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Reduced Field of View Diffusion Weighted Imaging of the Brain at 7T

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Abstract

Ventral and rostral regions of the brain are of emerging importance for the MRI characterization of early dementia, traumatic brain injury, and epilepsy. Unfortunately, standard single shot echo planar diffusion weighted imaging of these regions at high fields is contaminated by severe imaging artifacts in the vicinity of air-tissue interfaces. To mitigate these artifacts and improve visualization of the temporal and frontal lobes at 7T, we applied a reduced field of view strategy, enabled by outer volume suppression with novel quadratic phase radiofrequency pulses, combined with partial Fourier and parallel imaging methods. The new acquisition greatly reduced the level of artifacts in six human subjects (including four patients with early symptoms of dementia).

Introduction

Single shot echo planar imaging (EPI) has become the standard pulse sequence for diffusion weighted imaging of the brain due to its high speed and efficiency. Unfortunately, EPI suffers from significant image artifacts primarily due to inhomogeneities in the main magnetic field, which although mild in some areas of the brain make measurements of diffusion parameters or fiber tractography in other regions impossible (i.e. near air-tissue interfaces).

Rapid diffusion encoding and traversal of k-space minimize the $T_2^{(*)}$ dephasing that degrades the image quality. In practice, however, technical and biological constraints on gradient systems impose relatively long echo times (TE) and readout durations in order to achieve high spatial resolution and high b-values. The long TE reduces the image signal-to-noise ratio (SNR), causing total signal dropout in some regions. The long readout time results in geometric distortion and residual fat misregistration (results of low imaging bandwidth in the phase encoding direction), as well as T_2 blurring. These effects are exacerbated at higher field strengths, or when high spatial resolutions are desired (i.e. requiring a long readout).

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To mitigate these effects at high field, undersampling along the phase encoding dimension using a combination of parallel imaging and partial Fourier acquisition can be applied in order to shorten the readout and / or echo times required to attain standard clinical spatial resolutions (~ 2 mm in-plane) [1]. Despite these measures, geometric distortion remains severe in ventral and rostral regions of the brain near the air-filled paranasal sinuses and petrous apices, hence limiting characterization of the temporal and frontal lobes, which are key targets for evaluation in Alzheimer's disease [2], frontotemporal lobar degeneration [3], traumatic brain injury [4], and epilepsy [5]. Further readout shortening by higher parallel imaging reduction factors ($R > 3$) tends to incur prohibitive SNR losses by the g-factor [6], and multi-shot approaches such as multi-shot EPI [7-9] or PROPELLER [10] have the disadvantages of increased imaging time and specialized acquisition and processing (typically offline) to compensate for motion-induced phase differences (for in-plane motion only) among the shots.

Alternatively, readout shortening in EPI can be achieved by limiting the field of view (FOV) along the phase encoding direction [11-13], provided that aliasing from outer volume signals does not occur. The purpose of this study was to take advantage of the SNR gain of 7T to allow high resolution DWI in the frontal and temporal lobes, while reducing artifacts in these regions using outer volume suppression (OVS) -based reduced FOV methods enabled by a novel quadratic phase radiofrequency (RF) suppression pulse [14-17], in combination with parallel imaging and partial Fourier acquisition strategies.

Materials and Methods

Six human subjects (four exhibiting early symptoms of dementia) were scanned at 7T using both standard echo planar and the proposed reduced FOV diffusion tensor imaging (DTI) protocols. Imaging experiments were conducted on a 7T research scanner (GE Healthcare, Waukesha, WI), equipped with an eight-channel phased array head coil positioned within an insert volume transmitter coil (Nova Medical, Wilmington, MA). Prior to the DTI acquisitions, higher order shimming with multichannel B₀ mapping was performed using in-house software [18]. The standard 7T single shot spin echo EPI DTI protocol includes state of the art methods of axial, full brain coverage at 1.8-mm isotropic spatial resolution (FOV= 23cm, matrix= 128×128, 40 slices), with $b=1000$ s/mm². With $R=2$ ASSET parallel imaging and 62% fractional k -space phase encoding (40 lines acquired), a minimum TE of 62ms and readout duration of 25ms were achieved. For the reduced FOV acquisition, the number of acquired lines was further reduced by halving the phase FOV (anterior-posterior direction) to a 11.5-cm region covering both temporal lobes (24 lines). The readout duration was thus shortened to 16 ms, while the minimum TE remained unchanged, constrained mainly by limited gradient strength for diffusion encoding. The nominal spatial resolution was identical for both scans.

Outer volume suppression was achieved using a pair of custom designed quadratic phase 90° RF pulses [14-17] that were integrated into the DTI pulse sequence with graphic prescription capability and placed anteriorly and posteriorly around the temporal lobes. The pulse (Fig. 1) was designed for low peak power and high bandwidth, for reduced sensitivity to decreased RF coil efficiency and increased B₀ variation at 7T, respectively. The pulse was designed in MATLAB (Mathworks Inc., Natick, MA) using an extended version [17] of previously described routines [19], which allows specification of a quadratic phase, parameterized by a linear delay and a quadratic shift, over the passband of the desired frequency response function. The RF waveform was then back-calculated from the resulting A and B polynomials (B derived using the Parks-McClellan algorithm), using the usual piecewise constant approximation [19]. Finally, the magnetization response was simulated as a function of frequency offset, and a 90° pulse with the desired bandwidth and peak B₁ amplitude was designed by iteration over the parameter set.

The final chosen suppression pulse (Fig. 1) had a time-bandwidth product of 16, and a peak B_1 of 0.111 Gauss (G) for a 90° pulse with 5 ms duration. The effectiveness of suppression was compared to a standard linear phase SLR pulse optimized for 1.5T (time-bandwidth product = 6.4, peak B_1 = 0.089 G with 4 ms duration). The uni-axial crusher gradient area was 3000 G $\mu\text{sec} / \text{cm}$. For simpler evaluation of the effectiveness of suppression, the pulses were initially tested on a high dielectric head phantom (17-cm sphere, doped water) in a standard 2D gradient recalled echo (GRE) pulse sequence, using the quadrature transmitter coil in transmit-receive mode (i.e. without phased array receive).

The imaging time for each DTI protocol was 4 min, 12 sec (TR= 9 s, 6 directions, NEX=4). Rapid multi-slice low flip angle 2D GRE scans of the whole brain were acquired for image domain parallel imaging calibration (by the array spatial sensitivity encoding technique, or ASSET). Maps of the apparent diffusion coefficient (ADC) and fractional anisotropy (FA) were generated from images acquired using both protocols by processing of the diffusion weighted images in FSL [20].

Results

Suppression is greatly improved with the use of the optimized quadratic phase pulse. Comparative saturation profiles are shown in Figure 2. The suppression profile is substantially sharper for the quadratic phase pulse due to the higher bandwidth, in the presence of large B_0 variation at 7T. There is some observable spatial variation in the effectiveness of suppression due to B_1 variation, but it is small. Also, this effect is reduced in the transition to human studies due to smaller B_1 variation *in vivo*, as compared to a water phantom of similar size [21].

Reduced FOV acquisition dramatically reduced the level of distortions and blurring in diffusion imaging of the brain at 7T, especially in the ventral and rostral regions of interest in the frontal and temporal lobes, with no apparent artifacts due to incomplete suppression. The diffusion images in Figure 3 demonstrate the artifact reduction in the area of the medial temporal lobe. Furthermore, in addition to a smaller fat shift, the reduced FOV DWI has added fat suppression due to suppression of the scalp in the outer volume (beyond the standard chemical saturation pre-pulse already in the sequence).

Discussion

The most important result of this work is the improved visualization of the temporal and frontal lobes using reduced FOV 7T DWI over conventional full FOV DWI. The OVS approach [11] was selected here over other potential approaches. Reduced FOV acquisition is also possible by selective excitation of the inner volume with 2D RF pulses [12], or by selection of the intersecting region of tilted 90° and 180° pulses in a spin echo preparation, termed zonal oblique multisection EPI (ZOOM-EPI) [13]. However, 2D excitation pulses are currently unattractive for high field imaging, because of high power deposition and prolongation of the minimum TE, and the utility of ZOOM-EPI is reduced by wide minimum slice gaps for small targeted regions. Since only the imaged slice is excited, our approach is the most amenable to efficient multi-slice imaging.

The still relatively long minimum echo time cuts into the SNR advantage available at higher field for DWI, due to apparent T2 shortening. All other factors being equal, the SNR advantage for 7T over 3T is approximately

$$\frac{SNR_{7T}}{SNR_{3T}} = \frac{7}{3} \exp\left(\frac{TE}{T_{2,3T}} - \frac{TE}{T_{2,7T}}\right)$$

The exact extent of the T2 effect is unclear, as published estimates of white matter T2's at 3T vary widely from 48ms - 77ms [22-26], and few estimates exist for 7T, with one recent study reporting 47 - 50ms [22]. Using the average values among these measurements, the expected gain is 80% at the TE used in this study. However, a 3T / 7T comparison study reported retention of a SNR advantage of 80% at TE=89ms for 7T over 3T in spin echo single shot EPI diffusion [27]. Additional considerations include that (1) additional undersampling at higher field for reduced FOV or parallel imaging may cut into the SNR gain by signal averaging effects, and (2) reduced FOV will likely increase the g-factors for a given reduction factor, but not as much as for correspondingly larger reduction factors over the full FOV.

In EPI-based DTI, the OVS methods described here introduce the possibility for reduced artifacts for a given spatial resolution in difficult anatomic regions at high field (as demonstrated here), or higher spatial resolution at a fixed artifact level. The best implementation depends on the specific application. In the context of standard anatomic gradient or spin echo imaging, this approach would allow imaging at higher spatial resolution within a reduced acquisition time, which could be significant for high field imaging.

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Figure 1.
Quadratic phase RF pulse waveform amplitude (bottom) and phase (top).

Figure 2.

Saturation profiles for standard linear phase pulse (left image, blue line) and quadratic phase pulse (right image, red line) in a water phantom. Intensity variation across the phantom is due to B_1 inhomogeneity, which is typically corrected through postprocessing.

Figure 3.

Axial DWI data from patient with early symptoms of dementia. Left column-standard acquisition incl. ASSET R=2 (cropped to match coverage with reduced FOV data). Right column- reduced FOV acquisition. Row 1: b=0 images from slice through temporal lobes. Row 2: DWI images. Row 3: ADC maps. Row 4: FA maps. Top right: placement of axial slice (white line) and saturation bands (yellow) on sagittal localizer image.