Diffusion sensitized ophthalmic MRI free of distortion using multi-shot RARE at 3 T and 7 T

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Target audience: This work is of interest for basic MR researchers, imaging scientists and clinical scientists.

Purpose: MRI of the spatial arrangements of the eye segments and their masses is an emerging application. Ocular MRI holds the potential to provide guidance during diagnostic assessment and treatment of ophthalmological diseases [1,2]. Diffusion weighted MRI (DWI) probes tissue on a microscopic level. DWI sensitization has been applied to diagnose ocular lesions including intraocular masses and to differentiate ocular melanoma from retinal detachment [3-5] using an echo planar imaging (EPI) module. Notwithstanding this success DWI-EPI of the eye was reported to be prone to severe susceptibility and distortion artifacts which were pronounced at 3 T [4]. The propensity to image distortion renders DWI-EPI of the orbit challenging at 3 T where approximately 50% of the data were excluded from ADC analysis due to severe image distortion [4], which is expected to be further pronounced at 7 T. To offset geometric distortions, single-shot RARE has been proposed as an alternative approach for DWI of the orbit [5] but comes with the caveat that it is prone to point spread function broadening induced blurring artifacts and limited in spatial resolution. Realizing these constraints and realizing the clinical opportunities of ocular MRI, this study examines the applicability of diffusion sensitized multi-shot split-echo RARE imaging of the orbit.

Methods: Conventional RARE [6] was modified (according to [7]) so that the echo is separated in two groups to eliminate interferences between odd and even echoes (E1 and E2) [8]. Diffusion sensitizing gradients were placed around the first refocusing pulse. The first two echoes were acquired without phase encoding to support phase correction. E1 and E2 were reconstructed separately and added afterwards to provide the final image. Experiments were performed on a 3 T and on a 7 T whole body MR system (3 T: Verio, 7 T: Magnetom Siemens Healthcare, G_{max} = 40 mT/m, maximum slew rate: 200 mT/m/ms). At 3 T the body coil was used for signal transmission and a 32 element head coil (Siemens Healthcare, Erlangen, Germany) was employed for signal reception. The posterior elements of the RX coil were disabled to reduce the signal contributions from the posterior part of the head. A customized six-element transceiver RF coil array consisting of loop elements was used at 7 T [9]. To demonstrate the feasibility of the segmented DWI-RARE approach five healthy volunteers without any known history of ocular disease were scanned after approval by the local ethics committee. The imaging parameters for 3 T/7 T were: TR = 7000/3000 ms, TE = 71/87 ms, echo train length (ETL) = 15/12, spatial resolution = (0.5 x 0.5 x 5) mm^3/(0.2 x 0.2 x 2) mm^3, receiver bandwidth = 488/260 Hz/pixel, acquisition time = 2:04/1:11 min. Diffusion sensitization ranging from b = 9 s/mm^2 to b = 540 s/mm^2 was employed. For comparison, single-shot diffusion weighted spin echo EPI was performed at 3 T (TR = 6700 ms, TE = 120 ms, echo spacing (ES) = 0.97 ms, EPI factor = 156, receiver bandwidth = 1106 Hz/pixel, spatial resolution = (1.5 x 1.5 x 0.5) mm^3, b = 0 s/mm^2 and b = 500 s/mm^2). To reduce eye motion induced artifacts a triggering scheme was used, which comprised 3 s of acquisition followed by a 3 s break for eye blinking.

Results: The application of diffusion sensitized split-echo RARE afforded ophthalmic imaging free of distortion at 3 T and at 7 T as demonstrated in Figure 1b-e and Figure 2a-d. For comparison, Figure 1g shows an EPI image exhibiting severe geometric distortions. The sub-millimeter in-plane resolution achieved with segmented DWI-RARE is superior to that previously reported for single shot DWI-EPI of the eye. No major degradation in image quality due to eye motion was detected for segmented DWI-RARE. The SNR obtained for segmented DWI-RARE of the vitreous humor using one average was 13.7 $\pm$ 1.4 for b = 540 s/mm^2 at 3 T. The ADC maps of the eye shown in Figure 1f and Figure 2e were calculated using the diffusion-weighted images together with a linear fit to the logarithmized image data. For a region-of-interest placed in the vitreous humor an ADC of (2.93 $\pm$ 0.17) x 10^{-3} mm^2/s was observed at 3 T. The 7 T data yielded an ADC of (2.93 $\pm$ 0.41) x 10^{-3} mm^2/s for the same vitreous humor ROI. Both results compare well with ADCs previously reported for DWI-EPI of the eye at 1.5 T [5].

Discussion: Diffusion sensitized ophthalmic imaging free of distortion is feasible with segmented DWI-RARE at 3 T and at 7 T. The distortion-free images obtained with segmented DWI-RARE can be easily co-registered with morphological MR images for anatomical reference which is beneficial for the assessment of spatial arrangements of the eye segments and their masses with the ultimate goal to provide guidance during diagnostic assessment and treatment of ophthalmological diseases. We anticipate to extend our explorations to enhanced diffusion weighting with b-values of up to b = 1000 s/mm^2. Although ocular MRI at 3 T is still an emerging area, it may be expected to continue to drive future technological developments. The high spatial resolution requirements of ophthalmic MRI are likely to motivate further advancements including the move towards ophthalmic imaging at 9.4 T and even higher magnetic field strengths which will afford further spatial resolution enhancements for DWI of the eye [9]. Further to ocular imaging the proposed segmented DWI-RARE approach is also suitable for targeting deeper lying sections of the orbit, the optical canal and the optic nerve. Imaging of the optic nerve bears clinical relevance for optic neuropathies in neuroinflammatory diseases and also for the differential diagnosis of debilitating autoimmune or orphan diseases of the central nervous system that run the risk of visual impairment [10,11].

Conclusion: Segmented DWI-RARE of the eye and the orbit at 3 T and 7 T is feasible and provides diffusion sensitized images free of distortion together with a sub-millimeter in-plane spatial resolution.

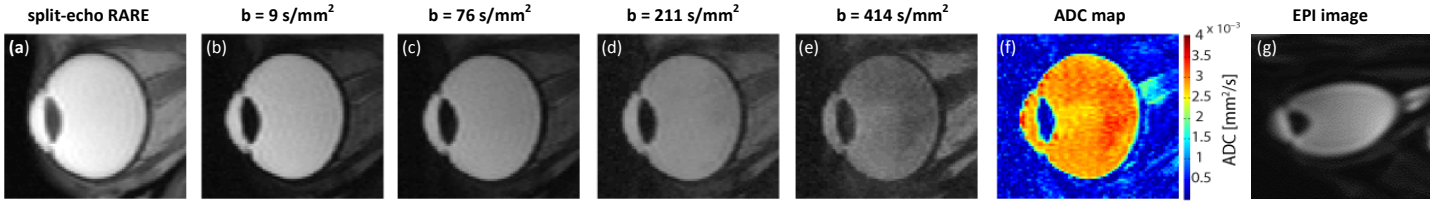

Figure 1: DWI of the eye at 3 T. (a) Split-echo RARE image of the eye serving as a reference. **(b)-(e)** Diffusion weighted images of the eye obtained with segmented DWI-RARE using b-values ranging from 9 s/mm^2 to 414 s/mm^2. **(f)** ADC map calculated from the diffusion weighted images. **(g)** EPI image (b = 0 s/mm^2). Please note the severe distortion.

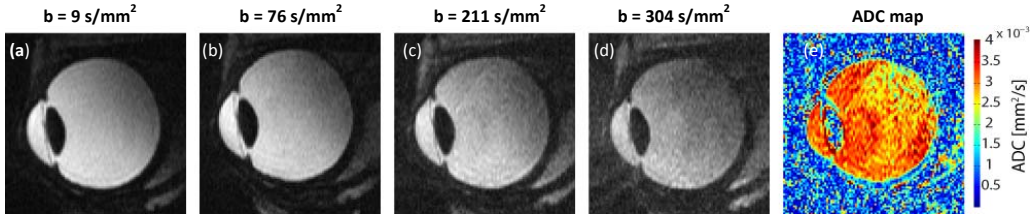

Figure 2: DWI of the eye at 7 T. (a)-(d) Diffusion weighted images of the eye obtained with segmented DWI-RARE using b-values ranging from 9 s/mm^2 to 304 s/mm^2. **(e)** ADC map calculated from the diffusion weighted images.

References: [1] Clark et al, *J Pediatr Ophthalmol Strabismus* 1999, 3:9; [2] Pineles et al, *J Pediatr Ophthalmol Strabismus* 2012, 16:529; [3] Sepahdari et al, *AJNR* 2012, 33:314; [4] Erb-Eigner et al, *Invest Radiol* 2013, 48:10; [5] de Graaf et al, *AJNR* 2012, 33:110; [6] Hennig et al, *MRM* 1986, 3:823; [7] Williams et al, *MRM* 1999, 41:734; [8] Schick, *MRM* 1997, 38:638; [9] Graessl et al, *Proc. Intl. Soc. Mag. Reson. Med. 21* (2013), p. 2747; [10] Wuerfel et al, *Mult Scler* 2012, 18:1592; [11] Sinnecker et al, *Neurology* 2012, 79:708