Advantages of isotropic voxel size for classification of trabecular bone struts and plates in micro-MR images

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INTRODUCTION

Trabecular bone is a complex network of bony struts and plates found mostly at the ends of long bones, the vertebrae and the ribs. Since most fractures occur at sites rich in trabecular bone quantification of its structure by in-vivo MR imaging can provide clinical information relevant for treatment as well as drug development. The relative number of plate-like and rod-like trabeculae as well as their spatial arrangement determine up to 40% of bone's mechanical strength, so there has been a significant effort to develop methods to extract and classify structural information from images acquired in-vivo[1,2]. A new method, dubbed local inertial anisotropy (LIA) [3], has recently been introduced to classify trabecular elements into rods and plates. It relies on a locally calculated tensor of inertia to estimate the class (rod/plate) to which each voxel in the image belongs as well as the orientation of the corresponding rod or plate. However, all in-vivo MR images of trabecular bone have, until recently, been acquired with an anisotropic voxel size which biased the LIA analysis to plate like structures oriented along the axis of anisotropy. While the structure of trabecular bone is itself anisotropic and could be used to justify the anisotropic voxel size, we show here that images acquired with isotropic voxel size have advantages in faithfully representing the underlying structure of trabecular bone. We perform analyses and numerical experiments on our first in-vivo scan acquired with an isotropic resolution of $(160\mu m)^3$ using the FLASE pulse sequence at 3T with custom receive coils and an acquisition time of 26min.

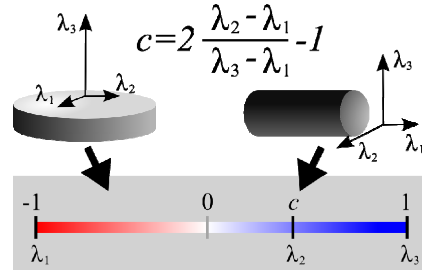

Fig 1. A disk (left) has two small and on large moment of inertia perpendicular to the disk plane. A cylinder (right) has two large and one small moment of inertia parallel to its axis. A color scale (bottom) assigning red to plates and blue to rods.

THEORY

Let us denote the image intensity at the voxel $\mathbf{r}$ with $m(\mathbf{r})$. In the case of an MR image of TB this intensity is proportional to the bone marrow density weighted by the coil sensitivity profile. If we invert the intensity values by subtracting them from their maximum value, the resulting image, $b(\mathbf{r})$, will reflect the local bone volume fraction. At each voxel $\mathbf{r}$ we calculate the tensor of inertia (TI), $\mathbf{I}(\mathbf{r})$, of $b(\mathbf{r})$ within a ball neighborhood of $\mathbf{r}$

$$I_{ij}(\mathbf{r})=\sum b(\mathbf{r}+\mathbf{r}')[|\mathbf{r}'|^2+r'_i r'_j],$$

where the vector $\mathbf{r}'=(r'_1, r'_2, r'_3)$ takes values within a ball of radius s centered at $\mathbf{r}$ and the second term in the sum is the diad formed by that vector. Voxels can be classified into rods and plates using a real-valued parameter $c=2(\lambda_2-\lambda_1)/(\lambda_3-\lambda_1)-1$, that takes values from -1 to 1, where λ_1, λ_2, λ_3 are the eigenvalues of $\mathbf{I}(\mathbf{r})$. The sign of c determines whether a structure is plate-like or rod-like, while $|c|$ measures how plate-like or rod-like the structure is. The orientation of rods/plates is determined (Fig.1) by the eigenvector corresponding to the largest/smallest eigenvalue.

LIA, as described above, produces a continuous classification of voxels as belonging to rod-like or plate-like structures and can be applied to both gray-scale or segmented images. Three parameters result from the above classification. The ratio of mean plate-likeness over the mean rod-likeness of voxels, where mean plate/rod-likeness is defined as the mean absolute value of c over all plate-like ($c<0$)/rod-like ($c>0$) voxels. We also calculate the entropies of the spatial distributions of rod and plate orientations.

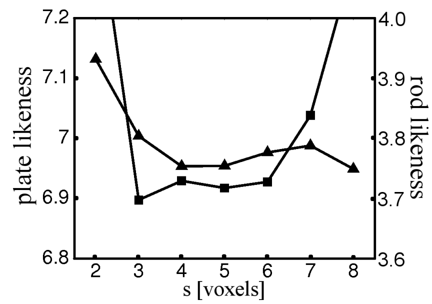

Fig 2. Mean plate (squares) and rod (triangles) likeness as a function of the neighborhood size.

METHODS

The grayscale version of the algorithm was applied to an in-vivo 3D dataset of distal tibia images acquired with a 3T (Siemens Trio) scanner at a voxel size of $(160\mu m)^3$. Minimal preprocessing was applied to the image: 1) a normalization procedure that removes coil shading, b) grayscale inversion to make bone regions high in intensity and marrow regions low in intensity and c) a reduction of voxel size to $(80\mu m)^3$ by sinc interpolation, i.e. zero-padding of the Fourier transform of the image. The only purpose of the last step was to increase the number of voxels in the neighborhood used to calculate the tensor of inertia, thus minimizing effects of the shape of the neighborhood on the calculation.

LIA was applied to the original image with different neighborhood sizes s to determine the optimal value for s. As Fig. 2 shows, the mean plate/rod-likeness are most stable around s=5 voxels (400μm) approximately corresponding to the mean trabecular spacing. After the optimal value of s was found, a series of images with progressively more anisotropic voxel sizes was produced from the initial in-vivo scan by setting to zero outer (k_x-k_y) planes in k-space thus reducing the z-resolution of the image. The effective voxel size was kept at $(80\mu m)^3$ by sinc-interpolation. Each of these anisotropically sampled images was then analyzed by LIA.

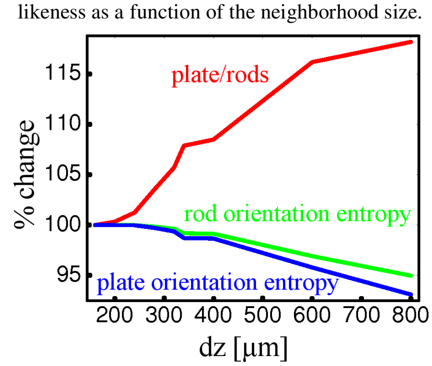

Fig 3. Plate/rods and rod and plate orientation entropies plotted as a function of the voxel size along the z-axis with the in-plane (x-y) resolution fixed at $(160\mu m)^2$ and s=5.

RESULTS

Fig. 3 shows that the plate-likeness to rod/likeness ratio quickly changes as the size of the voxel along the z-axis (dz) is increased. A ~10% change in these parameters can be seen between dz=160μm and dz=400μm which could easily mask expected physiologic effects. Similar changes due to increasing voxel anisotropy were observed for the rod and plate orientation entropies. An increasing prevalence of plate-like structures with increasing anisotropy is illustrated in Fig. 4. where it can be seen that rod-like structures were converted to plate-like structures when the voxel size was made anisotropic. The anisotropy also biases the orientation of the structures which is reflected in smaller orientation entropies at higher anisotropies. Isotropic sampling is particularly important for LIA classification since it significantly influences both the calculated type and orientation of trabeculae.

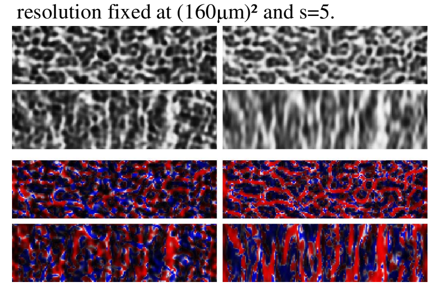

Fig 4. Left column: isotropic scan - $(160\mu m)^3$ voxel size. Right column: anisotropic scan $(160\mu m)^2$x600μm. Grayscale: top row-axial slice of normalized image; bottom row-coronal slice of normalized image. Color: classification weighted by intensity corresponding to images above.

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