High-Field Compatible Methods for Reduction of Cerebrospinal Fluid Partial Volume Effects in DTI

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Introduction. Conventional DTI can be impaired by partial volume effects, particularly for brain structures adjacent to isotropic, rapidly diffusing cerebrospinal fluid (CSF). Fluid attenuated inversion recovery (FLAIR) combined with DTI [1] improves tractography and the derived parameters of the fornix, for example, albeit at the expense of increased scan time (and significantly reduced brain coverage) and decreased SNR [2]. However, specific absorption rate (SAR) constraints at ultra-high magnetic fields preclude the practical use of FLAIR with DTI, necessitating alternative strategies for CSF removal, ideally without increasing SAR nor negligibly affecting scan time. The repetition time (TR) can be reduced markedly by acquiring DTI data in smaller sets of slices to achieve the steady state effects of stronger T_1 weighting, thereby reducing the relative contributions from long T_1 CSF. In addition, a small degree of diffusion weighting can be applied on the minimal b values to somewhat attenuate CSF with minimal effects on brain tissue (i.e. do not acquire b=0 images) [3]. The latter methodology has been investigated using an approach requiring twice the typical scan time [4]; here, it is demonstrated that the increase in scan time is not necessary. These methods can be used separately or in combination, and both decrease the CSF signal at the expense of overall brain SNR. The effectiveness of the techniques is evaluated using deterministic tractography of the fornix, as it is commonly affected by CSF.

Methods. Four Stejskal-Tanner DTI protocols were acquired in five healthy subjects on a Varian Unity Inova 4.7 T MRI using standard DTI (DTI_S), reduced TR DTI (DTI_{TR}), DTI with no b=0 acquisitions (DTI_b), and a combination of DTI_{TR} and DTI_b (DTI_{TR+b}). Each protocol had a scan time of 8 min and used: FOV = 24 cm; 120 x 120 matrix (interpolated to 240 x 240); 40 slices, thickness 2.0 mm; 2 averages; R=2 GRAPPA. The differences between the four protocols are summarized in Table 1. For DTI_{TR} and DTI_{TR+b}, the TR was reduced from 6.0 s to 1.2 s by acquiring the 40 slices in 5 slabs consisting of 8 sequential slices each. The TR of 1.2 s was experimentally chosen based on the maximum suppression of CSF with respect to white matter per unit SNR loss. For DTI_S and DTI_{TR}, 30 directions at b = 1000 s/mm^2 were acquired along with 5 b = 0 scans (TE = 55 ms). For DTI_b and DTI_{TR+b}, 6 directions at b = 300 s/mm^2 were acquired (instead of any b=0) along with 30 directions at b = 1300 s/mm^2 (TE = 58 ms). The b = 300 s/mm^2 was chosen to reduce the ratio of CSF signal to WM signal to less than one in the low-b acquisition for a TR of 1.2 s (see ratios in Fig. 1). SNR of the four cases was measured on one average at minimum b value in grey matter (caudate nucleus) to mitigate the effects of diffusion anisotropy. ExploreDTI was used for tractography using an FA threshold of 0.3 and angle threshold of 60°. The crus and body of the fornix were analyzed, where tracts were selected if they passed through a selection region halfway along the desired portion of the fornix (i.e. crus or body) and any of two selection regions drawn at the extremes of the portion [2]. Voxels for FA and mean diffusivity (MD) analysis were chosen from the tract mask obtained from DTI_{TR+b}.

Results & Discussion. Fig. 1 and Table 2 show that both methods and their combination reduce the CSF signal relative to brain. For all 5 subjects, tract selection of the fornix (crus in particular) was easiest and most reliable using DTI_{TR+b}. Significant decreases of MD occur in all cases while increases in tract volume and FA (in agreement with earlier studies [2,5]) are observed in both tract portions for DTI_b and DTI_{TR+b}, and in only the crus for DTI_{TR}. Overall, the largest changes are for the combined method (40% for MD, 24% for FA, 83% for volume of crus); however, DTI_b appears to be more effective overall than DTI_{TR}. Notably, these methods do not require post-acquisition corrections that have also been proposed as an alternative to FLAIR [6]. The results indicate that it is possible to reduce partial volume contamination from CSF without increasing scan time nor SAR (particularly useful at high static fields); however, we note that the SNR penalty for these methods is relatively large (Table 1). With that said, the optimum choice of TR and b-values is not yet clear, and more SNR efficient implementations may be possible.

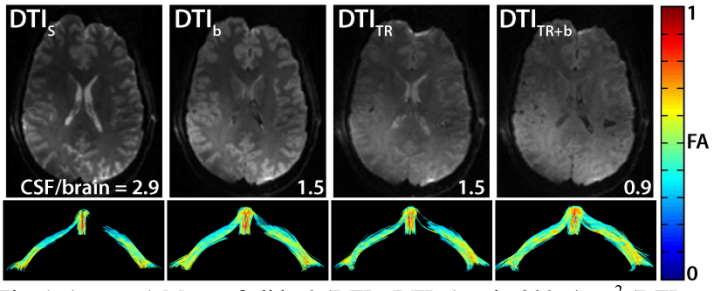

Fig. 1. (top row) Mean of all b=0 (DTI_S, DTI_{TR}) or b=300 s/mm^2 (DTI_b, DTI_{TR+b}) images for one subject (see Table 1 for protocol differences). The mean ratio (all subjects) of the CSF to deep grey matter is shown. (bottom row) Tractography of the fornix in one subject (coronal view). Note the improved tractography as the CSF signal is decreased.

Table 1: DTI Protocols

	DTI_S	DTI_b	DTI_{TR}	DTI_{TR+b}
Scan Time (min)	8	8	8	8
Min. b (s/mm^2)	0	300	0	300
Max. b (s/mm^2)	1000	1300	1000	1300
TR (s)	6.0	6.0	1.2	1.2
SNR; CSF (min. b, 1 ave)	165	67	60	21
SNR; Grey Matter (min. b, 1 ave)	58	45	39	23

Table 2: Diffusion Parameters and Volume of the Fornix in 5 Subjects

	DTI_S	DTI_b	DTI_{TR}	DTI_{TR+b}
Body				
FA	0.47 ± 0.06	**0.53 ± 0.04***	0.48 ± 0.03	**0.55 ± 0.03***
MD (10^{-3} mm^2/s)	1.3 ± 0.1	**0.99 ± 0.1***	**1.1 ± 0.1***	**0.81 ± 0.05***
Volume (10^3 mm^3)	0.9 ± 0.2	**1.2 ± 0.3***	0.9 ± 0.1	**1.2 ± 0.2***
Crus				
FA	0.41 ± 0.04	**0.47 ± 0.05***	**0.44 ± 0.05***	**0.51 ± 0.04***
MD (10^{-3} mm^2/s)	1.3 ± 0.1	**0.99 ± 0.08***	**1.0 ± 0.08***	**0.78 ± 0.04***
Volume (10^3 mm^3)	1.2 ± 0.7	**2.0 ± 0.9***	**1.7 ± 0.8***	**2.2 ± 1.1***

*: paired t-test p-value < 0.05, with respect to DTI_S.

References. [1] KK Kwong *MRM* 1991;21:157 [2] L Concha *AJNR* 2005;26:2267. [3] Proposed by D Le Bihan at ISMRM workshop on Methods for Quantitative Diffusion MRI of Human Brain, Lake Louise 2005 [4] ES Hui *ISMRM* 2009;3576. [5] MC Chou *AJNR* 2005;26:591. [6] O Pasternak *MRM* 2009;62:717.