Comparison of Sequences for Improved Diffusion Weighted Imaging at 7 T

P. S. Morgan[1], R. J. Coxon[2], J. Habib[1], P. A. Gowland[2], and R. Bowtell[2]

[1]Academic Radiology, University of Nottingham, Nottingham, United Kingdom, [2]Sir Peter Mansfield MR Centre, University of Nottingham, Nottingham, United Kingdom

Introduction

Diffusion weighted (DW) images are typically acquired using a single-shot, spin-echo, echo planar imaging (EPI) sequence. Due to its inherently low bandwidth per point in the phase encoding direction, EPI acquisitions are susceptible to inhomogeneous magnetic fields which manifest as spatial distortions in the image. As well as magnetic field inhomogeneities caused by spatial variation of magnetic susceptibility in the object being imaged, in DW imaging inhomogeneities may also be caused by eddy currents arising from the strong gradient pulses used to apply diffusion weighting[2]. Acquisition of suitable images from which the diffusion tensor, or other directional information required for tractography, may be estimated requires that diffusion weighting gradients be applied in multiple, non-co-linear directions. Gradients applied in each different direction may generate eddy currents with different characteristics and hence varying patterns of spatial distortion in the DW images. This results in misalignment of pixels between different diffusion weighting directions, which introduces errors into the calculated diffusion tensor. Therefore, to allow a better estimate of the diffusion tensor, spatial distortion between diffusion directions must be accounted for and ideally corrected.

The recent introduction of high field, whole body MR systems offers the promise of increasing the spatial resolution achievable in DW-EPI. However, the sources of spatial distortion described above would also be expected to increase at higher field, (due to higher field inhomgeneity and potentially larger eddy current effects from the stronger gradients required at high field) making the reduction or correction of distortion more crucial in order to obtain accurate diffusion parameters. A number of methods have been proposed to correct eddy current induced spatial distortion in DW-EPI, ranging from pure post-processing[1], to use of additional pre-scans to map the phase evolution throughout the EPI echo train[2], to modifying the acquisition so as to reduce eddy current effects[3]. Previously we have described a post-processing correction technique involving acquisition of two images, the second with reversed polarity of the blipped phase encoding gradient compared to the first[4,5,6,7]. While this technique performs well overall, it can produce poor results in regions of high spatial distortion. In order to address this, we have implemented and compared four DW-EPI pulse sequences at 7 T with the aim of reducing the effects of eddy currents from the large diffusion gradients. The performance of each pulse sequence was assessed in terms of average spatial distortion and resulting signal to noise ratio (SNR).

Method

Single-shot DW-EPI images were acquired using an Achieva 7 T MR scanner (Philips Medical Systems, Best, The Netherlands) with a 16 channel head coil (Nova Medical, Wilmington, MA, USA). All scanning was performed with approval from the local research ethics committee. 24 axial slices were acquired from the lateral ventricles to the top of the brain, with 2 mm slice thickness, 192 mm FOV, 96x96 matrix, 0.72 partial Fourier factor, TR=10 s. Fifteen diffusion directions were acquired using the Philips 'no overplus' scheme with b=800 s/mm^2. The acquisition bandwidth was fixed. The shortest accessible TE was used, although this varied for each sequence. The four pulse sequences investigated were: 1) Philips product single spin-echo DW-EPI 2) Twice-refocused spin-echo (TRSE) DW-EPI[3] 3) Stimulated echo (STE) DW, followed by a spin-echo (SE) EPI readout 4) STE-DW, followed by a gradient-echo (GE) EPI readout. The aim of the STE sequences was to temporally separate the eddy current inducing DW gradients from the imaging gradients (TM=50ms). In addition, the amount of cancellation of eddy currents in the TRSE sequence is influenced by the relationship between the rate of decay of the eddy currents and the two TEs used; in this study the ratio of the two TEs is represented by an asymmetry weighting factor, with a value of 0.5 representing equal TEs. For the most promising sequences, the use of parallel imaging was also investigated.

The overall spatial distortion present in each acquisition was taken as the mean pixel shift calculated by the reversed gradient correction scheme[4] over all DW directions in a volunteer's brain. The SNR for each acquisition was measured from the b=0 images acquired using the same acquisition of an agar phantom, with similar relaxivities to brain, allowing a uniform region in the images to be measured. Each sequence was assessed by a simple score of the ratio of SNR to mean distortion, to highlight results with both a high SNR and low distortion.

Results

An example of the reversed gradient correction is shown in Figure 1. Figure 2 details the mean spatial distortion measured for each sequence. Figure 3 shows the performance of each sequence in terms of the ratio of SNR to distortion, where a high score suggests a high SNR and low spatial distortion.

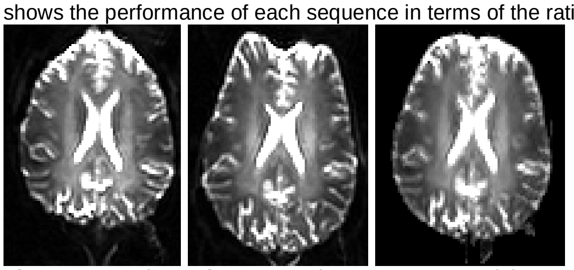
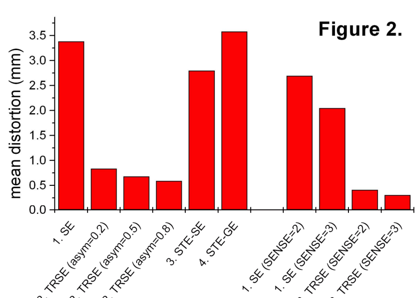
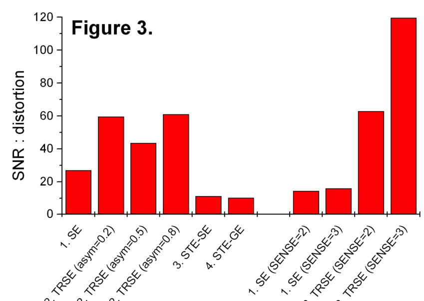


Fig. 1a. Normal b=0 **1b**. Reversed phase, b=0 **1c**. Corrected, b=0





Discussion

This study demonstrates the successful implementation and comparison of a number of DW sequences on a 7 T scanner. The spatial distortion was worst in the product single SE DW-EPI acquisition and the stimulated echo GE acquisition. A small reduction in distortion was seen when using the SE version of the STE acquisition. The greatest decrease in spatial distortion was observed with the twice-refocused sequence, with a trend for even less distortion when the second TE is made longer than the first TE. The application of parallel imaging results in the expected reduction in spatial distortion.

When the SNR is also considered, the STE sequences perform the worst, follow by the single SE sequence. The TRSE sequence performs the best in terms of both SNR and distortion. Unlike in the single SE case, where application of parallel imaging reduces the ratio of SNR to distortion, in the case of the TRSE sequence, parallel imaging improves this score. This suggests that in the case of the single SE, with a relatively short TE (~78 ms), the loss of SNR with application of parallel imaging dominates over the reduction in distortion, whereas for the TRSE sequence with a longer TE (~155 ms) and which already has lower distortion, the loss in SNR due to use of parallel imaging is outweighed by the effect of the reduction in minimum accessible TE.

Conclusion

Four DW sequences have been implemented and compared using a 7 T human scanner, considering both spatial distortion and SNR. Characterisation of the interplay between distortion, SNR, and parallel imaging is not straightforward. This study suggests that the use of a TRSE DW acquisition is preferable at 7 T, and unlike the single SE sequence, is further improved by application of parallel imaging.

References

1. Mangin J-F et al. Medical Image Analysis 2002;6:191-198.
2. Calamante F et al. Magn.Reson.Med 1999;41:95-102.
3. Reese TF et al. Magn.Reson.Med 2003;49:177-182.
4. Morgan PS, Bowtell RW *et al*. J.Magn.Reson.Imaging 2004;19:499-507.
5. Andersson JLR *et al*. Neuroimage 2003;20:870-888.
6. Morgan PS, *et al*. Proc ISMRM, p800 (2000)
7. Embleton K, *et al*. Proc British Chapter ISMRM (2005).
8. http://www.fmrib.ox.ac.uk/fsl/