# Adiabatic Inversion Recovery Prepared Ultrashort Echo Time (IR-UTE) Imaging of Bound Water in Cortical Bone

Shihong Li[1,2], Michael Carl[3], Eric Chang[1], Won Bae[1], Christine Chung[1], Graeme Bydder[1], and Jiang Du[1]

[1]*Radiology, University of California, San Diego, San Diego, CA, United States,* [2]*Huadong Hospital, Fudan University, Shanghai, China,* [3]*Global Applied Science Laboratory, GE Healthcare, San Diego, CA, United States*

## INTRODUCTION

Bone is a composite material consisting of mineral (~45% by volume), organic matrix (~30%) and water (~25%) (1). There is mounting evidence showing that there are age and disease related changes to the organic matrix (2). However, there are no techniques available for direct imaging of the organic matrix in vivo. Magnetic resonance imaging (MRI) has been employed to indirectly evaluate the organic matrix via direct imaging of water bound to collagen in cortical bone. For example, Wu et al developed water- and fat-suppressed proton projection MRI (WASPI) for bone imaging with efficient suppression of signal from muscle and fat (3). The WASPI signal has been shown to be highly correlated with bone organic matrix density (4). In this study we investigated the adiabatic inversion recovery prepared ultrashort echo time (IR-UTE) sequence to evaluate bone water bound to the organic matrix.

## MATERIALS AND METHODS

In IR-UTE an adiabatic IR pulse is used to invert the longitudinal magnetization of long T2 water and fat. Adiabatic pulses are insensitive to B1 inhomogeneities and so provide relatively uniform inversion. The UTE acquisition is begun at a delay time (TI) designed to allow the inverted long T2 water and fat magnetization to approach the null point (5). Bound water is not inverted and subsequently detected by the UTE acquisition.

Four bovine tibial midshatft samples and four human tibial midshaft samples were harvested for this study. The bovine cortical bone samples were cleared of all soft tissues and were cut into segments with length×width×height~20×10×10 $mm^3$. The human cortical bone samples were cleared of external muscle and soft tissue. Cross-sectional human cortical bone segments with a thickness of ~20 mm were prepared. All eight cortical bone samples were subject to UTE and IR-UTE imaging using a 3T GE scanner. The non-selective 2D UTE and IR-UTE sequences employed a short rectangular pulse (duration = 32 μs) for signal excitation, followed by radial ramp sampling (minimal nominal TE = 8 μs). The 2D non-selective axial imaging plane was centered in the middle of each sample so that the UTE signal intensity represented the integrated signal across the whole bone axial thickness. The 2D UTE imaging protocol used the following parameters: TR = 300 ms, field of view (FOV) = 8 cm, matrix = 256×256, band width = 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), 1.7 minutes per image. For IR-UTE, a series of TIs (20, 40, 60, 80, 100, 120, 140 and 160 ms) were used together with the above imaging parameters. A home-built birdcage coil (~2.5 cm in diameter) was used for signal excitation and reception. A semi-automated matlab program was developed for UTE bi-component analysis of bound and free water T2*s and the relative fractions (6). Finally a translational IR-UTE imaging protocol was developed for bound water imaging in vivo. This protocol included a TR of 300 ms, TI of 120 ms (a balance between muscle, fat and free water suppression), a FOV of 15 cm, 7 mm slice thickness and 5 min scan time. A rubber eraser with similar T1 and T2*s was used as a calibration phantom for water concentration measurement.

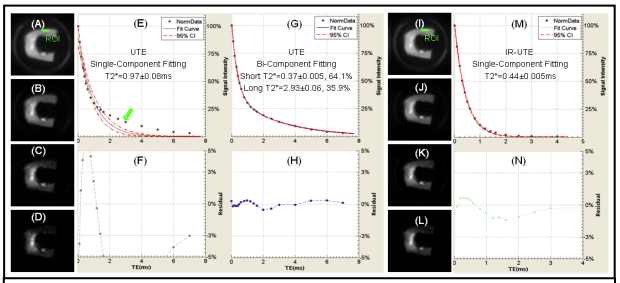


***Fig 1*** *Selected UTE images of a human tibia mid-shaft with TEs of 10 μs (A), 0.6 ms (B), 1.6 ms (C), 4 ms (D), single- (E) and bi-component (G) fitting as well as signal residues (F, H). Selected IR-UTE images with a TI of 100 ms and TEs of 10 μs (I), 0.6 ms (J), 1.2 ms (K), 2.5 ms (L), single-component fitting (M) and residues (N). UTE images show both bound and free components while IR-UTE images show only bound water component.*

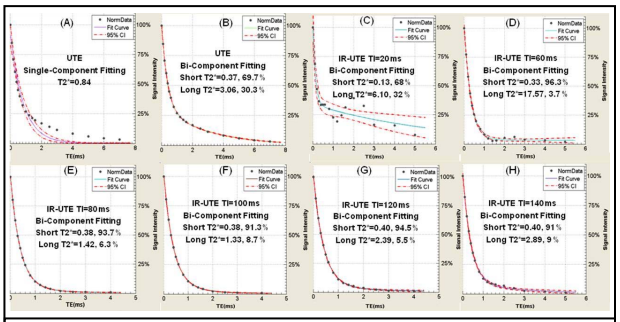


***Fig 2*** *Single- (A) and bi-component (B) analysis of UTE images of a human cortical bone, and bi-component analysis of IR-UTE images with a TI of 20 ms (C), 60 ms (D), 80 ms (E), 100 ms (F), 120 ms (G) and 140 ms (H). The signal oscillation in (C) might be due to fat, but needs further investigation.*

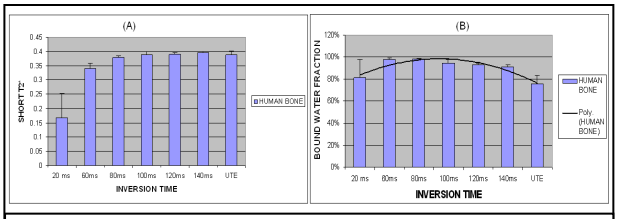


***Fig 3*** *Bound water T2*(A) and fraction (B) from bi-component analysis of UTE imaging. Bound water fraction approaches 100% while free water is well suppressed with a broad range of TIs from 60 ms to 140 ms.*

## RESULTS and DISCUSSION

**Figure 1** shows single- and bi-component fitting of UTE and IR-UTE images of the mid-shaft of a human tibia. Single-component model provided poor fitting but bi-component model provided excellent fitting of the data from the UTE images. The fit shows two distinct water compartments in cortical bone: one with a short T2* of 0.37 ms (64.1% by volume) and the other with a relatively long T2* of 2.93 ms (35.9%). The IR-UTE images show a single component with a T2* of 0.44 ms, consistent with detection of bound water only. The free water component with a longer T2* was selectively suppressed by the adiabatic IR pulse.

**Figure 2** bi-component fitting of IR-UTE images of a human cortical bone sample with a series of TIs (20, 60, 80, 100, 120 and 140 ms). **Figure 3** shows a summary of bound water T2*s and relative fractions with different TIs. Approximately a single component signal decay was observed on IR-UTE imaging with a broad range of TIs, from 60 to 140 ms for human cortical bone, and from 40 ms to 100 ms for bovine cortical bone. Free water has much longer T1 and T2, and is significantly suppressed by the adiabatic inversion and nulling approach. Bound water has a shorter T1 and much shorter T2, and is not inverted but saturated by the adiabatic IR pulse. A quick T1 recovery during TI contributes to IR-UTE signal, leading to selective IR-UTE imaging of bound water with a relatively broad range of TIs.

**Figure 4** shows conventional GRE, UTE and IR-UTE imaging of the tibia mid-shaft of a healthy volunteer obtained with a quadrature knee coil. A total water content of 22.3% was found with UTE and a bound water content of 18.1% was found with IR-UTE, indicating a free water content of 4.2% by volume.

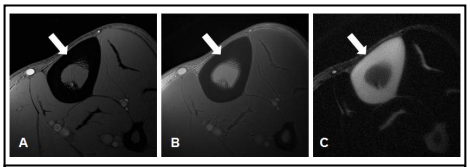


***Fig 4*** *Axial imaging of the tibia mid-shaft in a volunteer using GRE (A), UTE (B) and IR- UTE (C) sequences. A quadrature birdcage knee coil was used for signal reception to minimize errors associated with coil sensitivity inhomogeneities. The tibia shows pure signal void with GRE. UTE shows a total water content of 22.3%, while IR-UTE shows a bound water content of 18.1%, suggesting 4.2% free water by volume.*

## CONCLUSIONS

This study shows that both bound and free water can be detected by UTE imaging. IR-UTE is a robust technique for selective imaging of bound water and quantifying its content.

## REFERENCES

1. Wehrli FW, et al., NMR Biomed 2006.
2. Wang X, et. al., Bone 2002.
3. Wu Y, MRM 2003.
4. Cao H, et. al., MRM 2008.
5. Du, et al, MRM 2010.
6. Diaz E, et. al., NMR Biomed 2011.