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(Research Article)

Exploring regional structural differences of maxilla and mandible via fractal dimension

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Abstract

Background. The maxilla and mandible are two distinct anatomical structures that differ significantly in terms of functional loading, embryological development, and cortical-cancellous bone ratios In clinical practice, infiltrative anesthesia is often sufficient for the maxilla and anterior mandible, but regional anesthesia is frequently required for the posterior mandible. Study aims to provide objective and reproducible data to support the indirect clinical observations of bone structural differences in local anesthesia applications and surgical planning via fractal analysis.

Methods. In panoramic radiographs, a total of 8 regions of interest were selected from the right and left apical regions, including 2 anterior maxillae, 2 posterior maxillae, 2 anterior mandibles, and 2 posterior mandibles. These were evaluated for fractal dimension using the box counting method with ImageJ software.

Results. When evaluated according to these four regions, the fractal dimension ranking was highest in the mandibular posterior region and lowest in the maxillary anterior region. Notably, the maxillary posterior region has a lower mean value for trabecular organization compared to the mandibular anterior region. According to the Tukey post hoc test, there is no statistically significant difference between the maxillary anterior and posterior regions. However, the differences between all other regions are statistically significant. In all regions of interest fractal values of male individuals were higher than females.

Conclusion. This study demonstrated that differences in sex related and regional trabecular organization between the maxilla and mandible, as well as within the same jaw, can be revealed quantitatively using fractal analysis applied to apical regions of interest obtained from panoramic radiographs, in a low radiation imaging technique and open access software in terms of maximum accessability.

Keywords: Oral and Maxillofacial Radiology; Fractal Analysis; Panoramic Radiographs; Bone Quality; Maxilla; Mandible

1. Introduction

The maxilla and mandible are two distinct anatomical structures that differ significantly in terms of functional loading, embryological development, and cortical-cancellous bone ratios. The mandible has a thicker, more compact cortical bone structure because it primarily carries masticatory forces. In contrast, the maxilla has a relatively more porous structure due to its spongy bone organization and anatomy associated with sinus cavities. These differences have long been recognized in histological and radiological studies and have been confirmed in cone-beam computed tomography (CBCT) studies based on three-dimensional imaging techniques [2, 3].

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In addition to these general differences between the jaws, distinct structural differences exist between the anterior and posterior regions within the same jaw. The anterior region (symphysis–parasymphysis) of the mandible shows marked corticalization; however, cortical bone thickness and density increase further in the posterior mandible, which directly affects clinical applications. In clinical practice, infiltrative anesthesia is often sufficient for the maxilla and anterior mandible, but regional anesthesia is frequently required for the posterior mandible. This is due to the cortical barrier, which limits the diffusion of the anesthetic solution within the bone tissue [1].

However, it should be emphasized that the difference in "bone density" experienced in clinical settings cannot be explained solely by trabecular bone mineral density. In particular, the hardness felt in the anterior mandible is largely dependent on cortical bone thickness and compactness. CBCT-based studies evaluating bone density through Hounsfield Unit (HU) values reveal significant differences between jaw regions. However, these measurements reflect the overall bone structure and are dominated by the cortical component [2, 3].

Therefore, interpreting mandibular bone quality through densitometric measurements alone provides a limited view of trabecular microarchitecture [1].

Bone quality is a multidimensional concept that encompasses not only mineral content, but also the organization, connectivity, and geometric complexity of trabecular bone. In alveolar bone in particular, CBCT-based morphology studies have shown that density measurements alone cannot fully reflect morphological variations; trabecular architecture can exhibit meaningful regional differences [4, 5]. This situation increases the need for analysis methods that directly target trabecular organization.

In this context, fractal analysis is a valuable complementary method for quantitatively defining bone microarchitecture when evaluating trabecular patterns obtained from two-dimensional dental radiographs. Fractal dimension (FD) reflects the complexity and organization of the trabecular network, revealing structural changes independent of mineral density. Systematic and comprehensive literature reviews have demonstrated that fractal analysis is a reliable and reproducible method for evaluating alveolar bone in panoramic and periapical radiographs.

In dental literature, fractal analysis has been widely used to evaluate the effects of systemic diseases on mandibular trabecular bone, to monitor peri-implant bone changes, and to investigate regional differences between jawbones. Studies have reported that box-counting-based fractal analyses performed on panoramic radiographs using standardized regions of interest (ROIs) can reliably reflect changes in trabecular microarchitecture. Furthermore, panoramic radiographs allow for the comparative evaluation of bone structure in large populations, increasing the value of this method in epidemiological and clinical research.

On the other hand, studies that systematically compare structural differences between the anterior and posterior regions of the maxilla and mandible using fractal analysis on multiple ROIs selected from the apical region of panoramic radiographs are limited. These differences are clearly felt in the clinic. Using multiple ROIs obtained from the same individual allows for a more objective assessment of regional trabecular organization because it reduces inter-individual variability.

This study aims to apply fractal analysis using the box-counting method to quantitatively reveal differences in regional trabecular organization between jawbones. This approach aims to provide objective and reproducible data to support the indirect clinical observations of bone structural differences in local anesthesia applications and surgical planning.

2. Material and methods

2.1. Study Design

Since the present study is based on a fractal analysis of panoramic radiographs; images of the individuals aged 18-30 with permanent dentition were used. Cases involving tooth loss, impacted teeth, bone pathologies, or signs of trauma in the anterior or posterior regions of the jaw were excluded.

In panoramic radiographs, a total of 8 regions of interest (ROIs) were selected from the right and left apical regions, including 2 anterior maxillae, 2 posterior maxillae, 2 anterior mandibles, and 2 posterior mandibles. These were evaluated for fractal dimension using the box counting method with ImageJ software (NIH, Maryland, USA). (Figure 1).

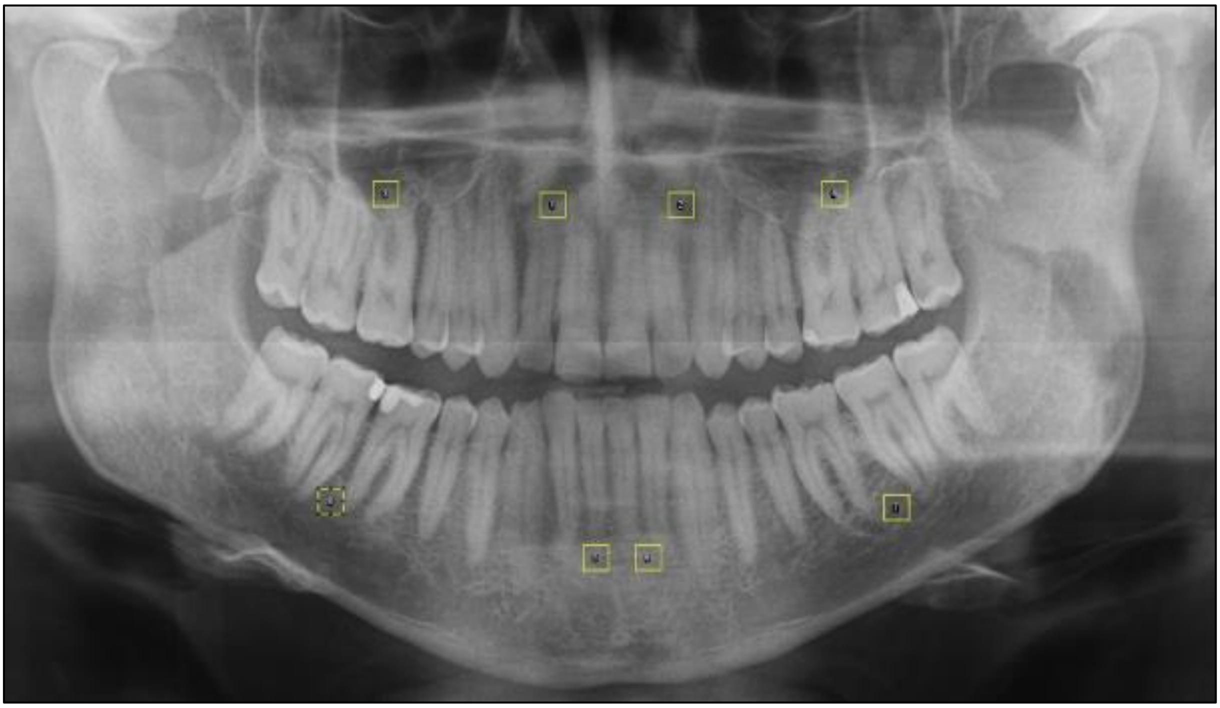

Figure 1 50 x 50 pixel ROIs selected on panoramic radiograph

The maxillary anterior (ROI 1, 2), maxillary posterior (ROI 3, 4), mandibular anterior (ROI 5, 6), and mandibular posterior (ROI 7, 8) regions were duplicated (Figure 2a). Then, the images were filtered with a Gaussian blur (Figure 2b), and the blurred images were subtracted from the originals (Figure 2c). Next, a constant value of 128 was added to each pixel location in the resulting image to shift the pixel intensity values into a more suitable range for subsequent processing (Figure 2d). Then, the images were converted into binary images (Figure 2e). After erosion, dilation, and inversion, the images were skeletonized (Figure 2f).

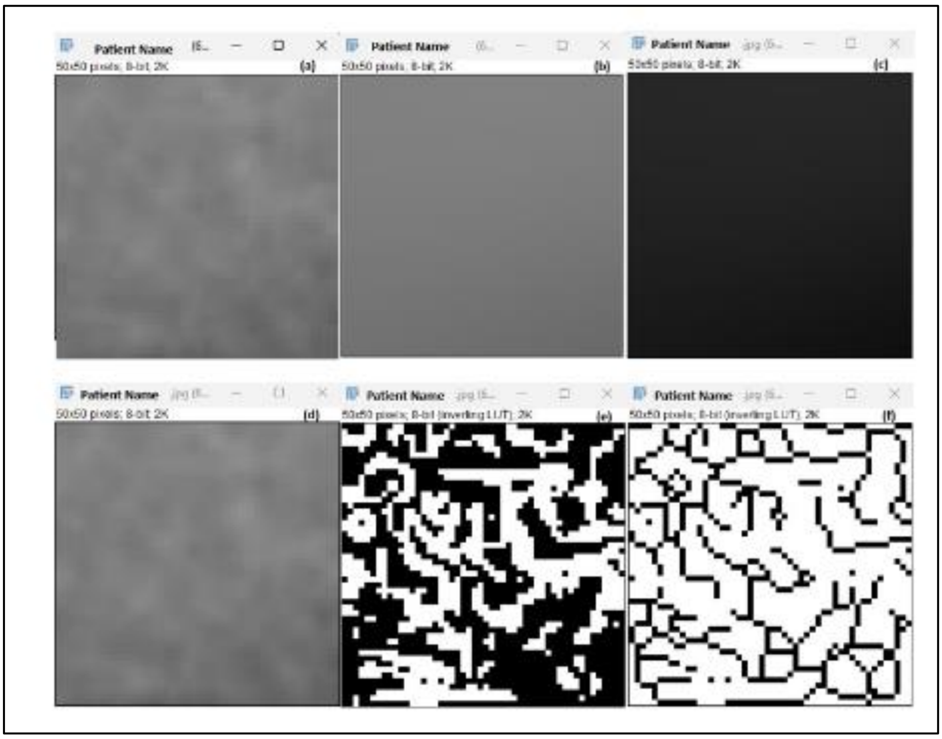

Figure 2 Steps before Fractal Analysis. a) Duplication, b) Gaussian Blur, c) Subtraction, d) Add, e) Make Binary, f) Skeletonize

After the preliminary stages, fractal analysis was applied to the skeletonized image using the box counting method with boxes of sizes 2, 3, 4, 6, 8, 32, and 64. The results were recorded for each ROI (Figure 3).

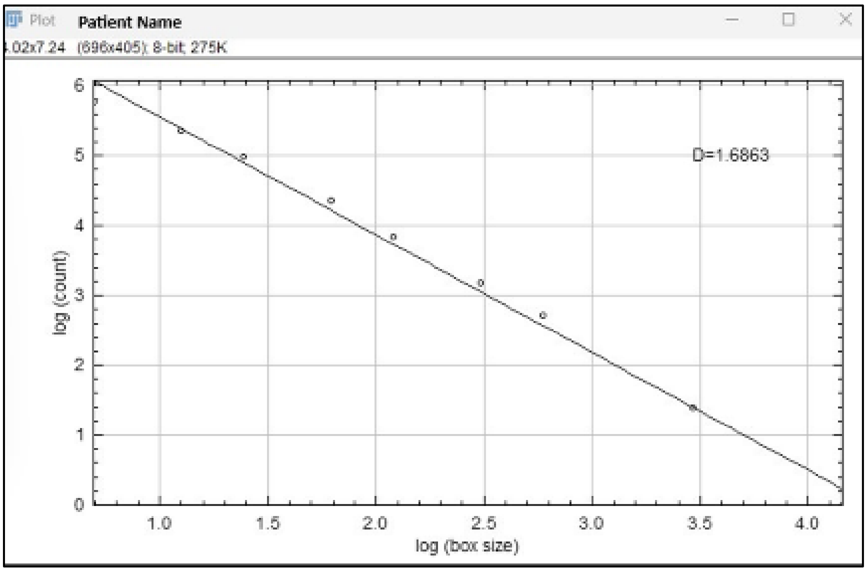

Figure 3 Fractal Analysis for a ROI.

2.2. Statistical Analysis

ROIs were divided into four main regions, and differences related to the binary gender factor were evaluated.

Using G-Power software, an effect size of 0.5 and a power of 0.8 were determined to require 48 samples per group for the four-group ANOVA test. The study aimed to achieve a power close to 1 with 432 ROI regions belonging to 108 individuals (54 female and 54 male).

The data will be analyzed using SPSS software. Descriptive statistics (mean, standard deviation, and percentage) will be calculated. Differences related to the gender factor will be evaluated using an independent t-test. Differences between ROI groups will be evaluated using an ANOVA test. Tukey's post hoc test will be applied to evaluate within-group differences.

3. Results

Examining the fractal dimension measurements for the maxillary anterior (ROI 1, 2), maxillary posterior (ROI 3, 4), mandibular anterior (ROI 5, 6), and mandibular posterior (ROI 7, 8) regions reveals that the fractal dimension value increases with region number (Table 1).

Table 1 FD Values of ROIs

ROIs	N	Minimum	Maximum	Mean	Std. Deviation
ROI1	108	1,481	1,743	1,586	0.086
ROI2	108	1,517	1,705	1,610	0.065
ROI3	108	1,464	1,756	1,622	0.084
ROI4	108	1,529	1,678	1,599	0.039
ROI5	108	1,467	1,836	1,645	0.110
ROI6	108	1,496	1,977	1,655	0.146
ROI7	108	1,651	1,864	1,73605	0.071
ROI8	108	1,602	1,899	1,74643	0.084

To analyze the data from the four regions, the ROIs were combined into four groups: ROIs 1-2, ROIs 3-4, ROIs 5-6, and ROIs 7-8. The maxillary anterior region was designated region 1, the maxillary posterior region region 2, the mandibular anterior region region 3, and the mandibular posterior region region 4.

When evaluated according to these four regions, the fractal dimension ranking was highest in the mandibular posterior region and lowest in the maxillary anterior region. Notably, the maxillary posterior region has a lower mean value for trabecular organization compared to the mandibular anterior region. The differences between regions were statistically significant at the 0.95 confidence level according to the ANOVA test when the data were statistically evaluated (Figure 4, Table 2).

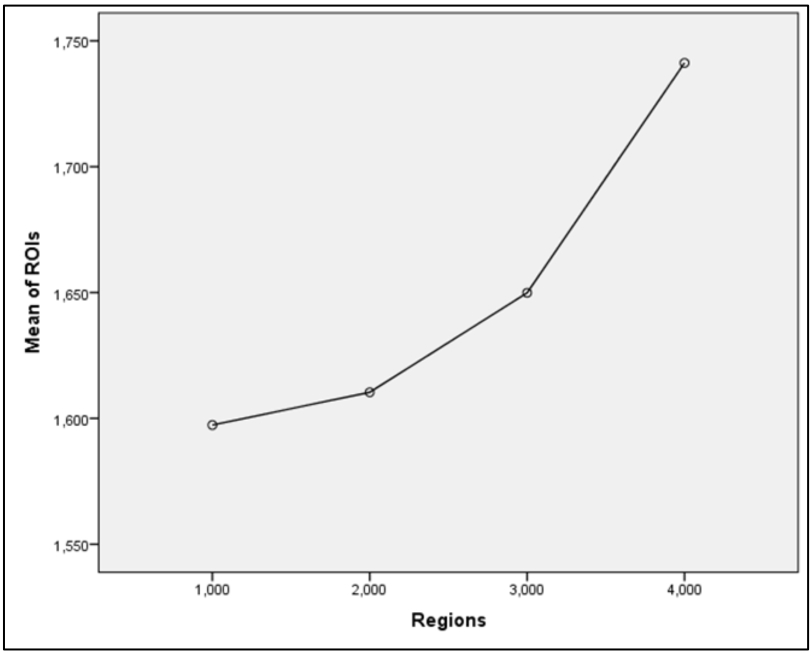

Figure 4 Fractal Dimension values of regions (1-Maksillary anterior, 2-Maksillary posterior, 3-Mandibular anterior, 4-Mandibular posterior)

Table 2 FD Values of different regions (1-Maksillary anterior, 2-Maksillary posterior, 3-Mandibular anterior, 4-Mandibular posterior)

Region	**N**	**Mean**	**Std. Deviation**	**Minimum**	**Maximum**	**ANOVA**
						p Value*
1,000	216	1,59736	0.077	1,481	1,743	
2,000	216	1,61037	0.066	1,464	1,756	
3,000	216	1,64990	0.129	1,467	1,977	
4,000	216	1,74124	0.078	1,602	1,899	
Total	864	1,64972	0.107	1,464	1,977	0.000*

*p<0.05 refers to statistical significance.

According to the Tukey post hoc test, there is no statistically significant difference between the maxillary anterior and posterior regions. However, the differences between all other regions are statistically significant (Table 3).

Table 3 Statistical analysis of FD Values of different regions (1-Maksillary anterior, 2-Maksillary posterior, 3-Mandibular anterior, 4-Mandibular posterior)

	(I) Regions	(J) Regions	Difference (I-J)	p Value*
Tukey's Post HOC	1,000	2,000	-0.013	0.444
		3,000	-0.053	0.000*
		4,000	-0.144	0.000*
	2,000	1,000	0.013	0.444
		3,000	-0.040	0.000*
		4,000	-0.131	0.000*
	3,000	1,000	0.053	0.000*
		2,000	0.040	0.000*
		4,000	-0.091	0.000*
	4,000	1,000	0.144	0.000*
		2,000	0.131	0.000*
		3,000	0.091	0.000*

*p<0.05 refers to statistical significance.

When the sex factor was evaluated, FD values were found to be higher in males than in females in all regions, and this difference was statistically significant according to the t-test results (Table 4).

Table 4 FD differences in association with the sex factor

		N	Mean	Minimum	Maximum	p Value*
ROIs1-2	Female	108	1,58416	1,481	1,678	
	Male	108	1,61056	1,482	1,743	0.011*
ROIs3-4	Female	108	1,57978	1,512	1,692	
	Male	108	1,64096	1,464	1,756	0.000*
ROIs5-6	Female	108	1,55670	1,467	1,655	
	Male	108	1,74309	1,571	1,977	0.000*
ROIs7-8	Female	108	1,68625	1,641	1,706	
	Male	108	1,79622	1,602	1,899	0.000*

*p<0.05 refers to statistical significance.

4. Discussion

This study used fractal analysis to demonstrate that regional differences between jawbones and within the same jaw can be quantitatively evaluated at the trabecular microarchitecture level. Eight apical ROIs were selected from panoramic radiographs for this analysis. The parallel increase in fractal dimension (FD) values as the number of ROIs increases suggests that the selected regions reflect anatomical and functional loading gradients, indicating that ROI classification is biologically meaningful. Additionally, FD changes related to anatomical location have been reported in previous fractal analysis studies [6, 7, 10].

A noteworthy finding of this study is that the mandibular anterior region (ROIs 5–6) exhibited significantly higher FD values than the maxillary posterior region (ROIs 3–4). The posterior maxilla has been reported in cone-beam computed tomography (CBCT)-based density and morphology studies to have lower bone quality and a more porous structure [2–4, 11]. However, it should be emphasized that FD values obtained from fractal analysis represent the organization and complexity of the trabecular network rather than bone mineral density. In this context, the high FD values detected in the anterior mandibular region suggest that cortical bone hardness and trabecular microarchitecture may both exhibit more complex, interconnected structures.

The absence of a statistically significant difference in FD between the anterior and posterior regions of the maxilla indicates that its trabecular structure exhibits more homogeneity than that of the mandible. CBCT studies have shown that morphological differences in maxillary alveolar bone are limited regionally, with a general porosity trend predominant, particularly in the molar region [4, 9, 11]. This may explain why fractal analysis values are similar in the anterior and posterior regions of the maxilla. Clinically, perceived differences in the maxilla have been suggested to be related to cortical bone thickness, sinus-related anatomical variations, and bone volume rather than trabecular organization [1, 13].

In contrast, significant FD differences detected between the anterior and posterior regions of the mandible support the notion that the mandible has a remodeling pattern more sensitive to functional loading. The mandible is directly exposed to masticatory forces, and it is known that this mechanical loading leads to regional adaptations in the trabecular microarchitecture. Previous histomorphometric and radiological studies have demonstrated that the organization of the trabeculae in the mandible is remodeled in response to functional stresses [10, 15]. In this context, fractal analysis is a useful tool for evaluating regional biomechanical adaptations of the mandible.

In sex-based analyses, FD values were found to be statistically significantly higher in males than in females across all regions, which is consistent with the reported gender-based differences in alveolar bone in the literature [5, 8, 16]. Higher muscle strength and mechanical loading in males have been suggested as contributing factors to the acquisition of a more complex and interconnected trabecular bone structure [14,16]. This finding is significant because it shows that fractal analysis is sensitive to not only anatomical location, but also biological and functional variables.

Fractal dimension quantitatively expresses the geometric complexity, connectivity, and spatial organization of the trabecular network rather than the mineral content of trabecular bone [6, 7, 12]. An increase in FD suggests a more irregular and denser branching pattern and a more complex organization. Conversely, low FD values suggest a sparser, less connected, and simpler pattern.

In this respect, fractal analysis is conceptually distinct from densitometric measurements. While cone-beam computed tomography (CBCT) or computed tomography (CT)-based Hounsfield Unit measurements predominantly reflect total bone density, especially the cortical component, fractal analysis focuses on the organization of trabecular microarchitecture through two-dimensional dental radiographs. Therefore, an increase in FD signifies a more organized and complex trabecular structure rather than "more dense bone."

In this study, the high FD values detected in the mandibular anterior region suggest that the trabecular bone may have a more developed structural organization beyond the cortical hardness felt in the clinic. Similarly, the low FD values detected in the maxillary posterior region indicate that this region has lower density and a less connected trabecular organization. These results support considering fractal dimension as a complementary biomarker for evaluating bone quality.

5. Conclusion

This study demonstrated that differences in regional trabecular organization between the maxilla and mandible, as well as within the same jaw, can be revealed quantitatively using fractal analysis applied to apical regions of interest (ROIs) obtained from panoramic radiographs. The mandibular anterior region exhibits higher fractal dimension values than the maxillary posterior region, suggesting that clinical bone structural differences may also be reflected at the trabecular microarchitecture level.

The absence of significant fractal differences between the maxillary anterior and posterior regions suggests that the maxilla's trabecular structure is relatively homogeneous. In contrast, anterior–posterior differences within the mandible and sex-related fractal dimension (FD) variations reveal that the mandible's bone structure is more sensitive to functional loading and biological factors.

Fractal analysis is a valuable tool for evaluating jawbone trabecular microarchitecture because it is repeatable and accessible. It is thought to provide objective information that complements density measurements for local anesthesia planning, surgical decision-making, and clinical assessments related to bone quality.

Present study defines regional differences of trabecular orientation of the jaws in a low radiation imaging technique and open access software in terms of maximum accessability.

Compliance with ethical standards

Disclosure of conflict of interest

The authors have nothing to disclose.

Statement of ethical approval

The study was approved by the İzmir Katip Çelebi University Health Researches Ethics Committee (decision number 2025-SAEK-1185).

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