Fuzzy logic applied to MRI trabecular bone analysis

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Introduction

The feasibility and potential of assessment of trabecular bone quality with high-resolution MRI has been shown by different authors. Image processing techniques based on microstrcutural parameters and textural analysis have been widely studied and validated to characterize trabecular bone with high-resolution MRI. However, few studies have taken into account the inherent fuzzy nature of these images [1] due to the spatial resolution which is in the order of the trabecular thickness causing substantial partial volume effects. The purpose of this work is the evaluation of different 3D geometrical and topological fuzzy parameters, as well as indices of fuzziness to characterize the trabecular bone with high-resolution magnetic resonance imaging. Because of the very high spatial resolution obtained with micro-CT, which allows the observation of "true" trabecular bone, this imaging modality was considered the gold standard along with well established structural indices for *ex-vivo* validation at 1.5 T. An *in*-vivo MR study on peri and post-menopausal women older than 40 years old at 3T was also performed to complete the validation based on standard apparent structural parameters.

Methods

High resolution MR images of 15 radius bone cubes from the distal radius of 15 individuals were used for the *ex-vivo* validation of this study. These images as well as their structural parameters together with those corresponding to micro-CT were borrowed from another project at our institution. MR images were acquired at 1.5 T with a receive-only wrist coil (Medical Advances, Milwaukee, WI) on a GE SIGNA 1.5 Tesla echo-speed system (General Electric Medical Systems, Waukesha, WI) using a 3D FGRE sequence with a partial echo acquisition with the following parameters: TR = 30 ms, TE = 3.7 ms, flip angle = 30º, BW = $\pm$ 15.6 kHz, FOV = 8 cm, slice thickness = 300 μm, and in-plane spatial resolution of 156 μm x 156 μm after reconstruction. High resolution MR images of the calcaneous of 12 peri and post-menopausal women older than 40 years old were acquired at 3T for the *in-vivo* validation of this study. These images were acquired using a phased array paddle coil (Nova Medical), using an SSFP sequence (FIESTA-C) with the following parameters: TR = 11.7 ms, TE = 4.3 ms, flip angle = 60º, BW = 31.25 kHz, FOV= 10 cm, matrix = 512 x 384, slice thickness = 0.5 mm and 2 NEX. Bone mineral density (BMD) values were also obtained for all the patients using DXA.

MR images of the radius were multiplied with themselves to increase contrast. This is a common linguistic hedge in fuzzy logic known as concentration. Then to reduce computational time for future processing, a threshold of the mean plus 0.25 times the standard deviation of the brightness of the whole volume of interest was applied. Voxels below this value were segmented into bone and marrow phases using fuzzy c-means clustering technique. However, instead of taking the final crisp segmentation based on the maximum membership values as is commonly done, these maximum values where only used to identify the fuzzy cluster corresponding to the bone pixels, i.e. the fuzzy cluster with the lowest average value of brightness based on a crisp segmentation. Once the bone fuzzy cluster was identified, it was converted into a new volume that represented the degree of membership of voxels to the category of "bone". In fact this volume was considered as a bone volume fraction (BVF) map and it was used for all the subsequent fuzzy logic analysis (Fig. 1). MR images of the calcaneous were also segmented using the procedure describe above but no pre-processing was required. The BVF values were compared to the corresponding BV/TV and app. BV/TV values of micro-CT and MR, respectively.

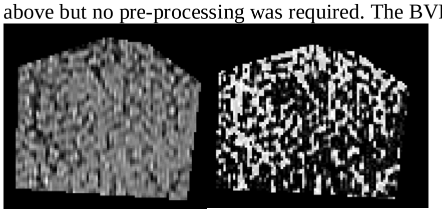

Fig. 1. MR image and its BVF map.

After the generation of BVF maps (for the *ex-vivo* validation they were multiplied with themselves) the fuzzy geometrical parameters known as perimeter and compactness were computed. The linear and quadratic indices of fuzziness, as well as the logarithmic and exponential fuzzy entropies were also calculated, followed by the topological fuzzy parameter known as connectedness [2]. All parameters were computed in 3D. These fuzzy parameters were then compared to the corresponding standard trabecular bone indices known as Tb.N., Tb.Sp., and app. Tb.N. , app.Tb.Sp. of micro-CT and MR, respectively. Based on the connectedness matrix, a threshold value for connectedness was chosen. For voxels with connectedness above this value, their distances to connected voxels were computed and a distance threshold was applied. For the voxels above this threshold the orientation of their connections was computed to get information about the main orientation of the trabeculae in 3D, i.e. anisotropy.

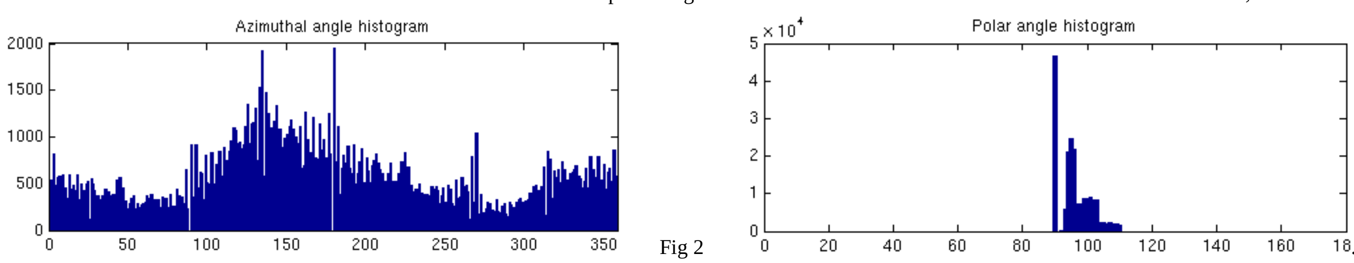

Fig 2

Results and discussion All the comparisons of the standard trabecular bone parameters of micro-CT and MR to those obtained by fuzzy logic were based on Pearson product-moment correlation coefficient as is shown on Table 1. For the radius specimens all the geometrical parameters and indices of fuzziness showed good correlation to the trabecular bone number obtained with micro-CT, as well to the corresponding MR apparent trabecular number obtained with a standard technique used in our laboratory. BMD values of the calcaneous of the human volunteers showed some correlation to the BVF values obtained by the fuzzy segmentation. Good correlation values for the calcaneous were obtained for the indices of fuzziness and entropies, but not for the geometrical parameters when compared to the apparent trabecular number. However, these geometrical values also showed low correlations when compared to the micro-CT data, which is the gold standard. Given the values presented on Table 1 it could be an indication that the fuzziness content in the images is related to the trabecular bone structure. Anisotropy information was also available in the form of histograms of polar and azimuthal angles (Fig. 2), and with vector plots of the connected voxels categorized as trabecular bone (not shown).

Table 1.	Micro-CT		Radius 1.5 T	MR	Calcaneous 3T	MR
Radius 1.5 T		**BV/TV**		**App. BV/TV**	**BMD**	**App. BV/TV**
BVF		0.924		0.990	0.671	0.527
	Tb. N.	**Tb. Sp.**	**App. Tb. N.**	**App. Tb. Sp.**	**App. Tb. N.**	**App. Tb. Sp.**
Perimeter	0.773	-0.813	0.796	-0.802	0.289	-0.248
Compactness	-0.752	0.850	-0.695	0.763	-0.327	0.202
Linear fuzziness	0.895	-0.874	0.931	-0.941	0.932	0.723
Quad fuzziness	0.875	-0.885	0.944	-0.962	0.941	0.715
Log Entropy	0.853	-0.858	0.906	-0.914	0.922	0.727
Exp Entropy	0.859	-0.863	0.915	-0.925	0.924	0.728

References [1] Saha PK, *et. al.* "Measurement of trabecular bone thickness in the limited resolution regime of in vivo MRI by fuzzy distance transform." *IEEE Trans Med Imaging.* 2004 Jan;23(1):53-62. [2] H. Haußecker *et. al.* "Fuzzy Image Processing," in *Handbook of Computer Vision and Applications*, vol. 2., pp. 683-727, 1999.

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