Selective Imaging of Bound and Pore Water in Human Cortical Bone

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Introduction

Human cortical bone MRI has become clinically feasible with modern ultrashort-echo time (uTE) imaging [1] and related methods. The cortical bone NMR signal relevant to uTE MRI is predominately derived from a combination of collagen-bound water ($T_2 \approx 400$ µs) and pore space water (T_2 = 1ms-1s) [2]. In a study of 40 donors, signals from bound and pore water were directly (r^2=0.68) and inversely (r^2=0.61) correlated with peak stress (and other mechanical properties), respectively; thus, the net signal was poorly correlated (r^2=0.06) [3]. Because a straightforward dual gradient echo subtraction (i.e., standard uTE) will not separate bound from pore water signals due to their similar T_2^*s [2], this work explores clinically-compatible methods for selective bound- or pore-water imaging in cortical bone based on known T_1 and T_2 differences [2]. We show that the bound water signal can be isolated in an inversion-recovery prepared spoiled gradient echo sequence, utilizing a T_2-selective adiabatic full passage (AFP) pulse similar to a previously used bone uTE imaging method with effective soft tissue suppression [4]. Separately, we show that the pore water signal can be isolated in a conventional fast spin echo (FSE) imaging sequence with a short effective echo time.

Methods

Human cortical bone was extracted from medial midshafts of human donor femurs (Mustuloskeletal Tissue Foundation, Edison, NJ) and machined into 5x2x10mm specimens. NMR measurements were performed at 4.7T, consisting of 1) a steady-state AFP inversion recovery gradient echo sequence (AFP-IR, Fig 1), which isolates bound water by selectively inverting and then nulling the pore water via appropriate choice of T_{IR} while accommodating uTE or related imaging schemes (5ms/5kHz hyperbolic secant inversion pulse, 10 µs excitation pulse, 300ms TR); and 2) an FSE imaging sequence, which isolates long-T_2 pore water by allowing short-T_2 bound water to relax fully (10ms TE_{eff}, 10s TR, 50x50µm in-plane/2mm slice, 0.5/1ms excitation/refocusing pulses, 8 shots). The bound-water selectivity was assessed with a CPMG measurement (100 µs echo spacing, 10000 echoes, and 90°/180° hard pulses of ≈ 5/10 µs) of the steady state AFP-IR signal, from which a T_2 spectrum was generated [5]. The pore water selectivity was assessed by including a 20µL water marker ($T_2 \approx 3$s) in the field of view and comparing the integrated areas of bone and marker image regions to the T_2 spectral areas of pore and marker water measured with CPMG.

Results and Discussion

Bound or pore water signals were successfully isolated in clinically-relevant bone MRI sequences. For bound water isolation, an AFP with sufficient bandwidth and pulse duration inverted the pore water magnetization (M_P) while largely saturating the bound water magnetization (M_B), thus resulting in a greater steady-state M_B when M_P was nulled by inversion-recovery. Fig 2 demonstrates that with aforementioned sequence parameters and T_{IR} = 110 ms, the steady state signal consisted of <0.5% of the equilibrium M_P while retaining ≈32% of equilibrium M_B. For pore water isolation, conventional FSE was employed with the slice direction parallel to the osteonal direction, thus creating a striated pattern showing haversian canal/pore water architecture (Fig 3, bottom). Using the water marker (Fig 3, top; color bar has been rescaled for display purposes), net FSE pore water signal was estimated to be ≈84% of equilibrium M_P, and at a TE_{eff} = 10 ms, no significant signal from M_B can be present.

References: 1) Techawiboonwong, A., et. al. *Radiology* 248(2008): 824-833. 2) Horch, R., et. al. *Magn. Reson. Med.* 64(2010): 680–687. 3) Horch, et. al. *Proc. 18th ISMRM*. (2010): 541. 4) Du, J. et. al. *Magn. Reson. Med.* 63(2010): 447–455. 5) Whittall, K., Mackay, A., *J. Magn. Res.* 84(1989): 134-152.

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Figure 1: AFP-IR Sequence for Bound Water Imaging

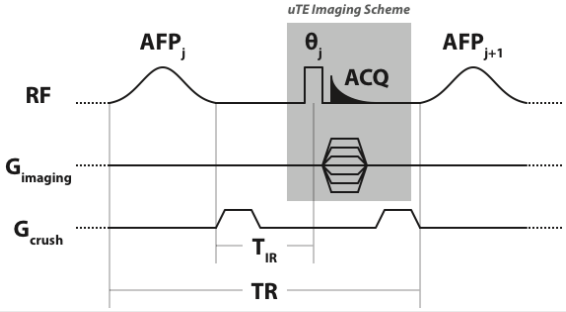

Figure 2: Bound water selectivity of AFP-IR Sequence

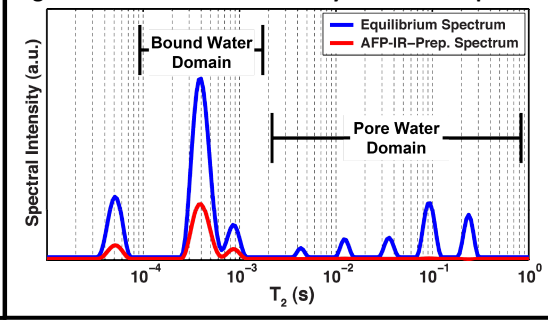

Figure 3: Pore Water Selection with Short-TE FSE