Fractal Analysis of Bone Radiographs Correlated with Histomorphometry

Khaled Harrar, Latifa Hamami and Rachid Jennane

***Abstract*— The bone fragility in osteoporosis is multifactorial and complex. At present, fracture risk prediction in the individual patient relies chiefly on bone mineral density (BMD) measurements. However, many lines of evidence indicate that the decreased bone strength characteristic of osteoporosis is dependent not only on bone mineral density, but also on other factors, most notably bone microarchitecture. The aim of this paper is the analysis of trabecular bone for osteoporosis detection. Two methods are used, texture analysis based on fractal dimension and hitomorphometry based on the bone microarchitecture analysis. A total of 24 images of calcaneus (heel bone) from subjects divided into 2 groups (osteoporotics and controls) were analyzed. Correlations are found between fractal dimension, histomorphometry parameters and osteoporosis, suggesting that these two methods are potentially useful in monitoring bone strength.**

***Index Terms*— Fractal dimension, texture, osteoporosis, histomorphometry, bone mineral density (BMD).**

I. Introduction

Osteoporosis is a condition that is characterized by low bone mass and microarchitectural deterioration of bone tissue, leading to enhanced bone fragility and a consequent increase in fracture risk [1]. The trabecular microarchitecture characterization has been recognized as an important factor [2]. It cannot be routinely obtained by noninvasive methods and requires a bone biopsy with histomorphometric analysis. This is why several attempts have been made to characterize trabecular bone microarchitecture by noninvasive methods [2-3]. A fractal describes a rough or fragmented geometric shape that can be subdivided into parts, each of which is, at least approximately, a reduced-size copy of the whole.

Paper Received October 27, 2011.
K. Harrar is with Université M'Hamed Bougara Boumerdes, 35000 avenue de l'indépendance Boumerdes. Algérie harrar_k@umbb.dz
& Ecole Nationale Polytechnique d'Alger, Laboratoire signal et communications, 10, Avenue Hassen Badi BP 182 El-Harrach Alger 16200.

L. Hamami is with Ecole Nationale Polytechnique d'Alger, Laboratoire signal et communications, 10, Avenue Hassen Badi BP 182 El-Harrach Alger 16200. latifa.hamami@enp.edu.dz

R. Jennane is with the PRISME Laboratory, University of Orleans, 12 rue de Blois BP 6744, 45067 Orléans Cedex 2, FRANCE.Rachid.Jennane@univ-orleans.fr

Contrary to classical geometry, fractals are not regular and may have an integer or non-integer dimension. Also, they are generally self-similar and independent of scale. Fractal dimension is a measure of how complicated a self- similar object is [2-4]. Such a property is also of interest in the study of the microarchitecture of trabecular bone.

Different osteoporotic stages cause differently deteriorated trabeculae, i.e. a higher irregularity and holes for a higher degree of osteoporosis.

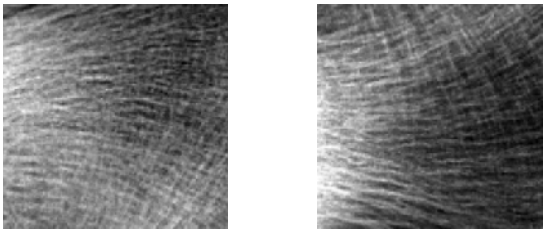
There are several others digital processing methods to assess bone architecture. In particular, histomorphometry, based on the principles of quantitative histology and stereology, helps evaluating the two-dimensional microarchitecture. This method supply information on trabecular width as well as on its distribution and on the organization of the different trabeculae in a bone section. several studies have been performed to characterize the trabecular bone: Nektarios et al. [2] used Fourier analysis dimension and lacunarity to characterize texture images, they showed that power spectrum intercept correlates well with the overall magnitude of visual roughness, and lacunarity has a discriminating power among the images qualities. Lespessailles et al. [3] worked on direct digital radiographic images, they showed the relationship between the bone texture analysis and bone mineral density. Also, they stated that the use of high-resolution digital X-ray device improves the reproducibility of parameter measurement compared to the indirect digitization of radiologic films previously used. Jennane et al [5] proposed a fractal analysis of bone X-ray tomographic microscopy (XTM) projections. The aim of the study was to establish whether or not there is a correlation between three-dimensional (3D) trabecular changes and two-dimensional (2D) fractal descriptors. The model of fractional Brownian motion (fBm) was used on bone XTM 2-D projections to characterize changes in bone structure that occur during disease, such a simulation of bone loss. Results indicate that fBm is a robust texture model allowing quantification of simulations of trabecular bone changes. The objective of this work is to find correlation between bone micoarchitectural parameters and fractal dimension for osteoporosis assessment.

II. METHODS

A. *Image Acquisition and preprocessing*

The radiographic images of calcaneus are obtained on a Kodak Min R screen-film system. The calcaneus was placed in contact with the film and the distance between the X-Ray focal source and the film was fixed at 1m. The region of interest (ROI) on the radiographs was located in an area of trabecular bone at the tuber calcanei, and defined by anatomic marks. The ROI was digitized with a CCD camera to the format 256 x 256 pixels in grayscale (Fig. 1). Subjects were classified into two groups (normal: for healthy (12 subjects), osteoporotics: for 12 subjects suffering from osteoporosis (i.e. of abnormal loss of calcium).

ROI images were first made binary using the algorithm described by White and Rudolph [6], which was used for measuring the morphologic features of the trabecular architecture. Each ROI image was first smoothed using a low pass Gaussian filter (sigma = 21 pixels, kernel size = 10) to remove large scale variations on the image. The smoothed image was then subtracted from the original, and 128 gray level value was added to each pixel of the subtracted image. The resulting image was then binarized using a global threshold value of 128 (Fig. 2) [6], which segmented the image into the bone (gray level of 255) and marrow (gray level of 0).



(a) (b)

Fig.1. Texture images. (a) control case and (b) an osteoporotic patient (of the calcaneus after the ROI extraction).

(a) (b)

Fig. 2. Binary images related to the previous ROI. (a) control case, b) osteoporotic patient.

B. *Fractal dimension*

Mathematically, a fractal is a set of points whose fractal dimension exceeds its topological dimension. The notion of dimension is not very useful since it does not distinguish between rather complex set of elements and a single point, which also has a vanishing topological dimension. To cope with this degeneracy, mathematicians have introduced alternative concepts of dimensions that give useful information for quantifying such sets. The simplest non-trivial dimension that generalizes the topological dimension is the so-called fractal dimension defined as follow:

$$D_c = \lim_{n\to\infty} \frac{\ln N_n}{\ln(\frac{1}{\varepsilon_n})} \qquad (1)$$

The fractal dimension Dc quantifies the rate at which the number N_n of observable elements proliferate as the resolution $1/\varepsilon_n$ increases. One of the widely used methods to calculate fractal dimension is the Box counting method, its widespread use is due mainly to its ease of calculation and well adapted to binary images. The idea is to cover the object S with sets of diameter ε. Call N_ε the number of such sets needed to cover S. The box dimension is then [7]:

$$D_b(S) = \lim_{\varepsilon\to 0} \frac{\ln N_\varepsilon}{-\ln(\varepsilon)} \qquad (2)$$

If the limit converges (otherwise replace lim by lim inf or lim sup, respectively the lower and upper box counting dimensions). The box dimension is therefore the power law behaviour of the measurement of the object at scale ε. The number of sets that can cover S is of order $\varepsilon^{-Db(S)}$. The previous definition remains the same if for $N\varepsilon$ we consider the smallest number of cubes of diameter ε that can cover S [8], hence the name box counting dimension. To obtain an estimate of D_b(S), it suffices to plot ln $N\varepsilon$ versus ln ε. The estimate by the least squares method of the slope of the group of dots (-ln (ε), ln (N (ε))), gives the estimate of fractal dimension [9].

C. *Histomorphometry*

The study of microarchitecture is based on the measure of width, number, and separation of trabeculae as well as on their spatial organization. The measurement of trabecular parameters on the bone sections was initially obtained using a microscope with an ocular equipped with a special grid. What we can measure are the TV (tissue volume), BS (bone surface) and BV (bone volume). The following parameters are determined [10]:

- The Bone Volume Fraction : $\frac{\mathrm{BV}}{\mathrm{TV}} \times 100$
- The Bone Surface Fraction : $\frac{\mathrm{BS}}{\mathrm{TV}} \times 100$
- The Tabecular Thickness : $TbTh = \frac{2}{BS/BV}$
- The Trabecular Number : $TbN = \frac{BV/TV}{TbTh}$

- The Trabecular Separation : $TbSp = \frac{1}{TbN} - TbTh$

These parameters describe the basic relationship between space and trabecular network. Conventionally, all these parameters are expressed as volume instead of area, even if they are evaluated in two dimensional sections, because they offer an inferred estimation of the spatial organization of the trabecular network. Similarly, the Trabecular Separation, defined as the distance between the edges of the trabeculae, is expressed in three-dimensional units [10].

D. Statistical analysis

The results are expressed as mean ± standard deviation (SD) for all subjects. Correlation analysis was done using Pearson's r, where y is the dependent variable and x the predictor variable. When nonlinear relationships between the variables were evident on graphic examination, linear model seemed inappropriate. According to the visual pattern on graphic examination, quadratic (model: $y = ax^2 + bx + c$) was found as the best model of regression to determine coefficients of correlation between Bone volume fraction and fractal dimension.

III. RESULTS AND DISCUSSION

Figure 3 illustrate the values of fractal dimension for all subjects. A higher value of fractal dimension corresponds to a higher irregularity of the trabecular structure and a greater loss of bone mass (osteoporosis), which goes well with the expected results (Fig. 3). Also it should be noted there is no overlap in fractal dimension values of healthy and osteoporotic patients, and leaves us to say that fractal analysis is a good predictor of bone loss. The range (side length ε) of the box used in the box counting method to calculate the fractal dimension is from 2 to 25 pixels.

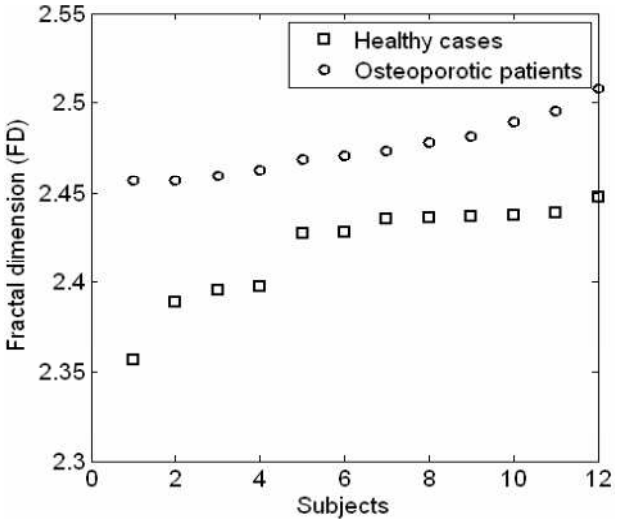


Fig. 3. Fractal dimension of the 24 subjects.

The bone volume fraction (BV/TV) is represented in figure 4. Contrary to fractal dimension, the bone volume fraction values of controls are higher than those of osteoporotic patients, due to stiffer bone structure. Osteoporotic patients present lower bone volume, due to high loss of connectivity bone architecture (Fig. 4).

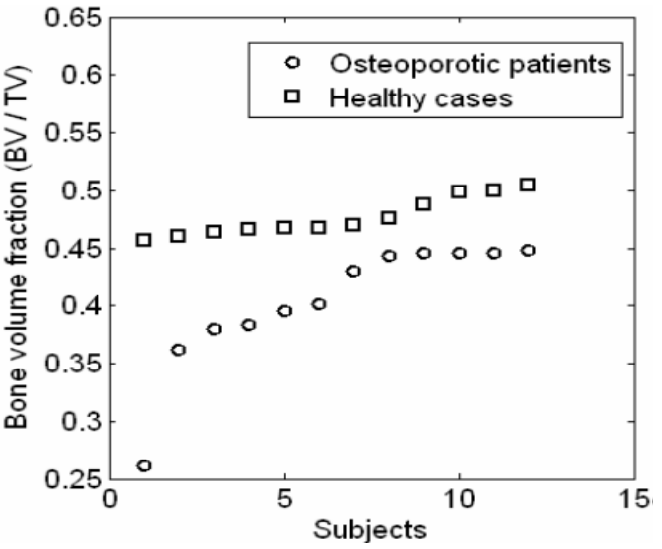


Fig 4. Bone volume fraction for healthy cases and osteoporotic patients.

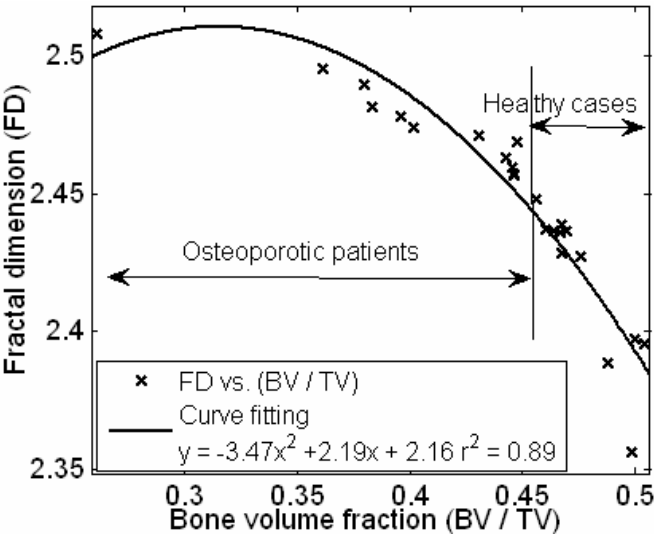


Fig. 5. Fractal dimension (FD) as function of bone volume fraction (BV / TV). Representation of the best curve fitting.

Figure 5 shows the correlation between fractal dimension and bone volume fraction for all the 24 subjects. An inverse correlation between these two parameters is observed on the curves. In fact, the fractal dimension is inversely proportional to bone volume fraction. Regression model is non-linear, quadratic type. The correlation coefficient is $r^2 = -0.89$. Coefficients (with 95% confidence bounds) and goodness of fits are reported on the figure.

Table 1. Correlations between fractal dimension (FD) and histomorphometry parameters in 24 human radiographs.

	Healthy cases (12 subjects)			Osteoporotic patients (12 subjects)		
Parameters	Mean ± SD	Range	Correlation with FD	Mean ± SD	Range	Correlation with FD
FD	2.41 ± 0.02	2.35 – 2.44	r = 1	2.47 ± 0.016	2.45 – 2.50	r = 1
BV	4765 ± 166.8	4563 – 5041	r = -0.88	4036 ± 544.9	2613 – 4477	r = -0.94
BS	2375 ± 299.6	1708 – 2739	r = 0.85	2315 ± 241	1658 – 2549	r = -0.82
TV	10000 ± 0	10000 – 10000	Ns	10000 ± 0	10000 – 10000	Ns
BV/TV	0.47 ± 0.016	0.45 – 0.50	r = -0.88	0.40 ± 0.05	0.26 – 0.44	r = -0.94
BS/TV	0.23 ± 0.029	0.17 – 0.27	r = 0.85	0.23 ± 0.02	0.16 – 0.25	r = -0.82
TbTh	4.09 ± 0.72	3.36 – 5.83	r = -0.92	3.47 ± 0.18	3.12 – 3.69	r = -0.84
TbN	12 ± 0.01	8.5 – 13.6	r = 0.85	11.5 ± 0.01	8.2 – 12.7	r = -0.82
TbSp	4.47 ± 0.56	3.93 – 5.87	r = -0.78	5.27 ± 1.25	4.36 – 8.91	r = 0.85

As shown in table 1, there is significant correlation between the fractal parameters and the bone volume, as well as between fractal dimension and such histomorphometry parameters as BS, BV/TV, BS/TV, TbTh, TbTn and TbSp. The best correlation was found with trabecular thickness (TbTh). Furthermore, there is no correlation with tissue volume (TV).

In our study, we have demonstrated a relationship between fractal dimension and histomorphometry parameters in the assessment of osteoporosis. The more fractal dimension increases, the more osteoporosis increase (Fig. 3).

We noticed a decrease of bone volume fraction in osteoporotic patients compared to controls. Such a decrease in this parameter in osteoporosis reflects alterations of the trabecular bone microarchitecture linked to the aging and menopausal (Fig. 4). According to the r^2 value, 89% of the variability of the fractal dimension (FD) parameter was determined by bone volume fraction for all subjects (Fig. 5). The simple correlation between FD and TbTh was also significant, with an r coefficient = -0.92, leading to a r^2 value = 0.84 for controls and r = - 0.84, leading to a r^2 value = 0.70 (Table 1). The fractal dimension which provides information about the regularity of bone structure is jointly linked to the histomorphometry parameters. The more the fractal dimension increases, the more the connectivity decreases, which goes well with the expected results and provide a good discrimination of the two groups (Fig. 5 and Table 1).

IV. Conclusion

The objective of this paper was to investigate the potential usefulness of two noninvasive methods in 24 subjects for osteoporosis assessment. Measurements were done on calcanei. Relationships between the various histomorphometry and fractal parameters were studied. Correlations between these parameters are found which provide a good discrimination between pathological subjects and controls. Histomorphometry and fractal analysis of bone texture on calcaneus radiographs, constitutes a new, simple, low radiation and reproducible assessment of bone status. These noninvasive analysis may provide information about the trabecular microarchitecture that is independent of bone density. These methods could be complementary to BMD measurements in assessing bone fragility.

Several techniques (fractal analysis, histomorphometry, structural methods…) need to be used in parallel to appreciate the pathophysiological mechanisms of osteoporotic states.

References

[1] Consensus development conference diagnosis, "Prophylaxis and treatment of osteoporosis", *American Journal of Medicine*, 94,1993, pp.646–650.

[2] A. Nektarios. Valous, F. Mendoza, D.W. Sun and P. Allen, "Texture appearance characterization of pre- sliced pork ham images using fractal metrics: Fourier analysis dimension and lacunarity", *Food Research International*, Vol. 42, no 3, 2009, pp. 353–362.

[3] E. Lespessailles, C. Gadois, G. Lemineur, J. P. Do-Huu and L. Benhamou, "Bone Texture Analysis on Direct Digital Radiographic Images: Precision Study and Relationship with Bone Mineral Density at the Os Calcis," *Calcified Tissue International*, Vol. 80, no 2, 2007, pp. 97-102.

[4] B.B. Mandelbrot, "The Fractal Geometry of Nature", Freeman, San Francisco, 1983, CA.

[5] R. Jennane; W.J. Ohley; S. Majumdar; G. Lemineur, "Fractal analysis of bone X-ray tomographic microscopy projections , *Medical Imaging, IEEE Transactions on*, Vol 20, no 5, 2001, pp. 443-449.

[6] S. C. White and D. J. Rudolph, "Alterations of the trabecular pattern of the jaws in patients with osteoporosis," *Oral Surgery, Oral Medecine, Oral Pathology, Oral Radiology and Endodontology*, Vol. 88, no 5, 1999, pp. 628–635.

[7] J. Li, Q. Du and C. Sun, "An improved box-counting method for image fractal dimension estimation", *Pattern Recognition*, Vol. 42, no 11, 2009, pp. 2460-2469.

[8] K. J. Falkoner, "*Techniques in Fractal Geometry*". John Wiley & Sons, Ltd. Chichester,1997.

[9] K. Harrar and L. Hamami, "Implementation of the box- counting method in radiographic images", in *Advances in Numerical Methods*, Springer Science Media, 2009, Ch.26.

[10] A. M. Parfitt, "Bone histomorphometry: techniques and interpretation," in *The Physiologic and Clinical Significance of Bone Histomorphometric Data*, CRC Press, Boca Raton, FL, USA, 1983, pp. 143–224.