A novel approach to investigate the impact of RF pulses on the BOLD contrast in steady-state pulse sequences

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Introduction:

Various mechanisms have recently been proposed to impact on the BOLD-contrast in steady-state sequences [1]. It has been speculated that magnetization transfer effects and/or relaxation during RF pulses, which are applied during a significant percentage of the imaging time, contribute to the detected signal changes. However, the investigation of various potential mechanisms has been hampered by the interaction of multiple effects. In this paper, we propose a novel acquisition and post processing approach, which allows adjusting pulse parameters independently in order to be able to systematically study various mechanisms, which potentially contribute to fMRI signal changes, such as relaxation during the pulse and magnetization transfer effects.

Method:

The imaging method is based on a spoiled GRE sequence using short repetition time creating a steady-state of the longitudinal magnetization. Since magnetization transfer and relaxation during slice-selective RF pulses vary spatially, when a gradient is applied during the excitation pulse for slice selection, no slice selection is used for the excitation pulse. A three-dimensional acquisition scheme with phase-encoding in two dimensions is applied. A quadrature surface RF coil detects signal only from the occipital lobe. The BOLD response in the primary visual cortex in response to a visual stimulation is captured as function of time.

In this acquisition scheme, the acquisition time for a whole 3D image exceeds the period of the stimulation paradigm. In order to generate activation maps from time series with an undersampled BOLD response, a postprocessing technique, the spectral side band analysis (SSBA) [2], is used. SSBA is based on correcting and quantifying periodic signal modulation, such as the BOLD response, in the pseudo-spectral dimension, which is obtained by Fourier-transformation of the complex-valued image time series along the temporal dimension.

In order to be able to separate stimulus related fMRI signal changes created during the RF-pulses and free magnetization evolution periods, multiple echoes are acquired for each transient. In the analysis, a T_2^*-decay can then be fitted to the signal decay as a function of echo time. The intercept of the fit at zero echo time provides the contribution to the signal change generated by the RF-pulse or changes in proton density, while the T_2^*-decay captures signal changes known from conventional imaging techniques with long evolution times, such as EPI. In order to be able to systematically investigate effects related to the RF-pulse a frequency-swept Chirp pulse is used for excitation. In this pulse, the excitation bandwidth, the pulse duration, and the sweep rate of the frequency-modulation function can be adjusted independently and, therefore, allows separating effects related to magnetization transfer and relaxation during the pulse.

Experimental and data analysis:

fMRI experiments were performed on 7 T scanners with Siemens console using a quadrature surface RF coil. Three volunteers participated in the study after written consent. For visual stimulation, 26 blocks of a shifting checkerboard alternating between 12 s of left and 12 s right visual hemifield stimulation. Functional time series were acquired using 3D GRE without slice selection (acquired matrix: 64×52×48: spatial resolution: (2 mm)^3, shot-to-shot repetition time: T_R = 25 ms, 8 echoes: shortest echo time: 3, echo time increment: 2 ms, excitation flip angle: 30º, number of repetitions: 10). Three scans with different parameter set for the Chirp pulse were used: (1) 500 Hz, 4 ms, (2) 2 kHz 4 ms, (3) 5 kHz, 400 µs for the pulse bandwidth and duration, respectively.

The amplitude of the relative signal change is derived from the spectral peak at the apparent (aliased) paradigm frequency using SSBA. As a result of undersampling of the BOLD response in one phase-encoded dimension, the spectral peak of the BOLD response is shifted by a number of voxels determined by how often the paradigm is aliased in the respective spatial dimension. This spatial shift has been corrected for in the presented activation maps (Figure 1).

Results and discussion:

Figure 1 shows coronal slices across the primary visual cortex (V1) of one subject. The maps representing the relative signal change in the time series of the eighth echo (T_E = 17 ms) at the paradigm frequency are superimposed onto the mean of the functional time series for the respective pulse parameters. The signal intensity of the time series acquired with the largest pulse bandwidth is lowest as a result of magnetization transfer effects in the tissue as a result of saturating exchanging sites with broader spectral line widths [3]. In all cases, activation can be reliably detected without blurring despite of the undersampling of the stimulation paradigm.

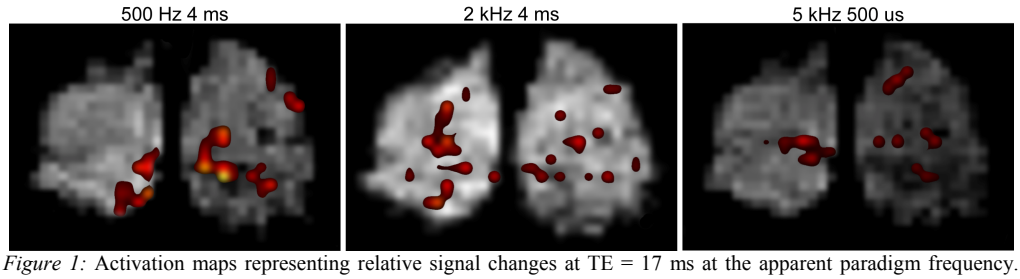

Figure 1: Activation maps representing relative signal changes at TE = 17 ms at the apparent paradigm frequency. Bandwidth and duration of the excitation pulse are written above the respective map.

The average relative signal change as function of echo time is plotted in Figure 2. The symbols represent the mean of the signal changes in a ROI in the primary visual cortex of two subjects. The error bars indicate the standard deviation of the variability between the subjects. The time series acquired with the narrowest pulse bandwidth shows the steepest increase of the relative signal change as a function of echo time compared to the other two time series. This finding suggests that a compartment responsible for high sensitivity to changes in blood oxygenation is potentially more suppressed in time series acquired with higher pulse bandwidth. Extrapolation of the curves to an echo time of zero shows no offset indication that the effect of the excitation pulse on the detected relative signal change is negligible with the used pulse parameters.

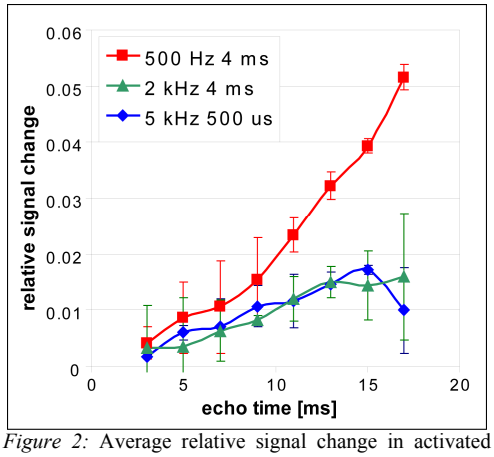

Figure 2: Average relative signal change in activated region in V1 as a function of echo time. The corresponding parameters of excitation pulse are written in the legend.

Summary:

The results demonstrate that reliable activation maps can be obtained combining a 3D GRE echo sequence with a novel post processing method, SSBA, to analyze time series undersampling the paradigm frequency. With this approach, mechanisms, which contribute to fMRI signal changes which are driven by relaxation during the RF pulse and free evolution of the transverse magnetization as well as magnetization transfer effects, can be systematically investigated by changing the various pulse parameters and sequence timing independently from each other. Initial results show differences in the amplitude of the BOLD response depending on the pulse bandwidth. Future experiments will explore these differences in more detail.

References and acknowledgments:

[1] Miller K *et al*., *NeuroImage* **37**: 1227 (2007), [2] Goerke U, Ugurbil K, *Proc. Intl. Soc. Mag. Reson. Med.* **17**: 19 (2009), [3] Ou X, Gochberg DF, *MRM* **59**: 835 (2008)

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