Reducing distortions in DW-EPI with a dual-echo blip-reversed sequence

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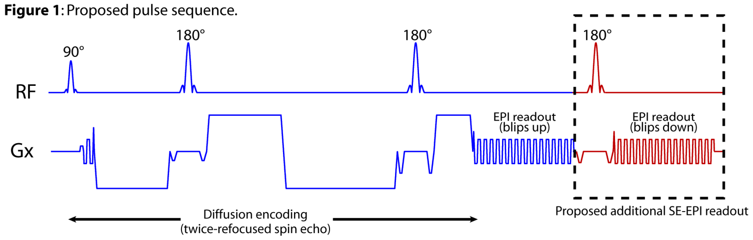
INTRODUCTION: EPI images are inherently degraded by distortions induced by B_0 inhomogeneities which make diffusion-tensor imaging (DTI) challenging in severely affected areas. One approach to reduce these distortions is to unwarp the image in post-processing; however, these procedures often fail in severely distorted regions such as the frontal or temporal lobes. Another approach is to reduce the (effective) echo spacing (time between adjacent k-space lines), which can be achieved with parallel acceleration techniques such as SENSE [1] or GRAPPA [2]. The accelerated images will still be affected by residual distortions in regions like the frontal lobes, which may then be more amenable to conventional unwarping algorithms. In this work we consider the combination of acceleration with "blip-up-blip-down" acquisitions, in which two images are acquired with opposite phase encode direction, and combined in post-processing to create an undistorted image. However, this method has the significant drawback that each diffusion-weighted image must be acquired twice, reducing the total number of measurable directions and ultimately increasing the uncertainty in the reconstruction of the diffusion tensor [3]. We propose an alternative approach in which the blip-up and blip-down images are acquired during consecutive spin echoes in a single repetition time, achieved by adding an additional refocusing pulse and EPI acquisition to the end of a standard spin-echo sequence (see Fig. 1), similar to a previous method used for BOLD fMRI [4].

Figure 1: Proposed pulse sequence.



THEORY: To reconstruct the corrected image, Andersson *et al* create matrices describing the positive and negative warps resulting from the B_0 field and invert the combined matrix [5], thus allowing regions of signal compression in one image to be informed instead by the other image where the signal will be stretched. However, using this method directly on images acquired using the pulse sequence shown Fig. 1 may cause problems due to the different T2-weighting resulting from the different echo times of the blip-up and blip-down images.

In DTI, it is very common to acquire multiple images with b=0 s/mm^2. We therefore propose that when the b=0 measurement is repeated, the order of the blip-up and blip-down images is swapped, resulting in high-SNR images with opposite distortions at both echo-times (i.e. 4 total images). This allows us to estimate the voxel-wise T2 attenuation between echo 1 and echo 2 for blip-up and blip-down images, which can then be used to correct the contrast in the diffusion-weighted images prior to the matrix inversion. Having two TE-matched images with opposing blips also allows direct estimation of the B_0 field [5] as an alternative to performing a separate field-mapping acquisition.

Should the inversion approach fail due to the differing contrast in the blip-up and blip-down images, part of the benefit of the blip-up-blip-down approach can still be achieved by separately unwarping the two images (using a method such as pixel-shifts [6]) and adding them together. This approach offers the added benefit of allowing the images to be combined with weighting chosen to maximise the total SNR.

In this work we compare the results of the reconstruction by the three methods described above: 1) Direct matrix inversion of blip-up/down images at different TEs; 2) Matrix inversion of T2-corrected blip-up/down images; 3) Weighted sum of separately unwarped blip-up/down images.

METHODS AND RESULTS: Data were acquired using a Siemens 3T TIM Trio system equipped with the vendor supplied 8-channel head coil. To investigate the proposed reconstruction methods, we collected diffusion-weighted data using the vendor-supplied diffusion-weighted, twice-refocused spin echo sequence. Assuming a matrix size of 96x96 (FOV 210x210 mm), partial Fourier sampling of 6/8 and b-value of 1000 s/mm^2, the minimum achievable TE was 93 ms which was reduced to 86 ms when using a GRAPPA acceleration factor of 2 (GRAPPAx2). The minimum achievable TE for a second echo following the accelerated image was calculated at 127 ms (assuming 10 ms for a refocusing pulse and spoilers). Images were acquired at these echo times in separate TRs to investigate the 3 reconstruction methods proposed above without requiring the implementation of the multi-echo pulse-sequence in Fig. 1 (which will be the focus of future work).

Fig. 2 (top row) shows the uncorrected images from a single diffusion-weighted slice with blips up and down for the unaccelerated and the GRAPPAx2 acquisitions. The distortions in the unaccelerated data are too great to unwarp effectively (data not shown), making acceleration an attractive option. All 3 proposed methods of combining the two GRAPPAx2 images produce visually better images than simply unwarping the first echo (Fig. 2, bottom row). Our preferred approach is method 2 (T2-corrected matrix inversion) as this is expected to produce the best estimate of the true data in severely distorted regions.

CONCLUSION: The blip-up-blip-down approach to correcting distorted DW-EPI images typically requires the acquisition of each image twice. In our method, the addition of the extra echo requires only ~25% longer total scan time. Despite the TR increase, accounting for the SNR gain due to the extra data from the second echo we predict a ~5% gain in SNR for the combined, multi-TE data relative to a single, accelerated echo. Moreover, our method is able to reduce distortions by combining blip-up and blip-down images to achieve drastically improved image quality compared to unaccelerated data. Future work will involve applying this method to diffusion tractography.

REFS: [1] Pruessmann *et al*, MRM 42 (5) 952-62 (1999); [2] Griswold *et al*, MRM 47 (6) 1202-10 (2002); [3] Jones, MRM 51 (4) 807-15 (2004)
[4] Weiskopf *et al*, Neuroimage 24 1068-79 (2005); [5] Andersson *et al*, Neuroimage 20 (2) 870-88 (2003); [6] Jezzard and Balaban, MRM 34 (1) 65-73 (1995)

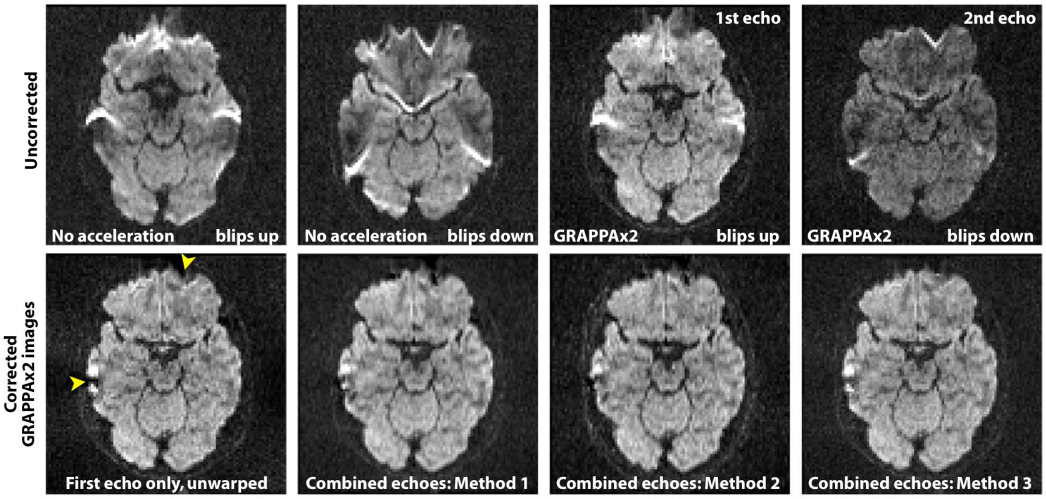


Figure 2: Top row shows comparison of uncorrected images with blips up and blips down. Bottom row shows result of different reconstructions of accelerated blip up/down data.