Minimization of Eddy Current Artifacts in Diffusion Tensor Imaging by a STEAM-EPI Sequence at 3.0 Tesla

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Synopsis

Using a stimulated echo instead of a spin echo preparation for diffusion tensor imaging of tissues with a low T1/T2 ratio leads to an increased SNR for large b-values especially at higher field strength. However, high diffusion gradient pulses cause significant eddy currents creating severe image artifacts in diffusion-weighted maps. In this work, additional gradient waveforms were implemented in a diffusion-weighted stimulated echo EPI sequence for minimizing the influence of given eddy currents without any increase in the minimum TE or acquisition time. Diffusion map calculations from diffusion tensor could be performed without significant image distorsion.

Introduction

Diffusion-Tensor-Imaging (DTI) with echoplanar readout imaging (EPI) using spin-echo (SE) preparation has become an established tool to provide additional information about microstructure and pathology in brain [1] as well as other tissue like kidney [2] or skeletal muscle [3]. However, tissues like kidney or skeletal muscle with a low T2/T1 suffer from a poor SNR for higher b-values. Using a stimulated echo sufficiently high b-values can be obtained by increasing the mixing time (TM) rather than TE. Therefore, no dramatical transverse relaxation losses but only moderate longitudinal relaxation losses occur for tissues with low T2/T1 ratios. Diffusion gradient pulses with high intensity can cause large eddy currents (EC) in EPI leading – especially for higher fields - to spatial distorsions dependent on the direction of the applied diffusion gradients. For DTI this can lead to misregistration artefacts in calculated diffusion maps from multiple images with different gradient directions. Herewith, a diffusion-weighted stimulation echo EPI sequence is proposed which drastically reduced eddy current-induced image distorsions.

Methods

Additional gradient waveforms are implemented in a diffusion-weighted stimulated echo EPI sequence for minimizing the influence of given eddy currents as proposed in [4] but without any increase in the minimum TE or acquisition time (Figure 1). Assuming a monoexponential decay with time constant λ, eddy current effects proportional to $e^{-\lambda t}$ vanish, if $t_1 = \lambda \cdot \ln(1 + e^{-s/\lambda} - e^{-(t0+s)/\lambda})$ and $t_2 = \lambda \cdot \ln(1/(1 + e^{s/\lambda} - e^{(t0+s)/\lambda}))$. As a main source of artifacts in DTI, eddy currents with a time constant $T/\lambda_0 \approx \ln 2$ are assumed where T is the time between start time of an EC causing gradient and the begin of the read-out. For $\lambda_0 >> t_0$ the first equation simplifies to $t_1 = t_0$. For t_2, λ_0 = 20 ms was chosen. Eddy currents with other time constants λ between 10 and 100 ms can also be drastically reduced (residual eddy current < 7%). In-vivo DTI measurements were performed in human calf musculature on a 3.0 T Siemens Trio unit. Measurement parameters were TE = 37 ms, TM = 100 ms, TR = 4000 ms, b = 0 resp. 500 s/mm^2, Matrix 64 x 64, FOV 200 mm, NEX = 10, slice thickness 7 mm. The chosen TE and TM values will maximize the SNR of the diffusion map. Diffusion weighting was applied in several directions in order to calculate the diffusion tensor and to demonstrate the elimination of the distorsion effects caused by eddy currents. The maximal gradient amplitude was 35 mT/m.

Results

Diffusion-weighted images of human calf musculature obtained with a stimulated echo EPI sequence were acquired without (Fig. 2a) and with (Fig. 2b) EC correction. Diffusion gradient pulses were applied in phase, readout and slice direction. In Fig. 2a obvious scaling and shearing distorsions occur whereas in Fig. 2b no significant distorsions are observed. Diffusion map calculations from diffusion tensor could be performed without significant image distorsion.

Discussion

Due to a long readout time, EPI is very senstitive to image distorsions caused by eddy currents due to strong diffusion gradients. The geometric distorsions depend on the direction of the diffusion gradients. A significant reduction of eddy current artifacts for DTI is therefore imperative to avoid severe misregistration in the calculation of the diffusion tensor and derived diffusion parameters. The method described here minimizes the effects of eddy currents without an increase of measurement time or addional post processing steps to correct the acquired images. At higher field strength T1 values of tissues are generally increased. Furthermore, eddy current effects are more pronounced. Therefore eddy current nulled DTI by a stimulated echo EPI sequence in tissues with low T2/T1 ratio will be especially superior to SE techniques for higher fields.

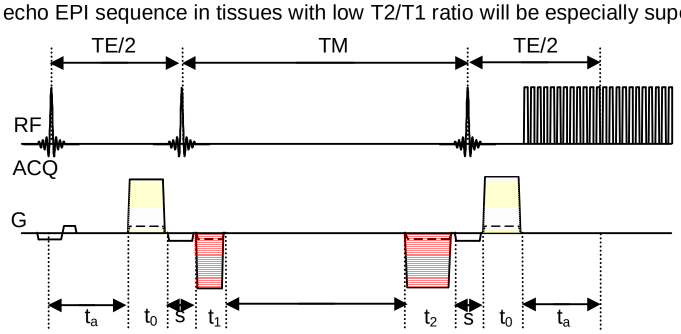

Figure 1: *Diffusion-weighted stimulated echo EPI sequence with additional gradient wave forms (red shaded) within the mixing time TM for minimization of the eddy current effects. Both, the gradients for EC correction as well as the diffusion gradients (yellow shaded), are also used as TM and TE crushers, respectively, ie. even for b = 0 s/mm² there are non-vanishing moments of all four gradients as indicated by the dashed lines. The amplitudes of the spoiler gradients amount to 1.45 mT/m. Therefore, the contribution of the crushers to the b value is neglected.*

References

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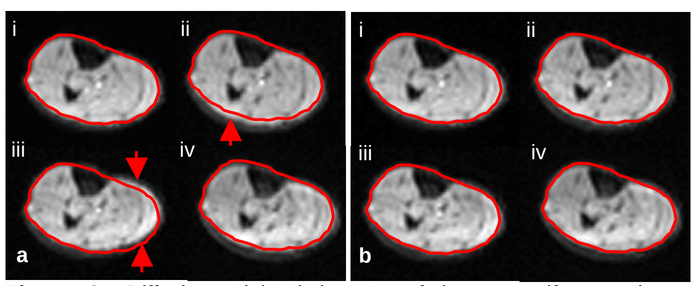

Figure 2: *Diffusion-weighted images of human calf musculature obtained with a stimulated echo EPI sequence without (a) and with (b) EC correction. Diffusion directions were none (i), phase (ii), readout (iii) and slice (iv). In (a) obvious scaling and shearing distorsions can be seen (ii,iii) whereas in (b) no significant distorsions are observed.*