Real-Time Field Control for Enhanced Temporal SNR in fMRI Time Series

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Introduction: In fMRI time series a high temporal signal-to-noise ratio (tSNR) [1] sets the basis for a meaningful statistical analysis of the BOLD signal. tSNR is reduced by field drifts as well as physiological noise such as stemming from breathing or limb motion, a problem that is emphasized at high field strength. In the image domain such field disturbance typically results in image shifting and an increase in (EPI) image ghosting during the scan.

To diminish these effects, respiratory gating, shortening echo times and the use of navigator echoes for interleaved EPI have been devised. However, these methods are of limited efficacy, and constrain sequence timings or the achievable BOLD contrast. Pre-processing methods attempt to filter or regress out signals based on independent physiological measurements [2,3] or de-noise data by Independent Component Analysis [4]. Such pre-processing correction strategies are ineffective if the BOLD response correlates with the subject's physiology. Furthermore these approaches rely on physiological models or on reproducible spatial footprints of the physiological fluctuations, an assumption that can be violated by variation of e.g. breathing during the scan or by coincidence of several sources of field perturbations.

To address these limitations we present the use of a real-time field control system (Fig.1) [5] to compensate for field fluctuations independently of the employed sequence without the need to alter image reconstruction or additional pre-processing. The system is capable of correcting for field drifts up to the 3rd spatial order which has so far been shown to improve T2* imaging [5] and MR spectroscopy [6] in the brain at 7T.

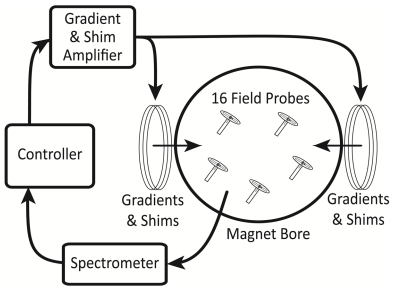

Figure 1: Schematic of the real-time field feedback control system.

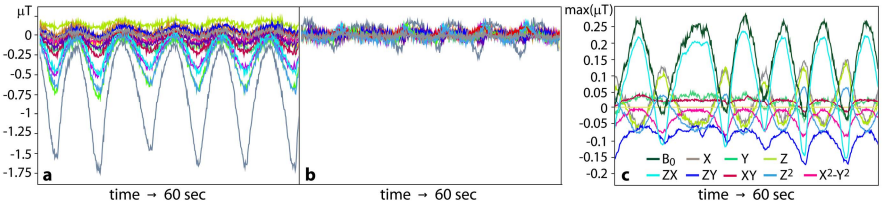

Figure 1: Measured field changes in the 16 field probes during the phantom scans with (b) and without (a) field control. The applied feedback (c) terms are plotted to show the maximum excursion within the imaging volume.

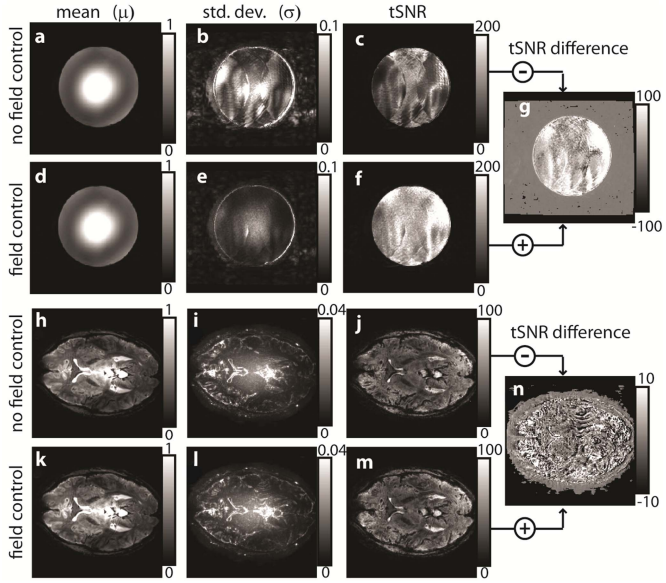

Figure 3: Phantom (a-g) and in-vivo (h-n) data with (d-f,k-m) and without (a-c,h-j) field control. Mean over all dynamics (a,d,h,k), standard deviation (b,e,i,l), tSNR maps (c,f,j,m) and the tSNR gain when using field control (g,n).

Methods: To evaluate the potential of field feedback control in fMRI, typical task-free fMRI acquisitions were performed such as used in resting-state fMRI. Dynamic single-shot EPI data of a spherical phantom (H_20+NaCl) was acquired (140dyn., FOV=220x200x50mm^3, TE=28ms, TR=2.8s, SENSE R=3, res=(1.4mm)^2, slice thickness=2mm, total dur=7min) on a 7T MRI system (Achieva, Philips Healthcare, Best, NL). In the phantom scans field perturbations similar to strong breathing effects were induced by moving a bottle (mineral oil, 3l) periodically along the z-direction. For real-time shim control (Fig.1), 16 fluorine based T/R NMR field probes [7] were mounted cylindrically between the employed 1H transmit coil and the 32 channel receive coil (Nova Medical, Wilmington, USA). During the scan, field sensing using a separate spectrometer [8] was repeatedly performed before each EPI acquisition, which was actuated by a TTL signal from the scanner. After each field measurement, the controller [5] updated the input to the shim amplifiers (Resonance Research Inc., Billerica, USA) in order to correct for deviations from the reference field defined by the field configuration right after static shimming. All scans were performed with and without field control. To allow for a fair comparison with standard fMRI procedures, image realignment was applied to each data set via SPM 12b (http://www.fil.ion.ucl.ac.uk/spm/). Thereafter, the mean image μ, the temporal standard deviation σ and tSNR maps were calculated. The method was also tested in a first in-vivo experiment with a subject performing normal and deep breathing. The difference in coefficient of variation ($\sqrt{\sigma^2_{no\ field\ control} - \sigma^2_{field\ control}}/\mu$) was calculated additionally as a measure of reduction of unwanted signal variation in the presence of underlying neurologically-induced signal changes.

Results: In the phantom experiments the induced field changes (Fig.2a) were largely corrected (Fig.2b) when applying field control (Fig.2c). In the images (Fig.3a-c) the effects of the strong field perturbations are directly visible as ghosting-like structures in the standard deviation (Fig.3b) and tSNR (Fig.3c) maps. When turning on field control these artifacts are reduced (Fig.3e-g) resulting in an increase in average tSNR from 33.8 to 85.2 (+77%). In-vivo (Fig.3h-n), an average gain in tSNR over all slices of 5% for normal breathing and 14% for deep breathing was observed, despite the presence of the neurologically-induced signal changes in these measurements. The difference in coefficient of variation was 0.8% and 2.1% for normal and deep breathing respectively. This renders feedback control promising to highly increase the sensitivity to detect the subtle BOLD signal changes.

Conclusion: We demonstrated the potential of real-time control in fMRI. The system allows for an increase in tSNR without the need of additional pre-processing. Removal of confounds in this order of magnitude will be instrumental in recovering subtle BOLD effects in task-based and resting-state fMRI. Since a stable field allows for consistent k-space sampling, the method might as well be tested for its benefit in dynamic (3D) interleaved EPI.

References: 1:Jezzard et al., Functional MRI(1999)173-181; 2:Hu et al. MRM(1995)34(2), 201–212; 3:Glover et al., MRM(2000)44(1), 162–167; 4:Beckmann et al., IEEE TMI(2004)23,137–152; 5:Duerst et al.,ISMRM'13,669; 6:Wilm et al.,MRM, in print; 7:DeZanche et al.,MRM(2008)60(1):176-86; 8:Dietrich et al., ISMRM'12,700