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Comparison of T2* mapping between regular echo time and ultrashort echo time with 3D cones at 3 tesla for knee meniscus

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Abstract

The objectives of this study were to compare the ultrashort T2* relaxation time with the T2* relaxation time using the 3 dimensional (3D) cones sequence in 3 groups of patients with normal, degenerated, and torn knee menisci, and to demonstrate the additional effect of the ultrashort echo time (UTE) signal intensity.

Following institutional review board approval, 42 knee magnetic resonance imaging (MRI) scans of 42 patients who presented with knee pain and underwent knee MRIs, with the 3D Cones of UTE sequence (minimum TEs: 32 μs) and a 3T MRI scanner (Discovery 750, GE Healthcare, Waukesha, WI), were analyzed. The enrolled patients were classified into 3 subgroups:

normal meniscus on conventional MRI, with no positive meniscus-related physical examination in medical records;

meniscal degeneration with signal changes on conventional MRI; and

meniscal tear.

For the quantitative assessment, the mean values inside user-drawn regions of interest (ROIs) of the medial menisci were drawn on UTE T2* map and T2* map. For statistical analyses, 1-way analysis of variance (ANOVA) with post-hoc analysis using the Tukey HSD test was conducted to compare groups, and effect size was used to compare the discrimination power.

The ultrashort T2* relaxation times were higher in patients with meniscal tear than in those with normal and degeneration groups ($P < .05$, respectively) whereas T2* relaxation times were not statistically significantly different. The ultrashort T2* relaxation times showed higher effect sizes than the T2* times between tear and normal/degeneration.

The ultrashort T2* relaxation times showed better delineation of meniscal degeneration or tears than T2* relaxation times. The ultrashort T2* relaxation times could be more sensitive at differentiating between normal and pathologic meniscal conditions in patients.

Abbreviations: 3D = three dimensional, MRI = magnetic resonance imaging, TE = echo time, UTE = ultrashort echo time.

Keywords: knee, magnetic resonance imaging, meniscus, ultrashort echo time

1. Introduction

The meniscus in the knee is the key tissue in the pathogenesis of osteoarthritis.[1] It has a cartilage-protective function, and pathology of the meniscus predisposes the adjacent articular cartilage to increased axial and shear stress, resulting in early pathogenesis of osteoarthritis.[2] Accurate and timely diagnosis of meniscal pathology is critical for proper treatment. Magnetic resonance imaging (MRI) provides a good soft tissue contrast between the different tissues of the body. It is possible to noninvasively visualize the meniscus with MRI using either the conventional T2-weighted sequence or the proton density-weighed sequence. However, in musculoskeletal imaging, the most interesting tissues including ligaments, tendon, meniscus, and bone are usually short T2 tissues, which provide little signal intensity on conventional images.[3,4] Moreover, the ability of current MRI techniques to detect subclinical changes in the meniscus is limited when using conventional MRI sequences. This limitation needs to be addressed, as meniscal degeneration and tear are well-known cofactors in the pathogenesis of osteoarthritis.[1,2]

The aim of ultrashort echo time (UTE sequence) is to shorten the echo time (TE) for the short T2 tissues. Although short T2 tissue imaging with UTE sequence is promising,[3–6] the image quality of tissue contrast and spatial resolution may be limited by current clinical MRI machines. High-resolution imaging is required to visualize the small structure of the meniscus, and quantitative imaging is needed to evaluate the meniscus objectively. In quantitative imaging, ultrashort T2* values in the menisci are known to be sensitive to subclinical changes. An elevated ultrashort T2* value is known to be an important biomarker in the evaluation of meniscal pathologies as well as subclinical meniscus degeneration.[7–9] Recently, UTE imaging with 3-dimensional cones trajectory was applied in clinical MR imager, which resulted in reduced scan time and high spatial resolution.[10–12]

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Table 1

Summary of meniscus groups.

	Normal	Degeneration	Tear	Total
Anterior horn of medial meniscus	21	18	3	42
Posterior horn of medial meniscus	7	13	22	42

In this study, we examined whether the ultrashort T2* relaxation time and the T2* relaxation time using 3 dimensional (3D) cones could be a solution to the visualization limitations of the short T2 in patients with knee pain. To our knowledge, no previous studies have compared the ultrashort T2* relaxation time with the T2* relaxation time using 3D cones sequence for visualizing knee menisci. Therefore, the objectives of this study were to compare the ultrashort T2* relaxation time with the T2* relaxation time with 3D cones sequence in normal, degenerated, and torn knee menisci; and to demonstrate the additional effect of the ultrashort echo signal intensity.

2. Methods

2.1. MRI protocol

All MRI scans were performed using a 3T scanner Discovery 750 (GE Healthcare, Waukesha, WI) with a maximum gradient amplitude of 50 mT/m and a maximum slew rate of 200 mT/m/ms. An 8-channel dedicated knee coil (HD TR knee coil PA: General Electric Healthcare, In vivo Corporation, Gainesville, FL) was used. The knee MRI sequence consisted of T2-weighted sagittal images, T1-weighted axial images, fat-saturated T2-weighted axial images, fat-saturated T2-weighted coronal images, fat-suppressed intermediated-weighted 3D Cube images, and the 3D Cones of UTE sequences in sagittal orientation.

Typical acquisition parameters of the 3D Cones sequences were as follows: field of view (FOV), 180 mm; repetition time (TR), 20.3 ms; 4 echo times (TEs) of 32 μs (started from the end of RF pulse), 3.8 ms, 7.568 ms, and 11.336 ms; bandwidth/pixel 416.667 Hz/Pixel; flip angle of 13 degrees; acquisition matrix 600 × 600, spatial resolution 0.3 × 0.3 mm^3; and slice thickness 3 mm with a total scan time of 7 minutes and 6 seconds.

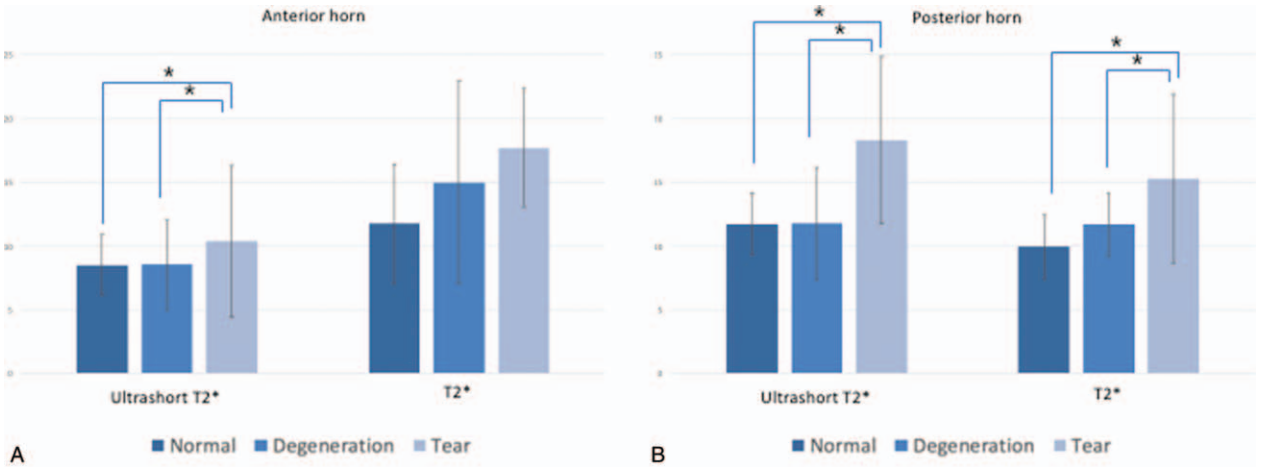

Figure 1. Bar graphs of the ultrashort-echo T2* and T2* relaxation times of the anterior and posterior horns of medial meniscus. Asterisk (*) indicates statistical significance in post-hoc test ($P < .05$).

Table 2

Comparison of UTE T2* relaxation times and T2* relaxation times (mean ± SD).

		Normal meniscus	Degeneration	Tear	*P* value in post-hoc	Overall *P* value
Anterior horn (n = 42)		8.536 ± 2.323	8.544 ± 3.503		.900	.034**
	UTE T2*		8.544 ± 3.503	13.661 ± 5.919	.034*	
		8.536 ± 2.323		13.661 ± 5.919	.031*	
		11.739 ± 4.676	14.989 ± 7.956		.258	.152
	T2*		14.989 ± 7.956	17.714 ± 4.698	.753	
		11.739 ± 4.676		17.714 ± 4.698	.288	
Posterior horn (n = 32)		11.699 ± 2.407	11.754 ± 4.385		.900	.005**
	UTE T2*		11.754 ± 4.385	18.318 ± 6.552	.008*	
		11.699 ± 2.407		18.318 ± 6.552	.026*	
		9.967 ± 2.496	11.672 ± 2.441		.711	.001**
	T2*		11.672 ± 2.441	15.299 ± 6.601	.004*	
		9.967 ± 2.496		15.299 ± 6.601	.002*	

SD = standard deviation, UTE = ultrashort echo time.
* statistically significant in post-hoc test.
** statistically significant in one-way ANOVA test.

2.2. Study population

Forty-two patients who presented with knee pain and underwent knee MRI including the 3D Cones of UTE sequence (minimum TEs: 32 μs) at a 3T MRI scanner (Discovery 750, GE Healthcare, Waukesha, WI) were included in this retrospective study. Exclusion criteria were:

(1) patient with mass (n = 12) and
(2) pediatric patient (n = 2).

The study protocol was reviewed and approved by institutional review board.

Based on conventional knee MRI findings of meniscus from routine MRI scans and the patients' medical records, the medial meniscus was classified into 3 groups, anterior and posterior horn, respectively:

(1) normal meniscus on conventional MRI scans, with no medical record of positive meniscus-related physical examination;
(2) meniscal degeneration with signal changes on conventional MRI, without extension of the signal changes to the articular side; and
(3) meniscal tear.

2.3. Rescaled subtraction 3D cones sequence

Both ultrashort T2* relaxation times and T2* relaxation times were reformatted using a multiecho technique and using the following exponential fitting:

$$\text{Signal intensity (TE)} = S_0 \times \exp(-\text{TE}/\text{T2}*)$$

Ultrashort T2* relaxation times were calculated from the 4 echoes including images with TE1 = 32 μs. T2* relaxation times were calculated from 3 echoes only; the ultrashort TE was excluded. The relaxation maps were reformatted using the dedicated software IDL (Interactive Data Language, ExelisVis, Boulder, CO) and MATLAB R2017b (MathWorks, Natick, MA).

2.4. Image analyses

All images were assessed by a musculoskeletal fellowship-trained radiologist with 10 years of MRI experience. Quantitative assessments were performed by drawing 7 to 8 mm^2 sized region-of-interest (ROI) at anterior and posterior horns of medial meniscus on the both ultrashort T2* map and T2* map, where the meniscus is bow-tie shaped, respectively.

2.5. Statistical analyses

For statistical analyses, 1-way analysis of variance (ANOVA) with post-hoc analysis using the Tukey HSD test was conducted to compare groups. Effect size was calculated to compare the discrimination power of ultrashort T2* relaxation time with the T2* relaxation time using the following equation:

$$\text{effect size} = \Delta\text{mean}/\text{standard deviation (SD)}$$

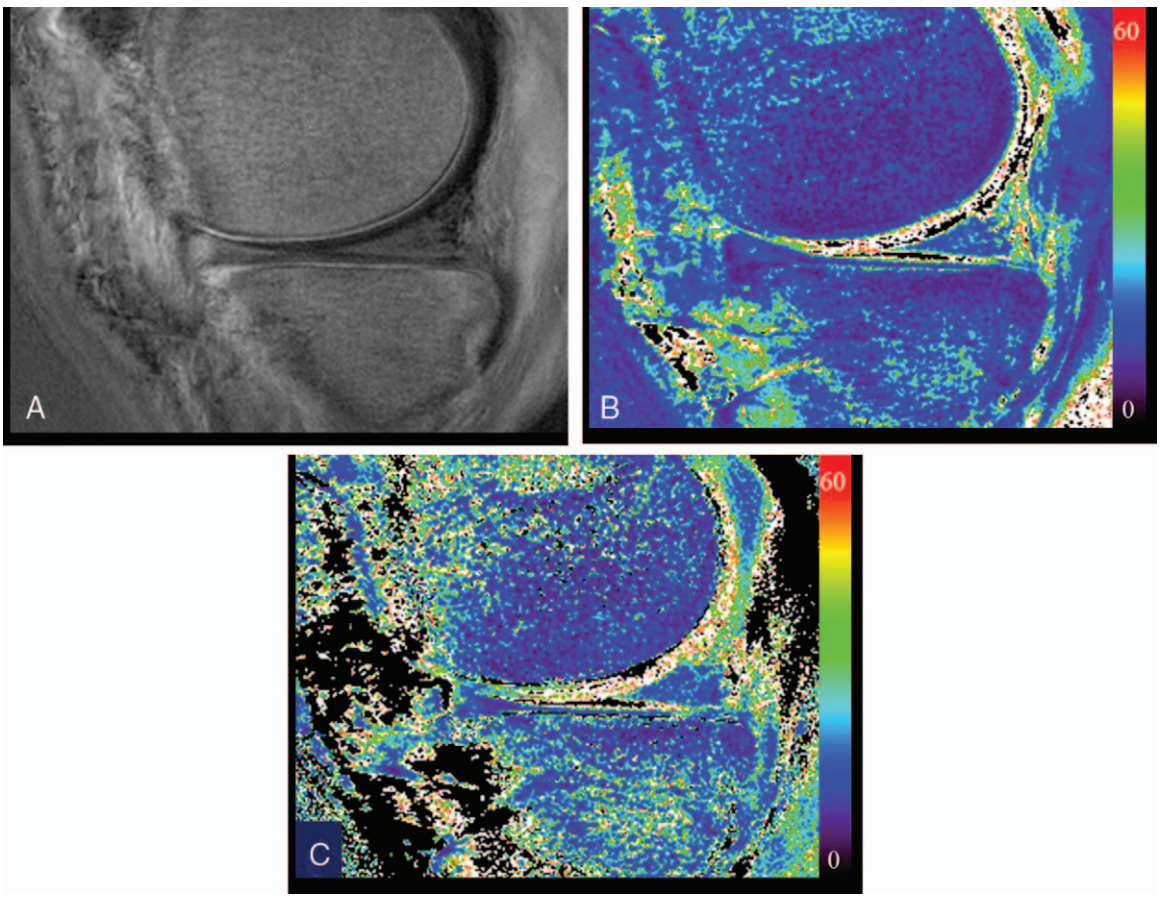

Figure 2. A 34-year-old man with knee pain and normal meniscus. Subtraction image (A) from the ultrashort echo time (TE = 0.032 ms) image and the second long echo (TE = 3.8 ms) image shows high signal intensities of the anterior horn and posterior horn of medial meniscus. Ultrashort-echo T2* map (B) and T2* map (C) show homogeneously low T2* relaxation times on meniscus. TE = echo time.

where $\Delta mean$ is the mean difference between normal and meniscal degeneration/tear, and SD is the pooled standard deviation of these 2 groups defined as:

$$SD = \sqrt{(n_1 - 1)SD_1^2 + (n_2 - 1)SD_2^2/(n_1 + n_2 - 2)}$$

where n_1 and n_2 are the sample sizes of these 2 groups, respectively, and SD_1 and SD_2 are the standard deviations of these 2 groups, respectively.

All statistical analyses were performed using statistical software (R package 3.1.2; The R Foundation for Statistical Computing, Vienna, Austria). A P value of less than .05 was considered to indicate statistically significant differences.

3. Results

The study population consisted of 21 male and 21 female patients. The age range of the 42 patients was 16 to 68 years (mean age ± SD: 42.8 ± 15.7 years). The subgrouping of meniscus in those 42 patients is summarized in Table 1. The cases of signal intensity of ultrashort echo being lower than that of second long echo was 10 cases among 42 cases of posterior horn (23.8%). The ultrashort T2* relaxation times were calculated in remained 32 patients. The T2* relaxation times were successfully calculated in all cases.

In anterior horns, the ultrashort T2* relaxation times were higher in group of meniscal tear compared to normal and degeneration groups (overall $P = .034$, $P = .034$, and $P = .031$, respectively) whereas T2* relaxation times were not significantly different (overall $P = .152$, $P = .753$, and $P = .288$, respectively). In posterior horns, the ultrashort T2* relaxation times (overall $P = .005$, $P = .008$, and $P = .026$, respectively) and T2* relaxation times (overall $P = .001$, $P = .004$, and $P = .002$, respectively) were higher in group of meniscal tear compared to normal and degeneration groups (Fig. 1 and Table 2).

For the group of normal meniscus, both ultrashort T2* relaxation times and T2* relaxation times were slightly low, and UTE images showed homogeneous intermediate to high signal intensity (Fig. 2). In the group with meniscal degeneration, the relaxation times were increased, and the UTE images showed homogeneous low signal intensity (Fig. 3). In the group of meniscal tear, the relaxation times were higher and the UTE

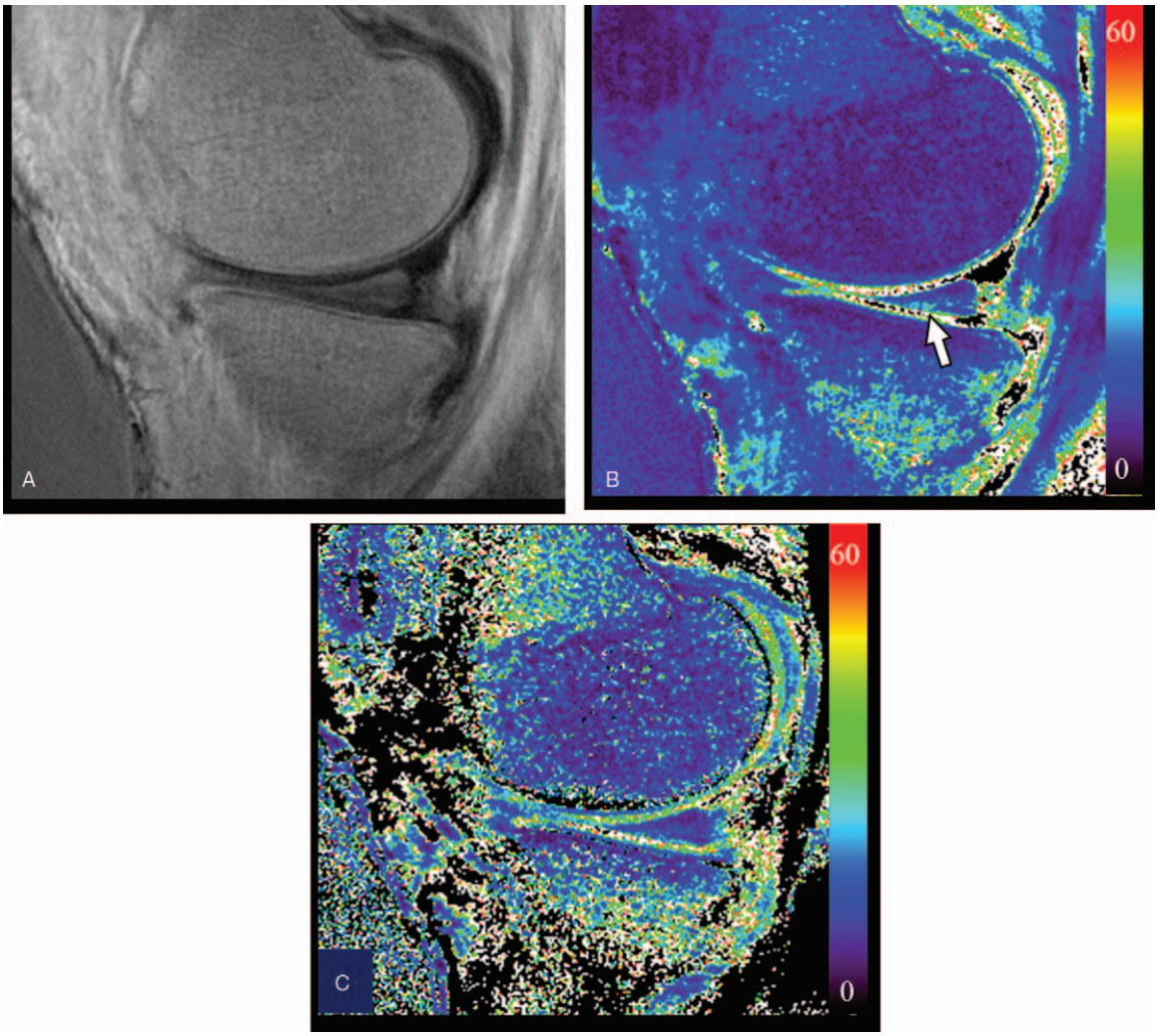

Figure 3. A 36-year-old woman with knee pain and meniscal degeneration. (A) Subtraction image from the ultrashort echo time (TE = 0.032 ms) image and the second long echo (TE = 3.8 ms) image shows heterogeneous low signal change in the posterior horn of medial meniscus. (B) Ultrashort-echo T2* map shows increased relaxation time at the posterior horn of medial meniscus (arrow). T2* map shows no definite changes. TE = echo time.

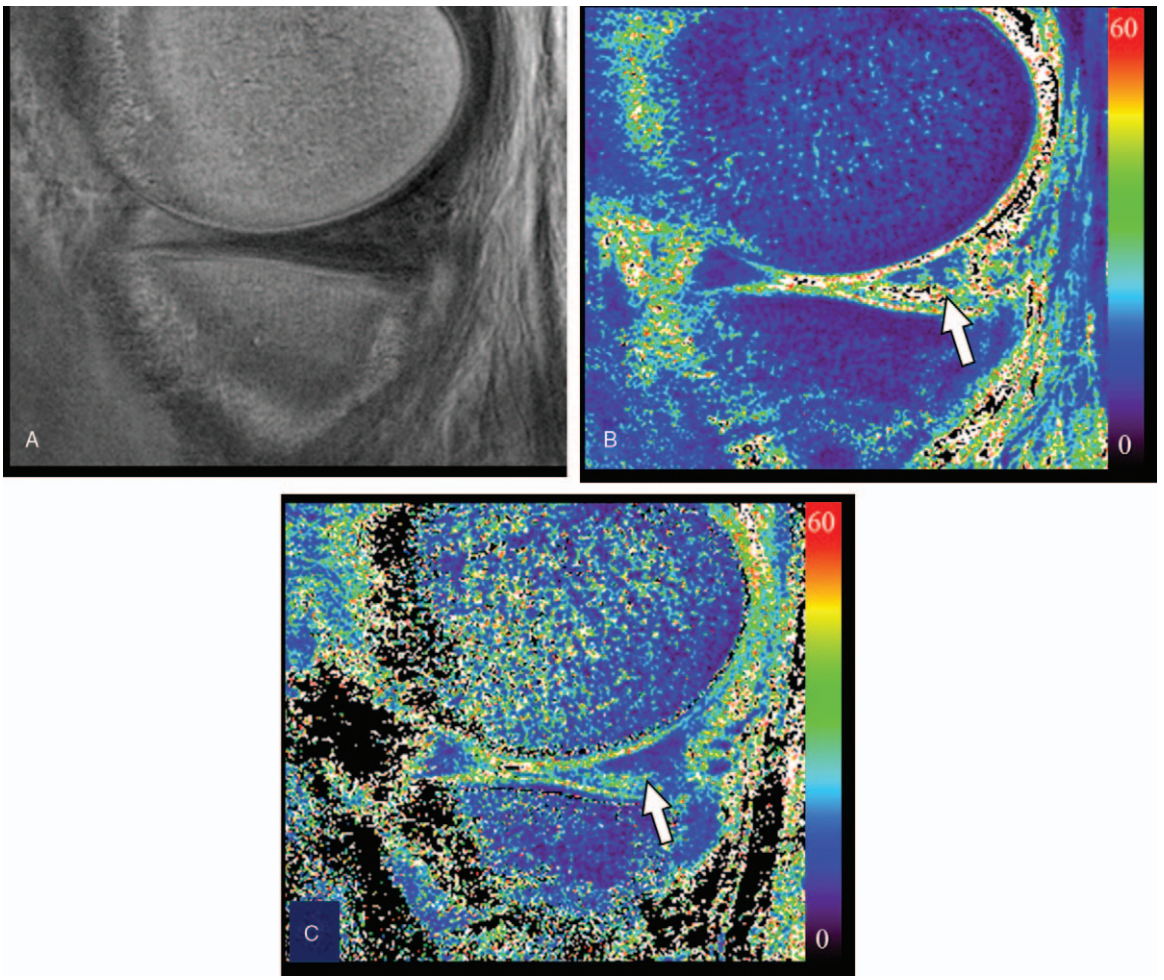

Figure 4. A 44-year-old man with diagnosed meniscal tear of medial meniscus posterior horn. (A) Subtraction image from the ultrashort echo time (TE = 0.032 ms) image and the second long echo (TE = 3.8 ms) image shows internal linear low signal intensity with diffuse signal change of the posterior horn of medial meniscus. Ultrashort-echo T2* map (B) and T2* map (C) shows increased relaxation time at the posterior horn of medial meniscus (arrows). TE = echo time.

images revealed low signal intensity irregularities and linear signal intensities (Fig. 4).

The ultrashort T2* relaxation times showed larger effect size than the T2* times between degeneration and tear and between normal/degeneration in both of anterior and posterior horns of medial meniscus (Table 3). However, the effect size was smaller in ultrashort T2* relaxation times than those of T2* relaxation times between normal and degeneration group in both of anterior and posterior horns of medial meniscus (Table 3).

4. Discussion

To visualize the low signal of short T2 tissue, it is necessary to use ultra-short echo time (UTE) imaging techniques with efficient k-space sampling.[13,14] There are several different sequences to maximize efficiency of k-space sampling: stack-of-stars (SOS),[15] kooshball 3D-spokes sampling,[16,17] twisted-projection-imaging (TPI),[18] and 3D cones.[19] The 3D cones ultrashort echo sequence can provide a minimum ultrashort echo of 0.032 ms with the clinical MRI scanner we used. As expected and as reported previously,[8,20] the degeneration or tear of the menisci were seen as low signal intensities, whereas the normal meniscus exhibited homogeneous relatively intermediate to high signal intensities on UTE images (Fig. 2). The UTE imaging technique showed limited spatial resolution on the clinical imager, which may be problematic. Two-dimensional UTE can be used as an alternative,[21–23] as it has better image quality. However, it cannot be easily applied to clinical imaging due to the relatively long scan time.

For anatomical delineations, high spatial resolution imaging can be acquired with 3D cones ultrashort echo sequence. Clinical

Table 3

Comparison of effect sizes in ultrashort T2* relaxation times and T2* relaxation times.

	Between normal and degeneration	Between degeneration and tear	Between normal/degeneration and tear
Anterior horn (n = 42)			
Ultrashort T2*	0.002	0.529*	7.982*
T2*	0.508*	0.355	0.111
Posterior horn (n = 32)			
Ultrashort T2*	0.014	1.187*	1.329*
T2*	0.693*	0.663	0.880

* higher effect size between ultrashort T2* and T2*.

application of the 3D cones ultrashort echo sequence can provide high spatial resolution of 0.3 x 0.3 mm^2 compared to previously reported UTE sequences that were used with clinical MR imagers.[20,24] We expect that the anatomical visualization of the ultrashort TE signal intensity will be utilized, which can reflect physiological or pathological changes.

In quantitative imaging, the ultrashort-echo T2* relaxation time is an important biomarker for subclinical meniscal pathological changes considering that the meniscus is a short T2 tissue. The 3D cones sequence has multi-echo imaging capability to reformat the ultrashort echo T2* map, which can be used for quantitative imaging. Previous studies have indicated that UTE T2* mapping could be used to detect subclinical meniscus degeneration.[7,8] In the present study, the ultrashort-echo T2* relaxation time was increased in the degenerated group compared to the normal group but this difference was not statistically significant. The meniscal tear group showed longer ultrashort echo T2* relaxation time than the degenerated group, although there was no significant difference in relaxation time on T2* map. Furthermore, the effect size of ultrashort echo T2* values were larger than that of T2* values between group of meniscal degeneration and tear, and between group of meniscal normal/degeneration and tear. And the effect size is a quantitative measure of the strength between 2 values.[25] Crues et al devised an MRI grading system for meniscal lesions, whereby grade 0 is normal, grade 1 (globular increased signal intensity) and grade 2 (linearly increased signal intensity) describe the degeneration of meniscus without a tear, and grade 3 is defined as a tear.[26] Meniscal degeneration (that is, grade 1 and grade 2) was not considered to correlate with a true tear. However, von Engelhardt et al reported that some grade 2 changes on MRI scans may represent a true tear on arthroscopy.[27] It would be helpful to discriminate meniscal degeneration from meniscal tear on MR imaging by using ultrashort echo T2* map.

In multi-echo UTE imaging, the following problem could occur: the signal intensity of the first echo of ultrashort echo signal could be lower than that of the second long echo. This could be problematic in the processing of exponential fitting of multi-echo images including ultrashort-short T2* echo. In the present study, the incidence of this problem (signal intensity of ultrashort echo image being lower than signal intensity second long echo) was 10 cases among 42 cases of posterior horn (23.8%). Considering the importance of UTE in imaging of short tissue T2 imaging, the researchers and radiologist should keep this problem in mind for quantitative imaging.

There are several limitations to this study. First, we could not compare the various UTE sequences. In present study, we normalized the ultrashort TE values to adjacent bone marrow signal intensity. The 3D cones showed a capacity of high spatial resolution and 0.032 ms of TE. Second, we did not perform radiologic-pathologic correlations for subclinical pathological state of the meniscus (meniscal degeneration or tear). This would be needed for further assessment of subclinical pathologic changes.

In conclusion, the ultrashort T2* relaxation times showed better delineation of meniscal tears than T2* relaxation times. The ultrashort T2* relaxation times might be helpful in differentiating between normal and pathologic meniscal conditions in patients.

Author contributions

Conceptualization: Young Han Lee.
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Methodology: Young Han Lee.
Writing – original draft: Jisook Yi, Young Han Lee.
Writing – review & editing: Jisook Yi, Young Han Lee, Ho-Taek Song, Jin-Suck Suh.

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