The effects of voltage of x-ray tube on fractal dimension and anisotropy of diagnostic image

Jee-Seon Baik, Sam-Sun Lee, Kwan-Soo Park*, Kyung-Hoe Huh, Won-Jin Yi, Min-Suk Heo, Soon-Chul Choi

*School of Dentistry and Dental Research Institute, Seoul National University, *Inje University, Sanggye Paik Hospital*

ABSTRACT

Purpose : The purpose of this study was to evaluate the effect of the kV on fractal dimension of trabecular bone in digital radiographs.

Materials and Methods : 16 bone cores were obtained from patients who had taken partial resection of tibia due to accidents. Each bone core along with an aluminum step wedge was radiographed with an occlusal film at 0.08 sec and with the constant film-focus distance (32 cm). All radiographs were acquired at 60, 75, and 90 kV. A rectangular ROI was drawn at medial part, distal part, and the bone defect area of each bone core image according to each kV. The directional fractal dimension was measured using Fourier Transform spectrum, and the anisotropy was obtained using directional fractal dimension. The values were compared by the repeated measures ANOVA.

Results : The fractal dimensions increased along with kV increase ($p < 0.05$). The anisotropy measurements did not show statistically significant difference according to kV change. The fractal dimensions of the bone defect areas of the bone cores have low values contrast to the non-defect areas of the bone cores. The anisotropy measurements of the bone defect areas were lower than those of the non-defect areas of the bone cores, but not statistically significant.

Conclusion : Fractal analysis can notice a difference of a change of voltage of x-ray tube and bone defect or not. And anisotropy of a trabecular bone is coherent even with change of the voltage of x-ray tube or defecting off a part of bone. (***Korean J Oral Maxillofac Radiol 2007; 37 : 211-5***)

KEY WORDS : KV; Anisotropy; Fractal Dimension

Introduction

Bone quality is important for diagnosis and treatment in dentistry. But, quality is ambiguous term in practice and it is difficult to evaluate the bone quality of jaw. Bone intrinsic strength is conditioned by several factors, including material properties such as bone mineral density (BMD), matrix quality and additional factors such as bone macro-architecture and trabecular micro-architecture.[1] Precise in vivo measurement of the trabecular bone's mechanical properties, such as strength, is very important in clinical practice. Incorporating both density and architecture improved the predictability of bone strength in an in vitro study.[2] A bone radiograph is a 2D projection of the 3D trabecular network, and several groups have considered that texture analysis of such images can provide valuable analysis of the trabecular architecture. Anisotropy and fractal dimension are interest in mechanics-architecture relations.[3] Anisotropy characterizes the degree of directional organization of a material. Mandelbrot's fractal dimension is used for an objective measures to quantify the complexity of bone structure.[4,5]

Dental researchers have suggested that fractal analysis may be a sensitive descriptor of bone structure and provide a diagnostic tool to objectively characterize trabecular bone structure. It was used to discriminate between normal and periodontally compromised subjects.[5] Fractal dimension has been used to evaluate complex interconnections or alveolar cancellous bone on dental images, distinguishing between patients with and without osteoporosis.[4,5]

Several investigations show that in vivo structural anisotropy measure can be useful for the diagnosis of bone quality and fracture risk in bone disease. Sugita et al. reported that anisotropy of the cancellous bone should be considered to predict the fracture risk.[6] Wigderowitz et al. considered the properties

*Supported by grant no 04-2006-0006 from the Seoul National University Dental Hospital Research Fund.

Received September 19, 2007; accepted November 9, 2007

Correspondence to : Sam-Sun Lee, DDS, MSD, PhD.
Department of Oral and Maxillofacial Radiology, School of Dentistry and Dental Research Institute, Seoul National University, 28 Yeongeon-dong, Jongno-gu, Seoul 110-768, Korea
Tel) 82-2-2072-3978, Fax) 82-2-744-3919, E-mail) raylee@snu.ac.kr

of Fast Fourier Transform to evaluate trabecular bone structure. He concluded that this quantification detects structural changes occurring with age and may be useful in osteoporosis studies.[7] The fracture risk evaluation could be improved by adding information related to the directional organization of trabecular bone.[1] Specimens from the proximal femurs of women with hip fractures had a significantly more anisotropic structure than the controls.[8]

Fractal dimension and anisotropy are used to predict bone quality in diagnostic imaging because changes in fractal dimension and anisotropy due to variations in image density caused by exposing, processing, and digitizing dental radiographs are negliable.[5,9-12] It can be an advantage that they aren't affected by changes of exposing condition. But, the study about the effect of kV changes on fractal dimension and anisotropy was rare. This study examined the affects of the fractal dimensions and anisotropy measurements depending on kV changes.

Materials and Methods

1. Image acquisition

We get the bone core images from University of Connecticut Health Center research center. Each bone core along with an aluminum step wedge was radiographed with No. 4 occlusal film at 0.08 sec and with the constant film-focus distance (32 cm). Bone cores (0.7 cm × 4 cm) are tibia bone particles from patients who had operated reconstruction of tibia in UCHC due to accidents. 16 bone cores were selected and its shape was made to cylinder form. Bone specimens that have any superficial damage, pore, and calcification or change of bone density were excluded.

All radiographs were acquired at 60, 75, and 90 kV (Fig. 1). All radiographs for each sample were identically illuminated and digitized with scanner with a pixel spatial resolution of 8-bit scale depth. A rectangular ROI was drawn at medial, distal part and the bone defect area of each bone core image according to each kV.

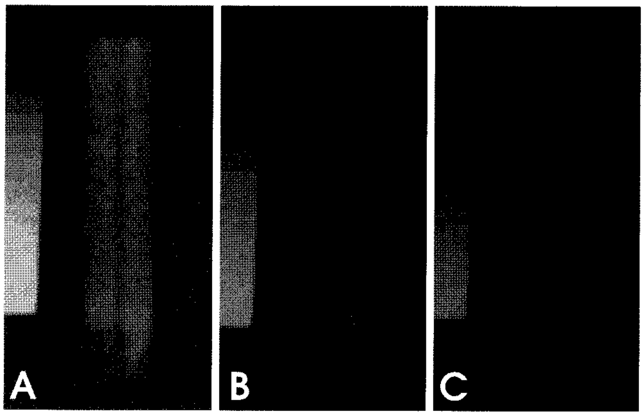

Fig. 1. Radiographs which were obtained at different kV: (A) 60 kV; (B) 75 kV; (C) 90 kV.

2. Determination of directional fractal dimensions and intercept length

The fast Fourier transform based technique was used for calculating the fractal dimensions (FD) of the 2D radiographs.[13-15] The power spectrum of a local region was converted into the polar coordinate system. Generally, averaged spectrum for all angular distributions was calculated as a function of spatial frequency. The FD was calculated from a curve determined by taking the logarithm of the spectrum versus the logarithm of frequency. The slope of the linear portion of the curve was related to FD by equation (Eq. 1).

$$FD = (7 - \text{slope})/2 \qquad (1)$$

According to the Fourier slice theorem (or central slice theorem), the values of the one-dimensional Fourier transform of a parallel projection of an image along a line with the direction θ are identical to the data along the same line in the 2D Fourier transform of the image. This means that the line through the 2D spectrum gives the spectral information obtained from a projection with the same orientation in the spatial domain. Particularly, the directional FDs were calculated as a function of orientation based on this theorem. First, the power spectrum was partitioned into sectors with the same central angle. The directional spectrum ($P\theta(f)$) of each sector was obtained by interpolating the spectrum values in all frequencies. Then, the directional FD for each sector was determined by taking the logarithm of $P\theta(f)$ versus the logarithm of f. The slope of the linear portion of the curve was related to the directional FD by the equation mentioned above. This FD gave the fractal information reflecting the spatial characteristics of the trabecular bone in each direction.

3. Anisotropy measurement by principle axes of inertia

We applied principal axes of inertia to quantifying the structural anisotropy of trabecular bone. A polar plot of directional FDs was defined as an ellipse of inertia. The directional FDs were calculated only in directions of 0 to 180 degrees. The FDs in the other directions were determined by symmetry with respect to the origin. The polar plot of FDs was constructed by 360 FDs, one per degree. It described the moment of inertia of an object as a function of the orientation. Two principal axis directions of inertia were determined by geometrical moments calculated from the polar plot of FDs (Eq. 2).[16] They differed by $\pi/2$. One value defined the axis of the maximum moment of inertia, and the other defined the axis of the minimum moment of inertia. The anisotropy (A) was directly calculated as the ratio of the two principal moments of inertia (Eq. 3). The ratio of the principal axes of inertia was used in measuring the eccentricity which was one of the statistical region descriptor for an arbitrary set of points.[17] The anisotropy was also determined by fitting an ellipse to the polar plot of FDs for comparison.[18] The anisotropy was quantified as the ratio of the major and minor axes of the best-fitting ellipse.

$$x_0=\frac{1}{N}\sum_{x=0}^{N-1}x,\quad y_0=\frac{1}{N}\sum_{x=0}^{N-1}y$$

$$M_{ij}=\sum_{x=0}^{N-1}\sum_{y=0}^{N-1}(x_0-x)^i(y_0-y)^j$$

$$\theta=\frac{1}{2}\tan^{-1}\left(\frac{2M_{11}}{M_{20}-M_{02}}\right)+n\left(\frac{\pi}{2}\right),\quad 0\leq\theta<180 \qquad (2)$$

$$I_{\substack{max\\min}}=\frac{M_{20}+M_{02}}{2}\pm\sqrt{\left(\frac{M_{20}-M_{02}}{2}\right)^2+M_{11}^2} \qquad (3)$$

$$A=I_{min}/I_{max}$$

(x, y) : Points of ellipse by a polar plot of directiona l FDs
N : Number of points composing a ellipse
M_{ij} : Moments
θ : Principal axis direction of moment of inertia
$I_{max(min)}$: Maximum (minimum) moment of inertia
A : Anisotropy

4. Statistical analysis

All the statistical analyses were performed using the repeated measures ANOVA (SPSS Version 12.0; SPSS Inc., Chicago, IL). *For each specimen analysis of variance was performed* to determine if a difference in fractal dimension and anisotropy value existed according to kV change.

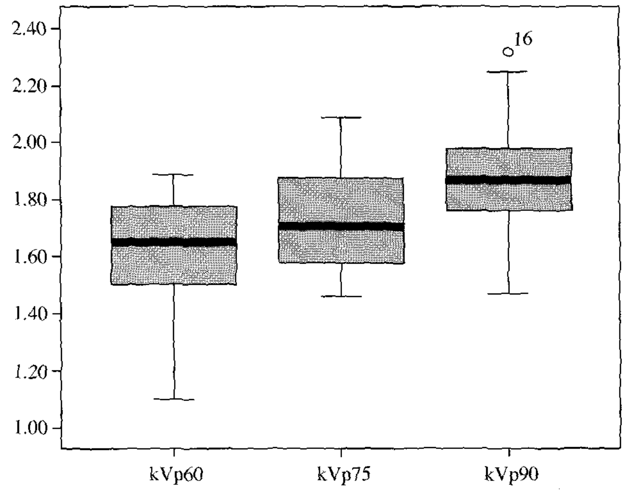

Fig. 2. *Fractal dimension according to kV change.*

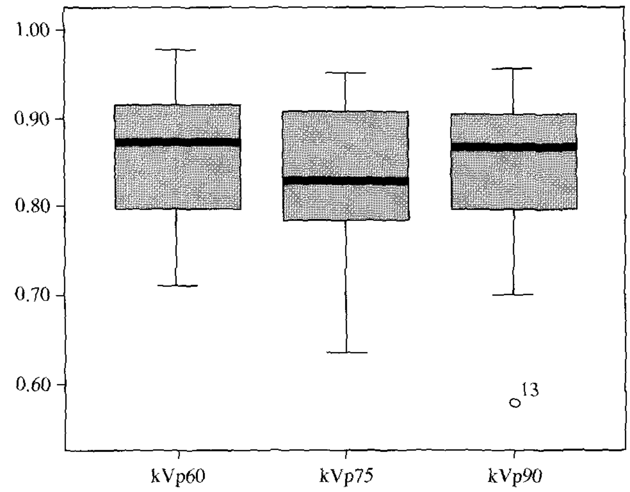

Fig. 3. Anisotropy according to kV change.

Results

The means of the fractal dimensions were 1.63+/−0.19, 1.74+/−0.19, 1.87+/−0.19 at 60 kV, 75 kV, 90 kV (Fig. 2), and increased along with kV ($p<0.05$). The means of the anisotropy were 0.86+/−0.08, 0.83+/−0.09, 0.84+/−0.09 at 60 kV, 75 kV, 90 kV (Fig. 3), and they were not statistically different. The means of the fractal dimensions of the bone defect areas of the bone cores were 0.92+/−0.13, 1.09+/−0.14, 1.21+/−0.15 at 60 kV, 75 kV, 90 kV, and increased along with kV ($p<0.05$). There was statistically significant correlation between mean fractal dimensions of the non-defect areas and the bone defect areas (Fig. 4). The means of the anisotropy measurements of the bone defect areas of the bone cores were 0.78+/−0.1, 0.84+/−0.09, 0.79+/−0.10 at 60 kV, 75 kV, 90 kV, and they were lower than the means of the anisotropy measurements of the non-defect areas of the bone cores. But there was no statistically significant relationship (Fig. 5).

Discussion

Various methods have been proposed to estimate the fractal

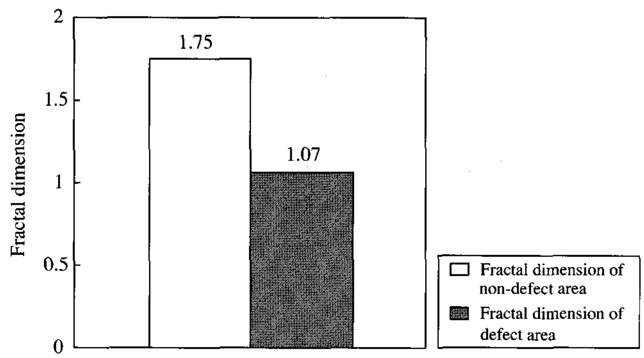

Fig. 4. Fractal dimension of non-defect area and defect area of the bone core.

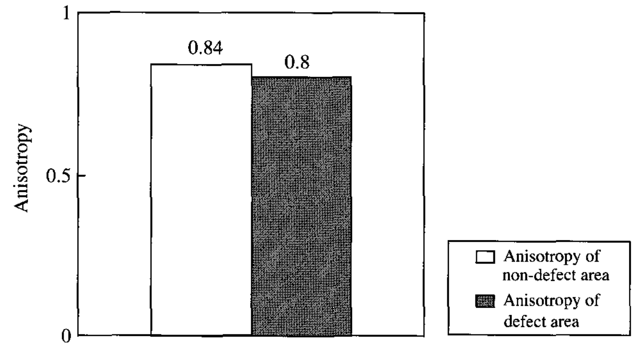

Fig. 5. Anisotropy of non-defect area and defect area of the bone core.

dimension, including box-counting and power spectral methods. In this study, the directional fractal dimension was measured using the Fast Fourier Transform spectrum, and the anisotropy was obtained using directional fractal dimension. Calculating the anisotropy based on the principal axes of inertia determined the parameters directly. The direct method developed here was computationally less expensive and faster. This can provide direct quantification of the local anisotropy of trabecular bone using directional FDs.

X-ray images of bones generally exhibit a variety of textures.[19] Fractal dimension of bone may vary with location, disease condition or variations in image densities caused by exposing, processing, digitizing radiographs. Ruttiman et al. estimated fractal dimension from radiographic images of mandibular alveolar bone before and after partial decalcification. They concluded that fractal dimension increased after acid-induced demineralization, and the projection angle (-5, 0, $+5$ degrees) had no significant effect on the final estimate of fractal dimension.[5] Buckland-Wright et al. stated that fractal analysis appears to be independent of projection geometry.[9] Shrout et al. reported that fractal dimensions are insensitive to small variation in x-ray exposure, beam alignment, and ROI position.[10] Southard et al. found that the fractal dimension was sensitive to small variations in radiographic geometry, a finding that conflicts with the reports of other investigators.[11] There were no studies about the effect of radiographic condition on anisotropy. Because the trabecular pattern may vary with exposing, we can predict that the fractal dimension and anisotropy to characterize trabecular bone is affected by changes of kV.

In our study, the mean value of fractal dimension increased according to kV. This result means that kV changes affect the fractal dimension. However, Shrout et al. reported that fractal dimensions as determined from ROIs of digital radiographic images of alveolar bone are insensitive to small variation in x-ray exposure, beam alignment, and ROI position.[10] We can guess that exposing condition of previous report was under range of which didn't represent the different trabecular pattern.

Our results showed that the means of the fractal dimensions of the bone defects area of the bone cores were lower than in normal bone core. Southard et al. stated that fractal dimension decreased with decalcification.[11] On the other hand, Ruttimann et al. concluded that fractal dimension increased after acid-induced demineralization.[5] A difference in the method for calculating the fractal dimension was offered as a possible explanation of this difference.[5] We think that the use of different methods to estimate the fractal dimension can produce different results. In our study, fractal dimension decreased in the areas of bone defects, similar to the finding by Heo et al.[20] It is meaningful that the values are showing statistical consistent results. Nevertheless, we can see different statistical results depending on the investigators. So we can conclude that the methodological consistency is probably needed.

The means value of anisotropy didn't show the significant differences statistically to kV changes. Hara et al. found that changes in the anisotropy due to variation in threshold are negligible.[12]

If the measurements to detect bone changes are independent of radiographic variation, which are probably inevitable when radiographs are produced over times, that technique may represent a reliable analysis.

In conclusion, fractal analysis can notice a difference of a change of voltage of x-ray tube and bone defect or not. And anisotropy of a trabecular bone is coherent even changing of the voltage of x-ray tube or defecting off a part of bone. Fractal value and anisotropy present different features of bone and they show different response with environmental change, kV and bone defect.

References

1. Chappard C, Brunet-Imbault B, Lemineur G, Giraudeau B, Giraudeau A, Harba R, et al. Anisotropy changes in post-menopausal osteoporosis: characterization by a new index applied to trabecular bone radiographic images. Osteoporos Int 2005; 16 : 1193-202.
2. Turner CH, Cowin SC, Rho JY, Ashman RB, Rice JC. The fabric dependence of the orthotropic elastic constants of cancellous bone. J Biomech 1990; 23 : 549-61.
3. Odgaard A. Three-dimensional methods for quantification of cancellous bone architecture. Bone 1997; 20 : 315-28.
4. Caligiuri P, Giger ML, Favus M. Multifractal radiographic analysis of osteoporosis. Med Phys 1994; 21 : 503-8.
5. Ruittimann UE, Webber RL, Hazelrig JB. Fractal dimension from radiographs of periodontal alveolar bone: a possible diagnostic indicator of osteoporosis. Oral Surg Oral Med Oral Pathol 1992; 74 : 98-110.
6. Sugita H, Oka M, Toguchida J, Nakamura T, Ueo T, Hayami T. Anisotropy of osteoporotic cancellous bone. Bone 1999; 24 : 513-6.
7. Wigderowitz CA, Abel EW, Rowley DI. Evaluation of cancellous structure in the distal radius using spectral analysis. Clin Orthop Related Res 1997; 335 : 152-61.
8. Ciarelli TE, Fyhrie DP, Schaffler MB, Goldstein SA. Variations in three-dimensional cancellous bone architecture of the proximal femur in female hip fractures and in controls. J Bone Miner Res 2000; 15 : 32-40.
9. Buckland-Wright JC, Lynch JA, Rymer J, Fogelman I. Fractal signature analysis of macroradiographs measurements trabecular organization in lumbar vertebrae of postmenopausal women. Calcif Tissue Int 1994; 54 : 106-12.
10. Shrout MK, Potter BJ, Hildebolt CF. The effect of image variations on fractal dimension calculations. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 1997; 84 : 96-100.
11. Southard TE, Southard KA, Jakobsen JR, Hillis SL, Najim CA. Fractal dimension in radiographic analysis of alveolar process bone. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 1996; 82 : 569-76.
12. Hara T, Tanck E, Homminga J, Huiskes R. The influence of microcomputed tomography threshold variations on the assessment of structural and mechanical trabecular bone properties. Bone 2002; 31 : 107-9.
13. Majumdar S, Lin J, Link T, Millard J, Augat P, Ouyang X, et al. Fractal analysis of radiographs: assessment of trabecular bone structure and prediction of elastic modulus and strength. Med Phys 1999; 26 : 1330-40.
14. Millard J, Augat P, Link TM, Kothari M, Newitt DC, Genant HK, et al. Power spectral analysis of vertebral trabecular bone structure from radiographs: orientation dependence and correlation with bone mineral density and mechanical properties. Calcif Tissue Int 1998; 63 : 482-9.
15. Geraets WG, van der Stelt PF. Fractal properties of bone. Dentomaxillofac Radiol 2000; 29 : 144-53.
16. Soutas-Little RW, Inman DJ. Engineering mechanics: statics. New Jersey: Prentice-Hall Inc; 1999. p. 454-8.
17. Ballard DH, Brown CM. Computer vision. New Jersey: Prentice-Hall Inc; 1982. p. 254-61.
18. More JJ, Wright SJ. Optimization software guide. Philadelphia: Society for Industrial and Applied Mathematics; 1993.
19. Lundahl T, Ohley WJ, Kay SM, Siffert R. Fractional Brownian motion: a maximum likelihood estimator and its application to image texture. IEEE Trans Med Imaging 1986; 5 : 152-61.
20. Heo MS, Park KS, Lee SS, Choi SC, Koak JY, Heo SJ, et al. Fractal analysis of mandibular bony healing after orthognathic surgery. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 2002; 94: 763-7.