Relaxometry of tendons, ligaments and menisci in the knee joint at 3 T
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Purpose
Over the last years, a number of MRI techniques have been introduced to study tissues with short $T_2$ values [1, 2]. Musculoskeletal tissues such as tendons, ligaments, or ligaments have short $T_2$ values in the range from one to several milliseconds. For the optimization of sequence parameters (TR, TE, acquisition bandwidth, flip angle) as well as for numerical simulations based on Bloch’s equations, the knowledge of tissue relaxation times is essential. However, the major problem in quantifying short tissue relaxation times is to get a reasonable signal intensity of the examined tissues. So far, there has been no comprehensive MRI regarding the systematic measurement of relaxation properties of ligaments, tendons and menisci. Therefore, the purpose of this study was to quantify the $T_{1p}$, $T_1$, $T_2$, and $T_2^*$ relaxation times of these tissues in the human knee joint at 3T in an acceptable examination time.

Materials and Methods
Nine healthy volunteers were examined on a 3T MR scanner using an 8-channel RX/TX knee coil. The measurements of $T_1$, $T_{1p}$, $T_2$, and $T_2^*$ relaxation times were performed with 3D spoiled gradient echo (GRE) sequences in a total measurement time of only 1 hour. The parameters of 3D GRE sequence preceded by different preparation schemes were identical in all measurements unless otherwise noted: TR/TE=100/1.82 ms, flip angle=25°, FOV=154×154×144 mm³, matrix 192×256×48, voxel size 0.8×0.6×3 mm³, BW=260 Hz/pixel, echo asymmetry of 75%. Acquisition time (TA) of 3:30 min for each sequence was possible due to parallel acquisition technique in both phase and slice direction with acceleration factor 2×2. The $T_1p$ and $T_2$ measurements were performed using adequate magnetization preparation methods [5, 6]. A B1-compensated spin-lock (SL) technique with a pulse series of 90°-(SL)-90° and a SL-pulse of 5.9 µT was used for $T_{1p}$ magnetization preparation. For $T_2$ magnetization preparation a pulse series of 90°-(2×2prep)-180°-(2×2prep)-90° was applied with variable length of $T_{2prep}$. In order to calculate $T_{1p}$ and $T_2$ maps pixel-by-pixel, measurements were performed with various spin-lock times (75L and $T_{2prep}$ of 2, 4, 8, 16, and 32 ms, respectively. For $T_{1p}$ mapping the variable flip angle method based on three optimal flip angles ($7°$, $34°$ and $42°$) was used with TR=40 ms, thus TA was 2:50 min [3, 4]. A multi-echo (n=12) approach using a GRE sequence with TE=1.5 ms and increment $\Delta$TE=3.7 ms was used for $T_2^*$-mapping; parameters were slightly adjusted: BW=450 Hz/pixel, NA=2, TA=6:40 min. For accurate quantification additional B1 maps were measured by the actual flip angle imaging (AFI) technique [7] with following parameters: TR/TR/TE = 20/100/5 ms, flip angle = 60°, matrix = 96×128×48. All images were co-registered using Statistical Parametric Mapping (SPM, Version 5.0) software. $T_1$, $T_{1p}$, $T_2$, and $T_2^*$ parameter maps were calculated using in-house software developed with Matlab (Mathworks, Natick, MA). The regions of interest (ROI) were evaluated by an experienced MR physicist.

Results
Table 1 shows the $T_1$, $T_{1p}$, $T_2$, and $T_2^*$ values (mean ± standard deviation (SD)) of the anterior and posterior cruciate (AC, PC) ligaments, lateral and medial menisci, quadriceps and patellar tendons. Mean $T_1$ values ranged from 915 ms for lateral meniscus to 1207 ms for AC ligament. Mean $T_{1p}$ values were 17 ms for menisci increasing to 29 ms for AC ligament. $T_2$ measurements revealed relatively low mean values for menisci (10 ms) in contrast to ligaments (22 ms) and tendons (17 ms). The $T_2^*$ values ranged from 3.6 for patellar tendon to 15.2 ms for AC ligament. Figure 1 shows representatively T2-w. fat-suppressed sagittal MR image of the knee joint (A) and the corresponding calculated $T_2$ (B), $T_1$ (C), $T_2$ (D), and $T_1$ (E) maps with a segmented medial meniscus.

Discussion
The relaxometry of musculoskeletal tissues such as tendons, ligaments and menisci is usually hampered because of their rapid signal decay as well as the small and complex anatomical structures involved. In the presented work, $T_1$, $T_{1p}$, $T_2$, and $T_2^*$ relaxation times of these tissues have been quantified by 3D GRE sequences. The application of short non-selective RF pulses (0.1 ms) and the use of a strong echo asymmetry (75%) allowed a short TE of 1.5-1.8 ms. Furthermore, the utilization of parallel acquisition technique with a total acceleration factor of 4, made an acceptable examination time of about 1 hour possible. The measurements were performed using a slice thickness of 3 mm which was chosen in consideration of measurement time and SNR. Thinner slices would reduce partial volume effects and thus increase the accuracy of the measurement. In conclusion, the results of this work might be useful to analyze degenerative and traumatic diseases of the knee joint.

References