TEXTURE ANALYSIS OF X-RAY IMAGES FOR DETECTION OF CHANGES IN BONE MASS AND STRUCTURE

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Abstract. An attempt is made to apply digital image analysis techniques to the evaluation of bone mass and internal structure, based on X-ray images. Images of distal forearm bone are investigated. A calibration phantom is included in the image to equalize the image intensity. Both raw and equalized images are analyzed and results are compared. A number of first-order texture parameters and fractal dimensions are evaluated. These texture-derived image features are correlated with the bone mineral density estimated by means of dual-photon absorptiometry (DXA), a standard diagnostic technique. The effect of image blur and noise on texture parameters is investigated as well, showing significant influence of image distortion on fractal features, and thus indicating the need for image preprocessing before texture analysis.

1. Introduction

There is a growing interest during the last decades in finding effective diagnostic methods for skeletal system diseases. Among these diseases, the osteoporosis is characterized by changes in bone mass density and structure that make the bone susceptible to fracture. Finding efficient means of preventing this disease, which affects primarily middle-aged and elderly people, is of growing importance to modern society whose average population age increases constantly. One of the techniques used for skeletal system diagnosis is standard X-ray examination (Czekalski 1993) that allows detection of changes not only in the outer – compact part of the bone, but also changes in the inner – spongy bone microarchitecture.

The advantages of the X-ray technique are common availability and low cost; however, interpretation of radiograms is not an easy task. It is estimated that by means of traditional X-ray analysis, changes related to calcium decrease can be noticed at 30-60% loss of the bone mass, which corresponds to an already advanced phase of the disease (Czekalski 1993; Southard 1996). Other examination techniques, such as densitometry, CT tomography and magnetic resonance imaging require expensive equipment. They are then of limited availability to a gross population of patients. There is a need for an inexpensive and simple diagnostic technique that would allow detection of early changes in the structure and mass density of the bone. Such a method would be very useful for prevention of the skeletal system diseases as well as for their treatment in a non-developed phase. It is postulated in this paper that texture analysis of digitized X-ray images can be considered as an alternative to standard techniques of skeletal system diagnosis.

At present, the only method widely accepted by physicians, that is able to detect a decreased mass of the bone (which is the most important risk factor for osteoporosis) is densitometry (Pluskiewicz 1996; Badurski 1994). The most popular densitometric technique, of high accuracy and sensitivity, is dual-energy X-ray absorpiometry DXA (Lunar 1993). This technique has been utilized in this paper as a reference method.

2. Materials

X-ray images of forearm distal bone were taken for a group of 50 subjects of different age. The same persons were measured the forearm bone mineral density using DXA. The X-ray images were all taken at 53 kV and 4 mAs, and films were developed using the same chemical process. A calibration phantom Agfa Mamoray of specified absorption of X-ray radiation was placed in each image. The images were digitized at 7 bit/pixel using a CCD camera. The digital images were brightness-standardized by making the phantom average brightness the same in all images. A 256×256-pixel region of interest (ROI) was defined in the field of every image, as shown in Figure 1. The image texture within the ROI was characterized by means of texture statistical parameters and image surface fractal dimensions, as described in the next section.

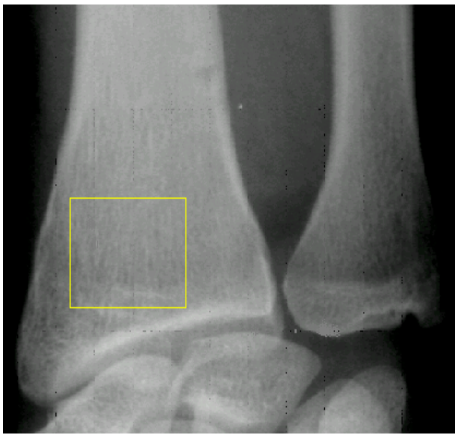
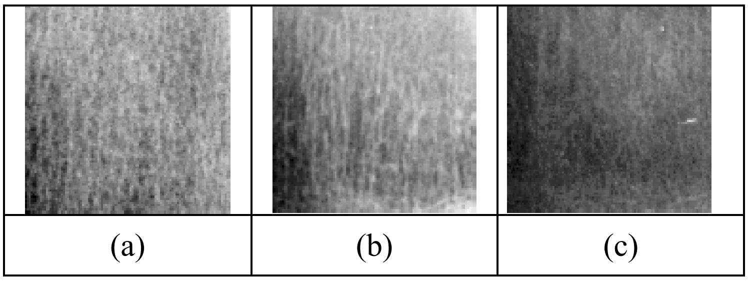


Figure 1 Example of an X-ray image of distal forearm bone with a square ROI.



(a) (b) (c)

Figure 2 Sample X-ray images of bone tissue for different BMD coefficients (a) BMD = 0.56 g/cm^2, (b) BMD = 0.31 g/cm^2, (c) BMD = 0.14 g/cm^2.

Figure 2 shows examples of ROI images that correspond to bones of different values of bone mineral density (BMD). One can notice the gradual brightness decrease and bone microarchitecture degradation with the reduced contents of calcium.

3. Methods

The reference method in our study is DXA densitometry, implemented using a Lunar DPX instrument at Polish Mother Memorial Hospital Institute, Lodz, Poland. To reduce the influence of the soft tissue on the analysis results, dual energy radiation was used, of respectively 38 keV and 70 keV. The Lunar DPX instrument allows measuring the distal forearm bone in a region 140×126 mm, using 117 scanning lines, each of 210 points. It is then a low-resolution examination. It lasts typically 5 min and the dose absorbed is less that 0.3 mrem. The *in vivo* accuracy is better that 1.5 %, with repeatability of 1 % (Lunar 1993).

First- and higher-order statistical parameters are often used to characterize image texture (Haralick 1979; Southard 1996). In this study, a number of image histogram-derived ROI parameters were investigated, including sample mean, standard deviation, skewness, kurtosis, energy and entropy. The complexity and self-similarity of texture at different scales are described by fractal dimension (Pentland 1984; Fortin 1992; Peitgen 1992; Ruttiman 1992; Dubuisson 1994; Chan 1995) which was also computed in the present work. From the variety of different methods of computing the fractal dimension, two techniques based respectively on Fourier transform and local image variance were employed that were simple to implement numerically. The FFT-derived fractal dimension was computed separately for vertical and horizontal direction. The image texture features were calculated using dedicated subroutines written in Matlab 5.2 language for a Pentium 120 MHz PC computer.

4. Results

Altogether, 50 X-ray bone images were digitally recorded. The images represented forearm bones of different BMD level that was independently measured for each subject by means of the DXA technique. Based on the densitometry results, the whole group of subjects was divided into 3 categories: normal – 19 subjects, of physiological loss of calcium (osteopenia) – 21 subjects, and of abnormal loss of calcium (osteoporosis) – 10 subjects. For every texture parameter, its mean and standard deviation were computed within each of the three groups of patients. Linear correlation coefficient with the bone mineral density was also computed for every parameter and for all subjects. The statistical significance of the correlation was evaluated as well. The results obtained for brightness-corrected images are presented in Table 1.

Table 1

# sub-jects	T-score		BMD g/cm^2	μI	SDI	sk	k	E	Ent	FD2v	FD2h	FDvar
19	sd> -1	μ	0.39	62.28	5.67	-0.32	-0.35	0.05	4.46	2.51	2.39	2.17
		σ	0.10	14.94	1.63	0.31	0.15	0.01	0.41	0.05	0.01	0.16
21	-1≥sd >-2.5	μ	0.32	50.24	4.13	-0.19	-0.33	0.08	3.98	2.56	2.41	2.32
		σ	0.06	9.29	0.15	0.33	0.42	0.00	0.03	0.04	0.02	0.22
10	sd≤ -2.5	μ	0.25	46.31	3.72	0.17	1.23	0.09	3.83	2.59	2.43	2.34
		σ	0.11	10.21	2.34	0.40	0.41	0.04	0.76	0.25	0.14	0.24
50	total	μ	0.33	54.05	4.63	-0.17	-0.03	0.07	4.13	2.55	2.40	2.27
		σ	0.06	8.89	1.46	0.33	2.2	0.03	0.49	0.08	0.06	0.19
Correlation with BMD, *R*			0.79	0.55	-0.57	-0.25	-0.51	0.54	-0.49	-0.36	-0.43	
p-value			1e-11 *	3.6e-5 *	3e-6 *	0.081	1e-4 *	4.6e-5 *	3e-4 *	0.0107	1.4e-3 *	

*T-score – result of DXA examination (difference to population BMD mean of young people, normalized to standard deviation), μ(σ) - mean value (standard deviation) of a given parameter, BMD – bone mineral density, μI – image mean, SDI – image standard deviation, sk – skewness, k - kurtosis, E - energy, Ent - entropy, FD2v (FD2h) – fractal dimension in vertical (horizontal) direction, FDvar- fractal dimension computed using variance method, * – $p<0.005$.*

Figure 3 demonstrates the relationship between the bone mineral density and selected texture parameters of X-ray images, whereas the correlation between the BMD and fractal dimension is illustrated in Figure 4. The data obtained for different groups of subjects are distinguished graphically using ‘o’ for normal subjects (sd > -1), ‘*’ for physiological loss of calcium (-1 ≥

sd ≥ -2.5), and '×' for lowest-density bones (sd < -2.5), where sd is the T-score (Lunar 1993). Table 2 shows the differences in the results of statistical texture analysis obtained for raw images and phantom-brightness-corrected images. The table contains also the values of linear correlation coefficient between the BMD and raw-image texture parameters and the results of *t*-test for correlation coefficients.

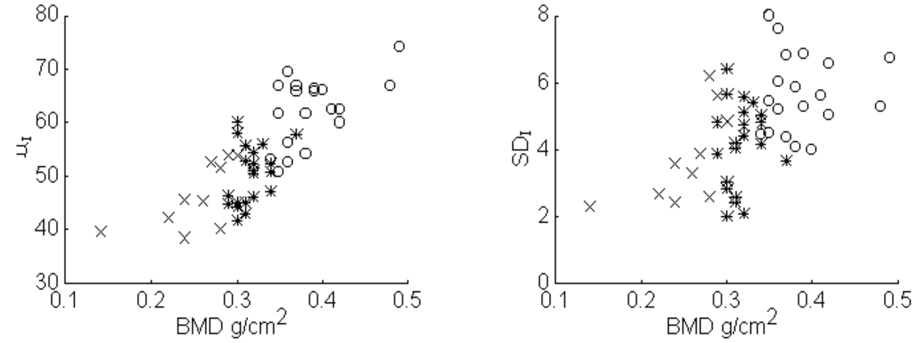


Figure 3 Image mean and standard deviation relationship to bone mineral density.

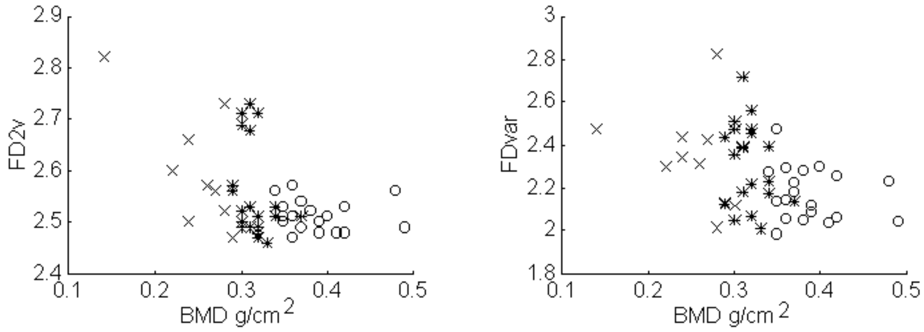


Figure 4 Fractal dimensions as functions of bone mineral density.

Table 2

# sub-jects	T-score		BMD g/cm^2	Δμl	ΔSDI	Δsk	Δk	ΔE	ΔEnt	ΔFD2v	ΔFD2h	ΔFDvar
19	sd>-1	μ	0.39	11.07	-0.03	-0.02	-0.01	0.00	0.00	-0.01	-0.01	0.00
21	-1≥sd >-2.5	μ	0.32	11.75	0.10	0.01	-0.01	0.00	0.05	-0.03	-0.02	0.00
10	sd≤ -2.5	μ	0.25	15.06	-0.04	-0.03	-0.12	0.00	0.00	-0.01	-0.01	0.00
50		μ	0.33	12.63	-0.01	0.01	-0.05	0.00	-0.02	-0.02	-0.01	0.00
Correlation with BMD (non-standardized image), R_0				0.61	0.53	-0.47	-0.24	-0.50	0.53	-0.46	-0.38	-0.43
Absolute difference $\|R-R_0\|$				0.18	0.02	0.10	0.01	0.02	0.01	0.03	0.01	0.00
p-value for R_0				2e-6 *	5e-5 *	4e-3 *	0.08	2e-4 *	6e-5 *	9e-4 *	6e-3	1e-3 *

Δ denotes differences between feature values obtained for standardized and non-standardized images

5. Discussion

Based on statistical analysis of the linear correlation coefficient, one can state that there is a significant correlation between the bone mineral density measured by the standard DXA technique and the image mean, standard deviation, skewness, kurtosis, energy, entropy, fractal dimension in vertical dimension, and variance-based fractal dimension.

The fractal dimension reflects roughness of the bone image texture that is related to the bone microarchitecture (see Figure 2). It is of high importance, because mechanical endurance of the bone tissue depends largely on the state of the bone internal structure. For a subject suffering from osteoporosis (BMD = 0.14 g/cm^2, T-score = -6.63), high values of fractal dimension in the vertical direction (FD2v = 2.82) and in the horizontal direction (FD2h = 2.55) were obtained. As seen in Table 1, the values of fractal dimension are lower for healthy subjects in this study. Differences between the fractal dimensions in horizontal and vertical directions reflect the anisotropy of the image texture, as seen in Figure 2.

Image brightness shows the highest correlation to BMD ($r = 0.79$, $p < 0.005$). This can be explained by the fact that lower calcium contents results in lower attenuation of X-rays in the bone, so the photographic film becomes darker and digital image brightness is reduced. This applies to brightness-equalized images. It is evident that image brightness standardization is a necessary preprocessing step for reliable analysis of image texture. The significance of this step is illustrated in Table 2. Correlation of image mean and skewness are significantly affected by a lack of brightness standardization. The other statistical parameters do not show much dependence on standardization, and the FDvar fractal dimension shows complete invariance to it.

One can conclude that by measuring changes in statistical texture parameters and fractal dimensions of X-ray images it is possible to monitor changes in calcium contents and internal structure of the bone. Texture analysis shows potential usefulness as an aid to the diagnosis of skeletal diseases. This initial research was carried out using first-order texture features only. Further work is needed to select optimum texture parameters from a variety of known approaches, including wavelet analysis and mathematical morphology derived features. It has been demonstrated also that there exist a degrading effect of image blur and noise, typical to X-ray images, on texture parameters. There is a need to elaborate techniques to reduce these effects, which is the subject of the current study. Also, high-resolution flat bed transparency scanner is being used at present for image digitization with an increased accuracy compared to the CCD camera. First experiments show that fractal dimensions computed for scanned radiographic films demonstrate significantly higher correlation to BMD compared with CCD-recorded images.

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