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# A pilot study of short T2\* measurements with ultrashort echo time imaging at 0.35 T

Xiuyuan Chen and Bensheng Qiu\*

\*Correspondence:  
bqiu@ustc.edu.cn  
Center for Biomedical  
Engineering, University  
of Science and Technology  
of China, Jinzhai Road, NO.96,  
Hefei 230026, China

## Abstract

**Purpose:** Ultrashort echo time (UTE) sequences play a key role in imaging and quantifying short T2 species. However, almost all of the relevant studies was conducted at relatively high fields. The purpose of this work was to further explore the feasibility of UTE imaging and T2\* measurement for short T2 species at low fields.

**Methods:** A 2D UTE sequence with an echo time (TE) of 0.37 ms was developed on a 0.35 T permanent magnet scanner. This sequence acquires multiecho images to fit the monoexponential signal decay model for quantitative T2\* calculations. In the phantom experiments, MnCl<sub>2</sub> solutions with different T2\* values were used to assess the curve fitting model in low fields. In the in vivo experiments, T2\* measurements were performed on the Achilles tendon of five normal volunteers.

**Results:** The phantom studies showed a significant linear relationship between the MnCl<sub>2</sub> solution concentration and R2\* (1/T2\*) values, which indicated the stability and accuracy of the T2\* quantification model. The in vivo studies demonstrated that mean T2\* value of Achilles tendon is 1.83 ± 0.21 ms, and the mean coefficient of determination (R-squared) was 0.996.

**Conclusions:** Both phantom and in vivo experiments showed that UTE imaging and quantification for short T2 components were feasible at low field 0.35 T scanner. This pilot study presents preliminary conclusions for future work.

**Keywords:** Low field MRI, UTE pulse sequence, T2\* measurement

## Background

Biological tissues frequently contain different water components, which results in different distinct transverse relaxation times (T2) or apparent transverse relaxation times (T2\*) during MR examination [1]. Quantitative relaxation time calculations are usually based on exponential fitting of data obtained from multiecho gradient echo sequences or Carr–Purcell–Meiboom–Gill sequences [2, 3]. However, there are a variety of short T2 tissues in the musculoskeletal system, and the average T2\* values for these tissues range from several milliseconds down to tens of microseconds [4, 5]. Conventional magnetic resonance imaging employs T1 and T2 weighted sequences has a relatively longer echo time (TE). Even with gradient echo (GRE) sequences with TEs down to about 2 ms, short T2 tissues have little signal that can be detected [6].

Ultrashort echo time (UTE) technique using radial ramp sampling and half pulse excitation can achieve a minimal TE before the transverse relaxation signal has significantly



decayed. Consequently, short T2 species that are invisible in conventional MRI can be imaged by UTE sequences [7, 8]. Multiecho images obtained from UTE sequences at varying TEs can be used to fit the exponential decay model for short T2\* measurements. Biochemical changes in human tissues may affect the T2\* values and thus can be detected and quantified with UTE sequences [9]. Therefore, researchers are paying more attention to quantifying short T2\* calculations as an objective measure of tissue properties and health [10–14].

Previous studies on UTE imaging for short T2 tissues were focused on high fields, such as 1.5 T, 3.0 T [11–18] and higher [10, 19]. High field MR devices have available signal scales with  $B_0^2$ . However, the superconducting magnets required to generate  $B_0$  fields above 0.5 T are a major cost of a typical MRI installation. The continuing interest in low field MRI is stimulated by potential reductions in equipment and maintenance costs [20]. Therefore, low field scanners are still widely used in the clinic. It is of practical meaning for UTE sequences to quantitate short T2 species in low fields. On the one hand, low field MRI is inferior to high field MRI in terms of field homogeneity and signal-to-noise ratio (SNR), which may influence image quality and result in quantitation deviation. To ascertain the accuracy and robustness of short T2\* measurements in low fields, we present a method, which employs the linear correlation between  $MnCl_2$  solution concentrations and  $R2^*$  ( $1/T2^*$ ) values, to assess the quantitative model.

In this pilot study, a typical 2D UTE sequence was developed at 0.35 T permanent magnet scanner. Both phantom (a series of  $MnCl_2$  solutions with different concentrations) and in vivo (Achilles tendon from 5 healthy volunteers) experiments were conducted to demonstrate the feasibility of short T2\* measurements at low fields.

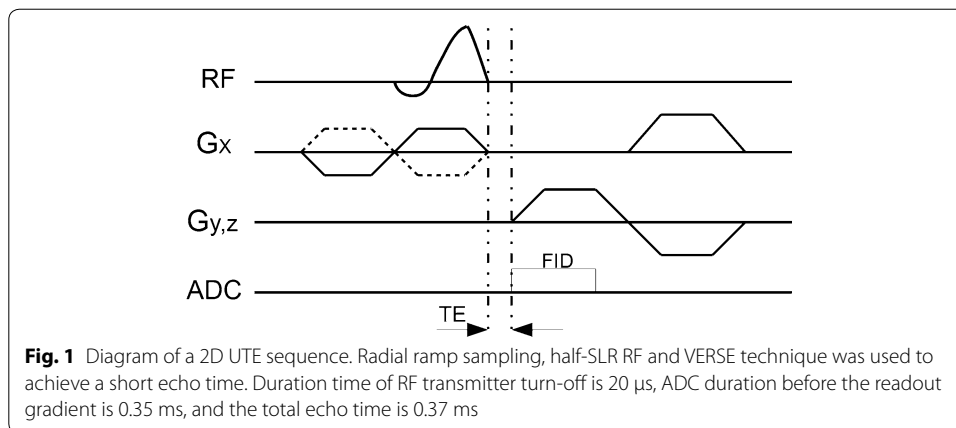
## Methods

### Pulse sequence

A 2D UTE pulse sequence was implemented on a 0.35 T MR system (PICA, Time Medical System, Taizhou, China) with a maximum gradient performance of 56 T/m/s and an amplitude of 28 mT/m. The pulse sequences used radial sampling and half-SLR radiofrequency (RF). The RF shape was redesigned by the variable-rate selective excitation (VERSE) technique to fit the down-ramp of the slice-select gradient. The sum of signals from two successive half RF pulse excitations with opposite polarity slice-select gradients composed a complete k-space line [11]. Data collection started before the readout gradient was ramped up in order to acquire the k-space center. Bipolar slice-select and readout gradients were used to reduce the eddy currents [12]. The minimum valid TE was only limited by the transmit/receive switching duration. A diagram of the UTE sequence is shown in Fig. 1. The actual TE can be as short as 0.37 ms.

### Phantom experiments

Manganese chloride ( $MnCl_2$ ) has been described as a contrast-variable MRI phantom [21]. In this study, highly concentrated  $MnCl_2$  solutions with short T2\* values were used as a phantom. They were placed in four cylindrical plastic containers (diameter of 2 cm and volume of 50 ml) with concentrations of 16, 8, 4 and 2 mM, respectively. The sequence parameters were as follows: slice thickness = 5 mm, FOV = 200 mm, TR = 6 ms, flip angle = 90°, receiver bandwidth = 20,833 Hz, reconstruction matrix



size =  $256 \times 256$ , 540 projections, 256 sampling points per projection, and 1.5 min per image. TEs of 0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4 and 5 ms were used in the data acquisition.  $T2^*$  values were calculated using the monoexponential attenuation model. The relation between  $T2^*$  values and  $MnCl_2$  concentrations was explored.

#### In vivo Achilles tendon experiments

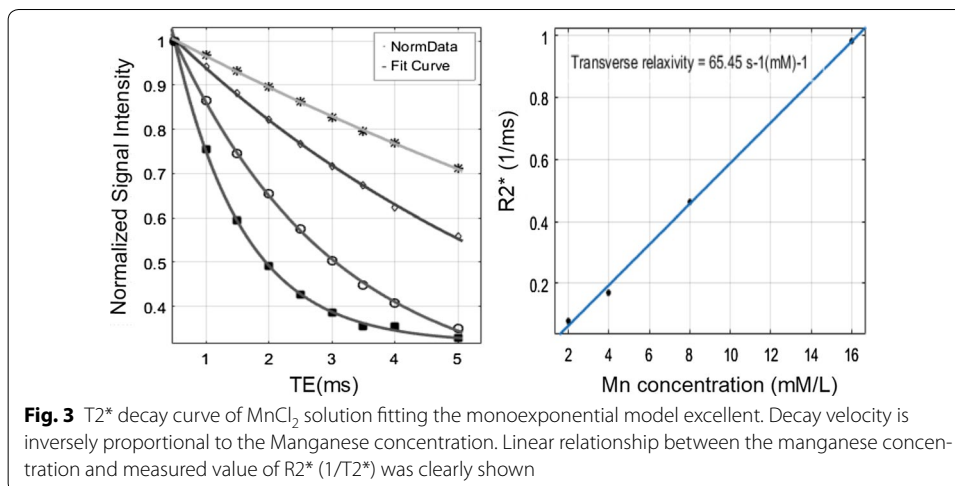
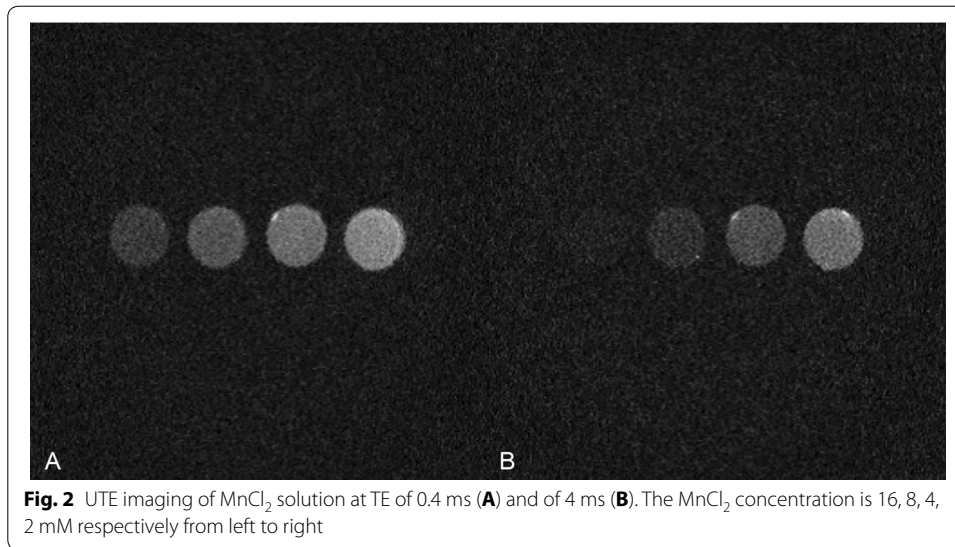
Five healthy volunteers (4 female/1 male, mean age  $24.8 \pm 3.2$  years, human ethics protocol Grant No. USTCEC201700006) were involved in this pilot study. Images were scanned by UTE sequence in the transverse plane. The signals from the ankles were collected by a knee receive coil. The sequence parameters were as follows: slice thickness = 5 mm, FOV = 200 mm, TR = 6 ms, flip angle =  $90^\circ$ , receiver bandwidth = 20,833 Hz, reconstruction matrix size =  $256 \times 256$ , 540 projections, 256 sampling points per projection, and 1.5 min per image. A conventional 2D spin echo (SE) sequence with a TE of 15 ms was used as a comparison. UTE sequences with TEs of 0.4, 0.6, 0.8, 1.4, 2.4 and 3.9 ms were performed for quantitative  $T2^*$  calculation.

#### Data processing

The data regridding technique was used in image reconstruction. The  $T2^*$  value was measured by fitting a monoexponential attenuation model:

$$S(TE) = S_0 \times e^{-\frac{TE}{T2^*}} + N \quad (1)$$

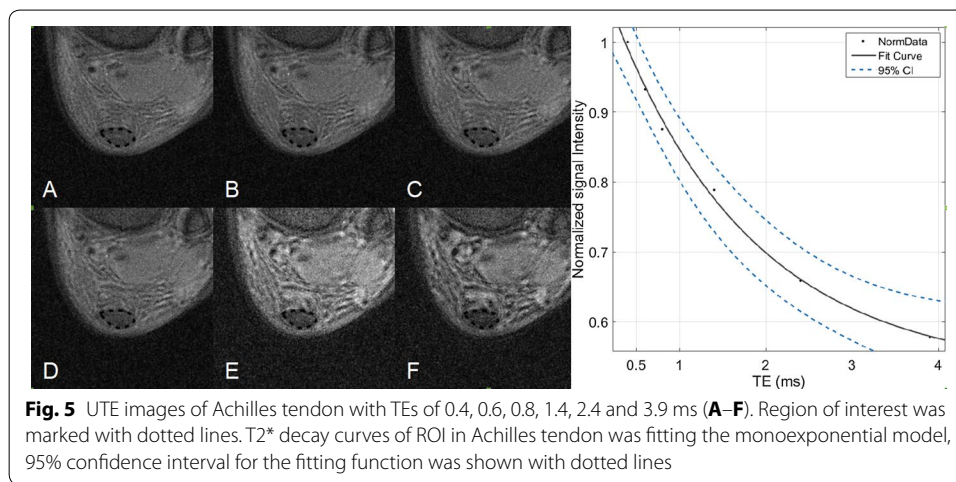
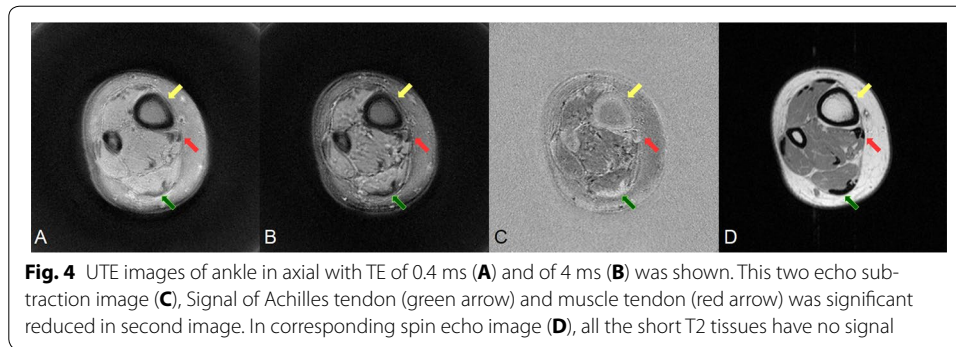
where N was the background noise. The region-of-interest (ROI) was selected from each sample image and copied to the corresponding regions in images acquired at varying TEs. In the phantom experiments, the ROI contained  $20 \times 20$  pixels in four  $MnCl_2$  solution regions. In the in vivo experiments, the manually selected ROI covered the whole Achilles tendon region. The signal Intensity within each ROI was used to fit the monoexponential model, and curve fitting was processed using the Curve Fitting Toolbox with the trust-region algorithm in MATLAB. The coefficient of determination (R-squared) was used for curve fitting quality evaluation. The relation between  $T2^*$  values and  $MnCl_2$  solution concentrations was explored.



## Results

### Phantom experiments

The UTE images of  $\text{MnCl}_2$  solutions at TEs of 0.4 ms and of 4 ms are shown in Fig. 2. It is known that the higher the Mn concentration is, the smaller the  $T_2$  value is [22]. Hence, the images of different solutions had different signal intensities. In Fig. 2B, when the TE was 4 ms, shorter  $T_2^*$  solution signals were remarkably weak compared to those in Fig. 2A, when the TE was 0.4 ms. Figure 3 shows that the  $T_2^*$ s measured using the monoexponential attenuation model were 1.02 ms for 16 mM, 2.18 ms for 8 mM, 5.88 ms for 4 mM and 12.56 ms for 2 mM. The mean coefficient of determination (R-square) of model fitting was 0.9987. The second figure in Fig. 3 shows the linear relationship between  $R_2^*$  ( $1/T_2^*$ ) values and  $\text{MnCl}_2$  concentrations. The relaxation rate was  $65.5 \text{ s}^{-1} \text{ mM}^{-1}$ , and the R-square of the linear fitting was 0.9983.



#### In vivo Achilles tendon experiments

UTE images acquired at a TE of 0.4 ms (A) and a TE of 4 ms (B), subtraction images (C) and the corresponding T1 weighted SE images (D) are shown in Fig. 4. In the SE image, the Achilles tendon, muscle tendon and cortical bone are completely black. In the UTE images, the signal of those short T2 tissues can be detected. Subtract the second echo image (B) from the first echo image (A) can get the echo subtraction image (C). It is known that the decay rate of short T2 tissues is quicker than that of long T2 tissues, so the gap between two echo images of short T2 tissues is larger. Therefore, the brighter signal of tendons in Fig. 4C means that signal of tendons was significant reduced in Fig. 4B. Echo subtraction suppresses the long T2 muscle and fat signals, increasing the contrast with the tendons. However, the residual long-T2 signal limits the achievable contrast [4].

Figure 5 shows the UTE images of healthy volunteer ankles at different TEs. The normalized signal intensity within the ROI was used for fitting the monoexponential decay model. The 95% confidence interval is shown by a dotted line. The experimental results are summarized in Table 1. T2\*s ranged from 1.63 to 2.15 ms, the mean and standard deviation was  $1.83 \pm 0.21$  ms, and the mean coefficient of determination (R-squared) was 0.996.

**Table 1 T2\* measurements of Achilles tendon in five healthy volunteers**

Subject	1	2	3	4	5
T2* (ms)	1.913	1.695	1.786	2.15	1.63
R-square	0.9983	0.9958	0.993	0.9955	0.998
Mean $\pm$ SD (ms)	1.8348 $\pm$ 0.2058				

## Discussion and conclusion

The purpose of this study is to investigate short T2\* measurement with UTE imaging in low field MRI. In general, T2 is not affected much by the main magnetic field strength [23, 24]. T2\* is related to T2 by  $1/T2^* = 1/T2 + \gamma \times \Delta B$ , so it is sensitive to multiple factors, such as the magnetic susceptibility effect, field strength and homogeneity. There is evidence that T2\* values increase as the field strength decreases, because the magnetic susceptibility effect is proportional to  $B_0$  [19, 25]. This means that lower fields have a potential advantage for short T2\* measurements. However, field inhomogeneity in permanent magnets is a negative factor, and the lower SNR in low fields is also a problem for quantitative processes, especially when the short T2 species present a low signal at a relatively longer TE. Generally speaking, T2\* value is vulnerable to MRI system changes. Quantitative UTE is a relatively novel technique to quantify short T2\* species. For short T2\*s, studies have found a linear relationship between the relaxation rate  $R2^*(1/T2^*)$  and the  $MnCl_2$  concentration [22, 26]. This relationship is not susceptible to device changes, and it can be used as a cross-platform reference to assess the precision of quantitation.

In this study, a set of phantom experiments was conducted and analyzed. The T2\* value of the high concentration  $MnCl_2$  solution was selected to approximate that of short T2 tissues. Phantom images and monoexponential decay curve fitting achieved good performance. More importantly, there was strong and linear correlation between  $R2^*$  and  $MnCl_2$  concentration, which indicated the accuracy and robustness of the short T2\* measurements in low field MRI.

For in vivo experiments, oversampling and small receiver bandwidth were used to overcome the relatively low SNR at low fields. It is known that T2\* varies with MR devices. In a study by Du et al. [18], a  $MnCl_2$  solution at 24 mM had a T2\* value of 0.4 ms at 3 T, and the corresponding value in our work at 0.35T was 0.64 ms according to the linear fitting. The decreased T2\* at higher field strengths is caused by magnetic susceptibility effects. According to previous reports at 3 T, T2\* values of a large normal central region of the Achilles tendon in vitro ranged from 1.76 to 2.64 ms [16], in another study, the T2\* of fresh in vitro Achilles tendon was  $1.18 \pm 0.45$  ms [17]. In our work, the mean T2\* value was  $1.83 \pm 0.21$  ms. This result is within the normal range, considering the differences in magnetic field and specimens.

We have shown that quantitative UTE for short T2\* species can be successfully implemented in low field MRI. However, there are several limitations to our study. First, our sample size was small, and more experiments on different tissue specimens will be carried out in future work. Second, T2\* measurement by a monoexponential model is only an approximation of all the components. Bicomponent analysis or monocomponent analysis after suppressing the long T2 component signal, can provide the relaxation time of a single component [1, 12]. Third, the valid echo time in this study is not sufficient



to image the cortical bone with a  $T2^*$  value of approximately 0.4–0.5 ms [15]. Higher-performance hardware can be used to reduce the TE and improve the signal strength of short T2 tissues.

In summary, in this pilot study, phantom experiments indicated the stability and accuracy of the  $T2^*$  quantification model. In healthy human subjects, the mean  $T2^*$  value of Achilles tendon was  $1.83 \pm 0.21$  ms. The feasibility of short  $T2^*$  measurements with UTE sequences at 0.35 T was demonstrated. Future work will include an increased number of normal subjects and patients for clinical applications.

#### Authors' contributions

XC participated in experimental design, data processing and paper preparation. BQ participated in experimental design and provided experimental facilities. Both authors read and approved the final manuscript.

#### Competing interests

The authors declare that they have no competing interests.

#### Availability of data and materials

All datasets and code related to the current study are available from the corresponding author on reasonable request.

#### Consent for publication

In this work, all of the experiments were agreed upon by the volunteers and School Hospital of the University of Science and Technology of China, Hefei, China.

#### Ethics approval and consent to participate

The ethical approval was given by the Medical Ethics Committee of the University of Science and Technology of China, Hefei, China. All participants were informed and volunteered to participate.

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#### References

1. Du J, Diaz E, Carl M, et al. Ultrashort echo time imaging with bicomponent analysis. *Magn Reson Med*. 2012;67(3):645–9.
2. Chavhan GB, Babyn PS, Thomas B, et al. Principles, techniques, and applications of  $T2^*$ -based MR imaging and its special applications. *Radiographics*. 2009;29(5):1433–49.
3. Graham SJ, Bronskill MJ. MR measurement of relative water content and multicomponent T2 relaxation in human breast. *Magn Reson Med*. 1996;35(5):706–15.
4. Du J, Takahashi AM, Bae WC, et al. Dual inversion recovery, ultrashort echo time (DIR UTE) imaging: creating high contrast for short-T2 species. *Magn Reson Med*. 2010;63(2):447–55.
5. Du J, Takahashi AM, Chung CB. Ultrashort TE spectroscopic imaging (UTESI): application to the imaging of short T2 relaxation tissues in the musculoskeletal system. *J Magn Reson Imaging*. 2009;29(2):412–21.
6. Holmes JE, Bydder GM. MR imaging with ultrashort TE (UTE) pulse sequences: basic principles. *Radiography*. 2005;11(3):163–74.
7. Gatehouse PD, Bydder GM. Magnetic resonance imaging of short T2 components in tissue. *Clin Radiol*. 2003;58(1):1–19.
8. Robson MD, Gatehouse PD, Bydder M, et al. Magnetic resonance: an introduction to ultrashort TE (UTE) imaging. *J Comput Assist Tomogr*. 2003;27(6):825–46.
9. Qiao Y, Tao HY, Ma K, et al. UTE-Analysis of diseased and healthy achilles tendons and correlation with clinical score: an in vivo preliminary study. *Biomed Res Int*. 2017. <https://doi.org/10.1155/2017/2729807>.
10. Juras V, Zbyn S, Pressl C, et al. Regional variations of  $T2^*$  in healthy and pathologic achilles tendon in vivo at 7 Tesla: preliminary results. *Magn Reson Med*. 2012;68(5):1607–13.
11. Techawiboonwong A, Song HK, Wehrli FW. In vivo MRI of submillisecond T2 species with two-dimensional and three-dimensional radial sequences and applications to the measurement of cortical bone water. *NMR Biomed*. 2008;21(1):59–70.
12. Du J, Carl M, Bydder M, et al. Qualitative and quantitative ultrashort echo time (UTE) imaging of cortical bone. *J Magn Reson*. 2010;207(2):304–11.

13. Sneag DB, Shah P, Koff MF, et al. Quantitative ultrashort echo time magnetic resonance imaging evaluation of post-operative menisci: a pilot study. *HSS J*. 2015;11(2):123–9.
14. Chang EY, Du J, Statum S, et al. Quantitative bi-component T2\* analysis of histologically normal Achilles tendons. *Muscles Ligaments Tendons J*. 2015;5(2):58.
15. Reichert ILH, Robson MD, Gatehouse PD, et al. Magnetic resonance imaging of cortical bone with ultrashort TE pulse sequences. *Magn Reson Imaging*. 2005;23(5):611–8.
16. Filho GH, Du J, Pak BC, et al. Quantitative characterization of the Achilles tendon in cadaveric specimens: T1 and T2\* measurements using ultrashort-TE MRI at 3 T. *Am J Roentgenol*. 2009;192(3):W117–24.
17. Chang EY, Bae WC, Statum S, et al. Effects of repetitive freeze–thawing cycles on T2 and T2\* of the Achilles tendon. *Eur J Radiol*. 2014;83(2):349–53.
18. Du J, Ma G, Li S, et al. Ultrashort echo time (UTE) magnetic resonance imaging of the short T2 components in white matter of the brain using a clinical 3T scanner. *Neuroimage*. 2014;87:32–41.
19. Krug R, Larson PEZ, Wang C, et al. Ultrashort echo time MRI of cortical bone at 7 tesla field strength: a feasibility study. *J Magn Reson Imaging*. 2011;34(3):691–5.
20. Kegler C, Seton HC, Hutchison JMS. Prepolarized fast spin-echo pulse sequence for low-field MRI. *Magn Reson Med*. 2007;57(6):1180–4.
21. Kurmis AP, Barber C, Slavotinek JP, et al. A MnCl<sub>2</sub>-based MR signal intensity linear response phantom. *Radiol Technol*. 2007;79(2):119–25.
22. Guo H, Au WY, Cheung JS, et al. Myocardial T2 quantitation in patients with iron overload at 3 Tesla. *J Magn Reson Imaging*. 2009;30(2):394–400.
23. Duewell SH, Ceckler TL, Ong K, et al. Musculoskeletal MR imaging at 4 T and at 1.5 T: comparison of relaxation times and image contrast. *Radiology*. 1995;196(2):551–5.
24. Stanisz GJ, Odobina EE, Pun J, et al. T1, T2 relaxation and magnetization transfer in tissue at 3T. *Magn Reson Med*. 2005;54(3):507–12.
25. Yu J, Xue Y, Song HK. Comparison of lung T2\* during free-breathing at 1.5 T and 3.0 T with ultrashort echo time imaging. *Magn Reson Med*. 2011;66(1):248–54.
26. Seevinck PR, Bos C, Bakker CJ. Ultrashort T2\* relaxometry using conventional multiple gradient echo sampling with S0 fitting: validation with quantitative UTE (QUTE) imaging. In: Proceedings of the 16th annual meeting of ISMRM, Toronto, Canada. 2008.

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