ORIGINAL RESEARCH

Fractal Dimension and Lacunarity Analysis in the Dentulous and Edentulous Mandibular Posterior Region Using Cone-beam Computed Tomography: A Cross-sectional Retrospective Study

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Abstract

Aims: This cross-sectional retrospective study was conducted to assess the differences in the microarchitecture of the trabecular bone of the posterior mandibular region at dentulous and edentulous sites with the help of fractal dimension (FD) and lacunarity using cone-beam computed tomography (CBCT).

Materials and methods: Ninety CBCT scans were analyzed for the purpose of the present study. Inclusion criteria included subjects with unilaterally missing mandibular molars or premolars and an with intact contralateral opposing tooth. The coronal view of the dentulous and edentulous sites was used, and the region of interest (ROI) was selected 2.6 mm below the apex of the tooth present. These images were then transferred to ImageJ Software, and fractal analysis was done using the box-counting method of the FracLac plug-in. A paired samples *t*-test was performed to compare the means of FD and lacunarity, and a Kendall correlation was performed to check correlations. A *p*-value less than 0.05 was considered to indicate statistical significance.

Results: Statistical analysis revealed that the mean FD of the edentulous side was significantly greater than that of the dentulous side (p-value = 0.011). Additionally, the mean lacunarity of the edentulous side was marginally significantly greater than that of the dentulous side (p-value = 0.089). A significant negative correlation was detected between the FD and lacunarity of the edentulous region (p-value = 0.017), and a marginally significant negative correlation was detected between edentulous lacunarity and dentulous lacunarity (p-value = 0.081).

Conclusion: The differences in occlusal forces exerted in dentulous and edentulous regions can lead to a change in the trabecular pattern of the bone in these regions. This change in the microarchitecture of bones can be detected by FD and lacunarity, which can further help us assess changes pre- and post-implant.

Clinical significance: The advanced technology, the assessment of microarchitecture of the bone has been made easy, using FD and lacunarity, as done in the present study. This analysis can further aid us in both pre- and post-implant analysis to prevent failure of the implant.

Keywords: Cone-beam computed tomography, Dentulous, Edentulous, Fractal analysis, Fractal dimension, Lacunarity, Mandible.

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Introduction

During mastication, forces exerted by the teeth are passed on to the cancellous (trabecular) bone. Analogous to masticatory forces, movement of teeth, and/or tooth loss, cancellous bone is modified and remodeled throughout life.[1,2] Furthermore, multiple factors, such as bone configuration, constituent tissue properties, and bone mass, play important roles in maintaining the structural integrity of the bone.[3] Research has shown that bone strength depends on bone mineral density and bone microarchitecture, which constitute the structure and morphology of the bone. For the evaluation of bone strength, the assessment of bone mass and quality is obligatory.[4,5] The microstructure of bones is of crucial importance since the microstructure of vital bones changes as they are exposed to mechanical stresses. In non-homogenous materials, like mandibles, the reaction to externally applied mechanical stresses is dictated by the exterior macroscopic form and alignment of the internal architecture.[6] The bone micro-architecture is typically assessed using histomorphometric procedures, but the main drawback of this method is that it is invasive because longitudinal studies are difficult to conduct.[7] Another method for assessing

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the microarchitecture of bone is fractal analysis (FA), which is a mathematical tool for evaluating complex and irregular structures. Lacunarity and fractal dimension (FD) are the quantitative results of this procedure.[8]

A fractal is any pattern governed by self-similarity and repetitiveness; it is a fine or detailed structure at small scales, the irregularity of which is not governed by Euclidean geometry. Fractal entities are geometrical formations that cannot be made out of basic forms such as lines, circles, spheres, or fundamental polygons.[9] Most structures found in nature are not perfect fractals. They have gaps in their texture. The measure of different gap sizes is known as lacunarity.[10] The trabecular bone of the mandible is made up of several interconnecting bone rods and plates isolated by marrow space. Trabeculae have two traits that define a fractal object: the randomized interconnection of bone plates and self-similarity.[9]

Greater FD values suggest more complicated textures, yet fractal sets with identical FDs might have widely diverse textures. Because FD alone is ineffective for distinguishing various textures, lacunarity is utilized to define the features of fractals of identical dimensions that have diverse textural appearances.[10] The geometric entities with lower lacunarity are homogenous since all gap dimensions are equal, whereas entities with higher lacunarity are heterogeneous.[11]

FA can be performed using plain imaging modalities, such as intraoral radiographs and orthopantomograms, or specialized imaging modalities, such as cone-beam computed tomography (CBCT), micro-computed tomography (micro-CT), multislice computed tomography, high-resolution peripheral quantitative computed tomography, and high-resolution magnetic resonance imaging (HR-MRI).[12,13]

Due to its enhanced availability for dental professionals, more compact technology, and lower radiation dosage and cost, CBCT is increasingly acknowledged for oral and maxillofacial imaging.[12]

The texture of cancellous bone in a radiograph may differ in dentulous and edentulous regions since the occlusal pressures produced while mastication is communicated to the maxilla and mandible via the teeth present. FD and lacunarity can be utilized to calculate this discrepancy.[14]

The bone structure of the mandible is more uniform, having a stepladder pattern and the changes in it could be more readily appreciated. This is supported by the fact that multiple diseases and metabolic alterations show readily visible alterations in the mandible.[15]

The anterior implant placement is more variable compared to the posterior implant in terms of the amount of bone available in buccolingual cortical plates. It is more uniform in the posterior region. This enables us to study the changes in microarchitecture in the mandibular posterior region more uniformly. Limited studies have been noted to measure FD and lacunarity in CBCT scans.

Hence, the current study was planned to assess the changes in the microarchitecture/trabecular pattern of the mandibular posterior region of the dentulous and edentulous sides via CBCT using FD and lacunarity, which could help in the assessment of bone microarchitecture both pre- and postimplant placement to prevent failure of the implant.

Materials and Methods

A cross-sectional retrospective study was performed after obtaining clearance from the Institutional Ethics Committee (protocol ref no – 19097). In the present study, 90 medium field of view (FOV) scans were procured from the Department of Oral Medicine and Radiology, Dental Institute in Mangalore, from November 2019 to March 2021. CBCT scans were acquired using the Promax 3DMid (Planmeca Oy., Helsinki, Finland) CBCT unit.

Sample Population Size

Using the sample size calculation formula for 2 means, using the formula with a pooled deviation of 0.10065 and a clinically significant difference of 0.03 units, the sample size arrived at 90.

$$N = \left\{ \frac{\left[\frac{Z_{1-\alpha}}{2} + Z_{1-\beta} \right] \times s}{D} \right\}^2$$

where N = population size, $Z_{1-\alpha} = 1.96$ (5% confidence interval), $Z_{1-\beta} = 0.84$ (80% power).[14]

The scans selected were of subjects who had unilaterally missing mandibular molars or premolars with intact contralateral and opposing teeth, and the scans excluded were those with any bone pathology, periodontal disease reaching the middle third of the root, a trabecular pattern showing signs of healing, or a history of osteoporosis or systemic diseases/medication affecting bone metabolism. All the details regarding the patient's medical history were collected from medical records and by telephone interviews. These scans were selected irrespective of the gender and age of the patient.

Selection of the Region of Interest (ROI)

In Planmeca Romexis software (version 6.2.1), a panoramic image was reconstructed, and cross-sectional images were examined to determine the course of the mandibular canal. The axial section of the area of interest on the mandible was adjusted at the level of the alveolar crest. The coronal section was then adjusted to correspond to the dentulous and edentulous sides of the mandible. In this section, a point was selected 2.6 mm below the root apex to avoid the effect of local factors,[16] and a horizontal straight line was drawn from this point to the contralateral side (so that measurements were taken from the same axis).

For the dentulous side, a vertical straight line was drawn along the long axis of the tooth. For the edentulous side, at a distance of 2 mm from the crest, a horizontal line was drawn. The midpoints of the crest and the lower horizontal line were marked, and a straight vertical line was used to join these two points (Fig. 1).

The image captured was saved in .jpg format in the appropriate folder. This image was then opened in ImageJ software for further analysis. The ROI was selected in ImageJ Software as inferior and lingual to the point of intersection of the horizontal and vertical lines. Along with this, the density of the ROI was noted in the Romexis software [in Hounsfield Unit (HU) value as shown in the software] according to Misch's classification of bone density.[17]

Image Processing

The images were analyzed using the ImageJ software (version 1.52a, NIH, Bethesda, MD). In the software, an ROI 8 × 8 pixels in size was selected immediately inferior and lingual to the point of intersection of the horizontal and vertical lines based on the markings. The ROIs did not include tooth or tooth-supporting structures or any anatomic landmarks. The images were segmented into binary images in a similar way as described by White and Rudolph.[18] The ROI was cropped (Fig. 2A) and duplicated. A Gaussian Blur filter (35 pixels) was applied to the duplicates (Fig. 2B), which were then subtracted from the original image, leaving only trabeculae behind. After this, a brightness value of 128 was added to the image to delineate the trabeculae from marrow spaces (Fig. 2C), and this image was then converted into binary format (Fig. 2D) and inverted (so that the trabeculae are represented with white pixels). The binary image was finally eroded, dilated, and outlined (Fig. 2E), and the FracLac plugin was used to calculate the FD and lacunarity of these images. The values generated were then subjected to statistical analysis. The flowchart of the methodology used in this study is depicted in (Fig. 3).

The data was analyzed using 'R' Software Version 4.1.2 (R Studio 2021-09-10 – Build 372).

For statistical analysis, the paired samples t-test was used to compare the FD and lacunarity of both sides, and the Kendall correlation was used to check the correlations. To compare FD and lacunarity with sex and density, the medians of these values were used, since they are more reliable measures of central tendency.

Results

The present study was performed to analyze the microarchitecture of bone in the dentulous and edentulous mandibular posterior regions by means of FD and lacunarity in 90 subjects. Of these, 54 (60.0%) were females and 36 (40.0%) were males. Five age-groups were observed on the date. These were the 20>–30 group (6%), 30>–40 (16%), 40>–50 (29%), 50>–60 (28%), and 60>–70 (21%).

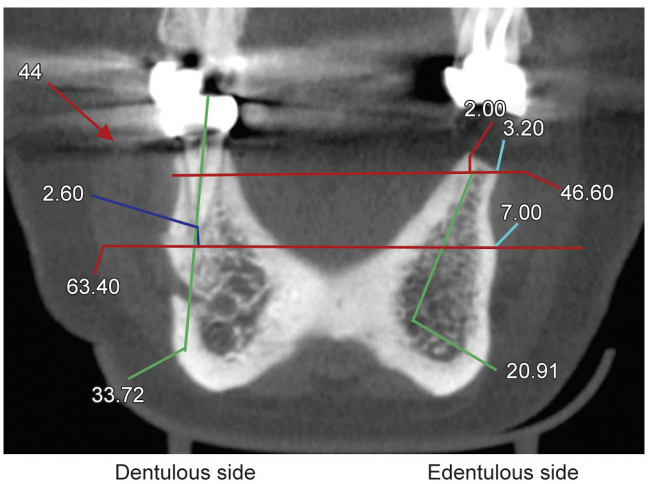
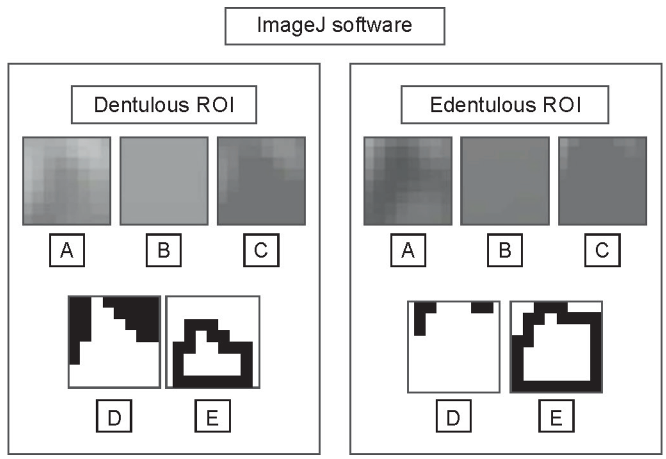
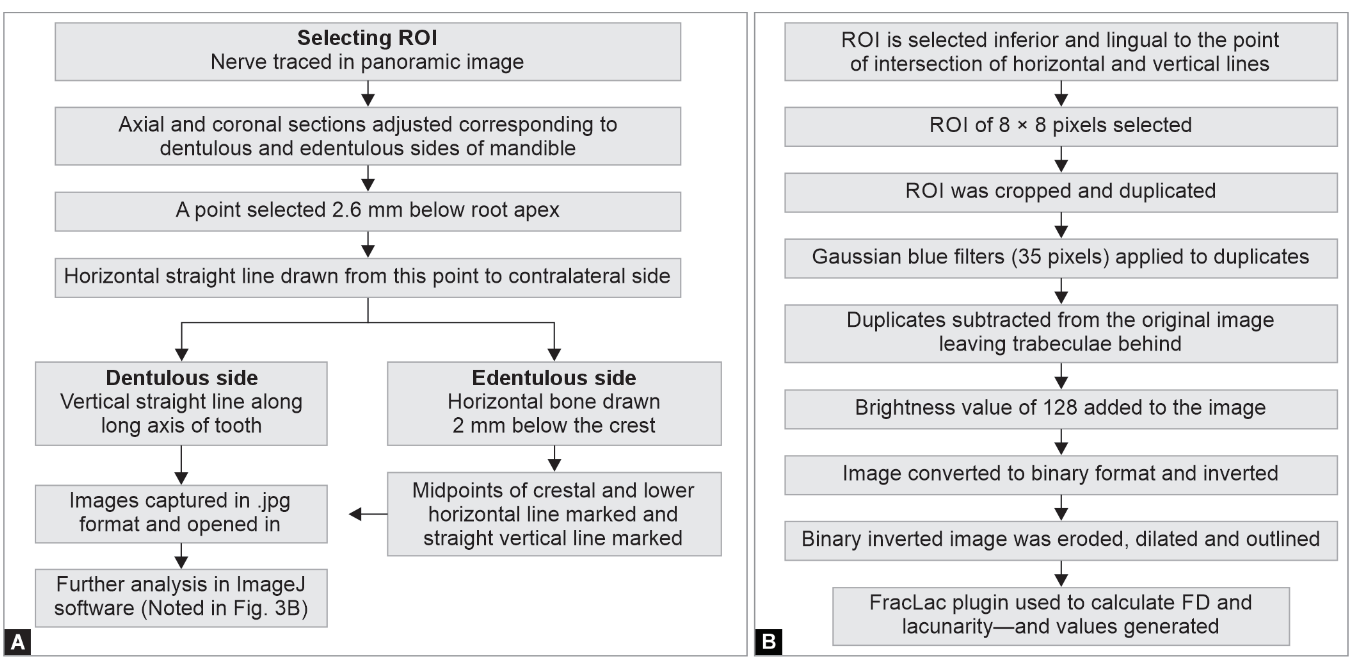


Fig. 1: CBCT image of the patient – selection of ROI in mandible



Figs 2A to E: Processing of image in ImageJ software. (A) The original selected ROI; (B) ROI after application of Gaussian blur; (C) The subtracted ROI with added brightness; (D) The converted binary format of ROI; (E) The final ROI after inversion, erosion and dilation of the binary format



Figs 3A and B: Flowchart depicting the Methodology. (A) Processing in Romexis software; (B) Processing in ImageJ software

Table 1: Comparison of fractal dimension and lacunarity of dentulous and edentulous regions (paired samples *t*-test)

Parameters	*Mean*	*SD*	*Difference in means*	*t-value*	*p-value*
Dentulous fractal dimension	0.881	0.75	0.27	–2.58	0.011
Edentulous fractal dimension	1.154	0.87			
Dentulous lacunarity	0.187	0.09	0.02	–1.71	0.089
Edentulous lacunarity	0.211	0.09			

Table 2: Correlation between fractal dimension and lacunarity (Kendall Correlation)

Parameters	*tau*	*p-value*
Lacunarity – fractal dimension (independent of region)	–0.064	0.201
Edentulous fractal dimension – dentulous fractal dimension	0.107	0.140
Edentulous lacunarity – dentulous lacunarity	–0.124	**0.081**
Dentulous fractal dimension – dentulous lacunarity	–0.008	0.908
Edentulous fractal dimension – edentulous lacunarity	–0.171	**0.017**

Significance of bold values is significant *p*-value

The density of the ROI was also noted and categorized using the Misch classification (HU values).[17]

Based on the Misch classification of bone density,[17] in the present study, 3 classes of densities were observed on both the dentulous and edentulous sides, namely D2, D3, and D4. On the dentulous side, 30% of the subjects (n = 27) had D2 density, 51.1% (*n* = 46) had D3 density, and 18.8% (*n* = 17) had D3 density. On the edentulous side, 15.5% (*n* = 14) had D2 density, 62.2% (*n* = 56) had D3 density and 22.2% (*n* = 20) had D3 density.

Paired sample *t*-tests were used to compare the FD and lacunarity between the dentulous and edentulous sides (Table 1). There was a significant difference in the mean FD between the dentulous and edentulous sides (*p*-value = 0.011), while in the case of lacunarity, the difference was marginally significant (*p*-value = 0.089).

Kendall correlation was used to study the correlation between the FD and lacunarity (Table 2). A nonsignificant negative correlation was observed between lacunarity and FD, independent of the ROI (*p*-value = 0.201). A nonsignificant positive correlation was detected between the edentulous FD and the dentulous FD (*p*-value = 0.140). A marginally significant negative correlation was seen between edentulous lacunarity and dentulous lacunarity (*p*-value = 0.081). A nonsignificant negative correlation was observed between lacunarity and the FD of the dentulous region (*p*-value = 0.908). A significant negative correlation was observed between lacunarity and the FD of the edentulous region (*p*-value = 0.017).

To compare FD and lacunarity with sex, the median was selected since it was a more reliable measure of central tendency. On the dentulous side, the median FD for males (0.754) was greater than

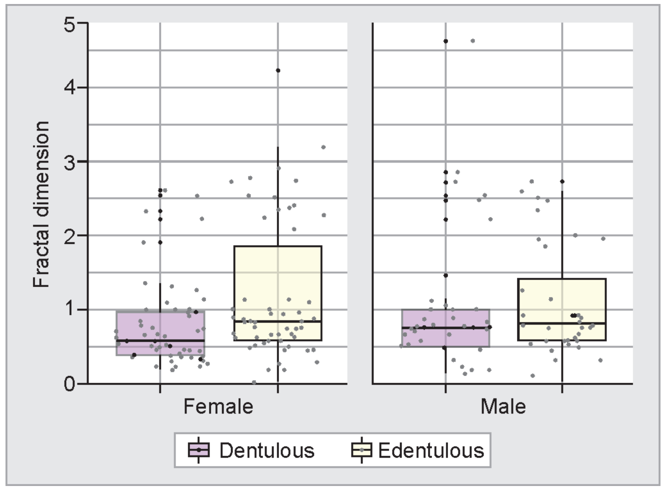


Fig. 4: Box-plot showing correlation between sex and fractal dimension on dentulous and edentulous side

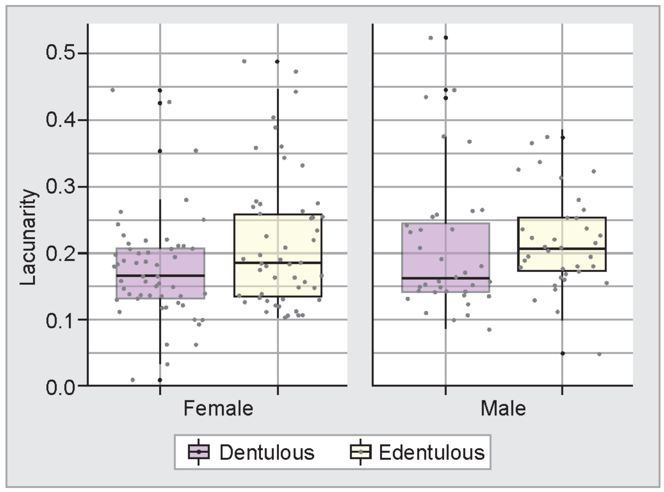


Fig. 5: Box-plot showing correlation between sex and lacunarity on dentulous and edentulous side

that for females (0.580), while the median lacunarity for females (0.165) was marginally greater than that for males (0.161) (Figs 4 and 5).

On the edentulous side, the median FD for females (0.838) was marginally greater than that for males (0.811), while the median lacunarity for males (0.204) was marginally greater than that for females (0.185) (Figs 4 and 5).

Similarly, to compare FD and lacunarity with the density of the ROI, the median was selected since it is a more reliable measure of central tendency. On the dentulous side, the median FD of subjects with a bone density of D2 (0.768) was the highest, followed by those with a bone density of D3 (0.646) and D4 (0.580). The median lacunarity of subjects with bone density D3 (0.183) was the highest among all 3, followed by that of D2 (0.164) and D4 (0.138) (Figs 6 and 7).

On the edentulous side, the median FD of subjects with a bone density of D2 (0.921) was the greatest, followed by those with a bone density of D3 (0.838) and D4 (0.772). The median

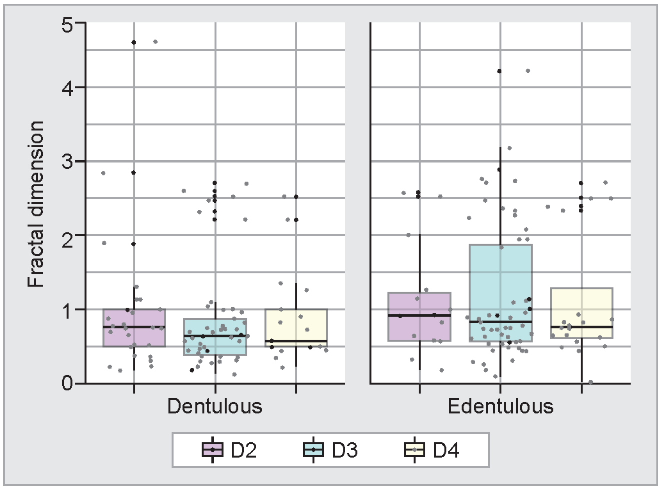


Fig. 6: Box-plot showing correlation between density and fractal dimension on dentulous and edentulous side

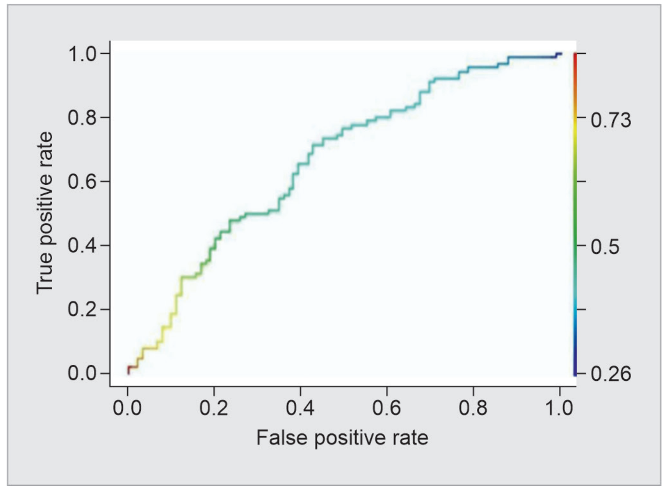


Fig. 8: Regression model

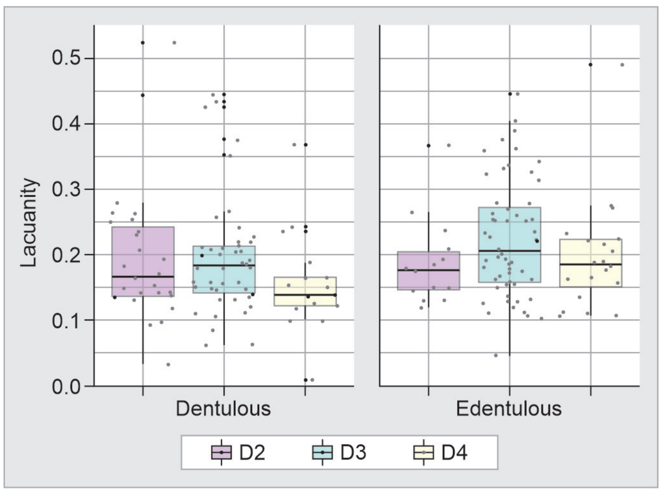


Fig. 7: Box-plot showing correlation between density and lacunarity on dentulous and edentulous side

lacunarity of subjects with bone density D3 (0.205) was the highest among all 3, followed by that of D4 (0.185), and then D2 (0.176) (Figs 6 and 7).

Regression Model

In the present study, we have attempted to predict the region (dentulous vs. edentulous) based on lacunarity and FD. As the outcome is binary, logistic regression was used. As each subject underwent two tests, repeated measurements of the subjects were taken into account. The values of continuous predictors were also mean-centered.

Using several models, it was observed that lacunarity and FD were significant predictors, with no other variable offering significance in prediction. This was tested by checking Akaike's information criterion (AIC) and Bayesian information criterion (BIC) values with the current model presenting the lowest AIC and BIC from available models.

To summarize, it was deduced that one observation had very high leverage, so it was dropped from the final model. While this model was not a good fit (area under the curve (AUC) = 0.66) (Fig. 8), lacunarity and FD did seem to be significant predictors (p-value for FD: 0.005; p-value for lacunarity: 0.036).

For a one-unit change in lacunarity from its mean, it was expected to be a 44.58% increase in the likelihood of the region being edentulous as opposed to dentulous, given that FD is constant. For a one-unit change in FD from its mean, it was expected to be a 1.84% increase in the likelihood of FD being an edentulous region as opposed to a dentulous region, given that L is constant.

Discussion

The current study was designed to analyze the trabecular pattern of bone in the mandible once a tooth is removed by comparing the dentate region with the edentate region via CBCT using FD and lacunarity. Additionally, a possible correlation was observed between Misch's classification of bone quality, FD, and lacunarity.

In terms of assessing bone components, the integrity of the cortical bone, and subcortical bone loss, CBCT is thought to be superior to plain radiography.[19]

In dentistry, FA has been widely used to evaluate osteoporotic disorders, compare dentate and edentate regions, assess the healing of periapical lesions after postendodontic treatment, and study bone changes due to bisphosphonate-associated osteonecrosis, and also gather more information regarding degenerative diseases of the temporomandibular joint.[14,20–26]

The FD and lacunarity values are quantitative metrics that measure how complex the self-similar structures are to trabecular bone. Previous research has shown that as bone complexity grows, the FD increases.[25]

FA can be performed on various radiographic modalities, which include 2D modalities like periapical films and panoramic, images and 3D modalities like CBCT, CT, micro-CT, etc. The greatest disadvantage of employing 2D imaging modalities is the superimposition of structures, due to which 3D imaging modalities were employed for the present study. Cone-beam computed tomography was selected as the imaging modality since there was no superimposition, and it has a lower radiation dose than other modalities. Multiple studies have been conducted to calculate FD and lacunarity in all the different radiographic modalities.[14,20–26]

The present study assessed FD and lacunarity in the dentulous and edentulous mandibular posterior regions in the coronal images using the box-counting method of the FracLac plug-in of ImageJ software. To the best of our knowledge, this site has not yet been studied for FA using CBCT. A study conducted by Muneer and Vandana[27] revealed that with the application of occlusal stress, maximum ligament stress is applied to the crestal alveolar bone. This stress decreases apically but is high again at the apex of the tooth. Additionally, research has shown that no effect of bacterial plaque has been detected beyond 2.5 mm of the apex.[16] For these reasons, the ROI was selected 2.6 mm below the apex of the tooth.

In the present study, it was found that the mean FD of the edentulous group was greater than the mean FD of the dentulous group. This was similar to the study conducted by Yasar and Akgünlü[14] who also studied the FD of the mandibular posterior region. This increase in the FD of the edentulous region signifies a more complex/finer pattern of arrangement of trabeculae in the bone observed in that region. This result was in contrast to the study conducted by Coşgunarslan et al.[21] who compared the FD of the condylar region. This contrast may be due to a difference in the anatomical location of the FD calculation. Further studies to compare the anatomic sites of dentulous and edentulous regions may shed some light on this difference.

Additionally, in the present study, the mean lacunarity of the edentulous group was greater than the mean lacunarity of the dentulous group, with a marginally significant *p*-value of 0.089, which was in contrast to the study conducted by Yasar and Akgünlü[14] in which he found that the mean lacunarity of the dentulous group was greater than that of the edentulous group. The increase in lacunarity signifies more heterogenous bone in the edentulous region than in the dentulous. Due to the absence of occlusal forces in the edentulous region, a haphazard arrangement of bone trabeculae is observed, which leads to heterogeneous bone microarchitecture. It is believed that due to the loss of occlusal stresses in the edentulous region, the bone appears to have a more sedentary structure than when stresses are applied.

Similar to the study conducted by Yasar and Akgünlü[14] in the present study, a nonsignificant negative correlation between lacunarity and FD was noted, independent of the ROI, a nonsignificant positive correlation between the FD of the edentulous and edentulous areas, and a marginally significant negative correlation between edentulous lacunarity and dentulous lacunarity. There was also a nonsignificant negative correlation between lacunarity and FD in the dentulous region and a significant positive correlation between lacunarity and FD in the edentulous region.

A study conducted by Muneer and Vandana[27] showed that occlusal stresses are greater in the apical region than in the interdental region. Studies conducted by Amer et al.[28] and Gaalaas et al.[29] also calculated the FD value in the dentulous mandibular posterior group. Amer et al.[28] compared the FD of various intraoral sites based on periapical radiographs. They selected the interdental region for the calculation of FD and observed a value of 1.50 ± 0.06 in patient archives at the University of Michigan, USA. Gaalaas et al.[29] studied multiple anatomic sites using CBCT, and this study was conducted at the University of Minnesota. They also studied the interdental region for FD calculations and observed a value of 1.313 for the left side and 1.309 for the right side. The present study was conducted in the Indian population, and the ROI was selected at 2.5 mm apical to the tooth root in the mandibular posterior region. In the present study, the mean FD for the dentulous site was less than that observed by Amer et al.[28] and Gaalaas et al.[29] We believe that due to increased occlusal forces at the apex, the trabeculae of the bone seem to be arranged more regularly, hence the FD is lower in the periapical region than in the interdental region. Since the locations of both sets of studies were different, this change may also be due to changes in the study location.

In the present study, the mean FD on the edentulous side was greater for males than for females. This finding was similar to that of the study conducted by Gaalaas et al.[29] However, on the edentulous side, it was found that the mean FD for females was marginally greater than that for males. This was in contrast to the study conducted by Coşgunarslan et al.[21] which revealed that for the edentulous side, the mean FD for females was lower than that for males (*p*-value = 0.01).

In the current study, for both the dentulous and edentulous sides, the median FD of subjects with a bone density of D2 was the highest, followed by that of D3 and D4. We believe that an increase in FD corresponds to increased complexity in the microarchitecture of the bone. This corresponds to increased trabeculae in the small area, thus increasing the density of bone according to the Misch classification.[17]

In the current study, on the dentulous side, the median lacunarity of subjects with a bone density of D3 was the highest among all 3, followed by that of D2 and D4. On the edentulous side, the median lacunarity of subjects with bone density D3 was the highest among all 3, followed by that of D4 and D2. Based on these results, it was seen that there is no correlation between lacunarity and bone density according to the Misch classification and that lacunarity is influenced by multiple other factors, one of which is the occlusal load and the direction of forces.

Bone strength can be assessed using bone density and bone microarchitecture. To our knowledge, research regarding bone microarchitecture is limited, and there is more scope for these studies. Elani et al.[30] noted an increase in the use of dental implants, with a prevalence of 14% per year. Lee CT et al.,[31] in their meta-analysis and systematic review, reported a high incidence of peri-implant diseases, which is by no means a small value. Hence, the assessment of bone microarchitecture might provide new insights into recognizing these problems before implant placement.

In the current study, binary logistic regression analysis showed no significant prediction of the site of the bone, i.e., dentulous or edentulous, based on the FD or lacunarity. The prediction proportion was only 44.58%, with an AUC of 0.66. This indicates that FD is dependent not only on the presence or absence of tooth, but also on various environmental factors. We must remain cognizant of the various hormones, bacteria, quality bone structure, vitamin D, calcium regulators, etc. that influence bone quality when deriving predictive equations.

However, the limitations of the study were the small sample size, the unequal distribution among males and females, and similarly, unequal distribution among the different age-groups of the study. There was also a lack of analysis of confounding agents, such as the amount of occlusal stress applied to the ROI, the direction of occlusal stress, and whether any changes were observed in patients with trauma from occlusion. FA, which is a histomorphometric analysis, has not been compared with the gold standard for analyzing the microarchitecture of bones. In addition, FA and bone mineral density could be compared. Hence, it is recommended that further studies be performed while considering these limitations.

Conclusion

The main objective of the current study was to analyze the trabecular changes in the mandibular posterior region in dentulous and edentulous areas. After the analysis, it was found that FD and lacunarity are promising tools for studying the microarchitecture of bone. The present study also concluded that there are differences in occlusal forces exerted in dentulous and edentulous regions, which can lead to a change in the trabecular pattern of the bone. These changes can be detected by means of FD and lacunarity using CBCT.

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