Echo train shifted multi-echo FLASH for functional MRI of the human brain at ultra-high spatial resolution

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Introduction

The purpose of this work was to develop a novel T2*-weighted imaging technique that specifically matches the requirements for a further refinement of functional MRI studies of the human brain at very high spatial resolution. A key to this problem is sequence with optimum image quality that achieves the desired resolution without potentially critical post-processing corrections and by using `true' acquisitions, that is without zero filling or other interpolation techniques. The approach chosen here attempts to take the best of both FLASH and EPI and therefore emerges as a multi-echo FLASH sequence that allows for functional MRI at 0.135 µl voxel resolution for a whole brain section.

Methods

To achieve optimum image quality, the approach is based on unipolar traversals of k-space in the frequency-encoding dimension. Echo train shifting (Fig.1) [1] was found to be necessary to avoid amplitude discontinuities in the phase-encoding dimension. Together, these strategies ensure a smooth point-spread function and eliminate image ghosting artefacts without the need for any phase correction or other post processing. Signal-to-noise losses due to the considerably reduced voxel sizes are compensated for by single slice acquisitions, optimized bandwidths, and an experimental 4-channel shoulder coil matched to the posterior portion of the head. Experimental data were obtained at 2.9 T using a Siemens Trio (Erlangen, Germany) [2].

Results

Fig. 2 clearly demonstrates the successful elimination of any ghosting artefacts after the implementation of echo train shifting for multi-echo FLASH. Figure 2 shows the result of a functional MRI study of the human brain at 300 µm resolution (no interpolation) and 1.5 mm slice thickness. Although arbitrary numbers of echoes are possible, the actual implementation employed 7 echoes with a 200 Hz/pixel bandwidth and an effective (mean) echo time 36 ms. The acquisition time/temporal resolution was 6 s. As shown in Fig. 3 pertinent maps revealed robust activations in primary visual areas in response to binocular visual stimulation – and no false positive activations outside.

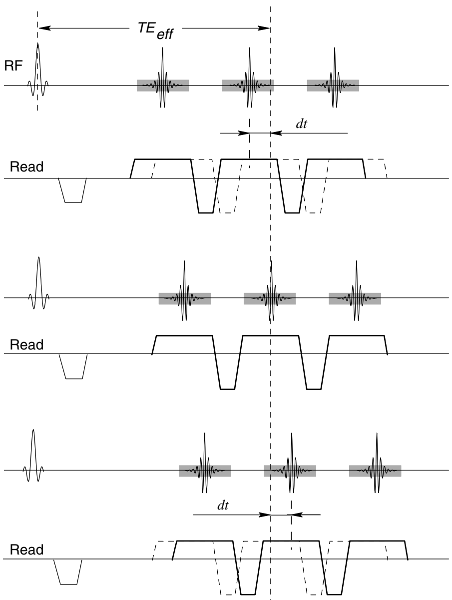

Fig. 1. Echo train shifting of the readout gradient of multi-echo FLASH sequences (here: 3 echoes, 3 different repetitions shown) avoids amplitude discontinuities along the phase-encoding dimension of k-space. The slotted curves in the top and bottom row correspond to the unshifted gradient waveform of the central acquisition and serve as a reference for the temporal shift dt.

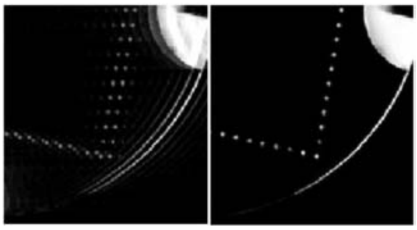

Fig. 2. Multi-echo FLASH images of a structural water phantom obtained (left) without and (right) with echo train shifting.

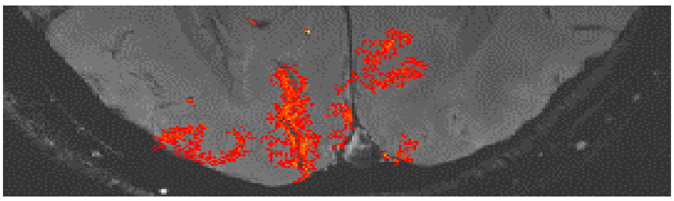

Fig. 3. Ultra-high resolution activation map of the human brain for binocular visual stimulation using echo train shifted multi-echo FLASH at 0.3 mm x 0.3 mm resolution and 1.5 mm section thickness (temporal resolution 6 s).

Discussion

This work presents a new method for functional MRI of the human brain at 0.135 µl voxel size for a (single) whole brain section. In comparison to conventional studies at 3 mm isotropic resolution or 27 µl voxel size the method yields an improvement by a factor of 200. With a truly acquired in-plane resolution of only 300 µm linear pixel dimension, that is without interpolation, a section thickness of 1.5 mm resulted in robust activations in primary visual areas in response to binocular stimulation.

The actual achievement represents the optimum result for the given hardware (field strength, radiofrequency coils, etc). In general, the minimum voxel size is determined by (i) technical constraints due to the available gradient power, (ii) physiologic limitations due to peripheral nerve stimulation (gradient slew rate), and (iii) a reasonable SNR and temporal resolution as required for reliable functional MRI. Using optimized bandwidths and RF coils matched to the area under investigation, multi-echo FLASH with echo train shifting emerges as a technical approach to reach the limits.

The new method holds promise for refined studies of the columnar organization of specific brain systems as well as for functional assessments of the gray matter at laminar resolution.

References

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[2] Voit D and Frahm J. *Magn Reson Imaging* 2005, in press