Towards High Spatial Resolution Diffusion-Sensitized MR Imaging of the Eye and Orbit at 3.0 T and 7.0 T: Quantitative Assessment of the Anatomic Fidelity of EPI and RARE Variants

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

Purpose: MRI of the spatial arrangements of the eye segments and their masses is an emerging application increasingly used in (pre)-clinical imaging and diagnostic radiology[1-5]. Diffusion-weighted MRI (DWI) probes self-diffusion of water in tissue on a microscopic level and holds the promise to enhance the diagnostic accuracy over anatomic imaging[6]. Single-shot echo planar imaging (ss-EPI) is most widely employed for neurovascular DWI. EPI is prone to magnetic susceptibility artifacts that manifest themselves as signal loss and image distortion. These detrimental effects are more severe at high field strengths, and particularly pronounced in regions with poor main magnetic field (B_0) homogeneity. For this reason diffusion weighted ss-EPI of cranial regions adjacent to cavities and sinuses or in close proximity to skin/muscle/bone/brain boundaries is prone to geometric distortions especially at (ultra)high magnetic field strenghts. This constraint constitutes a severe challenge for diffusion-sensitized EPI of the eye and orbit[7]. Readout segmented EPI (rs-EPI) was shown to afford DWI of the brain with largely reduced susceptibility artifacts[8,9]. Fast spin-echo imaging techniques are largely insensitive to B_0 inhomogeneity related image distortions and present a valuable alternative to EPI particularly at (ultra)high magnetic field strengths. Recognizing the clinical opportunities of ocular MRI this work examines the applicability of diffusion-sensitized multi-shot RARE (ms-RARE)[10] for the pursuit of anatomically accurate DWI of the eye and orbit at 3.0 T and 7.0 T. To meet this goal a quantitative assessment of the geometric fidelity of ss-EPI, rs-EPI and ms-RARE imaging of the eye is examined in healthy volunteers.

Methods: To examine the geometric fidelity of ms-RARE, ss-EPI and rs-EPI in vivo imaging was performed at 3.0 T and at 7.0 T (Siemens Healthcare, Erlangen, Germany) including (i) a transaxial slice covering the cerebral ventricles but excluding the eye and the orbit and (ii) a more caudal, transaxial slice covering the eyes and the orbit. At 3.0 T data were acquired with ms-RARE/ss-EPI/rs-EPI and: TR = 4000/6200/2000 ms, TE = 93/142/140 ms, ESP = 5.36/1.39/0.40 ms, receiver bandwidth = 232/416/228 kHz, spatial resolution = (0.9 x 0.9 x 5) mm^3. At 7.0 T imaging parameters for ms-RARE/ss-EPI/rs-EPI were: TR = 8160/9400/2000 ms, TE = 62/111/59 ms, ESP = 8.84/1.31/0.32 ms, receiver bandwidth = 334/526/275 kHz, spatial resolution = (0.9 x 0.9 x 1.5) mm^3. To elucidate the propensity of diffusion-sensitized ms-RARE, ss-EPI and rs-EPI to geometric distortions ADC mapping of the eyes was conducted at 3.0 T. Diffusion sensitization included six b-values ranging from 0 s/mm^2 to 500 s/mm^2. Imaging parameters were: TR = 3300 ms, TE = 85/171/88 ms, ESP = 4.98/1.22/0.32 ms, receiver bandwidth = 192/370/208 kHz, spatial resolution = (1 x 1 x 3) mm^3. To visualize the extent of geometric distortions, contours around the brain boundary, the cerebral ventricles and the eyes were defined in the ms-RARE images and transferred to the EPI variants. Quantification of geometric distortion was performed using center of gravity analysis. For this purpose, the areas within the contour around the eye were determined and the center of gravity was calculated. The deviation of the center of gravity (in pixels) was calculated with respect to the ms-RARE image.

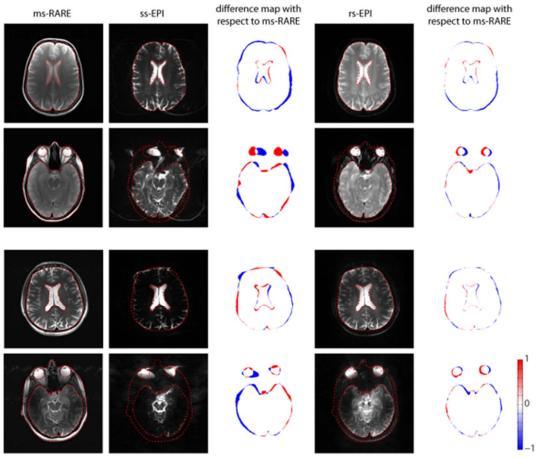

Figure 1: Comparison of ms-RARE, ss-EPI and rs-EPI (b = 0 s/mm^2) images acquired at 3.0 T (top) and 7.0 T (bottom) for two brain slices including (i) a transaxial cranial slice that covers the ventricles and (ii) a more caudal transaxial slice including the eyes and the orbit.

Results: For the cranial slice excluding the eyes and the orbit, ss-EPI images exhibited slight deviations from the actual anatomy, for both 3.0 T and 7.0 T as illustrated by the difference maps in Fig. 1. The prefrontal cortex and regions close to the sinuses showed distortions, which were pronounced at 7.0 T. Unlike ss-EPI, the anatomy of the brain was correctly maintained in the ms-RARE and the rs-EPI images for 3.0 T and 7.0 T. The more caudal slice including the eyes and the orbit showed stronger distortions, particularly for ss-EPI. The distortions in ss-EPI and rs-EPI primarily occurred in regions where air filled cavities and sinuses hamper the B_0 homogeneity. However, ms-RARE provided distortion-free images of the eye and orbit. To illustrate the propensity of diffusion-sensitized ms-RARE, ss-EPI and rs-EPI to geometric distortions, ADC maps acquired at 3.0 T are presented in Fig. 2. Severe geometric distortions were observed for ss-EPI while rs-EPI showed moderate distortions. For ss-EPI the center of gravity of the masked eyes was displaced by (20.2 ± 0.9) pixels versus the ms-RARE reference. In comparison, the displacement was reduced to (11.3 ± 0.8) pixels for the rs-EPI variant. For ms-RARE, no distortions and no other imaging artifacts were detected as indicated by the match between the ADC superimposed to anatomic reference images (Fig. 2). High spatial resolution diffusion-sensitized ms-RARE free of geometric distortion (Fig. 3) revealed mean ADCs of $(2.91 \pm 0.14) \cdot 10^{-3}$ mm^2/s at 3.0 T and $(2.93 \pm 0.41) \cdot 10^{-3}$ mm^2/s at 7.0 T for the vitreous body.

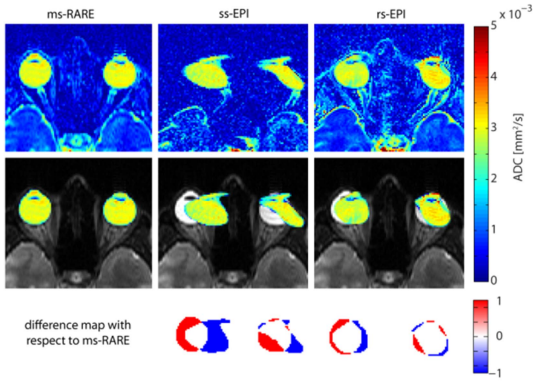

Figure 2: Comparison of ADC maps of the eyes acquired at 3.0 T. The ADC maps (top) were masked to only show the eyes and were superimposed to a T_2-weighted (middle) anatomic RARE image. The difference maps (bottom) demonstrate the extent of geometric distortions for both EPI variants.

Discussion: RARE-based techniques offer immunity to B_0 inhomogeneities and hence are particularly suited for ophthalmic DWI. This is of clinical relevance since ss-EPI is prone to magnetic susceptibility artifacts induced by the air filled nasal cavities and frontal sinuses surrounding the eye. Our results demonstrate that the propensity of ss-EPI to geometric distortions is exacerbated at 3.0 T and 7.0 T which constitutes a severe obstacle for DW-EPI of the eye and orbit at (ultra)high fields. State-of-the-art rs-EPI versions help to enhance geometric fidelity for ophthalmic DWI. However, our study demonstrated that rs-EPI still has some shortcomings in eliminating image distortion. ms-RAREs geometric fidelity underscores its value for advancing the capabilities of high spatial resolution DWI of the eye and orbit.

Conclusion: This study showed that diffusion-sensitized ms-RARE provides images of the eye and orbit free of geometric distortion. The results underline the challenges of ocular EPI at 3.0 T and 7.0 T and demonstrate that these issues can be offset by using fast spin echo based imaging techniques.

References: [1] Mafee et al, *Neuroimag Clin N Am* 2005, 15:23; [2] Apushkin et al, *Neuroimag Clin N Am* 2005, 15:49; [3] Sepahdari et al, *AJNR* 2012, 33:314; [4] Beenakker et al, *NMR Biomed* 2013, 26:1864; [5] Graessl et al, *Invest Radiol* 2014, 49:260; [6] Norris et al, *NMR Biomed* 1994, 7:304; [7] Erb-Eigner et al, *Invest Radiol* 2013, 48:10; [8] Porter et al, *MRM* 2009, 62:468; [9] Heidemann et al, *MRM* 2010, 64:9. [10] Williams et al, *MRM* 1999, 41:734.

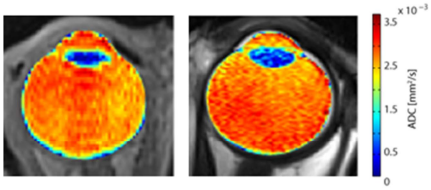

Figure 3: High spatial resolution ADC maps of the eye acquired with ms-RARE at 3.0 T (left, spatial resolution = (0.5 x 0.5 x 5) mm^3) and 7.0 T (right, spatial resolution = (0.4 x 0.4 x 3) mm^3) superimposed to anatomic images.