Original Article

Prediction of Bone Strength from Cancellous Structure of the Distal Radius: Can We Improve on DXA?

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Abstract. Recent studies show that structural parameters of bone, obtained from computerized image analysis of radiographs, can improve the noninvasive determination of bone strength when used in conjunction with bone density measurements. The present study was designed to assess the ability of image features alone to predict the mechanical characteristics of bones. A multifactorial model was used to incorporate simultaneously a number of characteristics of the image, including periodicity and spatial orientation of the trabeculae. Fifteen pairs (29 specimens) of unembalmed human distal radii were used. The cancellous bone structure was determined using computerized spectral analysis of their radiographic images and the bones were tested to failure under compression. Multilayered perceptron neural networks were used to integrate the various image parameters reflecting the periodicity and the spatial distribution of the trabeculae and to predict the mechanical strength of the specimens. The correlation between each of the isolated image parameters and bone strength was generally significant, but weak. The values of mechanical parameters predicted by the neural networks, however, had a very high correlation with those observed, namely 0.91 for the load at fracture and 0.93 for the ultimate stress. Both these correlations were superior to those obtained with dual-energy X-ray absorptiometry and with the cross-sectional area from CT scans: 0.87 and 0.49 respectively. Our observation suggests that image parameters can provide a powerful noninvasive predictor of bone strength. The simultaneous use of various parameters substantially improved the performance of the system. The multifactorial architecture applied is nonlinear and possibly more effective than traditional multicorrelation methods. Further, this system has the potential to incorporate other non-image parameters, such as age and bone density itself, with a view to improving the assessment of the risk of fracture for individual patients.

Keywords: Bone strength; Fracture risk; Image analysis; Neural network; Osteoporosis; Spectral analysis

Introduction

Bone strength is a major factor in determining the risk of fracture. In everyday clinical practice this is commonly assessed by densitometric techniques [1,2]. While bone mineral density has been shown to have a good correlation with bone strength, other characteristics of the bone also contribute; these include trabecular structure and connectivity, the size of the bone and its cortical thickness [3–6]. These factors have been shown to have a lower correlation with bone strength than bone density and, on their own, are unlikely to improve clinical evaluation. However, a few recent studies have suggested that multifactorial models, utilizing bone density and structural parameters, can predict bone strength better than densitometry alone [7,8].

Several attempts have been made to assess the complex structure of trabecular bone in computerized radiographs [9–16]. Computerized analysis of such complex images allows the retrieval of information which is otherwise very difficult to assess. Parameters that reflect the orientation and periodicity of trabeculae offer a unique tool for the comparison of subjects

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[12,17]. Cancellous bone may be resorbed up to 9 times faster than cortical bone and this differential effect has been observed in clinical cases of distal radius fractures [18–21]. The surface area to volume ratio of cancellous bone is substantially higher than that of cortical bone [22]. Bone resorption is controlled by bone multicellular units (BMUs), which act primarily on the periosteal, endosteal or pericanalicular surfaces of bone [23,24]. The clinical interest in such measurements reflects the fact that they may lead to earlier, more accurate and less expensive evaluation of fracture risk.

Most studies relating computerized analysis of radiographs to the density and mechanical strength of bone have used space-domain image analysis techniques [12–14,25]. Studies using spectral analysis of radiographic images (SA) of cancellous bone are few. Caligiuri et al. [13] showed that SA of the second lumbar vertebrae can predict fractures elsewhere in the spine better than dual-energy X-ray absorptiometry (DXA). Oxnard [26] demonstrated that the Fourier transform can detect structural alterations in the vertebrae of subjects with osteoporosis, but did not provide numerical parameters to express such alterations. Wigderowitz et al. [17] proposed a series of spectral indices that reflect both the number of trabeculae and their orientation. The changes in such spectral indices with age are very similar to those of densitometry.

In the present study, we report on mechanical testing of the human distal radius. Our observations indicate that the evaluation of bone structure may provide important additional parameters for the prediction of fracture risk; they imply that it is possible to predict bone strength by simultaneous integration of a number of characteristics of the image, including the periodicity and the spatial orientation of the trabeculae.

**Materials and Methods**

The distal 120 mm of 29 radii from 15 cadavers (3 women, 12 men) with an average age of 61.5 years (range 43–77 years; SD ± 10.48) were obtained during post-mortem examinations. The bones were immediately wrapped in plastic film and frozen at −70 °C until they were examined and tested. This kept the bones as close as possible to their in vivo condition, avoiding dehydration and thawing. While still frozen they were submitted to a series of noninvasive radiologic tests, including standard radiographs, DXA and CT scans. Linde and Sorensen [27] showed that several thawing, testing and refreezing sequences did not change the stiffness of the bones. In our study, although the bones were tested mechanically only once, they had to be partially thawed to conduct the complementary examinations. The period for which the bones were out of the freezer was kept to a minimum.

The bones were examined by DXA using a Lunar DPX-α dual energy absorptiometer (Lunar, Madison, WI) and were radiographed on a Philips CM-80 system (Philips, Eindhoven, The Netherlands), 55 keV, 2.5 mA, with the tube placed 1 m above the specimens. The images were registered on standard cassettes and films in everyday clinical use at the radiological department (Dupont Cronex Quanta Detail Screen with Cronex 10s double emulsion film). The resolution in such conditions

![Fig. 1. The radiographs of two specimens with the regions of interest (ROIs) marked. The ROIs were selected at the mid-line of the bone as distal as possible without including articular structures. This ensured that the area selected corresponded to the area where the DXA measurements were performed. Note the difference between the two specimens, the one on the left displaying more obvious osteopenia.](image-url)