Single-shot Multi-echo Parallel EPI for DTI with Improved Efficiency and Accuracy

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Introduction

Single-echo EPI [1] is the most widely used acquisition strategy for diffusion tensor imaging (DTI) due to its insensitivity to motion. However, limited spatial resolution, sensitivity to field inhomogeneity, and low signal-to-noise ratio (SNR) are serious limitations that come with EPI. Parallel imaging and high field have been demonstrated to effectively mitigate these limitations [2]. Parallel imaging reduces EPI acquisition window, permitting the acquisition of multiple images with multiple echoes after a single excitation and providing a SNR gain when these images are properly combined. The present work investigates the benefits of acquiring multi-echo images using parallel EPI for DTI. In addition to the expected gains of reduced distortion artifacts and increased spatial resolution, the multi-echo approach is expected to improve SNR, reduced number of measurements needed, and to provide a T2 map. Three strategies for combining the echoes are evaluated in terms of SNR against the first echo alone. The three strategies are image summation with equal weights (simple sum), sum of the square of the image (SOS), and image summation in which each echo image is pixel-wise weighted by the ratio of its intensity to the first echo image (weighted summation). The SNR in each image is based on images obtained in normal volunteers with b=0. The benefit of the method is further demonstrated by the calculated fractional anisotropy (FA) images and T2 maps.

Table 1. Echo times used for different acceleration factors

R	TE(1) (ms)	TE(2) (ms)	TE(3) (ms)	TE(4) (ms)	TE(5) (ms)
2	96	148	200	252	-
3	85	124	163	202	-
4	80	110	140	170	200

Materials and Methods

Starting from a standard DTI sequence (4), the multi-echo pulse sequence was implemented by adding additional RF refocusing pulses and EPI acquisition of each additional echo. Phase encoding gradients are rewound between consecutive echoes.

All experiments were performed on a 3T Siemens Tim™ whole-body MR scanner (Siemens Medical Solutions, Malvern, PA) using a 12-channel volume coil for reception and the body coil for transmission. Data acquisition was performed on five healthy subjects (average age of 30±4) with imaging resolution of 2×2mm^3, a matrix size of 128×128, a slice thickness of 2 mm and 10 slices. Three imaging protocols with acceleration factors (R) of 2, 3, and 4 were considered. The following imaging parameters were used: 4 echoes with possible minimum echo spacing, TR = 3 s, bandwidth = 1562 Hz/pixel, FOV = 256 mm, 10 axial slices, b=1000 s/mm^2, and 12 diffusion weighting directions (plus b=0). The specific parameters used for each imaging protocol are summarized in Table 1. GRAPPA [3] was used for image reconstruction.

Echo combination was performed offline assuming no motion between the acquisitions of different echoes. The SNR was defined as the ratio of the mean of the signal of a region of interest (ROI) to the standard deviation of the background. Six different regions of interest, corresponding to major white matter (WM) tracts (genu and splenium of corpus callosum, FA = 0.63-0.78), subcortical WM (superior temporal gyrus and middle temporal gyrus, FA = 0.42-0.48), and cortical gray matter (GM) (GM regions adjacent to the 2 gyri mentioned above, FA = 0.13-0.19), were analyzed. Each ROI was defined based on the visible outline of the corresponding structure on a 2D section and cross-referenced with b0 images to avoid inclusion of CSF-filled spaces. FA map was generated after distortion correction with FSL (FMRIB, Oxford, UK). T2 maps were calculated by mono-exponential fitting of b=0 echoes images. All custom computer programs were implemented in Matlab (The MathWorks, Inc., Natick, MA, USA).

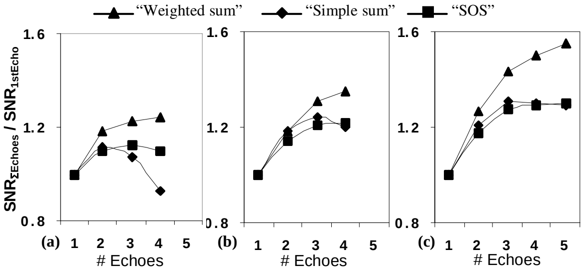

Fig.1. Relative SNR change between the combined echoes image and the 1st echo image as a function of the number of echoes for different echoes combination strategies and for different parallel MRI acceleration factors: (a) R = 2; (b) R = 3; (c) R = 4.

Results and discussion

Figure 1 shows plots of the ratio of the SNR of the combined echoes to that of the first echo as a function of the number of echoes for the three combination strategies and for the 3 acceleration factors: R = 2 (Fig. 1a); R =3 (Fig. 1b); R = 4 (Fig. 1c). Each plot reflects the average of the relative SNR across the ROIs, the slices and the subjects. The weighted sum combination results in the highest gain in SNR in all cases. These results suggest that the SNR of the combined echoes tapers off after about 2 echoes at R = 2 whereas at higher reduction factors, SNR plateaus at more echoes. This is understandable because the shorter echo spacing at higher R allows the inclusion of more echoes before the signal drops out due to T2 decay. At R = 4 the weighted sum of 3 echoes gives an SNR increase of 43% relative to the first echo. This value is comparable to a theoretical increase of ~ 41% that would be expected from two averages, suggesting that the gain in SNR can be used to reduce the number of measurements and thereby leading to reduced scan time. To validate this observation, we generated FA maps from three situations as depicted in Fig.2. Fig.2a illustrates FA map obtained from the first echo image without any averaging corresponding to a total scan time of 57 s. Fig. 2b shows the FA map obtained by averaging the first echo image twice resulting to an acquisition time of 1min 36 s. Fig.2 c presents the FA map generated by weighted sum combination of 3 echoes acquired with the same scan time as in Fig. 2a. While the FA map generated from the first echo images without averaging exhibits significant noise level (Fig. 2a), the noise level in the FA map generated from the 3 echo combination is significantly reduced (Fig. 1c), on par with that in the FA map generated with 2 averages (Fig. 1b). Fig. 3a shows the T2 weighted image and corresponding T2 map (Fig. 3b) generated from 4 echoes of the R=4 multi-echo data set. The T2 map is of high quality, demonstrating the potential for providing complementary information with an accurate estimation of T2.

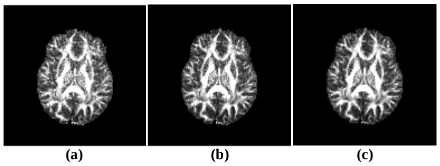
(a) (b) (c)

Fig.2. Comparison between FA maps generated from multi-echo DTI data sets of a healthy subject from: (a) 1st echo image without averaging; (b) 1st echo images with 2 averages; (c) combination of three successive echoes of a single excitation without averaging

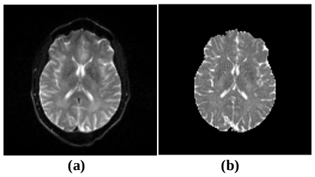
(a) (b)

Fig. 3. T2-weighted image (a) and corresponding T2 map (b) generated from 4 echoes of the same single excitation multi-echo data set as in Fig.2c.

Conclusion

We have implemented and demonstrated the effectiveness of a single-shot multi-echo parallel DW EPI sequence in improving the SNR and accuracy in diffusion tensor imaging. Weighted sum of echoes leads to highest SNR gains relative to the first echo. This SNR gain can be used to reduce the number of measurements needed or improve the image resolution. Furthermore, these additional echoes can be used to calculate the T2 map, providing complementary information that might be useful in some applications.

References:

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