Gradient Preemphasis Calibration in Diffusion-Weighted Echo-Planar Imaging

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Introduction - A series of techniques [1]-[4] have been proposed that address well-known distortions in diffusion-weighted (DW) spin-echo (SE) echo-planar-imaging (EPI) due to DW gradient induced eddy-currents (e.c.). All accept the existence of e.c., and focus on minimisation of image distortions, rather than directly addressing their possible elimination. This study describes a method that allows rapid and objective adjustment of a standard e.c. compensation (preemphasis) system.

Method - The method involves first the measurement of the e.c. field induced by the DW gradients in a standard DW-SE-EPI sequence, following the method by Duyn et al. [5]. This is achieved by measuring the phase difference of two DW-EPI signals (read and phase-encoding gradients set to zero) acquired with and without DW gradients (Fig. 1).

By applying the DW and the slice-selective gradients along directions $i$ and $j$ respectively ($i, j$ in $x, y, z$), and positioning the slice at a distance $r_j$ from the magnet isocentre, the phase evolution of the transverse magnetisation $\Phi_i(r_j, t)$ at the respective slice during EPI acquisition of duration $T$ ($0 \leq t \leq T$) due to the generated e.c. is described by:

$$\Phi_i(r_j, t) = \gamma \int_0^t (B_{0i}(t') + G_{ij}(t')r_j) dt' = \Phi_{0i}(t) + \Phi_{ij}(t)r_j \quad (1)$$

where $\Phi_{0i}(t)$ and $\Phi_{ij}(t)$ are the components of $\Phi_i(r_j, t)$ due to the spatially invariant and linear (along $j$) components of the e.c. field, $B_{0i}(t)$ and $G_{ij}(t)$ respectively. $\Phi_{0i}(t)$ and $\Phi_{ij}(t)$ were determined by fitting the phases $\Phi_i(r_j, t)$ of a multi-slice data set to Eq. (1), for each time point $t$.

Uncompensated $\Phi_{0i}$ and $\Phi_{ij}$ were used to determine parameters for input to a standard preemphasis unit, to minimise the e.c. field. Our preemphasis unit approximates the e.c. field, $\Phi(t)$ and $G_{ij}(t)$ respectively. Time-bases were adjusted individually (slowest first) by entering the amplitude of the respective unit to minimise the phase variation linear with time.

$$\Phi_{0i}(t) = A_{0i}^r \exp\left(-\frac{t}{T_{0i}}\right) + A_{0i}^m \exp\left(-\frac{m}{T_{0i}}\right) + A_{0i}^s + A_{0i}^p \quad (2)$$

$$\Phi_{ij}(t) = A_{ij}^r \exp\left(-\frac{t}{T_{ij}}\right) + A_{ij}^m \exp\left(-\frac{m}{T_{ij}}\right) + A_{ij}^s + A_{ij}^p \quad (3)$$

Time-bases were adjusted individually (slowest first) by entering time-constants (from the fitting of Eqs. (2),(3), with exception of the slow time-base constant which was set equal to the maximum available) to the preemphasis unit, and iteratively adjusting the amplitude of the respective unit to minimise the e.c. field in the time window relevant to that time-constant.

Experiments - Experiments were performed using an actively shielded wholebody gradient set on a Bruker 3T scanner. Preemphasis calibrations were done using a uniform phantom of silicone oil (due to its small diffusion coefficient). Parameters were: TE=112ms, $\delta=27ms$, $\Delta=58ms$, DW gradient strength $G_b=10.55kHz/cm$ (b-value $B=15/08/mm^2$). 128x64 EPI data matrix, 7µs dwell time, 7 slices (5mm slice thickness, 10mm interslice distance) Diffusion tensor imaging (DTI) was performed on a uniform phantom of doped water (transverse slices, 25cm FOV) using single-shot DW-SE-EPI and 3 preemphasis settings as described in the Results. 37 acquisitions: 1 baseline and 36 DW (6 directions, 6 acquisitions per direction), b-values equally spaced between $B=0$ and $486s/mm^2$, maximum $B$ achieved using $G_b=10.55kHz/cm$ and $\delta=15ms$. Other parameters were identical to the e.c. calibrations.

Results and Discussion - Figure 2 shows the measured $\Phi_0(t)$ (a) and $\Phi_{ij}(t)$ (b) for $i,j=x,y,z$ for the 3 compensation settings: none, manufacturer supplied and by the proposed method. For both uncompensated and manufacturer preemphasis, there is a systematic phase accrual over the acquisition window which is clearly reduced to a negligible level after application of the proposed method. Other parameters were identical to the e.c. calibrations.

Conclusions - A method is described enabling fast and objective preemphasis calibration for DW-SE-EPI, using standard pulse sequences and hardware. It can also be applied to any desired pulse sequence, for sequence-specific preemphasis calibrations. The calibration reduced e.c. to a negligible level, resulting in DTI maps free of e.c.-induced artifacts, making the use of e.c. correction techniques (post-processing [1],[2], pulse-sequence modification [2]-[4]) redundant.