Signal dropouts in EPI caused by susceptibility-induced gradients in the readout direction: modeling and compensation

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Introduction: Gradient-echo echo-planar imaging (GE-EPI) is widely used for functional magnetic resonance imaging (fMRI) based on the blood oxygen level-dependent (BOLD) effect. GE-EPI can suffer from substantial signal dropout caused by inhomogeneities of the static magnetic field near air-/tissue-interfaces in the basal brain, especially at the long echo times required for fMRI [1,2]. Various studies have assessed how susceptibility-induced gradients in the through-plane and phase-encoding (PE) direction cause dropouts and compensation techniques have been developed [2-5]. In this study it is shown that using typical fMRI EPI parameters susceptibility-induced gradients in the readout (RO) direction cause dropouts. A theory describing this dropout mechanism in EPI is presented and an approach for its compensation is proposed.

Theory: In gradient echo imaging, a susceptibility-induced gradient in the RO direction may shift the main echo (center of k-space) out of the data acquisition window by partly counteracting the applied RO imaging gradient [6,7]. The maximally tolerable susceptibility gradient G_x depends on the echo time (TE) and the spatial resolution in the RO direction (Δx): $|G_x| < \pi/(\gamma * TE * \Delta x)$. We extend the existing model for GE imaging [7] by taking into account that for EPI the local TE may deviate considerably from the nominal TE_0 (as entered on the scanner interface) due to susceptibility gradients in the PE direction [4]. Signal losses can be avoided by reducing Δx, reducing TE, or by applying an additional compensation gradient pulse in the RO direction prior to the EPI readout [3].

Methods: We assessed the dependence of the dropouts on G_x, the compensation prepulse moment (M_{cmp}), the nominal TE_0, the local TE, and Δx. Three healthy volunteers were scanned on a 1.5 T Sonata whole-body scanner and a 3 T Allegra head scanner (Siemens Medical, Erlangen, Germany) with informed consent. We compared the theoretically predicted dropouts due to G_x with the EPI measurements. Predictions were based on G_x maps derived from measured field maps (double echo FLASH, 3x3x3mm^3). To assess the dependence of signal losses on M_{cmp} and TE, EPI were acquired at 1.5 T with a constant resolution of 3x3x2mm^3, while M_{cmp} was varied from -4 to +4 mT/m*ms, TE_0 was 35/50/65/70 ms, and the PE gradient polarity was alternated to induce variations in the local TE [5]. Local TE maps were estimated from the phase evolution of the complex EPI data according to [4]. All images were coregistered using SPM2 (Wellcome Dept. Imaging Neuroscience, London) after correcting geometric distortions using the FieldMap toolbox [8]. To assess the dependence of signal losses on Δx, EPI were recorded at 3 T with TE_0 = 25 ms and a high resolution of 1.5 mm in the RO direction (resolution 1.5x3x2mm^3). EPI images were reconstructed at the original high resolution and a reduced lower resolution of 4 mm in the RO direction by limiting the k-space data in the RO direction. BOLD sensitivity (BS) maps were estimated from the high and low resolution EPI data by voxel-wise multiplying the TE map with the EPI magnitude image (BS = TE*I) [4].

Results: ***Dependence on x-shimming:*** Fig. 1a shows a map of G_x and the areas that according to the theory should suffer from signal dropouts due to susceptibility-induced gradients in the RO direction for M_{cmp} = 0. The predicted dropouts in the orbitofrontal cortex (OFC) were in line with the signal losses observed in the EPI images (Fig. 1b, additional dropouts are due to gradients in the slice selection and PE direction). As expected from the susceptibility-induced gradient (Fig. 1a), a positive M_{cmp} recovered signal from the left OFC, but increased the signal loss in the right OFC; and vice versa (Fig. 1b, left/right).
Dependence on TE: The following results show that a shorter TE recovers signal dropouts. Fig. 2a shows the difference of the local TE of two EPI scanned with opposite PE gradient polarities. In a U-shaped region of the posterior OFC, TE is increased for the positive PE gradient, resulting in stronger dropouts in the corresponding EPI image (Fig. 2b, yellow circle).
Dependence on Δx: Fig. 3 shows BS maps estimated from EPI data at 3 T. Using a higher resolution in the RO direction (right image), the bilateral BS dropouts in the OFC were recovered (yellow circle).

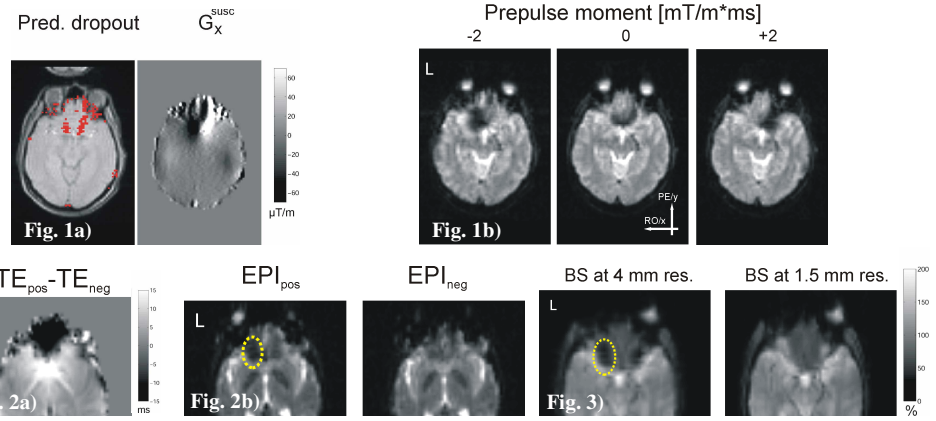

Figure 1: Dropouts due to susceptibility-induced gradients in the RO direction.
a) Dropout predicted from the measured susceptibility-induced gradient (M_{cmp}=0),
b) EPI acquired with varying M_{cmp}.

Figure 2: Dependence of signal loss on local TE.
a) Difference in local TE for EPI acquired with opposite PE polarities but otherwise identical parameters,
b) corresponding EPI magnitude images.

Figure 3: BOLD sensitivity (BS) maps estimated from the complex EPI data at 4 mm and 1.5 mm resolution in the RO direction.

Discussion: We have presented a theory describing how field gradients in the RO direction shift the main gradient echo outside the EPI acquisition window – yielding severe signal loss. It is shown experimentally that this effect is responsible for signal losses in certain brain areas, such as the OFC. In agreement with the theory, these dropouts depend on the compensation gradient moment, TE, and spatial resolution in the RO direction. In particular, the results show that the local TE [4] rather than the nominal TE_0 determines the dropout. In principle, the signal loss can be reduced by decreasing the TE, increasing the spatial resolution in the RO direction, or applying a compensation gradient prepulse in the RO direction. However, a compensation approach based on gradient prepulses would require multiple acquisitions, increasing the scan time and reducing the temporal resolution. A too short TE would compromise the BS. Therefore, a combination of an increased spatial resolution in the RO direction and shortened TE seems to be the most efficient approach to compensate this type of dropout. Based on the theory it is straightforward to determine the minimal spatial resolution given the chosen TE and the maximal $|G_x|$ in a region of interest. For example at 3 T and TE_0 = 25 ms, a spatial resolution of 1.5 mm in the RO direction will recover signal losses for $|G_x| < 300$ µT/m which is the case in most brain areas.

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