The Effect of the Phase Encoding Scheme on Susceptibility-Induced Signal Losses in EPI

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Introduction: Echo-planar imaging (EPI) is widely used in functional magnetic resonance imaging (fMRI). However, a major problem associated with EPI is its susceptibility to macroscopic magnetic field inhomogeneities, which may result in local image distortions and signal losses. Magnetic field inhomogeneities typically occur near boundaries of abrupt changes in magnetic susceptibility, such as air/tissue interfaces. This often hinders the observation of task-induced brain activation in regions such as the orbitofrontal cortex and the inferior temporal lobes. Recently, Deichmann et al. [1] presented a theoretical description of the effect of the susceptibility-induced magnetic field inhomogeneities B^{susc} on the EPI image intensity (I) and the BOLD sensitivity (BS) in terms of the magnetic field gradient components along the phase ($G_P^{susc} = \partial B^{susc}/\partial x$) and the slice ($G_S^{susc} = \partial B^{susc}/\partial z$) directions. Here, we extend this theoretical description by including the phase encoding scheme as an additional parameter. We demonstrate that the phase encoding scheme has a significant effect on susceptibility-induced signal losses in EPI. In particular, we consider two different phase encoding schemes (cf. Fig. 1): (i) the k-space raster goes from negative to positive values using positive phase blips (EPI_{pos}), (ii) the k-space raster goes from positive to negative values using negative phase blips (EPI_{neg}).

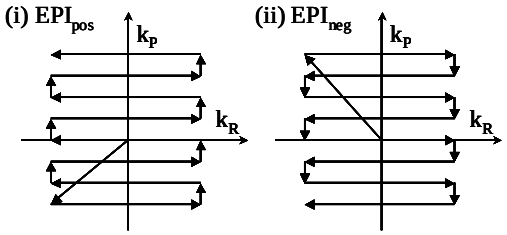

Figure 1: EPI_{pos} and EPI_{neg} encoding schemes

Theory: The effect of the magnetic field gradients on the EPI image intensity (I) can be described by considering a dimensionless factor *Q* an effective echo time TE_{eff} and a factor Ψ describing the amount of dephasing along the slice direction. *Q* depends on the phase encoding scheme used in the blipped EPI sequence: $Q = 1 \pm (\gamma \cdot \Delta t/2\pi) \cdot FoV \cdot G_P^{susc}$ [Eq. 1], where the + sign refers to EPI_{pos} and the – sign to EPI_{neg}, γ is the gyromagnetic ratio, Δt is the inter-echo spacing during the EPI readout, and FoV is the field of view in the phase encoding direction. The effective echo time is $TE_{eff} = TE/Q$ [Eq. 2], where TE is the EPI sequence echo time. The dephasing is given by: $\Psi = \gamma \cdot \left(\Delta z/4\sqrt{\ln(2)}\right) \cdot G_S^{susc} \cdot TE_{eff}$ [Eq. 3], where Δz is the slice thickness for a Gaussian excitation profile. These factors can be used to calculate I:

$I = (I_0/Q)\exp\left[-\left(TE_{eff} - TE\right)/T_2^*\right] \cdot \exp(-\Psi^2)$ [Eq. 4], where I_0 is the image intensity in absence of field inhomogeneities, and T_2^* is the effective transverse relaxation time. Eq. 4 is valid if the echo formation occurs inside the acquisition window of length *TA*. For symmetric k-space sampling this condition is given by: $TE - TA/2 \le TE_{eff} \le TE + TA/2$. If TE_{eff} is outside the acquisition window, there will be complete signal dropout, I=0. The BOLD sensitivity is given by $BS = TE_{eff} I$ for $TE - TA/2 \le TE_{eff} \le TE + TA/2$ and *BS=0* elsewhere.

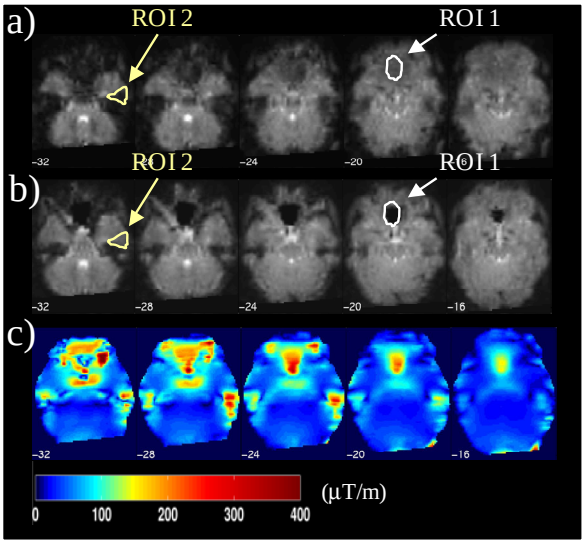

Figure 2: a) EPI_{pos} b) EPI_{neg} c) susceptibility gradient map magnitude

Method: All data were acquired using a 3 Tesla Bruker MEDSPEC 30/100 scanner. EPI imaging parameters were: 32 slices, 3 mm slice thickness, 1 mm inter-slice gap, Δt = 0.6336 ms, TE=27.5 ms, matrix size 64 x 64 and field of view 24 x 24 cm. The EPI images were undistorted and normalised using SPM2. Maps of the magnetic field gradients (G_S^{susc}, G_P^{susc}) were calculated from a multi-echo EPI reference scan [2].

Results and Discussion: Fig. 2 shows the effect of the phase encoding scheme on susceptibility-induced signal losses. Comparing the EPI_{pos} to EPI_{neg}, a prominent difference in image intensities is visible in regions of high magnetic field inhomogeneity. Such regions (e.g. orbitofrontal cortex, lower temporal lobes) can be easily identified in the colour-coded susceptibility gradient maps. The observed differences in EPI_{pos} and EPI_{neg} image intensities are complementary in their nature. The EPI_{pos} images are considerably more robust against susceptibility-induced signal losses in the orbitofrontal cortex, however, they show substantially more signal losses in the temporal lobes than the EPI_{neg} images. The average of the normalised EPI signal (I/I_0) in ROI 1 is 0.78 for EPI_{pos} and 0.13 for EPI_{neg}, whereas in ROI 2 it is 0.48 for EPI_{pos} and 0.71 for EPI_{neg}. A computer simulation based on Eq. 4 yielded 0.75 for EPI_{pos} and 0.11 for EPI_{neg} in ROI 1, and 0.34 for EPI_{pos} and 0.72 for EPI_{neg} in ROI 2. The simulated values are in good agreement with the experimental results. We have shown that the extent of susceptibility-induced signal losses largely depends on the phase encoding scheme used in gradient-echo EPI. This additional degree of freedom may be used in combination with previously described compensation methods [1] to further optimise I and BS without compromising temporal resolution.

References: [1] Deichmann, R., Josephs, O., Hutton, C., Corfield, D.R., Turner, R., NeuroImage **15**, 120–135, 2002. [2] C. De Panfilis and C. Schwarzbauer, Neuroimage, In press.