiographs, was applied well in this study, as there was sufficient resolution of the bone trabecular in the CBCT images for this procedure to be correct applied.

The association between apical root resorption and quality of alveolar bone has been discussed in the literature[3,39]. In the present study, after the control of the individual factors associated with AAR, the alveolar bone adjacent to the incisors with ARR exhibited lower FD values than the bone of the incisors without ARR bone, but this difference was not significant, which corroborates with other authors[3,39] that did not consider the bone quality, assessed by mineral density, as a predisposing factor for ARR during orthodontic movement. However, we did not find any study in the literature that evaluated bone quality by FD in the region of upper permanent incisors with ARR in CBCT images so that we could compare them.

In addition, in this study, the absence of a significant difference in the FD values of the alveolar bone of incisors with and without ARR may have been influenced by the size of the ROIs, which may not have been sufficient to adequately represent the trabeculae of the alveolar bone, but which was the methodology applied, due to a limitation of the anatomy of the bone, which can be seen in the sagittal slice. For this reason, the average of the three ROIs of the lingual region of the incisors was also calculated to represent the DF value of this region. Thus, according to the results of this study, bone quality, as assessed by trabecular texture, does not appear to be an influencing factor in the occurrence of ARR.

CONCLUSION

No significant difference was observed in the fractal dimension values of the adjacent alveolar bone between upper incisors with and without apical root resorption of the same orthodontic patient.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

1. Harris EF, Kineret SE, Tolley EA. A heritable component for external root resorption in patients treated orthodontically. Am J Orthod Dentofacial Orthop. 1997;111:301-309.

2. Lee RY, Artun J, Alonzo TA. Are dental anomalies risk factors for apical root resorption in orthodontic patients? Am J OrthodDentofacialOrthop. 1999;2:187-195.

3. Otis LL, Hong JSH, Tuncay OC. Bone structure effect on root resorption. Orthod Craniofac Res. 2004;7:165-177.

4. Sameshima GT, Sinclair PM. Predicting and preventing root resorption: part I. Diagnostic factors. Am J Orthod Dentofacial Orthop. 2001;119:505-510.

5. Goldie RS, King GJ. Root resorption and tooth movement in orthodontically treated, calcium-deficient, and lactatingrats. Am J Orthod. 1984;85:424-430.

6. Rygh P, Reitan K. Ultrastructural changes in the periodontal ligament incident to orthodontic tooth movement. Trans Eur Orthod Soc. 1972;393-405.

7. Midgett RJ, Shaye R, Fruge JF Jr. The effect of altered bone metabolism on orthodontic tooth movement. Am J Orthod.1981;80:256-262.

8. Hsu J.T, Chang HW, Huang HL, Yu JH, Li YF, Tu MG. Bone density changes around teeth during orthodontic treatment. Clin Oral Investig. 2010;15:511-519.

9. Endo M, Tsunoo T, Nakamori N, Yoshida K. Effect of scattered radiation on image noise in cone beam CT. Med Phys. 2001;28:469-474.

10. Schulze D, Heiland M, Thurmann H, Rother UJ. Radiation exposure during midfacial imaging using 4- and 16-slice computed tomography, cone beam computed tomography systems and conventional radiography. Dentomaxillofac Radiol. 2004;33:83-86.

11. Hua Y, Nackaerts O, Duyck J, Maes F, Jacobs R. Bone quality assessment based on cone beam computed tomography imaging. Clin Oral Implants Res. 2009;20:767-771.

12. González-Martín O, Lee EA, Veltri M. CBCT fractal dimension changes at the apex of immediate implants placed using undersized drilling. Clin Oral Implants Res. 2012;23:954-957.

13. Jolley L, Majumdar S, Kapila S. Technical factors in fractal analysis of periapical radiographs. Dentomaxillofac Radiol. 2006;35:393-397.

14. Kato CNAO, Barra SG, Tavares NPK, Amaral TMP, Brasileiro CB, Mesquita RA, Abreu LG. Use of fractal analysis in dental images: a systematic review. Dentomaxillofac Radiol. 2019;48:20180457.

15. Southard TE, Southard KA, Lee A. Alveolar process fractal dimension and postcranial bone density. Oral Surg Oral Med Oral Pathol Oral Radiol Endod. 2001;91:486-491.

16. White SC, Rudolph DJ. Alterations of the trabecular pattern of the jaws in patients with osteoporosis. Oral Surg Oral Med Oral Pathol Oral Radiol Endod. 1999;88:628-635.

17. Harris DA, Jones AS, Darendeliler MA. Physical properties of root cementum: part 8. Volumetric analysis of root resorption craters after application of controlled intrusive light and heavy orthodontic forces: a microcomputed tomography scan study. Am J Orthod Dentofacial Orthop. 2006;130:639-647.

18. Kocadereli I, Yesil TN, Veske PS, Uysal S. Apical root resorption: a prospective radiographic study of maxillary incisors. Eur J Dent. 2011;5:318-323.

19. Janson GR, De Luca Canto G, Martins DR, Henriques JF, De Freitas MR. A radiographic comparison of apical root resorption after orthodontic treatment with 3 different fixed appliance techniques.Am J Orthod Dentofacial Orthop. 2000;118:262-273.

20. Bayir F, Gumus EB. External apical root resorption after orthodontic treatment: Incidence, severity and risk factors. J Dent Res Dent Clin Dent Perspectivas. 2021;15:100-105.

21. Campos MJ, Silva KS, Gravina MA, Fraga MR, Vitral RW. Apical root resorption: the dark side of the root. Am J Orthod Dentofacial Orthop. 2013;143:492-498.

22. Yi J, Sun Y, LiY, Li C, Li X, Zhao Z. Cone-beam computed tomography versus periapical radiograph for diagnosing external root resorption: A systematic review and meta-analysis. Angle Orthod. 2017;87:328-337.

23. Consolaro A, Furquim LZ. Extreme root resorption associated with induced tooth movement: A protocol for clinical management. Dental Press J Orthod. 2014;19:19-26.

24. Smale I, Årtun J, Behbehani F, Doppel D, Van't Hof M, Kuijpers-Jagtman AM. Apical root

resorption 6 months after iniciation of fixed orthodontic appliance therapy. Am J Orthod Dentofacial Orthop. 2005;128:57-67.

25. Kurol J, Owman-Moll P. Hyalinization and root resorption during early orthodontic tooth movement in adolescents. Angle Orthod.1998;68:161-165.

26. Roscoe MG, Meira JB, Cattaneo PM. Association of orthodontic force system and root resorption: A systematic review. Am J Orthod Dentofacial Orthop. 2015;147:610-626.

27. Nomura Y, Watanabe H, Honda E, Kurabayashi T. Reliability of voxel values from cone-beam computed tomography for dental use in evaluating bone mineral density. Clin Oral Implants Res.2010;21:558-562.

28. Araki K, Okano T. The effect of surrounding conditions on pixel value of cone beam computed tomography. Clin Oral Implants Res.2013;24:862-865.

29. Kim D-G. Can Dental Cone Beam Computed Tomography Assess Bone Mineral Density? J Bone Metab. 2014;21:117-126.

30. Campos MJ, Souza TS, Mota Jr SL, Fraga MR, Vitral, RW. Bone mineral density in cone beam computed tomography: Only a few shades of gray. World J Radiol. 2014;6:607-612.

31. Santos IG, Faria FR, Campos MJS, Barros BAC, Davi Rabelo GD, Devito KL. Fractal dimension, lacunarity, and cortical thickness in the mandible: Analyzing differences between healthy men and women with cone-beam computed tomography. Imagem Sci Dent. 2023;53:153-159.

32. Sànchez I, Uzcàtegui G. Fractals in dentistry. J Dent. 2011;39:273-292.

33. Alman AC, Johnson LR, Calverley DC, Grunwald GK, Lezotte DC, Hokanson JE. Diagnostic capabilities of fractal dimension and mandibular cortical width to identify men and women with decreased bone mineral density. Osteoporos Int. 2012;23:1631-1636.

34. Güngör E, Yildirim D, Çevik R. Evaluation of osteoporosis in jaw bones using cone beam CT and dual-energy X-ray absorptiometry. J Oral Sci. 2016;58:185-194.

35. Silva MEB, Santos HS, Ruhland L, Rabelo GD, Badaró. Fractal analysis of dental periapical radiographs: A revised image processing method. Oral Surg Oral Med Oral Pathol Oral Radiol. 2023;135:669-677.

36. Wagle N, Do NN, Yu J, Borke JL. Fractal analysis of the PDL-bone interface and implications for orthodontic tooth movement. Am J Orthod Dentofacial Orthop. 2005;127:655-661.

37. Oczeretko E, Borowska M, Kitlas A, Borusiewicz A, Sobolewska-Siemieniuk M. Fractal analysis of medical images in the irregular regions of interest. 8th IEEE international conference on bioinformatics and bioengineering. 2008.

38. Ahammer H. Higuchi dimension of digital images. PloS One. 2011;9:1-8.

39. Scheibel PC, Ramos AL, Iwaki LCV, Micheletti KR. Analysis of correlation between initial alveolar bone density and apical root resorption after 12 months of orthodontic treatment without extraction. Dental Press J Orthod. 2014;19:97-102.