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Research paper

Oriented fractal analysis for improved bone microarchitecture characterization

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ABSTRACT

Trabecular bone microarchitecture and bone mineral density (BMD) are two main factors related to osteoporotic fractures. Currently, however, microarchitecture is not evaluated in the clinical routine. In this paper, an oriented analysis method combining an anisotropic fractional Brownian motion model (ap-fBm) with an efficient estimator of the fractal dimension called anisotropic piecewise Whittle estimator (ap-WhE), are proposed to better characterize trabecular changes on bone radiograph images. To validate our approach several well-known estimators were compared on isotropic and anisotropic synthetic fractional Brownian motion images in different orientations of multiple 45°. Results of a real application on radiographic bone images to discriminate between two populations composed of 87 osteoporotic patients and 87 control subjects are presented. A comparison with well-known texture analysis methods is also provided. The results obtained demonstrate the performance of the proposed approach to characterize synthetic isotropic and anisotropic fractal textures as well as natural textures for a medical application.

1. Introduction

Osteoporosis is a skeletal disease characterized by low bone density and alteration in the microarchitecture, which increases fracture risk [1]. The most commonly used method to assess osteoporosis is based on estimating the Bone Mineral Density (BMD) by dual-energy X-ray absorptiometry (DXA) [2], but the detection rate for osteoporotic fractures captured by BMD is low. The trabecular bone microarchitecture plays an important role and its characterization would be useful to complete the diagnosis of osteoporosis by BMD [3]. However, the assessment of bone microstructure in detail usually requires a bone biopsy. Two-dimensional (2D) texture analysis provides a simple way to characterize bone microarchitecture on radiographic images [2,4]. Several studies have shown that the 2D texture analysis provides an indirect evaluation of the three-dimensional (3D) microarchitecture [4–6].

The question is how to screen osteoporosis sufficiently early and assess the bone microstructure in a textured radiographic image? Mathematics is used to develop models in which parameters can be estimated, and enable to detect people suffering from osteoporosis. Different approaches have been proposed to characterize the bone texture in order to provide a diagnosis of the disease. One can find co-occurrence matrices [7], run-length matrices [8], Markov models [9], autoregressive models [10], filtering methods [11], structural methods [12], and space-frequency approaches [13]. Due to the complexity and the nonstationarity of the trabecular bone images, these methods fail to diagnose osteoporosis.

The advent of fractals and chaos theory to describe complex data has been recognized as an effective tool that can offer very realistic models of images. Among these models, the fractional Brownian motion (fBm) has shown its potential utility to characterize the trabecular bone texture [14]. The fractal dimension is a measure that describes the irregularity of a texture [15]. Several methods for estimating the fractal dimension have been used to characterize the bone microarchitecture; most of them do not take into account the nature of the data to be analyzed (fractal or not). Moreover, these

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methods do not check the adequacy of the fBm to model the bone microarchitecture [16–18].

Two important properties are to be considered for the characterization of the bone texture: anisotropy and nonstationarity. The bone is submitted to compression and tension forces in different orientations, produced by the walking and the gravity. The evolution of the orientations of the trabeculae enables quantifying the degree of deterioration of the bone. For a normal subject, the trabeculae are uniformly distributed. For an osteoporotic case, the number of tensile and compressive trabeculae decreases gradually, which leads to an anisotropic structure.

If intensity pixels of an extracted line from a bone radiograph are plotted (Fig. 2.b), the resulting signal presents a nonstationary behaviour. In this case, the data are unpredictable and difficult to be forecasted. The process does not evolve around its mean value, but rather in an increasing or decreasing manner.

Various approaches to characterize the anisotropy can be found in the literature [19–21], but most of them fail to characterize complex textures such as the bone images due to the nonstationarity of the data. In fact, these studies assumed the data of their experimentations as stationary. Moreover, the experimentations were conducted on less challenging textures. Trabecular bone images are anisotropic, nonstationary and piecewise fractal. The evaluation of the osteoporosis disease from bone radiograph images presents a major challenge for pattern recognition and medical applications. Textured images from osteoporotic and healthy subjects radiographs show a high degree of similarity, thus drastically increasing the difficulty of characterizing such textures.

Several studies have shown that fractal methods provide interesting results, but most of them use the classical isotropic fBm model, which is not sufficient to fully describe natural anisotropic textures such as trabecular bone X-ray images [22–24]. Anisotropic characterization of gray level images in a nonstationary context is still a challenging problem. Lemineur et al. [22] proposed a technique to characterize nonstationary anisotropic textures. The results revealed the effectiveness of the Directional Averages Method (DAM) for analyzing anisotropic images. DAM consists in averaging (projecting) the parallel lines of the image and in estimating the H parameter of the resulting projection. This process can be repeated for several orientations θ. The variance method of Pentland [23], was used to estimate $H(\theta)$ over several orientations θ. Richard et al. [24] proposed a new generic methodology for the analysis of anisotropic textures. Their methodology is based on stochastic modeling of the textures using the anisotropic fractional Brownian fields. It includes statistical tests that are based on the estimation of directional parameters of the fields by generalized quadratic variations. Their results showed that digital mammograms could be considered as anisotropic with a high level of confidence. Kersh et al. [25] calculated the preferential orientations of the bone texture, and the extent to which bone is deposited more in one direction than in another. Using 100 femoral trabecular samples, the principal directions and degree of anisotropy were calculated with a Gradient Structure Tensor (GST) and a Sobel Structure Tensor (SST) using clinical-level CT. The results were compared to those calculated with the Mean-Intercept-Length (MIL) fabric tensor using micro-CT images. The authors stated that their methodology has the promise to predict the structural anisotropy of bone, and may improve the *in vivo* characterization of bone. All these studies were conducted on bone images where the authors assumed the model of the textures as monofractal, whereas these textures are bifractal (characterized by the piecewise fractal property).

The objectives of our paper are: first to introduce anisotropy in the piecewise fractional Brownian motion (ap-fBm) model, which generalizes the class of fBm signals and provides a more suitable context for anisotropic piecewise fractal data. Then, to emphasize the anisotropy by applying adequately an efficient technique to estimate the fractal dimension. This approach which is based on the Whittle estimator considers the piecewise fractal character as well as anisotropy in the same estimator and is applied in an oriented manner. Our approach was tested and validated on synthetic isotropic and anisotropic fractal images. The proposed estimator was compared to different methods on these test images. The purpose was to evaluate the efficiency of different estimators for oriented analysis of anisotropic textures to estimate the fractal dimension. To this end, two oriented analysis methods are compared. The first one called “Image Rotation” is based on rotating the image and extracting lines; the second method called “Directional Lines Extraction” is based on extracting the lines directly in the desired direction without rotating the image.

The proposed approach was also tested on real radiographic images in order to discriminate between two populations composed of 87 osteoporotic patients (OP) and 87 control subjects (CS). The proposed estimator was also compared to other effective methods existing in the literature to evaluate its robustness to separate OP and CS groups.

This paper is organized as follows: in Section 2, the fBm and ap-fBm models are presented. Various anisotropic estimators of the fractal dimension are also described. In Section 3, the results obtained on isotropic and anisotropic synthetic images as well as on radiographic images are presented. This work is discussed in Section 4, followed by concluding remarks in Section 5.

2. Methods

2.1. The fractional Brownian motion model

The fractional Brownian motion (fBm) of parameter H $(0 < H < 1)$ is a nonstationary model representing stochastic fractal signals [15]. The increments of this process called fractional Gaussian noises (fGn) are stationary. These models were first used for modeling signals from physical phenomena such as 1/f-noises [26]. In two dimensions, the H parameter quantifies the intuitive notion of the roughness of an image [27]. It is used to characterize textures or to analyze medical images [24,28]. The Hurst exponent which governs the isotropic fBm is linked to the fractal dimension by the expression $H = E + 1 - D$, where E is the Euclidian dimension and D is the fractal dimension. The spectral representation of the isotropic fBm, $B_H(t)$ is given by [29]:

$$B_H(t) = \frac{1}{2\pi} \int_{\Re} \frac{(e^{it\xi} - 1)}{|\xi|^{H+1/2}} dB(\xi) \qquad (1)$$

The isotropic fBm (Fig. 1.a) is a class of continuous zero-mean Gaussian, centered, and nonstationary second-order processes, with the following properties: self-similarity, long-range dependence, and stationary fGn increments (Fig. 1.b).

2.2. Anisotropic piecewise fractional Brownian motion model

The fBm model has been applied successfully in many domains. In some experimental cases, however, it is not sufficient to fully characterize natural data, due to the 1/f process which cannot be present practically for low and high frequencies. In some cases, there is not one, but two fractal regimes with two different slopes for the Power Spectral Density (PSD): H_o and H_i for low and high frequencies, respectively. These two regimes are separated by a cutoff frequency γ. Such process can be modeled by the piecewise fractional Brownian model (p-fBm) [30].

Both fBm and p-fBm models, do not take anisotropy into account which is an important characteristic of numerous existing textures.