Measurement of T2* and T1 of bound and pore water in cortical bone using UTE sequences

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INTRODUCTION

Bone water exists in different states with the majority bound to the organic matrix and mineral, and a smaller fraction in 'free' form in the microscopic pores of cortical bone [1,2]. It is of critical importance to develop noninvasive techniques to evaluate bound and pore water since they make different contributions to the mechanical properties of cortical bone [3]. Ultrashort echo time (UTE) magnetic resonance imaging (MRI) allow direct detection of signal from both bound water (T2* ~ 0.3 ms) and pore water (T2* ~ 2 ms) in cortical bone[4], while adiabatic inversion recovery prepared UTE (IR-UTE) sequences allows selective imaging of bone water bound to the organic matrix [5,6].In this study we aimed to develop and compare a series of UTE and IR-UTE techniques for measurements of T2* and T1 of bound and pore water in cortical bone in vitro. A 3D Cones sequence was also introduced for fast volumetric imaging and quantification of T2* and T1 of different bound water components in vivo using a clinical whole-body 3T scanner.

$$SI(t) = M_{z0,b} \times e^{-t/T_{2b}^{*}} + M_{z0,p} \times e^{-t/T_{2p}^{*}} + noise \quad [1]$$

$$S(TSR) = S_0 \times [1 - (1-k) \times e^{-TSR/T1}] + C \quad [2]$$

$$S(TR) = S_0 \times (1 - e^{-TR/T1}) / (1 - \cos\theta \times e^{-TR/T1}) + C \quad [3]$$

$$M_{xy}^{IR-UTE} \approx M_0 \times (1 - e^{-TI/T1}) \quad [4]$$

MATERIALS AND METHODS

We implemented a 2D non-slice selective UTE and a 3D Cones sequence for bone imaging at 3T. A short rectangular pulse (duration=32 µs) was used for signal excitation. An adiabatic inversion recovery preparation pulse (duration=8.64 ms) was used to invert and null the longitudinal magnetization of pore water, thus allowing selective imaging of water loosely bound to the organic matrix. The following approaches were proposed to measure T2* and T1 of bound and pore water in cortical bone: a bi-component model to measure T2* of bound and pore water based on Eq. [1]; a saturation recovery approach to measure effective T1 of bound and pore water based on Eq. [2]; a variable TR approach to measure the effective T1 of bound and pore water based on Eq. [3]; an IR approach with different TR and TI combinations to measure the T1 of bound water based on Eq. [4]. In the last approach, each TR/TI combination should satisfy the condition that a single T2* was evident (pore water was nulled and only bound water was detected).

Five bovine cortical bone mid-shaft samples cleared of muscle and marrow were prepared for this study. T2* and T1 imaging protocols were shown in Table 1. Other imaging parameters include a FOV of 15 cm, bandwidth = 125 kHz. A wrist birdcage coil (~12.5 cm in diameter) was used for signal excitation and reception. The 3D Cones and IR-Cones protocol were applied to 5 healthy volunteers using an 8-channel knee coil for signal excitation and reception. A semi-automated Matlab program was developed for bi-component analysis of bound and free water T2*s and the relative fractions, as well as T1 analysis.

	Sequences	TR/TI/TE/TSR	Matrix	FA	Thickness [mm]	Scan Time [min]
T1	2D UTE-TSR	TR=1000;TSR=7,25,50,100,200,400,600,800	192x192	20	-	25
	2D UTE-TR	TR=12,25,50,100,200,400,600,800,1000	128x128	20	-	19
	IR-UTE-TI	TR/TI=1000/184;750/172;500/147;400/131;300/11; 200/81;100/45;50/24	128x128	20	-	10
	3D Cones-TR	TR=3.6,12,25,50,100,200,400,600,1000	128x128	45	7	119
	3D Cones-TI	TR/TI=1000/184;750/172;500/147;400/131;300/11; 200/81;100/45;50/24	128x128	20	7	32
T2*	2D UTE	TR=100,TE=0.01,0.1,0.2,0.3,0.4...8 (18 TEs)		20	-	11
	IR-UTE	TR/TI=300/110,TE=0.01,0.1,0.2...4 (14 TEs)	160x160	10	-	10
	3D Cones	Dual TE=0.03/2.3;0.2/4.4;0.4/6.6;0.8/8.8;1.2/11;1.6/13	160x160	10	7	8
	IR-Cones	Dual TE=0.03/2.3;0.2/4.4;0.4/6.6;0.8/8.8;1.2/11;1.6/13	160x160	10	7	14

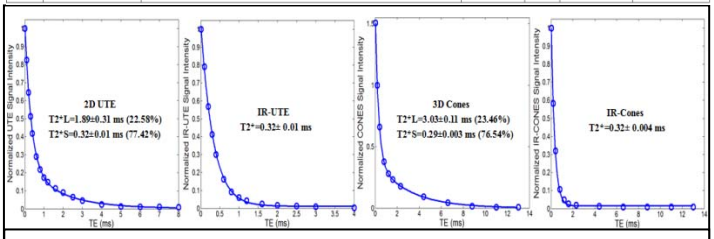

Fig 1 T2* measurements of the bovine bone with four sequences.

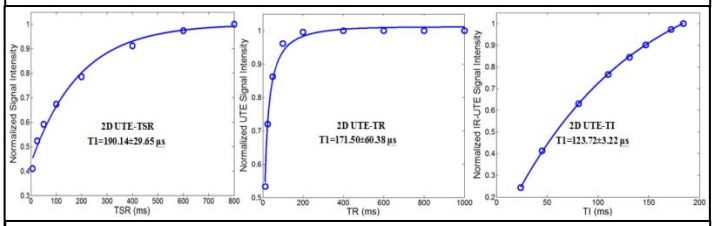

Fig 2 T1 quantification of the bovine bone with 2D UTE sequences.

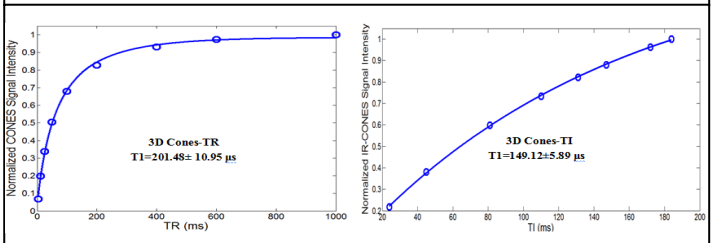

Fig 3 T1 values of total and bound water quantified using variable TR 3D cones and 3D IR-Conessequences.

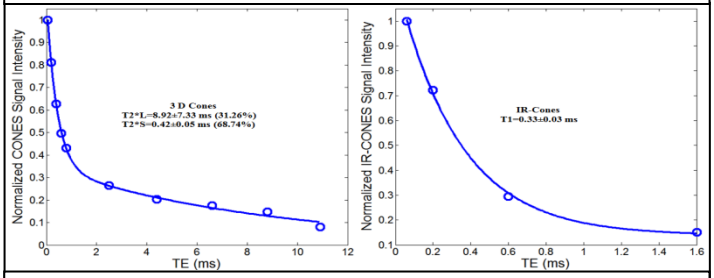

Fig 4 Tibia T2* quantification in a healthy volunteer with 3D Cones and IR-Cones sequences

RESULTS AND DISCUSSION

Figure 1 shows T2* measurements of a bovine bone with 2D UTE and 3D Cones sequences. Both bound and pore water T2*s and their fractions are consistent, suggesting that 3D Cones can accurately measure T2* of bound and pore water, while 3D IR-Cones can accurately access bound water in a time efficient way.

Figure 2 shows T1 measurements of a bovine bone with 2D UTE sequences. Consistent T1 values were measured with all three 2D UTE techniques, with bound water T1 slightly lower than the effective T1 of bound and pore water.

Figure 3 shows T1 measurement of bound water with 3D IR-Cones and the effective T1 of total water with variable TR 3D Cones sequence. Again 3D Cones allows fast measurement of bound water T1 (via IR-Cones) and effective T1 (via variable TR Cones).

Figure 4 shows T2* measurements of the tibial mid-shaft of a healthy volunteer with 3D Cones and IR-Cones sequences, respectively

CONCLUSIONS

This study shows that both T2* and T1 of bound and pore water in cortical bone can be effectively measured with 3D Cones and IR-Cones sequences in a time efficient way using a clinical whole-body scanner.

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