Assessment of cortical porosity at 11.7 T and its correlation with µCT porosity and biomechanics

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INTRODUCTION

Cortical bone consists of mineral, organic matrix and water[1]. The structural integrity of cortical bone has largely been attributed to the mineral content, but water and the organic matrix also play an important role in biomechanics of bone [2]. Water has been found to contribute to hierarchial poroelasticity [3]. The use of magnetic resonance imaging (MRI) for non-destructive and non-invasive evaluation of bone water would be a useful tool. Conventional long echo time (TE) imaging sequences are not applicable to short T2 tissues such as cortical bone. However, water residing in the macroscopic pores of cortical bone has a short T2* but relatively long T2, and can be detected with high resolution spin echo (SE) sequences. In this study we evaluated long T2 pore water of cadaveric human cortical bone using a Bruker small bore 11.7T MR scanner, and compared water fraction and pore size to ultrashort echo time (UTE) magnetization transfer ratio (MTR) [4], µCT measurements of cortical porosity, and biomechanical properties derived from 4-point bending test.

MATERIALS AND METHODS

124 rectangular (~4x2x40 mm) cortical bone samples were resected from cadaveric (n=38, 30-94 yrs, 65.7±16.3 yrs) femora and tibiae using a precision saw. For each sample, porosity was determined using µCT of 9 µm resolution. Four point bending-to-failure biomechanical testing [5] was performed to obtain measures of Young's modulus, yield stress, and failure stress. The relation between SE Cluster analysis, cortical porosity, and biomechanical properties of human cortical bone samples was assessed.

The bone samples were placed in a 20 ml syringe filled with perfluorooctyl bromide (PFOB) during MR imaging to maintain hydration and minimize susceptibility effects at air tissue junctions. A 3D SE sequence on a 11.7T Bruker scanner (Paravision 6.0 Bruker Biospin) was used with following imaging parameters: TR = 1500 ms, TE = 8 ms, FOV = 4 cm, slice thickness = 0.4 mm , slice spacing 0.5 mm, in-plane resolution of 0.04 mm. Nx/Ny/Nz = 400/400/120, 3 averages. MRI porosity measurements included % water fraction and pore size cluster analysis. The noise threshold was defined as the signal intensity where the cumulative density function equaled 0.999. All voxels with signal greater than this threshold were included in the cluster analysis and the % water fraction. Matlab was used to perform the analysis. ROIs were manually selected using in-house software. Two different methods were used to estimate porosity. i) %water fraction defined as the volume greater than the threshold divided by the entire ROI volume, ii) cluster calculations applied the k-means approach, where the number of clusters is defined as the minimum Euclidian distance between all clusters when the number of clusters is increased from 2 to the number of voxels greater than the threshold.

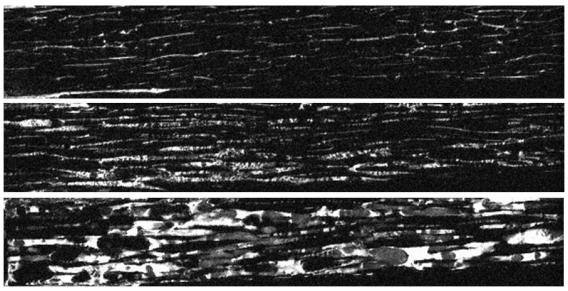

Fig1: SE imaging of 3 bone samples at 11.7 T shows increased porosity.

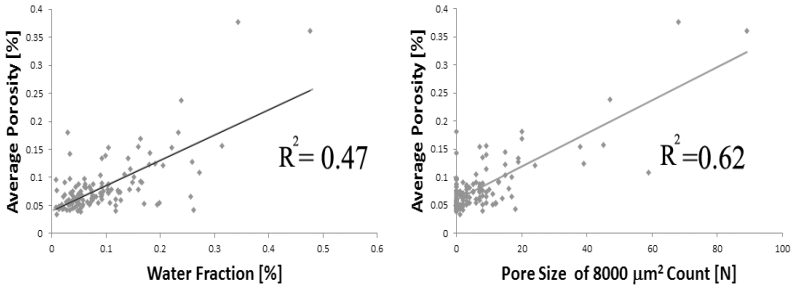

Fig 2: SE measures of water fraction and pore size correlation to average µCT porosity.

A 2D UTE-MT sequence was developed on a clinical 3T scanner (GE Healthcare Technologies, Milwaukee, WI). The UTE sequence employed a short half pulse excitation followed by 2D radial ramp sampling with a minimal nominal TE of 8 µs. The MT pulse was a Fermi pulse (duration = 8 ms, maximal saturation flip angle = 1000°) which provided a much improved spectral profile compared to a rectangular square pulse, and much higher efficiency than conventional Gaussian or sinc pulses in suppressing short T2 signals. The 2D UTE-MT sequence was first applied to a piece of rubber and bovine cortical bone (both have similar T1s and T2*s), and then to cadaveric human cortical bone samples. The UTE-MT imaging protocol included: TR=300 ms, TE= 8 µs, FOV=4 cm, slice thickness=3cm, MT pulse power=1000°, a series of MT frequency offset (Δf = 1.5, 3, 5, 10, 20 kHz). Results from the UTE-MT were previously reported[4].

RESULTS AND DISCUSSION

Fig 1 shows SE imaging of three cortical bone samples. Water residing in the Haversian canals is shown with high signal and contrast. Increased cortical porosity was observed for the four samples, consistent with µCT results (not displayed).

Fig 2 shows the correlation of µCT porosity measurements to morphological analysis results from pore water (water fraction and pore size). The correlation to pore size corresponding to N=5 pixels has the best goodness of fit statistic (R^2=0.62). This pore size was determined by examining correlation as a function of increasing pore size as shown in **Fig 4**. Table 1 presents a summary of correlations (p<0.001) between morphological analysis (water fraction and pore size) to A) µCT data, B) MT-UTE data and C) Biomechanical data. Young's modulus, failure stress, and yield stress of the 124 human bone samples correlated to both % water fraction and pore size (p<0.001). The best goodness of fit to porosity was measured with cluster analysis pore size equal to 8000µm^2. Water fraction correlated positively with porosity (R^2=0.047, p<0.001) and UTE-MT 1.5 kHz correlated negatively with porosity as previously reported[4] (R^2=0.50, p<0.001).

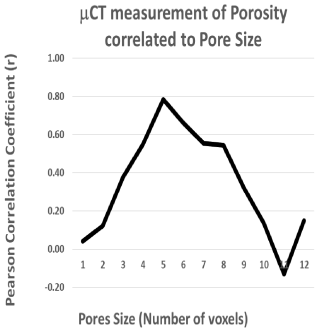

Fig 3: Pearson correlation coefficient (R) between Pores Size and Cortical Porosity as measured by µCT

A)	µCT	Spin Echo	R	R^2
	Porosity Avg	cluster(n=5)	0.78	0.62
	Porosity Avg	% water	0.69	0.47
B)	MTR	Spin Echo	R	R^2
	MTR 1.5kHz	% water	-0.85	0.72
	MTR 3kHz	% water	-0.83	0.68
	MTR 5kHz	% water	-0.81	0.65
	MTR 10kHz	% water	-0.81	0.65
	MTR 20kHz	% water	-0.77	0.59
	MTR 1.5kHz	cluster(n=5)	-0.81	0.66
C)	Biomechanical	Spin Echo	R	R^2
	Yield Stress	%water	-0.61	0.37
	Yield Stress	n=5	-0.60	0.36
	Fracture Stress	%water	-0.58	0.34
	Fracture Stress	n=5	-0.59	0.35
	Modulus	%water	-0.44	0.19
	Modulus	n=5	-0.43	0.18

Table 1: Pearson correlation coefficient (R) between Spin Echo analysis and A) µCT , B) UTE-MT C) biomechanical properties *(p<0.001)*

CONCLUSIONS

Morphological analysis of pore water in cortical bone is significantly correlated with µCT measurements of porosity and provides an alternative approach to non-invasively evaluate bone quality. Although water fraction and pore size correlated with porosity, neither correlated with biomechanical properties with a R^2 greater than 0.37. UTE-MT can evaluate pore water residing in the microscopic pores and water bound to the organic matrix of cortical bone as previously hypothesized [4], and provides information about cortical porosity. The development of novel imaging contrast to increase correlation with bone mechanics is an area of ongoing work.

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4. Du et al, Proc. of ISMRM 2014 : 510. 5. W.Bae et al. JBMR 2012: 27(4): pp 848–857