Anisotropic Variogram Assessment of DXA Images of Human Lumbar Vertebrae

Xuanliang Neil Dong, Minqing Dong
University of Texas at Tyler, Tyler, TX
ndong@uttyler.edu

Disclosures: None

INTRODUCTION: Vertebral fractures are a common form of osteoporotic fractures and the current standard for predicting osteoporotic fractures relies on quantifying bone mineral density (BMD) through dual-energy x-ray absorptiometry (DXA) [1]. However, BMD measurements alone account for only about 64% of overall bone strength, suggesting the potential influence of other factors, such as microarchitecture, on bone strength. Novel approaches, like trabecular bone score (TBS) and stochastic predictors (correlation length and sill variance), have utilized variograms, a representation of variability between data points in relation of distance, to indirectly evaluate trabecular bone microarchitectures through DXA scans of the lumbar spine [2, 3]. While both TBS and stochastic predictors have employed isotropic variograms, which assume uniform directional effects, it is important to note that trabecular bone inherently exhibits anisotropic characteristics, signifying varying properties across distinct orientations. Hence, the objective of this study is to employ anisotropic variograms in the analysis of DXA images of human lumbar vertebrae and offer insights into the directional variations within trabecular bone microarchitecture.

METHODS: Eighteen cadaveric lumbar vertebrae were procured from five tissue donors, consisting of 4 males and 1 female, with an average age of 70.0±10.4 years. The posterior-anterior projection DXA scans were conducted on the lumbar vertebrae using a Hologic densitometer (QDR Discovery W). Subsequently, BMD maps of the lumbar vertebrae were generated from the DXA scans using a custom MATLAB script from our previous studies (Fig.1a) [3]. Anisotropic variograms of the BMD map (Fig.1b) were generated at different angles, each separated with a 30° interval. A hole-effect model, represented as $\gamma(h) = c_0 + c[1 - \frac{sin(\pi h/L)}{\pi h/L}]$, was fitted on the variogram data for determining the correlation length (L), sill variance (c) and nugget variance (c_0) in each lag direction. The sum (c+c0) reflects the overall variance of the BMD map, which may indicate the maximum variance observed within the BMD map. Furthermore, the correlation length, L, describes the spatial scale of the variance in the BMD map. The correlation length for each lag direction was plotted against the lag angle using a polar plot (Fig.1c). Then, conversion of the polar plot to Cartesian coordinates (Fig.1d) allowed for the fitting of an ellipse to these data points. Major radius (L_1), minor radius (L_2), and major angle (φ) of the correlation length were derived from the ellipse fit. The degree of anisotropy (DA) was determined by calculating the ratio of major radius to minor radius (DA = L_1/L_2). The anisotropic variogram at any lag direction (θ) and lag distance (h) was represented by the following equation:

$$\gamma(h,\theta) = c_0 + c[1 - \frac{sin(\pi h/L(\theta))}{\pi h/L(\theta)}], \text{ where } L(\theta) = \sqrt{L_1^2 cos^2(\theta - \varphi) + L_2^2 sin^2(\theta - \varphi)}$$

RESULTS: The anisotropic variogram assessment of DXA images for eighteen human lumbar vertebrae revealed an average anisotropy degree of 1.7±0.7, with values ranging from 1.1 to 3.9. An anisotropy degree (DA) close to 1 signifies isotropic behavior, while deviation from 1 indicates increased anisotropy. In this study, two lumbar vertebrae with similar bone mineral density (BMD) were observed: one with a BMD of 0.916 g/cm² (Fig.1a) and another with 0.921 g/cm² (Fig.1f), both falling within the range of osteopenia (low bone mass). Despite their similar BMD values, they exhibited differing degrees of anisotropy when subjected to anisotropy variogram analysis of their DXA scans. One specimen demonstrated higher anisotropy, with a ratio near 2.4, implying that the major axis is approximately 2.4 times the length of the minor axis (Fig.1d). The other specimen displayed isotropic behavior, as indicated by a major-to-minor axis ratio close to 1.1 (Fig.1i). MicroCT images in the frontal plane of the anisotropic specimen showed aligned trabecular plates (Fig.1e), whereas the isotropic specimen exhibited a different pattern (Fig.1j).

DISCUSSION: The current study has several limitations. First, the sample size is modest, including only five subjects and 18 specimens of human lumbar vertebrae. Additionally, a direct comparison between the degree of anisotropy obtained from anisotropic variograms of DXA scans and the MicroCT images of trabecular bone in lumbar vertebrae is lacking. Despite these limitations, our study underscores that anisotropic variogram analysis of DXA scans has the potential to offer supplementary information regarding trabecular microarchitecture, independent of bone mineral density (BMD). This approach holds promise as a valuable tool for enhancing the accuracy of predicting spine fractures.

SIGNIFICANCE/CLINICAL RELEVANCE: Between 35% and 50% of all women over age 50 had at least one spine fracture. Therefore, it is critical to identify those at highest risk in the population and reduce the number of spine fractures. This study aims to enhance the development of a robust, precise, and cost-effective methodology for evaluating bone fragility through clinical imaging modalities.

REFERENCES: [1] Choksi et al. Clin Diabetes Endocrinol. 2018;4:12; [2] Hans et al. J Clin Densitom. 2011;14(3):302-312; [3] Dong et al. J Biomech. 2015;48:2968-2975.

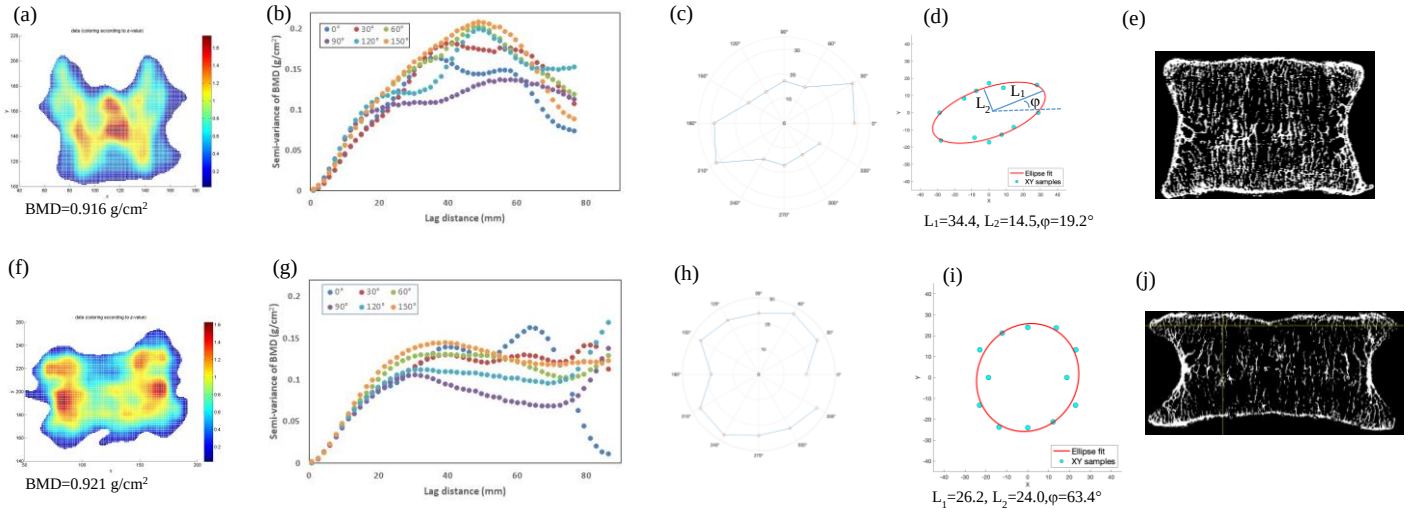

Fig.1. Comparison of two lumbar vertebrae with similar BMD values and different degrees of anisotropy. (a) and (f) BMD maps generated from DXA scans; (b) and (g) anisotropic variograms at various lag directions; (c) and (h) polar plot of correlation length vs. lag angle; (d) and (i) ellipse fitting of correlation lengths; (e) and (j) MicroCT image slices of vertebral body in the frontal plane (i.e., corona plane).