In vivo DTI of articular cartialge at 3T with a spin echo radial diffusion tensor imaging (RAISED) sequence

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Purpose: Diffusion tensor imaging (DTI) of the articular cartilage has demonstrated high accuracy (90%) for the early diagnosis of osteoarthritis (OA).[1] First in vivo DTI of articular cartilage including OA subjects has been performed at 7T, which seriously limits its clinical applicability. To perform DTI of articular cartilage in vivo on clinical scanners (3T) we developed a new radial spin-echo diffusion tensor imaging (RAISED) sequence. Spin-echo sequences provide high signal-to-noise ratios (SNR), which is critical due to the low T2 values in articular cartilage (~30 ms). Spin-echo radial sequences are also robust against motion[2,3] and allow acquisition of DTI with whole knee coverage in less than 20 min. The aim of this work is to demonstrate the feasibility of measuring DTI of articular cartilage at 3 T with the RAISED sequence.

Methods: Sequence development and optimization: The RAISED sequence was implemented on a 3T scanner (MAGNETOM Skyra, Siemens AG) with a gradient strength of 45 mT/m and a maximum slew rate of 200 mT/m/s. RAISED sequence was optimized for cartilage. Due to the short T2 times of articular cartilage, echo time was kept as short as possible. To avoid eddy-current effects, which may be caused by the proximity of diffusion and imaging gradients, we used a moderate slew rate (100 mT/m/s) with a maximum gradient strength of 35 mT/m. We also enforced a minimum delay of 0.5 ms between the end of the diffusion sensitizing gradients and the imaging gradients. To keep the total acquisition time within 20 minutes with our target 208×208 matrix we used an undersampling ratio of 2.87 using 114 radial views per image instead of the 327 radial views per image required to fulfill the Nyquist condition. To compensate for the decrease in SNR due to undersampling we decreased the in-plane resolution from 0.6×0.6 mm^2 (7T) to 0.75×0.75 mm^2 (FOV=156×156 mm^2) and reduced the maximum b-value to 300 s/mm^2 (diffusion time (Δ) = 21 ms, diffusion gradient duration (δ) = 16 ms), which allowed us using an echo time of 40 ms. For DTI we use six diffusion directions (DSM schema).[4] A total of 21 3-mm slices were acquired with a repetition time of 1.5 s. RAISED images were calculated using gridding of the radial views to a Cartesian grid.

Phantom validation: We tested the presence of eddy-current by acquiring phantom images with inverted polarity of the diffusion gradients in readout, phase, and slice direction as well as in the 6 diffusion directions. Images were segmented using in house software (PaCaSe) to check for geometric differences.[6] Errors in the calculated diffusivity with opposite polarity of the diffusion gradients were compared to the errors in diffusivity of successive acquisitions. Measured diffusivity in water at different temperatures (15.3 ℃, 18.8 ℃ 20.3 ℃, 21.3 ℃ and 22.2 ℃) were correlated with the diffusivity values available in the literature.[5]

Clinical validation: Two healthy subjects (age 36±5 y) and three OA subjects (63±8 y, Kellgren-Lawrence grade II) were included for a first clinical evaluation. All subjects underwent MRI with the optimized RAISED sequence. From the RAISED images we calculated the mean diffusivity (MD) and the fractional anisotropy (FA). All six cartilage plates (patella, femoral trochlea, lateral and medial femoral condyles, and lateral and medial tibia) were segmented on the b0 image. Averaged MD and FA were calculated in each cartilage plate. One healthy volunteer was scanned with fully-sampled radial acquisition (327 radial views per images, 57:15 min) and with the optimized RAISED protocol (20:00 min) in the same imaging session without knee repositioning. One volunteer was measured with both the optimized RAISED and a fully sampled Cartesian sequence (matrix 256×208, 36:24 min). Relative differences in MD and FA between the RAISED and the fully sampled RAISED and Cartesian sequences were calculated. SNR was assessed in cartilage in all the subjects.

Figure 1: Example of a 62-years old male OA subject (OA 1) and a 40-years old male control (H 1). Asterisk indicate areas of increased MD and reduced FA in the OA subject.

Results: Phantom validation: There were no signs of eddy currents in the optimized RAISED sequence. The difference in segmentation among all images with all polarities was (0.07±0.11) mm, i.e. 10% of in-plane resolution. Differences in MD and FA with opposite directions were (1.9±0.8)% and (3.3±1.2)%, which is similar to the error by rescanning with the same gradient polarity (MD: (1.7±0.3)%, FA (3.1±0.7)%). For the temperature dependence MD showed an excellent correlation with the literature values (r^2 = 0.98, P<0.0001, mean relative error (1.4±0.8)%). Relative errors in MD and FA between the optimized RAISED and the fully sampled RAISED/Cartesian sequences were 2.7%/6.8% and 14.1%/9.5% respectively.

Clinical validation: Figure 1 shows examples of the MD and FA parameter maps on a healthy and OA subject. OA subject presented increased MD and reduced FA in the posterior part of the lateral femoral condyle and the lateral tibia as compared to the healthy subject. The summary of the averaged data over all subjects is shown in Table 1. Mean SNR in the cartilage was 30.0±3.1 without diffusion weighting and 17.5±2.5 in the diffusion-weighted images. There was no clear trend of MD and FA between the healthy volunteers and the OA subjects. Two OA subjects showed increased MD in LT and LFC.

Table 1: MD/FA for each subject in all cartilage plates [1]					
	OA 1	OA 2	OA 3	H 1	H 2
Patella	1.9/0.35	1.6/0.43	–	2.2/0.30	2.0/0.48
Trochlea	1.9/0.32	1.9/0.39	1.7/0.42	2.0/0.32	1.9/0.41
LFC	2.5/0.36	2.1/0.45	1.9/0.39	1.8/0.38	2.3/0.50
MFC	2.1/0.38	2.2/0.46	1.8/0.39	1.9/0.36	2.1/0.49
LT	2.4/0.32	2.4/0.55	1.3/0.56	1.9/0.38	2.1/0.54
MT	2.3/0.40	1.9/0.46	1.6/0.51	1.7/0.43	2.1/0.50

[1] Mean MD (×10^{-3} mm^2/s)/mean FA over each cartilage plate
[2] OA=OA subject; H=Healthy subject; LFC=Lateral femoral condyle; MFC=medial femoral condyle; LT=Lateral tibia; MT=Medial Tibia.

Discusion: DTI of articular cartilage at 3T using the RAISED sequence provides excellent image quality and is very robust against motion artifacts as often seen in conventional spin-echo sequences. Optimization for 3T requires slight decrease of the in-plane resolution and reduction of the diffusion weighting as compared to 7T.[1] Validation of the sequence with phantoms demonstrated absence of eddy-current artifacts. There was a good agreement in MD parameters acquired with the optimized RAISED sequence and the fully sampled RAISED and Cartesian acquisitions. The slightly higher FA values are most likely due to the lower SNR. Due to the small sample size we could not see differences between the healthy and OA subjects in the averaged DTI parameters.

Conclusion: The RAISED sequence provides high quality DTI of articular cartilage at 3T with whole knee coverage in less than 20 min.

References: [1] Raya et al. Radiology 2012;262:550. [2] Trouard TP et al. Magn Reson Med 1999; 42:11 [3] Dietrich O et al. MAGMA 2001;12:23. [4] Skare S, et al. J Magn Reson. 2000;147:340. [5] Tofts PS, et al. Magn Reson Med. 2000;43:368. [6] 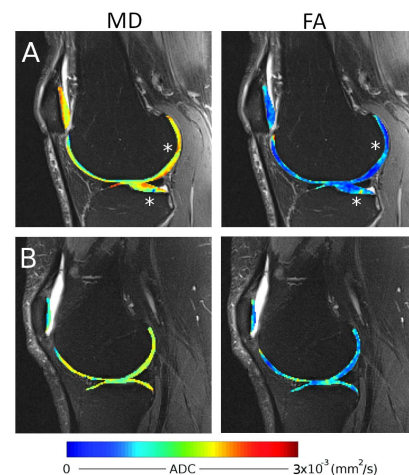Koenig et al, Bildverarbeitung für die Medizin. 2007;17:404.