Selective Imaging of Bound Water in Cortical Bone with Inversion Recovery Prepared Ultrashort Echo Time Sequences

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INTRODUCTION

Cortical bone is a composite material containing approximately ~25% water by volume [1]. Bone water occurs at various locations and in different binding states. In normal bone the majority of bone water is loosely bound to the organic matrix, with a small fraction tightly bound to bone mineral [2-4]. There is also a significant amount of free water residing in the pores of the Haversian and lacunocanalicular systems which is responsible for nutrient diffusion and contributes to the viscoelastic properties of cortical bone [5]. Separation of bound water from free water is of critical importance since the two make different contributions to the mechanical properties of bone [6]. In this study we aimed to investigate the effects of inversion time (TI) on bone free water signal using an adiabatic inversion recovery prepared ultrashort echo time (IR-UTE) sequence on a clinical whole body 3T scanner.

MATERIALS AND METHODS

We implemented a 2D non-slice selective IR-UTE sequence which employed an adiabatic inversion recovery preparation pulse (duration=8.64 ms) to invert the longitudinal magnetization of free water (FW) with a longer T2*, and a short rectangular hard pulse (duration=32 μs) to excite both bound water (BW) with a short T2* (T2* ~ 0.3 ms) and free water with a longer T2* (T2* ~ 1-3 ms) [7]. The short rectangular pulse together with radial ramp sampling and fast transmit/receive switching allowed the use of a very short nominal TE of 8 μs. This allowed detection of both free water residing in the microscopic pores of cortical bone, and water loosely bound to the organic matrix. Water tightly bound to mineral was still "invisible" due to its extremely short T2*s (T2* ~ 10 μs or less). With the IR-UTE sequence an adiabatic IR pulse is used to invert and null the longitudinal magnetization of free water. Bound water is not inverted due to significant transverse relaxation during the relatively long adiabatic inversion process, and is subsequently detected by the UTE data acquisition.

Ten bovine cortical bone samples were cleared of all soft tissues for this study. The 2D UTE imaging protocol used the following parameters: TR = 300 ms, FOV = 8 cm, matrix = 128×128, 211 projections, bandwidth = 125 kHz, 20 TEs (0.01, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6, 2, 2.5, 3, 4, 5, 6, 7, 8 ms), 1 minute per image. For IR-UTE, a series of TIs (10, 20, 30, 40, 80, 120, 160, 200 and 240 ms) were used together with the above imaging parameters. A wrist birdcage coil (~12.5 cm in diameter) was used for signal excitation and reception. Both magnitude and phase images were reconstructed. A semi-automated Matlab program was developed for bi-component analysis of bound and free water T2*s and the relative fractions [8]. Phase images were used to demonstrate the effect of free water inversion and signal nulling as a function of TI. The effect of TI on bound water fraction was also analyzed.

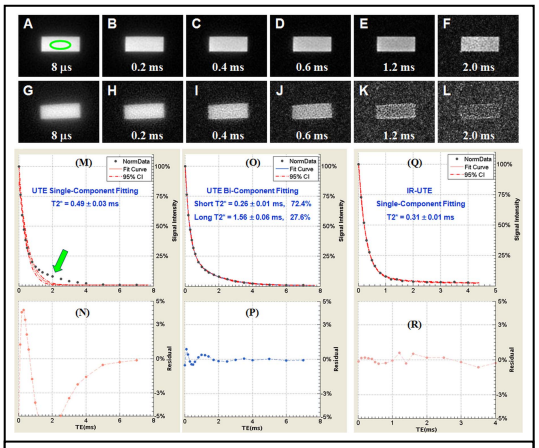

Fig 1 *Selected UTE(A-F) and IR-UTE (G-L) images of a bovine cortical bone sample, and the corresponding single- (M,N) and bi-component (O,P) fitting for UTE images and bi-component fitting for IR-UTE images (Q, R).Two water components were observed in UTE and a single component in IR-UTE data.*

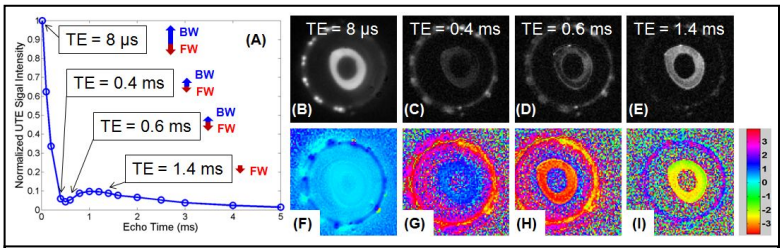

Fig 2 *Signal decay curve for IR-UTE images with a TR of 300 ms and TI of 20 ms (A), and selected magnitude and phase images with a TE of 8 us (B, F), 0.4 ms (C, G), 0.6 ms (D, H) and 1.4 ms (E, I). There is a large phase shift between TEs < 0.5 ms: ϕ = 0.27 for TE of 8 μs (F), ϕ = 0.74 for TE of 0.4 ms (G), and TEs > 0.5: ϕ = -2.47 for TE of 0.6 ms (H) and ϕ = -2.03 for TE of 1.4 ms, suggesting the transition from positive to negative net magnetization is at TE ~0.5 ms.*

RESULTS AND DISCUSSION

Figure 1 shows selected UTE and IR-UTE images of a bovine bone sample as well as single- and bi-component fitting. UTE images show excellent bi-component decay behavior consistent with two distinct water components in cortical bone. The IR-UTE images show a single component decay, suggesting that free water with a longer T2* was selectively inverted and nulled by the adiabatic IR pulse.

Figure 2 shows selected magnitude and phase images of IR-UTE imaging of a bone sample with a TR of 300 ms and a short TI of 20 ms. A positive phase was observed with TEs shorter than 0.4 ms, and a negative phase was observed with TEs in the range of 0.8~1.6 ms, which further demonstrate the inversion of free water magnetization.

Figure 3 shows a summary of bound water T2*s and relative fractions with different TIs. A low bound water fraction was observed with very short TIs (TI < 40 ms) or long TIs (TI > 120 ms). In these TI ranges free water is not nulled and contributes to the IR-UTE signal. Single component decay was observed on IR-UTE imaging with TIs of ~80 ms, suggesting effective nulling of free water in bovine cortical bone.

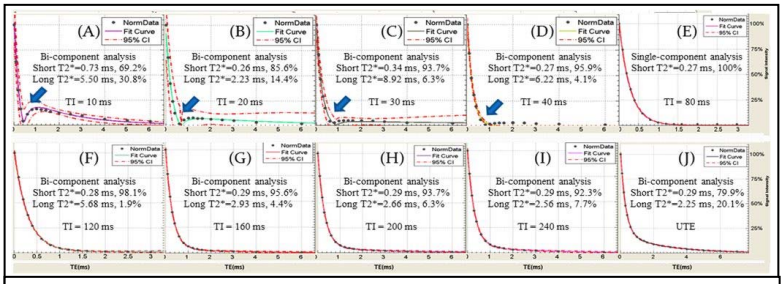

Fig 3 *Bi-component fitting of IR-UTE (A-I) and UTE(J) images of cortical bone with TIs of 10 ms (A), 20 ms (B), 30 ms (C), 40 ms (D), 80 ms (E), 120 ms (F), 160 ms (G), 200 ms (H), 240 ms (I).*

Figure 4 shows bound water fraction as a function of TI for four bovine bone samples. A similar trend was observed: excellent nulling of free water was observed with a TR of 300 ms and TI of 80 ms, and increased free water signal was observed with lower or higher TIs.

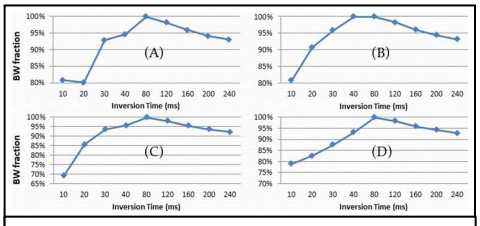

Fig 4 *IR-UTE assessed bound water fractions as a function of TI for 4 bovine cortical bone samples (A-D).*

CONCLUSIONS

This study shows that both bound and free water can be detected by UTE imaging. Excellent nulling of free water can be achieved with an IR-UTE sequence when an appropriate TI is chosen. The IR-UTE sequence allows selective imaging of bound water and potentially quantifying collagen content.

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