Single shot BOLD fMRI with signal-loss compensation using Interleaved Dual-Echo Acquisition (IDEA) EPI

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Introduction

Gradient-echo EPI is popular in fMRI owing to its acquisition speed and BOLD sensitivity. A great shortcoming is the vulnerability to susceptibility gradients, which cause in-plane distortion and through-plane signal loss and obscure the BOLD signal in several regions. Furthermore, EPI suffers from N/2 ghosting that arises in case of poorly estimated phase terms, required to correct for eddy current induced k-space shifts between alternate lines. We recently proposed 'Interleaved Dual-Echo Acquisition (IDEA) EPI' (1) to alleviate ghosting. By omitting alternate phase encode blips and doubling the EPI train, two inherently ghost-free images are simultaneously acquired, one each under the positive and negative gradient lobes.

In this abstract we extend IDEA EPI to perform ghost *and* signal loss compensation in a single shot by adding a z-shim (2) to one of the images. Successful correction of signal voids near frontal and aural air cavities is shown with high-resolution EPI and breathold fMRI at 3T.

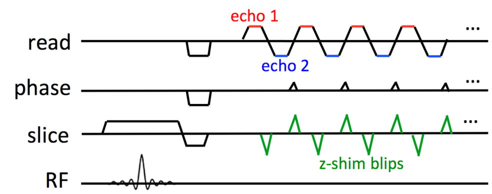

Fig 1. IDEA EPI sequence with z-shims. Two echoes are acquired in a single shot, and the z-blips affect a shim on the second (blue) echo. This lengthens the readout by only ~10%. The two images are averaged.

Theory

Through-plane signal loss compensation

An unwanted gradient $\mathbf{G}_s(r)$ through the slice profile results in phase cancellation, and causes signal loss that follows a *sinc* modulation depending on slice thickness Δz, G_s and echo time TE:

$$S(r) \propto M_0(r) \int_{-\Delta z/2}^{+\Delta z/2} \mathrm{rect}(z/\Delta z) e^{-i\gamma G_s(r) zTE} dz = M_0(r) \mathrm{sinc}[\gamma G_s(r) \Delta z TE/2]$$

Signal can be recovered using z-shims that oppose the unwanted local dephasing. This will also reduce originally intact signal, so two or more scans with different shims must be averaged, which is impractical due to increased imaging time. A single shim is often used as compromise (3,4), or multi-echo EPI with different shims for each echo (5). The latter only works with EPI readouts sufficiently short to acquire the multiple echoes at appropriate TEs for BOLD contrast. For high-resolution EPI this condition is challenging (large matrix size requires long readouts), especially at high field where T_2* is short. Another solution for single-shot z-shim is hence desirable, that delivers near optimal T_2* weighting also at high resolution.

IDEA EPI with z-shimming

The two TE's in IDEA EPI are nearly identical, making it well suited for dual-echo z-shims at high spatial resolution. Alternating z-gradient blips were inserted into the previously described IDEA EPI sequence as shown in Fig. 1, providing a shim on the even (blue) echoes. The operator specifies the gradient $\mathbf{G}_s(r)$ to be compensated; they can be estimated by differentiation of a field map (3).

Methods

Data were acquired on a Siemens 3T Trio with 32ch head coil. Three subjects were scanned with IDEA EPI without and with z-shims: 1.5x1.5x3mm^3 voxels, 36 slices, matrix 128x128, GRAPPA 3, 6/8 partial Fourier, BW=1954Hz/px, TE=30ms, TR=2.5s, 96 volumes (4min) for breathold. In the shim scan the blip was set to balance G_s=145μT/m, which raised echo spacing by 9% from 0.77 to 0.84ms. The shim was estimated from susceptibility gradient maps, obtained by differentiation of a dual-echo GRE field map. 4min breathold fMRI (20/20s on/off) was acquired for each protocol. Analysis was done in FSL FEAT using default parameters (5mm smooth, z>2.3, p<0.05). The two IDEA EPI echoes were combined by sum-of-squares averaging irrespective of the shim being active.

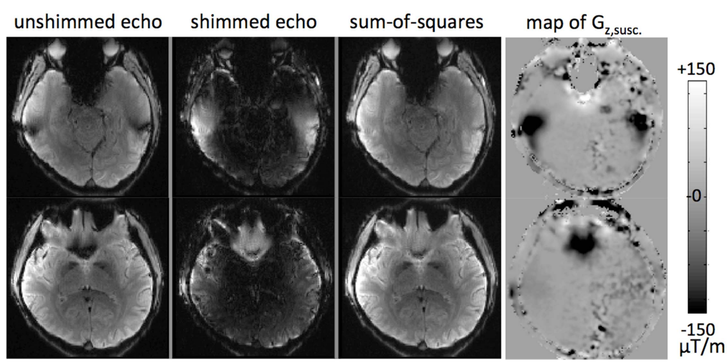

Fig 2. High-resolution IDEA EPI slices with z-shim. Unshimmed and shimmed echoes are acquired simultaneously. The sum-of-squares averaged images are essentially artifact free demonstrating the efficacy of the method.

Results

Fig 2 shows typical unshimmed, shimmed and combined images for two slices with ear canal (top) and frontal (bottom) signal voids. The voids are clearly highlighted in the shimmed echo, and the combined image appears effectively artifact free. Also shown is the susceptibility gradient map at the same slice locations. Fig 3 shows BOLD activation maps with and without shim in another subject. An increase in super-threshold voxels is clearly seen for frontal cortex and ear canals. All IDEA EPI images were ghost free as expected.

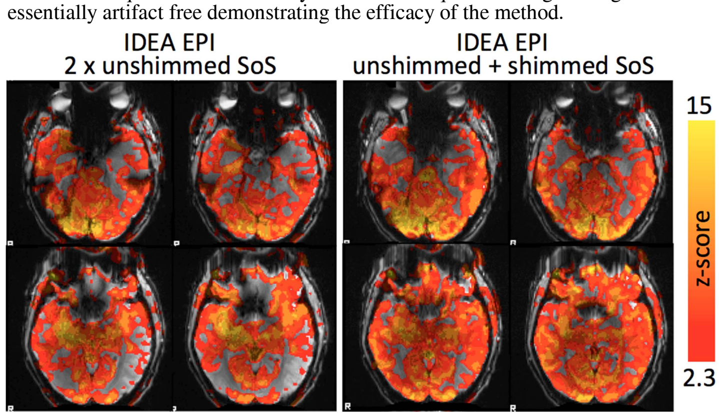

Fig 3. Example breathold activation maps for IDEA EPI without (left) and with (right) z-shim correction. Both ear canals (top) and frontal cortex (bottom) a considerable increase in activation is seen with the shim on.

Discussion

Effective EPI signal void correction was achieved in a single-shot by sampling one shimmed and unshimmed echo. The proposed IDEA EPI z-shim can deliver any two shims per excitation, and multiple shots with a different shim pair could be averaged if required. The shim moments could also be made slice-dependent, as the superior brain typically requires no correction. IDEA EPI with simultaneous multi-slice (SMS) acquisition is being implemented, this will further increase the acquisition efficiency.

References [1] Poser BA MRM 2012 (in press) [2] Frahm J, JMR 1994;103:91 [3] Constable RT, JMRI 1995;5:746 [4] Deichmann R, NI 2002; 15:120 [5] Weiskopf N, MAGMA 2007;20:39 [6] Posse S, NI 2003;18:390

Grants: NIH R01DA019912, R01EB011517, K02DA020569, DFG Po1576/1-1