Bi-exponential T2* Analysis of Meniscus

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Abstract. *A quantitative MRI of meniscus is challenging due to high level of collagen fibers organization resulting in short T_2 and hence low MR signal. The development of the new MRI techniques allows for decreasing echo time dramatically. This opens many possibilities of quantitative assessment of collagen matrix and water content in meniscus. In this study, we utilized a novel MRI technique, variable echo time sequence (vTE) which is capable of delivering the echo time below 1 ms. MR images from this sequence were fitted with bi-exponential curve to separate short and long T_2* component known to be related to the bound and free water, respectively.*

Keywords: Meniscus, MRI, T_2, Collagen Matrix, Tear, Degeneration*

1. Introduction

The degeneration of the meniscus is usually accompanied by weakness of the meniscal tissue, which can no longer distribute load sufficiently, and may eventually result in a meniscal tear (1). Grades of meniscal degeneration correlate with grades of articular cartilage degeneration. According to statistics, 85% of osteoarthritis (OA) patients who underwent joint replacement surgery suffer from degenerative menisci (2). Conventional morphological MR imaging is currently the preferred imaging modality for evaluating the menisci (3). On images with longer echo times (TE), menisci usually appear dark. The recently introduced, three-dimensional, spoiled gradient echo sequence with a variable echo time scheme (3D vTE Cartesian SPGR, hereafter referred to as vTE) minimizes the above-mentioned issues and was shown to be useful for visualizing MSK structures with a short T_2, within short and clinically adequate scan times (4). Since the relaxation constants, such as T_2, T_2*, or T1ρ, reflect the collagen structure organization in the meniscus, they are regionally dependent.

When calculating T_2 or T_2* using a simple mono-exponential fitting, the results may be remarkably underestimated, particularly in the areas with clear bi-component decay. To the best of our knowledge, there is no study that has comprehensively discussed the multiple compartment T_2* mapping of the human menisci in vivo.

Therefore, the aim of this study was to compare the ability of mono- and bi-exponentially calculated T_2* to differentiate between normal, degenerative meniscus, and meniscal tears.

2. Subject and Methods

Seventeen subjects enrolled in this study (eight males, 34±10 years; and nine females, 36 ±14 years). All MRI examinations were performed on a 3T MR system (Tim Trio, Siemens Healthcare, Erlangen, Germany) with an eight-channel knee coil (In vivo, Gainesville, FL, USA). A custom 3D Cartesian spoiled gradient echo (SPGR) technique was adapted to enable the use of a variable echo time (vTE) approach in combination with an asymmetric readout (5). The vTE sequence was applied with 10 echoes: TE = [0.75, 3.51, 5.87, 8.23, 10.6, 12.96, 15.33, 17.69, 20.06, and 22.42] ms, and the rest of the parameters were as follows: flip angle 13 degrees; repetition time (TR) 29 ms; and one signal average. The bandwidth was 320 Hz/ pixel; 144 sections; with a total acquisition time of 12 minutes and 16 seconds. The field of view (FOV) was 120 x 180 mm, with a consecutive in-plane resolution of 0.47 x 1.02 mm; a slice thickness of 0.7 mm; and matrix size was 256 x 176 pixels. All menisci segments were graded morphologically into three groups: normal (grade 0); degenerated (grade 1-2); and meniscal tear (grade 3). Images from the vTE sequence were analyzed using a custom-written script in IDL 6.3 (Interactive Data Language, Research Systems, Inc, Boulder, CO, USA). A mono- as well as a bi-exponential fitting procedure was employed on all MR data sets on a pixel-by-pixel basis. For mono-exponential fitting, a three-parametric function was used to fit the signal intensity

$$S_m = A_0 e^{-TE/A_1} + A_2 \tag{1}$$

where A_0 is the signal intensity at a TE of ~ 0ms, A1 corresponds to the actual $T_2{}^*{}_m$ (mono-exponentially calculated $T_2{}^*$), and A_2 is the baseline (mostly the noise). The same dataset was also processed bi-exponentially, using the function

$$S_b = B_0 e^{-TE/B_1} + B_2 e^{-TE/B_3} + B_4 \tag{2}$$

where B_1 corresponds to the short component of $T_2{}^*$ ($T_2{}^*{}_s$), B3 corresponds to the long component of $T_2{}^*$ ($T_2{}^*{}_l$), and B_0 and B_2 are the component ratios expressed further as a percentage value of $B_0 + B_2$: $F_s = 100*B_0/(B_0 + B_2)$ and $F_l = 100*B_2/(B_0 + B_2)$. B_4 is the offset given primarily by noise. During the calculation of $T_2{}^*$, only those pixels that satisfied the following condition were considered bi-exponential: $4 \times T_2{}^*{}_s < T_2{}^*l$.

Descriptive statistics were performed in order to calculate the mean and standard deviation (SD) of age, $T_2{}^*{}_m$, $T_2{}^*{}_s$, $T_2{}^*{}_l$, component ratios, and M/B values separately for normal, degenerative, and torn menisci. In order to compare average $T_2{}^*{}_m$, $T_2{}^*{}_s$, $T_2{}^*{}_l$, and M/B of different meniscal parts (anterior/posterior, medial/lateral, healthy/degenerated/tear) a hierarchical linear model (HLM) was used in order to consider multiple measures per patient. In addition, ROC analyses were performed to compare healthy with combined degenerated and torn meniscal parts.. A p value equal to or below 0.05 was considered to indicate significant results.

3. Results

From a total of 68 evaluated menisci segments, 48 were graded as normal, 12 as degenerated, and eight as torn. Six patients underwent a surgical procedure after the MR examination. One normal meniscus, one degenerated meniscus, and four meniscal tears were confirmed by a surgeon through visual examination to be in agreement with the results of the MRI evaluation. Examples of $T_2{}^*$ maps for a degenerative meniscus are depicted in Figures 1. The results from descriptive statistics for all relaxation parameters are summarized in Table 1. When considering the red and white zones of the menisci separately, from 48 cases of normal menisci, the mean and SD of $T_2{}^*{}_m$ was 7.89±1.25 ms in the white zone, and 10.49±3.26 ms in the red zone. This difference was statistically significant ($p = 0.026$, 95% CI -4.25 to -0.27). As for the results of bi-exponential analysis, the difference between the red and white zones was statistically significant only for the M/B ratio ($p = 0.017$, 95% CI 0.55 to 3.49).

Table 1. Summary of mean values for mono-exponential T_2*_m, the short and long components of T_2* calculated bi-exponentially, T_2*_s, and T_2*_l , respectively, and the ratio between mono- and bi-exponential pixel count (M/B ratio) calculated from both horns of the lateral and medial menisci.

	Units	Status	Number of Cases	Mean Value	Standard Deviation	R^2
T_2*_m	ms	normal	48	7.61	2.49	0.985
		degenerated	12	9.54	2.25	0.981
		tear	8	14.59	5.24	0.974
T_2*_s	ms	normal	48	0.82	0.38	0.991
		degenerated	12	1.29	0.53	0.986
		tear	8	2.05	0.73	0.979
T_2*_l	ms	normal	48	15.0	5.4	0.991
		degenerated	12	19.97	5.59	0.986
		tear	8	26.83	7.72	0.979
M/B	a.u.	normal	48	3.88	1.73	-
		degenerated	12	2.7	0.88	-
		tear	8	2.13	0.49	-

Table 2. The difference in mono- and bi-exponentially calculated T2* between normal and degenerated menisci and meniscal tears. The asterisk represents statistical significance.

interactions	T_2*_s	T_2*l	M/B	$T*_m$
MED/LAT	0.704	0.547	0.274	0.626
ANT/POS	0.661	0.563	0.461	0.256
STATUS	0.000*	0.000*	0.000*	0.000*
MED/LAT × ANT/POS	0.057	0.857	0.493	0.556
MED/LAT × STATUS	0.001*	0.509	0.272	0.225
ANT/POS × STATUS	0.898	0.404	0.014*	0.097
MED/LAT × ANT/POS × STATUS	0.150	0.433	0.744	0.749

The acronyms have the following meaning: MED - medial meniscus; LAT - lateral meniscus; ANT - anterior horn of meniscus; POS - posterior horn of meniscus; STATUS - normal, degenerative, or tear.

4. Discussion

In this paper, we proposed a technique for in vivo, quantitative, bi-component T_2* analysis of the human meniscus based on a 3D vTE Cartesian SPGR sequence with sequentially shifted echo times. The results of this study showed that bi-exponential analysis of the human meniscus in vivo may better distinguish between normal and degenerative menisci, as well as meniscal tears, compared to uncorrected, mono-exponential decay. These differences most likely reflect the compositional alteration of the collagen matrix, which is most pronounced in meniscal tears, but is also present in degenerative menisci. To the best of our knowledge, meniscal degeneration was previously studied using quantitative MR imaging by only a few groups. Williams and colleagues studied mono-exponential T_2*, measured by UTE, as a potential marker for degenerative menisci (6). They observed significantly lower T_2* values in asymptomatic volunteers (9.8ms) than in patients with meniscal degeneration (18.3ms). T_2* also correlated strongly with the degree of joint pathology. Rauscher and colleagues successfully used T_2 as a marker for detecting early OA stages through meniscal matrix analysis, and also showed that T_2 relaxation times in menisci correlate with the morphological score of cartilage in OA (7). Our study has some limitations. no histological assessment was performed in order to confirm the MRI findings. Some bias may have also been introduced by choosing the bi-exponential condition to $4 \times T_2{*}_s < T_2{*}_l$, which was based on empirical findings.

5. Conclusions

In conclusion, the results of this study suggest that a bi-exponential analysis of meniscal tissue is more robust than a mono-exponential approach. The short component of T_2* better reflects the anisotropy of collagen fibers and the change in degeneration processes that may result in meniscal tear.

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