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Equivalence of mean intercept length and gradient fabric tensors – 3d study

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ABSTRACT

In this study the relationship between the mean intercept length (MIL) method – the current standard histomorphometric method of assessing structural anisotropy and an alternative method of the gray-level structure tensor (GST) is investigated. Both methods are applied to a set of 25 three-dimensional binary μCT images of trabecular bone. It is shown that there is a very strong correlation between the logarithms of the principal values of the MIL and the GST fabric tensors (Pearson's coefficient of correlation higher than 0.98) and between the logarithms of the invariants of the MIL and the GST fabric tensors (Pearson's coefficient of correlation higher than 0.999). There is also a good correlation between the degree of anisotropy calculated from the MIL and from the GST tensors (Pearson's coefficient of correlation equal to 0.90). The principal anisotropy directions of the MIL and the GST fabric tensors coincide at the 5% significance level. Additionally, the performance of both methods is tested, based on a set of artificial structures with prescribed orientations.

1. Introduction

One of the most striking properties of trabecular bone is its structural anisotropy. To quantify structural anisotropy, Cowin [1] introduced the term "fabric tensor" and proposed model equations to compute the elastic constants based on fabric tensor and density. It has been shown [2–5] that variations of structural anisotropy and bone volume fraction, derived from high-resolution μCT images, explain at least 90% of the variation of the apparent elastic constants.

The current standard method of quantifying structural anisotropy, applicable to binary images only, is based on the measurement of the angular dependence of the mean intercept length (MIL) [6]. Actually, MIL is implemented both in commercially available analyzers of trabecular bone images and in open source packages for performing histomorphometry [7]. Images of trabecular bone, captured with clinical devices like CT or MRI deliver low-resolution gray-level images. Segmentation of such images, which is a prerequisite of computing the MIL fabric tensor, is however a delicate step and currently no consensus exists about the proper segmentation method of the low resolution images of trabecular bone. It becomes nowadays widely recognized that further progress in the analysis of the low-resolution images of trabecular bone requires developing novel tools, based directly on gray-level data and thus not requiring prior segmentation. This was the main motivation for introducing grayscale image-based methods for quantifying fabric tensor [8–14]. The existing gray-level approaches span a wide range of numerical methods like wavelets, Fourier analysis, moment of inertia or gradient computation. It should be noted that gray-level image-based alternatives for other histomorphometric parameters have also been proposed. Besides the gray-level methods of quantifying structural anisotropy, methods based on fuzzy logic have been developed to estimate trabecular thickness [15] and trabecular separation [16] in the regime of limited resolution. Methods of mathematical morphology were used to derive the structure model index from gray-level data [17]. Complementary methods of texture analysis of gray-level data were also used to improve the prediction of the mechanical competence of trabecular bone [18].

In the light of the successful application of the MIL method to the analysis of μCT data, there is an obvious question how the aforementioned gray-level approaches and the MIL method are related. A method to compute structural anisotropy, based on spatial autocorrelation function was proposed in a study of Rotter et al. [13]. MIL and autocorrelation function-based approaches were compared in the study of Wald et al. [14]. Comparison of the moment of inertia-based approach and MIL was presented in the study of Varga and Zysset [19]. Wolfram et al. [20] have compared the performance of three approaches to compute fabric tensor, based on the moment of inertia, gradient and MIL, but the comparison is based on a single case only. Recently an equivalence between the MIL and the gray-level gradient-based (GST) fabric tensors was proven analytically for the case of 2D images [21]. However, a comprehensive evidence of the equivalence of the MIL and the GST approaches for

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high-resolution 3D data has not been presented so far. This kind of a test is necessary before introducing a novel standard of structural anisotropy estimation. Thus, in the present study the MIL and the GST fabric tensors are calculated for a set of 3D μCT images. The relation between both tensors is analyzed.

2. Materials and methods

2.1. Materials

3D μCT images of distal radius trabecular bone were obtained from 15 individuals. The details of sample preparation and image acquisition procedures were described in the previous studies of Laib et al. [22]. The samples (side length 12 mm) were harvested about 10 mm from the endplate of the radius and scanned with a μCT-20 scanner (Scanco Medical, Brüttisellen, Switzerland) with an isotropic voxel size of 34 μm. The 3D μCT images were filtered with a 3D Gaussian filter. In each case the gray-level histograms of filtered images contained two peaks corresponding to marrow and bone and thus images were binarized, using a global threshold equal to the minimum between the peaks. The craniocaudal direction was identified with the *z*-axis of each sample. Then a total of 25 volumes with size of $200 \times 200 \times 200$ voxels were selected from all μCT images and further analyzed.

To test the performance of the methods of estimating structural anisotropy, synthetic images were also generated. In particular, the structural anisotropy of structures built of three mutually perpendicular families of parallel equidistant planes of prescribed orientation was estimated with different methods.

2.2. Methods

The principle of the MIL method is to count the number of intersections between a family of equidistant, parallel lines and the bone/marrow interface as the function of the 3D orientation of the family of lines. Decreasing the inter-line distance and increasing the number of orientation for which the number of intersections is counted improves precision of MIL estimation at the cost of increased computational burden. To measure the mean intercept length along a given direction, a plane crossing the center of the analyzed 3D image and perpendicular to that direction was determined. Then, a square grid of voxels contained within the plane was generated, with inter-voxel distance being an adjustable parameter. Next, lines perpendicular to the plane and crossing the voxels forming the square grid were found. Finally, the digital lines were traced voxel by voxel and the number of intersections between the lines and the bone–marrow interface as well as the total length of the lines were recorded. The mean intercept length $\mathrm{MIL}(\theta,\phi)$ for a direction specified by a pair of the inclination and azimuth angles (θ,ϕ) is the total length L_{TOT} of the sectors of lines belonging to the given family of equidistant lines and contained in the analyzed region of interest divided by the number of intersections $N_{\mathrm{I}}(\theta,\phi)$:

$$\mathrm{MIL}(\theta, \phi) = \frac{L_{\mathrm{TOT}}}{N_{\mathrm{I}}(\theta, \phi)} \tag{1}$$

In the implementation of the MIL method, used in the present study, a 3D version of the well known Bresenham's digital line algorithm [23] was adopted. Five thousand directions were sampled uniformly over the unit sphere [24] and the families of parallel, equidistant lines pointing along these directions were generated. To compute the MIL fabric tensor, an ellipsoid is fitted to the directional data $\mathrm{MIL}(\theta,\phi)$. The step of an ellipsoid fitting is typically split into two sub-steps. The first sub-step – the determination of an ellipsoid orientation – is usually accomplished using principal component analysis of the $\mathrm{MIL}(\theta,\phi)$ data [25]. The principal directions of the ellipsoid are equal to the principal directions of a 3×3 covariance matrix with the components MIL_{ij} equal to:

$$\mathrm{MIL}_{ij} = \sum_{(\theta,\phi)} \mathrm{MIL}(\theta, \phi)^2 \cdot x_i(\theta, \phi) \cdot x_j(\theta, \phi) \tag{2}$$

where the summations run over 3D orientations specified by the inclination θ and the azimuth ϕ and $x_i(\theta,\phi)$ stands for the ith component of a unit vector pointing along the direction given by the (θ,ϕ) pair. Having an ellipsoid orientation determined, the lengths of the ellipsoid axes are estimated by the means of the least square method. Then, the degree of anisotropy $\mathrm{DA}_{\mathrm{MIL}}$ of the MIL fabric tensor is defined as the ratio of the longest to the shortest axes of the ellipsoid fitted to the MIL data.

The estimation of the structural anisotropy with the GST method involves calculating the components of the gradient of the intensity at every voxel of the analyzed image. To estimate the gradient components at a specified voxel, three one-dimensional five point formulas for the first derivative (one for each direction) were used [26]. Prior to computing the gradient components, the binary images were eventually blurred with a Gaussian filter. The size of the blurring kernel ranged from 3 to 5 voxels. Then, the components GST_{ij} of the GST fabric tensor are equal to:

$$\mathrm{GST}_{ij} = \sum_{v} G_i(v) \cdot G_j(v) \tag{3}$$

where $G_i(v)$ stands for the ith component of the gradient vector at voxel v and the sum runs over all image voxels. Finally, the GST principal values and the GST principal direction were determined for the GST fabric tensor and then the degree of structural anisotropy $\mathrm{DA}_{\mathrm{GST}}$ is defined as the ratio of the largest and the lowest principal values of the GST fabric tensor.

Besides the structural anisotropy, other structural parameters were also calculated to test whether the set of the analyzed samples is representative of a broader range of trabecular architecture. Bone volume fraction BV/TV, trabecular thickness Tb.Th, trabecular separation Tb.Sp and the structure model index SMI were computed for that purpose, using BoneJ software [7].

The Pearson's coefficient of linear correlation r was computed to test the dependence between the same parameters computed using different approaches. Methods of spherical statistics were also used in the present study. The correlation between directions in 3D was quantified with the use of the spherical coefficient of correlation [27]. The difference between means of the same parameters, determined using different approaches was tested with the paired t-test.

3. Results

The MIL and the GST fabric tensors were calculated for artificial structures and the principal anisotropy directions were determined for both methods. The estimated inclination and the azimuth of the MIL principal anisotropy direction, corresponding to the largest principal value of the MIL fabric tensor are plotted vs. the prescribed inclination and prescribed azimuth in Fig. 1. The estimated inclination and the azimuth of the GST principal anisotropy direction, corresponding to the smallest principal value of the GST fabric tensor are plotted vs. the prescribed inclination and prescribed azimuth in Fig. 2. Prior to computing gradient of images of artificial structures, images were blurred with a Gaussian filter with kernel size equal to 5 voxels. The results presented in the figures were obtained for artificial structures with volume fraction in the range from 0.12 (closed squares) to 0.4 (open circles). The spherical coefficient of correlation between prescribed and computed principal anisotropy directions is equal to 0.924 and 0.998 for MIL and GST methods, respectively. The values of the Pearson's coefficient