Fractal dimension of bone texture in radiographs correlates to ultrasound broadband attenuation T-score

G. Bianciardi[1], S. Bisogno[2], I. Bertoldi[2], L. Laurini[3], G. Coviello[4], B. Frediani[2]

[1]Department of Medical Biotechnologies, and [2]Department of Clinical Medicine and Immunological Sciences, Division of Rheumatology, University of Siena, Siena, Italy; [3]Department of Clinical Pathology, Institute of Pathologic Anatomy, Ospedale S. Donato, Arezzo, Italy; [4]Department of Radiology, Azienda Ospedaliera Senese, Siena, Italy.

Abstract

Objective

We aimed to measure the fractal dimension on x-ray images and ultrasonographic parameters of the os calcis of bone from 4 districts in osteoporotic patients and in control subjects, in order to test the hypothesis that ultrasonographic parameters correlate to the fractal dimension obtained on x-ray images.

Methods

Fractal analysis on radiological images from 4 bone districts (proximal femur, calcaneus, metacarpus and 3rd phalanx) was performed in a study comparing ultrasonographic evaluation of the os calcis *in severe osteoporotic patients and in control cases. We studied 86 x-ray-views from patients with severe reduction of ultrasound Stiffness Index and in healthy women. Ultrasound measurements of left os calcis were performed using the Lunar Achilles-Plus instrument. Fractal analysis was performed using the box-counting method.*

Results

In healthy subjects, fractal dimension, D, measure of structural complexity, resulted close to the topological dimension (no fractal structure), TD, in femur (1.99±0.03)and phalanx (1.96±0.03), D differed significantly from TD in calcaneus (D=1.90±0.02; p<0.001) and metacarpus (D=1.89±0.03, p<0.001). In osteoporotic subjects, in calcaneus and metacarpus, D was higher (1.94±0.03, 1.93±0.03, respectively) than in healthy subjects (1.90±0.02, 1.89±0.02, respectively, p<0.01). In all the subjects, fractal dimension and ultrasound broadband attenuation T-score correlated significantly in calcaneus and metacarpus (p<0.03 and p<0.02, respectively).

Conclusion

Parameters based on a combination of ultrasonic examination and fractal analysis on radiographic images may add useful structural information regarding the patients' skeleton using non invasive procedures.

Key words

fractal analysis, ultrasonography, bone

*Giorgio Bianciardi, MD, PhD**
Stefania Bisogno, MD
Ilaria Bertoldi, MD
Lorella Laurini, MD
Giuseppe Coviello, MD
*Bruno Frediani, MD**

Please address correspondence to:
Dr Giorgio Bianciardi,
Dipartimento di Biotecnologie Mediche,
Anatomia Patologica,
Università di Siena,
Via delle Scotte 6,
53100 Siena, Italy.
E-mail: gbianciardi@unisi.it

**These authors contributed equally to this study.*

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Introduction

Fractal geometry describes the irregular and complex shape of many natural objects and has successfully been used since two decades in many field of pathology (1-3), giving useful information for the diagnosis of diseases and patient prognosis (4-7). Fractal analysis has also been showed able to investigate the structure of the bone (8-11). A very common fractal parameter is the fractal dimension, D, that quantitatively describes how an object fills its space, measure of structural complexity. Many methods has been used to measure D but the box-counting method is the most adapted, also in the study of radiographic images (12).

Cortical and trabecular bone structure is altered in osteoporosis as well as in other pathologies and in ageing, consisting in quantitative (decrease of bone mass) and qualitative changes (abnormalities in the trabecular network) (13-16). While quantitative changes may be analyzed by non-invasive methods and by dual-energy x-ray absorptiometry (DXA), gold standard for the WHO guidelines, qualitative analysis requires the invasive procedure of bone biopsy. Ultrasound bone densitometry is a non-invasive, radiation-free technique, able to give information not only about bone density but also about bone architecture and elasticity (17-21).

In this paper we measured the fractal dimension on x-ray images and ultrasonographic parameters of the *os calcis* of bone from 4 districts in osteoporotic patients and in control subjects, in order to test the hypothesis that ultrasonographic parameters correlates to the fractal dimension obtained on x-ray images.

Material and methods

Patients

We studied in women 86 x-ray views from 22 patients with severe reduction of ultrasound Stiffness Index or in healthy subjects (n=9) (see *Ultrasonographic evaluation*).

The subjects were all Caucasian, 64±9 years of age. There was no reference to oestrogen medication in the medical history of the patients. They did not present any fractures or neoplastic lesions.

Images

Radiographs of the left proximal femur, calcaneus, metacarpus and 3rd phalanx (Fig. 1) were obtained at high resolution according to standard procedures, with fixed focal bone distance. Images were acquired with a B/W camera putting the radiographs on a lighting table. The binarisation process was performed with an Oculus 300 frame grabber (Coreco-Canada), 492 X 512 pixels, 8 bit). The lens aperture of the CCD camera, gain and offset of the frame grabber were set in order to have a correct histogram with maximum dynamic but without saturation. The acquisition field was kept constant for each bone district. Images were stored and then submitted to image analysis.

Image analysis

The trabecular contours present in the image were extracted by a Canny edge detection algorithm (Vision sw, DTA, Pisa, Italy), resized to a standard dimension and converted to a single pixel outline (Image Pro-plus, Image Pro-Plus Media Cybernetics, Silver Spring, USA). Fractal analysis was performed using the box-counting method (software developed at Anatomia Patologica, University of Siena, using Visual Basic language). Briefly, each image was covered by nets of square boxes (1-160 pixels) and the amount of boxes containing any part of the outline was counted (Fig. 2).

Log-log graphs were plotted of the reciprocal of the side length of the square against the number of outline-containing squares (Fig. 3). The slope of the best liner segment of the graph, calculated performing the least-square method iteratively over all line segments ranging from 30 to 160 points, represented the fractal dimension, D, of the image (22).

The method was previously validated by computer generated shapes of known fractal dimensions (Triadic Koch island =-0.9%, Sierpinski's Triangle =-1.5%, circumference =-0.7%, square = +0.4%).

The analysis of the x-ray images was reproducible with mean intra- and inter-observer coefficients of variation of <3% and 5%, respectively.

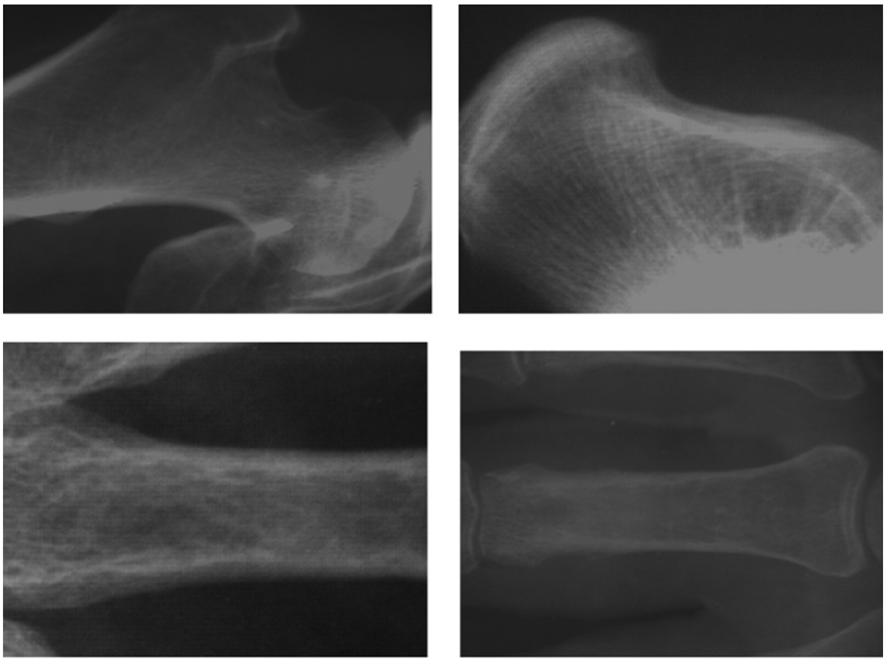

Fig. 1. Radiographs of the left proximal femur, calcaneus, metacarpus and 3rd phalanx

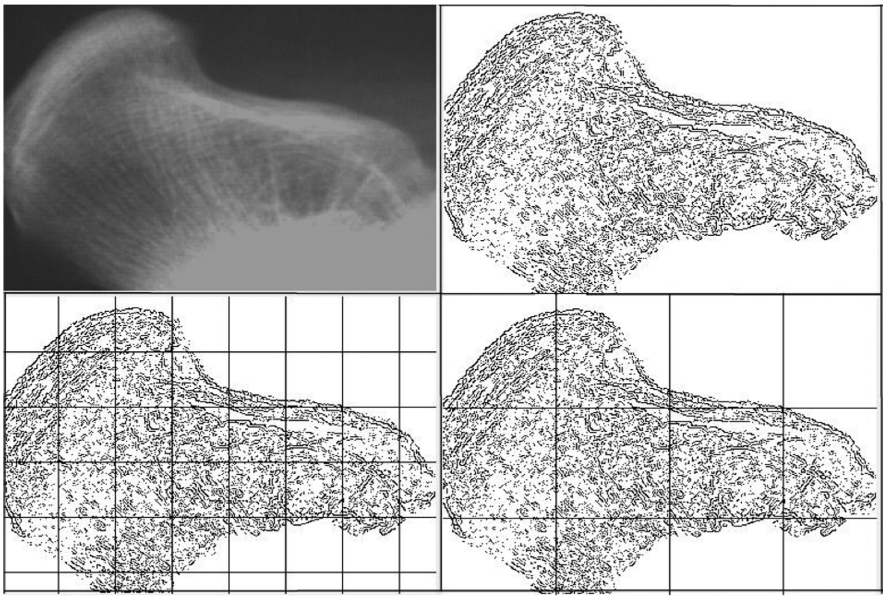

Fig. 2. Top left: Radiograph of calcaneus. Top right: The trabecular contours present in the image were extracted by a canny edge filter. Bottom: The trabecular contours were covered by nets of square boxes (ranging from 1 to 160 pixels) to perform fractal analysis according to the box-counting method.

Ultrasonographic evaluation

Ultrasound measurements of *os calcis* were performed using the Achilles-Plus instrument (LUNAR Corporation, Madison, WI). Parameters for ultrasonometry were Broadband Ultrasound Attenuation (BUA, decibels per megahertz) and Speed of Sound (SOS, meters per second). Stiffness Index (SI) is an empirical parameter that combines BUA and SOS; SI is defined as (0.28 SOS) + (0.67 BUA) – 420. The Achilles Ultrasound Bone Densitometer determines SOS and BUA parameters in the *os calcis* using broadband acoustic pulses (0.1–2.0 MHz) transmitted and received by a pair of focused transducers in a heated (35°C) water bath. The ultrasound signal sent from one transducer and passed through the bone immersed in a water bath is received by the opposing transducer. This signal is digitised and stored in the control box. When the measurement is complete, the stored data are transmitted to the computer, which analyses the data to calculate SOS, BUA and SI. Ultrasound measurements were expressed as T-score [T = (measured SI – young adult mean SI) / young adult standard deviation]. Patients were classified as "healthy subjects" (T-score >-1) and "osteoporotic subjects" (T-score <-2.5), according to the WHO guidelines.

Statistical analysis

Variance analysis was used to compare healthy *vs.* osteoporotic subjects and to compare D to the Topological Dimension (TD =2). The linear regression analysis was used to ascertain the correlation between D and ultrasonographic T-score evaluation.

Results

In healthy subjects, D in femur (1.99±0.03) and phalanx (1.96±0.03) was closed to TD, while D was lower in calcaneus (D=1.90±0.02; p<0.001) and metacarpus (D=1.89±0.03, p<0.001) (Fig. 4) and significantly different to the topological dimension (p<0.001, p<0.001).

In osteoporotic subjects, in calcaneus and metacarpus, D was higher (1.94±0.03, 1.93±0.03, respectively) than in healthy subjects (1.90±0.02, 1.89±0.02, respectively, p<0.01) (Fig. 5).

A linear correlation resulted between D and ultrasound broadband attenuation T-score in metacarpus (p<0.02) and calcaneus (p<0.03) (Fig. 6).

Discussion

Fractal analysis on radiographic images is able to characterise mechanical properties of the bone. We can recall the work by Lin *et al.* in which, in an *ex-vivo* analysis, fractal dimension correlated with biomechanical properties of the bone (23), the work by Buckland-Wright *et al.* (24) in which fractal analysis was able to quantify the horizontal and vertical trabecular organisation present on radiographic images of lumbar vertebrae, the work by Lespessailes *et al.*, where fractal analysis on calcaneus radiographs was able to reflect the trabecular microarchitecture

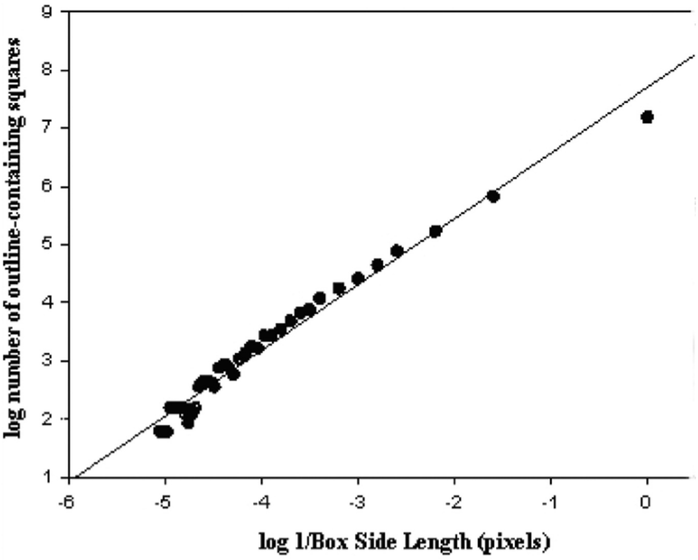

Fig. 3. A log-log plot. The slope represents the fractal dimension, D.

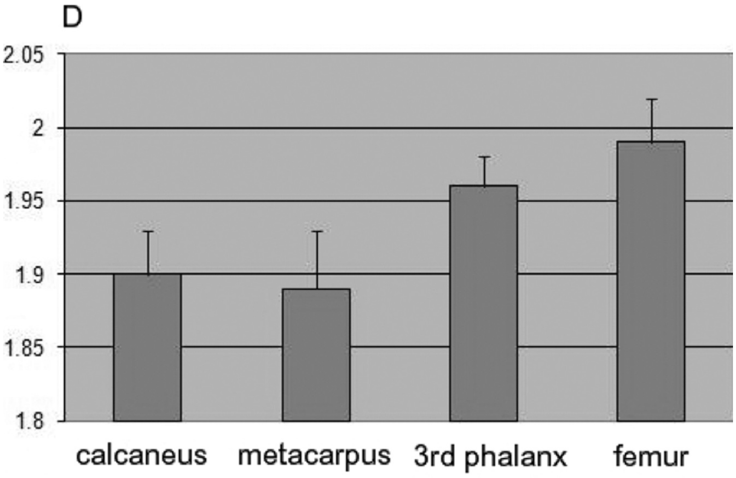

Fig. 4. In healthy subjects D differed significantly from the topological dimension, TD=2, in calcaneus (D=1.90±0.02; p<0.001) and metacarpus (D=1.89±0.03, p<0.001); D was closed to TD in the 3rd phalanx and femur.

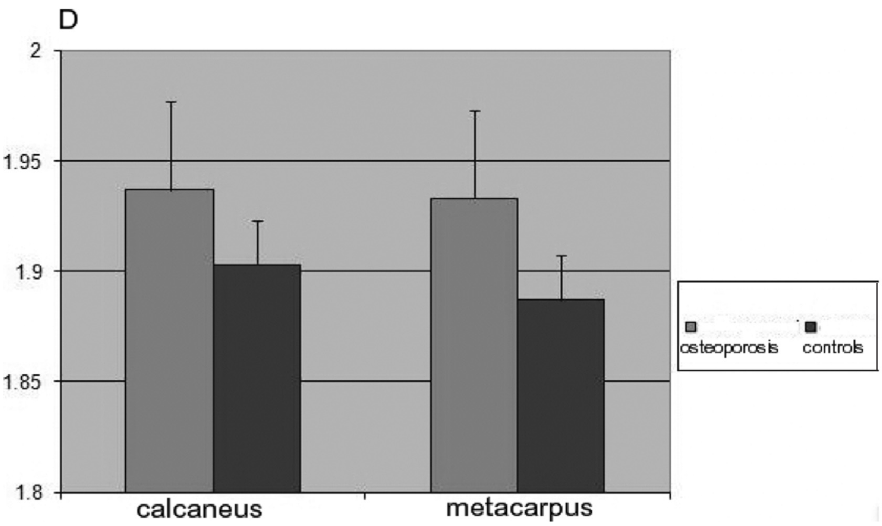

Fig. 5. In osteoporotic subjects , in calcaneus and metacarpus, D was higher (1.94±0.03, 1.93±0.03, respectively) than in healthy subjects (1.90±0.02, 1.89±0.02, respectively).

of the bone measured by histomophometry (25).

In our hands, radiologic images of calcaneus and metacarpus appeared with an evident fractal structure (D<TD) while, with our technique, femur and 3rd phalanx appeared close to the Topological Dimension: presenting no any fractal structure, they are less adapt to investigate further. In calcaneus and metacarpus, D was significantly higher in osteoporotic patients in comparison with healthy subjects. These results are in agreement with the above-cited work by Lespessailles *et al*. (23) and the case control multicentre study by the same Author, in which bone fractal texture analysis in osteoporotic subjects appeared of high clinical interest (26).

Moreover, interestingly, D in calcaneus and metacarpus correlated with the ultrasonographic T-score evaluation (all the subjects). These data are in agreements with the preliminary works by Rho *et al*. (27) and by Langton *et al*. (28) where, in an *ex-vivo* analysis, correlations between broadband ultrasound attenuation and fractal parameters resulted and with the work by Harrar *et al*. showing a correlation between fractal dimension and DXA T-score (10).

We can recall how, for many years now, in a large number of studies, ultrasonic parameters have been shown to be clinically useful and in relationship with bone properties, in healthy subjects as well in patients (17-21, 29-31). On the other hand, DXA T-score, even if accurate in determining bone mass and good predictor of fracture risk in osteoporosis, present a considerable overlap for patients with osteoporosis and healthy subjects without fracture risk (32), while ultrasound parameters appears better able to reflect the bone microarchitecture than the bone mass (33-35).

From the above-cited papers and our results we can assess that the use of parameters based on combination of ultrasonic examination and fractal analysis performed on radiographic images in selected body districts may add useful structural information regarding the patients' skeleton, altered in osteoporosis as well in other pathologies, *e.g*. in rheumatic disorders, also in order to avoid an invasive procedure of bone biopsy.

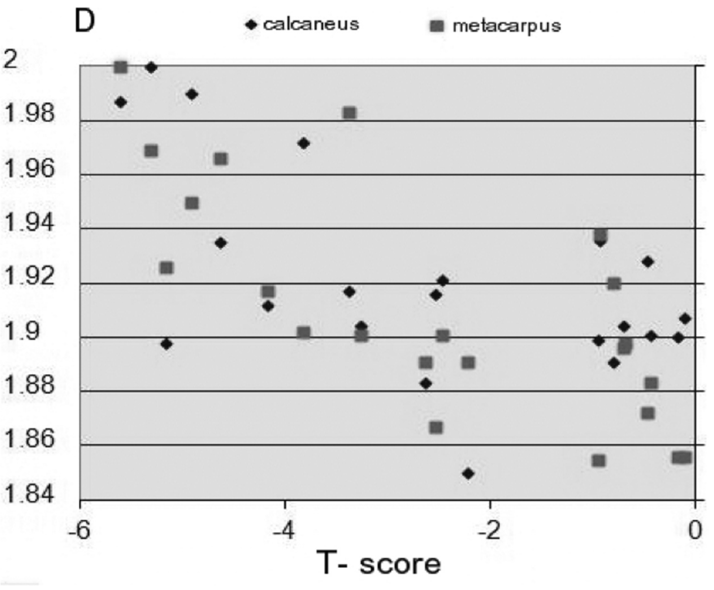

Fig. 6. Linear correlations resulted between D and ultrasound broadband attenuation T-score in metacarpus (y=-0.0163 X + 1.8697, $p<0.02$) and calcaneus (y=-0.0114 X + 1.8915, $p<0.03$)

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