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Fractal analysis of dental radiographs to detect periodontitis-induced trabecular changes

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Background and Objective: The aim was to evaluate fractal analysis as a tool to quantitatively measure the impact of periodontal disease on surrounding bone. The diagnosis of periodontitis is based on information obtained from clinical and radiographic examinations. The current standard use of dental radiographs is visual inspection, often with no quantitative analysis. Fractal analysis can be used to examine trabecular bone patterns among periodontal patients.

Material and Methods: Patients ($n = 108$) from the University of Southern California School of Dentistry were classified into three groups: healthy, moderate and severe periodontitis. A region of interest was selected from periapical radiographs. Image processing was applied to correct for lighting irregularity, and the box-counting method was used to calculate a fractal dimension. ANOVA and ANCOVA were used to measure fractal dimension differences between all groups.

Results: According to the statistical tests, significant differences in average fractal dimensions were measured between healthy and moderate periodontitis groups ($p < 0.01$) and between healthy and severe periodontitis groups ($p < 0.001$). Higher fractal dimensions were measured in healthy periodontal patients.

Conclusion: Fractal analysis evidenced significant differences between patients affected and not affected by periodontitis. The box-counting method quantitatively describes the severity of bone disease and can be used to improve current diagnostic techniques.

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Periodontitis is diagnosed based on a considerable amount of information obtained from clinical and radiographic examinations. Unfortunately, the current standard use of dental radiographs does not include quantitative analysis. Radiographic measurements (e.g. distance from alveolar crest to cemento-enamel junction (CEJ), angle of the intrabony defect and presence of the alveolar lamina dura) are not consistently utilized in periodontal diagnosis. In contrast, some clinical measurements (e.g. probing depth, gingival recession and attachment level) are noted at four to six sites per tooth. Most clinicians are proficient in recognizing radiographic features of anatomy and pathology, but the information embedded in the relative location of image features under different projection conditions is often underutilized (1).

A retrospective study by White and co-workers (2) reported that periapical film could be used to study bone quality in osteoporotic patients. Using similar analytical approaches to those established by White and co-workers, radiographic data can be used to document hard tissue integrity, such as stability and density. Thus, more information can be obtained from dental radiographs to complement the clinical signs of periodontal disease and to provide an accurate treatment strategy.

Periodontitis can result in loss of bone mass and microarchitectural deterioration. Trabecular structure (trabecular thickness, connectivity of the trabeculae, distribution of mineral content, and trabecular pattern) is important in studying the effect of periodontal disease on its supporting bone. The trabecular bone has a branching pattern that exhibits fractal properties, such as self-similarity and lack of well-defined scale. Because of this, the application of fractal geometry and the measurement of fractal dimensions can be used to determine trabecular complexity and bone structure (3). Fractal analysis is a technique for identifying scale-invariant structure that is not affected by exposure or minor alignment variations of radiographs (4–6). This makes it well suited to analyse trabecular bone patterns in radiographs. Fractal analysis is a non-invasive tool that can describe biological systems in clinical studies (7). Researchers have used this technique to analyse iliac crests (7), axial bones (8) and tumours (9), but little has been studied in the craniofacial region.

Fractal analysis is usually performed on digital images and can generate a unique value for an image: its fractal dimension. This parameter describes the extent to which the object fills space, and characterizes its self-similarity. There are many approaches for estimating fractal dimension, but the box-counting method is the most widely used and is suited for binary image analysis. The objective of this study was to use radiographs to determine the relation between fractal dimension of the trabecular bone and periodontal disease. This made it possible to quantify the impact of periodontal disease on the surrounding bone.

Material and methods

Sample selection

After obtaining Institutional Review Board approval (UP-05-00078), 832 dental charts were reviewed from the University of Southern California School of Dentistry (USCSD) until 36 adult subjects were identified in each of the three categories: healthy ($n = 36$), moderate periodontitis ($n = 36$) and severe periodontitis ($n = 36$). The inclusion criteria were the following: (1) diagnostic periapical radiographs taken at the USCSD; (2) written periodontal diagnosis; and (3) documented medical history, basic demographic information (age and sex), drug usage, personal habits (e.g. cigarette smoking, alcohol consumption) and reproductive history (e.g. oestrogen replacement therapy). The exclusion criteria were the following: (1) radiographs had poor diagnostic quality or contained scratches or distortions; and (2) teeth in the region of interest (ROI) had previous root canal therapy or periapical lesions or were involved in orthodontic treatment. Within each periodontal group, male and female subcategories were formed to study the effect of gender.

Group classification

The healthy group consisted of patients with < 3 mm pocket probing depth and no other periodontal problems, such as clinical attachment loss, in the region of interest (attachment loss is defined as gingival recession plus the probing depth). The moderate periodontitis group consisted of patients with 3–4 mm of clinical attachment loss in at least 66% of the teeth in the region of interest. The severe periodontitis group consisted of patients with ≥ 5 mm of clinical attachment loss in at least 66% of the teeth and with many involved teeth having guarded to poor prognosis in the region of interest.

Image preparations

Periapical radiographs were digitized into Windows Bitmap (BMP) format at a resolution of 600 d.p.i. (Epson Expression 1680, Nagano, Japan). The radiographs were produced by certified radiology technicians by the USC radiology department. Parallel techniques at 70 kilovoltage (kVP) and 7 mA were used. Films were processed in an automatic film processor. A ROI was selected unmasked by one author (S.X.U.) from the apical site of the periapical radiographs located: (1) horizontally between mesial of tooth no. 22 and mesial of tooth no. 27; and (2) vertically from the apices of the teeth to the border of the image or a major structure such as mandibular symphysis. One ROI in the mandibular anterior area was selected from each subject.

The ROIs were selected in the apical region, which contains the largest area of uninterrupted trabecular bone required by the analysis. Also, there were less overlapping structures in the apical area to obscure the data.

The ROIs were cropped using Adobe Photoshop. Parameters inherent to the patients and the capture of images led to different ROI sizes. Tooth size, the location of major structures, the angulations of radiographic projection and the distance of radiographic films to the teeth affected the size of the ROI.

The following image processing, modified from White *et al.* (2) in their 2005 paper, was performed on each ROI image to remove low-frequency noise: (1) a 10-pixel Gaussian filter was applied to each image to create a blurred version of the original image; (2) the blurred image was subtracted from the original image; and (3) the resulting image was normalized by setting the intensity mean to 128, the center of the intensity range for an eight-bit image. This process allowed each image to have a uniform density on a scale much larger than the size of individual trabeculae (Fig. 1). The density-corrected image was converted to a binary format, making it easier to recognize the trabeculae and marrow spaces. ImageJ (10,11), public software distributed by the National Institutes of Health (NIH), was used for the binarization process (Fig. 2).

Fractal analysis

After correcting for lighting irregularity and binarizing each image, fractal analysis from ImageJ was applied to quantify density of the trabecular bone pattern. A grid of various square sizes, s, was placed over the ROI, and the number of boxes, $N(s)$, containing trabeculae was counted with each changing box size. The fractal dimension, D, was calculated by creating a

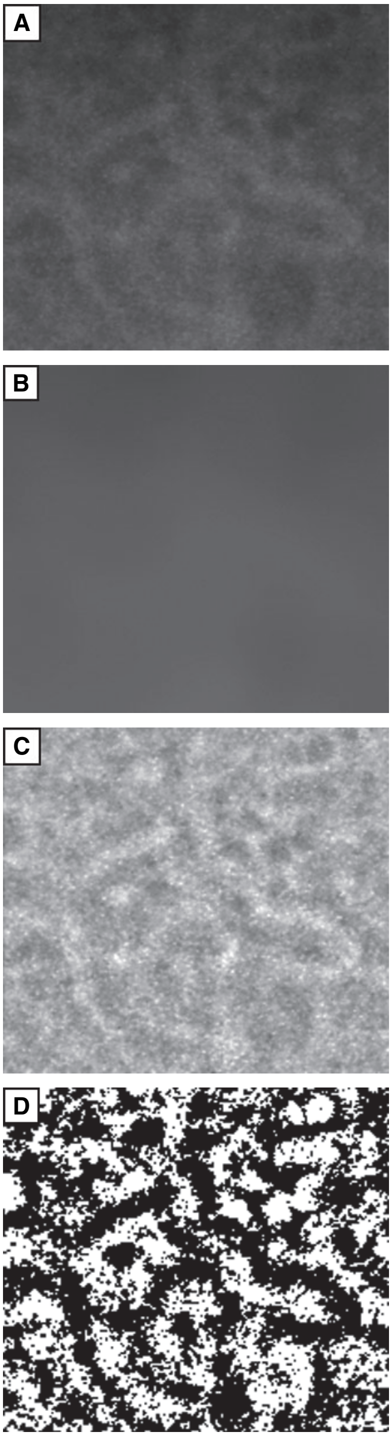

Fig. 1. Steps used in image processing. (A) Original dental radiograph in anterior mandible. (B) Blurred image created using a Gaussian filter with a sigma of 10 pixels. (C) Image of original radiograph made uniform in overall lighting intensity by subtracting blurred image (B) from original (A). (D) Binary image, derived from Fig. 1 panel (C) using ImageJ software.

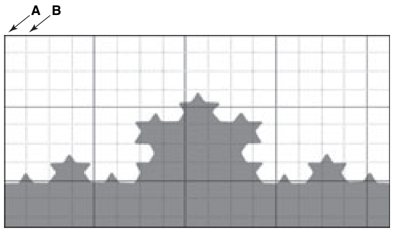

Fig. 2. Grids were superimposed over the object of interest and were shifted to sample all possible offsets. The continuous lines represents the grid, and the dotted lines represent pixel borders, shown for $n = 4$ radiographs. The first set of boxes could begin at co-ordinate (0,0), at location A. Then the second set of boxes could begin at co-ordinate (1,0), at location B, and so forth.

Richardson plot of N vs. s and solving for the slope of the linear regression, according to the formula: $\log(N) = -D.\log(s)$. This algorithm was repeated for grids of squares with side-lengths 2, 3, 4, 6, 8, 12 and 16 pixels, determined by Kaye's recommendation that grid size should fall between 2 and 30% of maximal trabeculae projection. We estimated the relevant trabeculae size to be about 0.1–2 mm. Passing either extreme, the outline of the object becomes Euclidean (12,13). In other words, the lower bound of the measuring stick should be near the magnitude of the smallest feature of interest and the upper limit should not surpass the largest feature of interest.

Since there was no preferred spatial origin for the grids of boxes, multiple measures for $N(s)$ were computed for different mesh origins. For example, given a fixed box size, the entire image was covered with a grid of boxes, and the total number of boxes with binarized trabeculae present was counted. The grid was then shifted to all possible offsets, and the number of boxes containing trabeculae was counted each time, yielding an average for that fixed box size (Fig. 3).

A spreadsheet was generated to record the fractal dimension of each subject and to tie this parameter to age and medical information.

Statistical analysis

Statistical tests were performed using SPSS 10.1 (SPSS Inc., Chicago, IL, USA) and Microsoft Excel. Descriptive statistics (e.g. mean, standard deviation, minimum, maximum, variance, sample size and standard error of mean) were calculated for different periodontal groups and for males and females in each group. Univariate Analysis of Variance with age as a covariate (ANCOVA) was used to compare fractal dimensions among the three periodontal groups; Tukey's honestly significantly different (HSD) *post hoc* tests were used to determine pairwise significance. Unpaired student's t-tests measured differences

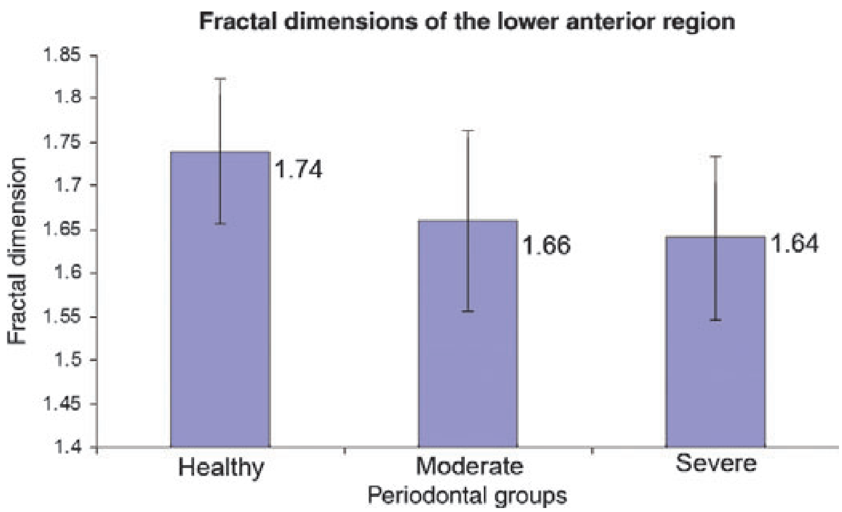

Fig. 3. Fractal dimensions of the three periodontal groups in the mandibular anterior area. The error bars extend one standard deviation away from the means.

between males and females in each periodontal group (p-value, 0.05).

Sensitivity and specificity of the fractal analysis

In order to determine the usefulness of a diagnostic test, clinical research often investigates the statistical relationship between the test results and the presence of disease. Subjects were classified into two groups: the healthy group and the periodontal group, with the latter consisting of both moderate and severe periodontitis patients. A receiver-operating characteristic (ROC) curve was used to provide a global view of the relationship between sensitivity and specificity for our fractal tool.

Results

Data set description

One hundred and eight subjects had periapical radiographs of the anterior mandible available for analysis. The mean age for all three combined groups was 48 years; the mean age for the control (healthy) subgroup was 33 years; the mean age for the moderate periodontitis subgroup was 58 years; and the mean age for the severe periodontitis subgroup was 53 years. (Table 1). The sex distribution of each group is shown in Table 2.

Fractal dimensions in the lower anterior region

The average fractal dimension for the control (1.74 ± 0.083), moderate periodontitis (1.66 ± 0.104) and severe periodontitis groups (1.64 ± 0.095) was measured in the mandibular anterior region. According to the Tukey HSD one-way ANOVA *post hoc* tests, significant differences in fractal dimensions were measured between the control and moderate periodontitis groups ($p < 0.01$) and between healthy and severe periodontitis groups ($p < 0.001$; Table 3). Healthy periodontal patients had higher fractal dimensions. The result allowed us to reject the null hypothesis and conclude that fractal dimension was not the same in subjects with or without periodontal disease in the mandibular anterior region. The ANCOVA showed that fractal dimension is still significantly related to periodontal status after the variation due to age has been removed. (Table 4).

Fractal analysis as a diagnostic tool

The ROC curve was constructed to assess the ability of the fractal tool to differentiate between healthy and periodontal patients. In this case, the area under the curve is 0.758.

When the ROC curve was plotted to compare among groups, the areas were 0.726 (healthy vs. moderate periodontitis), 0.791 (healthy vs. severe periodontitis) and 0.577 (moderate vs. severe periodontitis).

The ROC results indicate that fractal analysis could be considered a fair to good diagnostic tool to differentiate between subjects with healthy and either moderate or severe periodontitis. However, it was a poor tool to detect differences between the two types of periodontal conditions.

Effects of age

Since the three periodontal groups studied had subjects with age ranging from 18 to 78 years, a graph was constructed to compare the effect age on the fractal dimension. There did not seem to be much correlation between age and fractal dimension, since only 6.64% of the variance in fractal dimension was explained by age ($r^2 = 0.0664$).

Effects of gender

Since the data set combined males and females in each group, a secondary study was designed to test the effect of gender on fractal dimension. The effect of gender on fractal dimension was examined within each group using unpaired student's t-test. The p-values for each intra-group comparison were 0.79, 0.77 and 0.12 (healthy group, moderate periodontal group, severe periodontal group). When data were combined from the three groups, the p-value was 0.51. The data did not disprove the null hypothesis that there is no statistical significant difference between gender and fractal dimension.

Discussion

Fractal analysis, a quantitative method used to evaluate complex structures by examining elementary components, has been used to analyse biological images for the past several years. The aims of some of these applications were to assess changes in bone, to measure

Table 1. Descriptive statistics for patients' ages

Patient group	n	Mean age	SD age
Control	36	33.2	13.1
Moderate periodontitis	36	58.2	11.1
Severe periodontitis	36	52.5	10.6
Combined	108	48.2	15.9

Table 2. Description of patient's gender

Patient group	Number of males	Number of females	Total
Control	18	18	36
Moderate periodontitis	17	19	36
Severe periodontitis	21	15	36
Total	56	52	108

Table 3. Tukey's HSD *post hoc* test comparisons

Group A	Group B	Mean difference (A−B)	Significance
Healthy	Moderate	0.077	0.002*
Healthy	Severe	0.100	0.000*
Moderate	Severe	0.023	0.552

*The mean difference is significant. The adjusted p-value is set at 0.016 for multiple comparisons.

Table 4. Univariate analysis of variance with age as a covariate

Source	Type III sum of squares	Degrees of freedom	Mean square	F	Significance	Noncent. parameter	Observed power[a]
Corrected model	0.199[b]	3	6.649×10^{-2}	7.448	0.000	22.343	0.983
Intercept	16.328	1	16.328	1828.874	0.000	1828.874	1.000
Age	3.037E-05	1	3.037×10^{-5}	0.003	0.954	0.003	0.050
Perio	0.125	2	6.231×10^{-2}	6.979	0.001	13.958	0.920
Error	0.928	104	8.928×10^{-3}				
Total	305.101	108					
Corrected total	1.128	107					

[a]Computed using $\alpha = 0.05$.
[b]$r^2 = 0.177$ and adjusted $r^2 = 0.153$.

bone fragility and to show the increased risks for fracture or osteoporosis. In the dental field, researchers have detected signs of osteoporosis through dental images. Yet, some investigators have used panoramic radiographs, instead of the higher resolution periapical radiographs, to detect trabecular pattern changes. Tosoni and colleagues (14) used fractal analysis to study osteoporotic-associated bone density changes on panoramic radiographs. This study had high sensitivity but lower specificity, which explained the lack of statistical significance in their results. In 2006, Jolley and colleagues (15) showed that periapical radiographs could provide a reliable method for determining fractal dimension to analyse changes in alveolar bone density in various bone diseases.

There have been few studies that quantitatively analysed trabecular bone pattern on radiographs under different periodontal conditions. Shrout *et al*. (16) used a calliper method of fractal analysis to compare the trabecular pattern differences among healthy and moderate periodontal patients. It is known that there are many fractal techniques, such as the pixel-dilation method, the mass-radius method and the box-counting method, and different types of fractal methods produce different fractal dimensions. Investigators recognized the difficulty in calculating and comparing fractal values between studies, but we are curious to see the trend of previous fractal studies, such as Shrout's. The authors decided to use one of the most common techniques, the box-counting method provided by ImageJ, to detect pattern changes induced by periodontitis. Our goal was to develop an additional protocol to analyse trabecular bone pattern quantitatively. The box-counting method could be used in conjunction with other image analysis tools and additional clinical information through linear regression to provide a more accurate tool to explain properties of cancellous bone structure under the effect of periodontal disease. Inclusion of other variables may improve accuracy of classification.

The fractal results at the mandibular anterior region disproved our null hypothesis and indicated that fractal dimensions can detect differences in cancellous bone structure between healthy and periodontal patients. Although there is no statistical difference between subjects affected by moderate periodontitis and subjects affected by severe periodontitis, there is still a positive trend between periodontal condition and fractal index. Periodontal health seemed to be positively correlated with the fractal index; as periodontal health deteriorated, fractal index decreased. When the periodontium becomes less healthy due to periodontal involvement, alveolar bone loss occurs, and this affects trabecular bone pattern. Trabecular arrangement becomes less complex and less space-filling, and therefore fractal dimension decreases with declining periodontal health. The relationship between fractal dimension and periodontal condition is similar to that found in Shrout's calliper method of fractal analysis. Although our ROIs were selected from the apical region of the teeth and periodontitis affects mainly the marginal portion of the alveolar process, there is a difference in the fractal index between healthy and periodontal groups. This could be explained by the fact that trabecular bone arrangements are affected in patients with more advanced periodontitis (moderate and severe periodontitis). Patients affected by periodontitis have reduced bone level, and trabecular integrity may be altered before further bone loss is demonstrated on radiographs. Fractal analysis could detect small changes before further bone loss occurs.

At this time there is no consensus on the relationship between fractal dimension and trabecular bone complexity. Some findings support the idea that fractal dimension increases in the diseased, osteoporotic state. Many others support our finding that the diseased state reduces trabecular complexity and decreases fractal dimension. It is possible that both may be correct, depending on the disease that affects trabecular bone and how it destroys the fine trabeculae in different parts of the body.

Our periodontal diagnosis was based on clinical attachment and alveolar bone loss. It was difficult to obtain objective and quantitative measurements despite our observation that every diagnosis came from calibrated clinical faculty members. In order to make the three categories more distinct, mild periodontitis with 1–2 mm clinical attachment loss (CAL) was omitted from the study. Furthermore, many subjects within the severe periodontitis group had a guarded to hopeless prognosis. Nevertheless, our results show that there is no statistical difference between the two periodontitis groups. A larger sample size may be required to validate the positive trend with statistical significance.

In the present study, the ROI was selected below the apex of the mandibular anterior teeth. Fractal analysis required a large uninterrupted trabecular bone area for computation. In both moderate and severe periodontitis groups, tissue destruction happened near our cropped ROIs, and it was reasonable to expect trabecular pattern changes. Owing to the difference in individual anatomy, different amounts of bone were available, and this made it difficult to select ROIs with the same size. Despite the appeal of a fixed ROI size, in the end we chose to retain as much useful information as possible, rather than cropping to the smallest common size. In the future, with higher resolution radiographs, we expect to obtain more data from each image and gain the ability to unify ROI size.

This study did not detect statistically significant differences between gender and fractal dimension. While gender-dependent differences in iliac and vertebral cancellous bone have been reported, other studies have not detected significant differences (17). Individual differences in mandibular size and shape, medical background and dynamics of bone metabolism can negate gender-specific factors. A larger sample size is needed to conduct a separate experiment for studying the effects of gender on trabecular bone architecture.

Periodontal groups on average were older than the control, healthy group. However, when we studied the effect of age on trabecular bone pattern, age could only explain about 7% of the variance in fractal dimension (r^2 = 0.07). When we accounted for age as a covariate, the relation between fractal dimension and periodontal status was still significant. Owing to the small sample size, only age and gender were controlled in this study. More subjects are needed to determine whether other factors play a role in a patient's periodontal health.

Our study focused on alterations of trabecular architecture seen on periapical radiographs. We measured radiographic characteristics on a two-dimensional projected image of a three-dimensional structure. While it is preferable to work with three-dimensional image data such as that obtained from NewTom machines, this three-dimensional technology is not widely available to many clinicians currently, and it is therefore difficult to use as a mass screening tool. Three-dimensional image analysis may become much more important in the future as the technology improves.

It would be difficult to do a longitudinal study of the same individual with our fractal protocols. Since it is hard to select the same ROI in two images of the same anatomical region over a period of years, this is a limitation. Techniques in image registration could solve this problem and make it possible to analyse trabecular bone in the same region.

Conclusion

Dental radiographs provide high-detail images of bone for adults and are common diagnostic tools used in dental practices. Image analysis of radiographs allows clinicians to extract data from pre-existing resources and has a great potential to be used as a screening aid for the onset of trabecular pattern changes. In this study, the box-counting method of fractal analysis was able to detect differences in trabecular bone architecture quantitatively between healthy subjects and periodontal patients. Age and gender did not play a significant role in our results. The box-counting method of fractal analysis could be used as an aid to our clinical diagnosis.

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