Frontal Cortex fMRI at 7T: Escaping Flat Minimum Traps in Higher-Order B0 Shimming Algorithms

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INTRODUCTION

To exploit the full potential of functional MRI (fMRI) at high and ultra-high field strengths, excellent B_0 shimming is crucial to minimize distortions and signal dropouts when using Echo Planar Imaging (EPI) readout. The most severe B_0 inhomogeneities are caused by susceptibility differences of adjacent tissue types or tissue-air boundaries within the patient. Usually shim routines are based on least squares minimization algorithms, which fit the shim fields to the B_0 inhomogeneities. These algorithms, however, are prone to "get trapped" in a local minimum, i.e. a suboptimal set of shim parameters might be found. **THIS WORK** presents a B_0 shim optimization approach that avoids flat local minima and additionally overcomes the problem of uncontrollably large B_0 inhomogeneities in the vicinity of the ROI that might induce artifacts in the ROI itself [1].

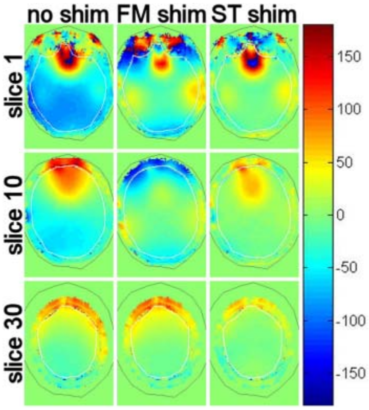

***Figure 2:** B_0 maps of three different slices of a volunteer's brain (volunteer 1) with no shim, a FM shim and an ST shim. The images are overlaid with the ROI (white) and the ROLI (black) that have been used for the calculation of the ST shim.*

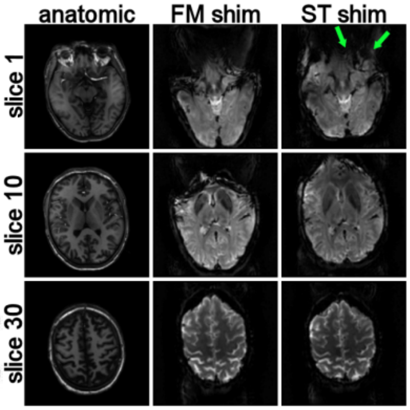

***Figure 1:** EPIs of three different slices of a volunteer's brain (volunteer 1) acquired with a FM and a ST shim, and an anatomical reference image (first column). The green arrows indicate the restored signal of the eyes and the brain structure between them*

MATERIALS AND METHODS

A Localized Shimming Tool (ST) [2] implemented in IDL (Exelis, Inc., Boulder, USA) was used to fit the field distribution, as induced by the subject, to spherical harmonic shaped fields of up to 3rd order, using a constraint Levenberg-Marquardt algorithm [3]. As this algorithm follows the slope of the squared difference function to find a minimum which is then considered the best approximation for the problem, the probability of getting trapped in a local minimum is significant. Furthermore this probability increases with an increasing number of considered shim terms. The local minimum actually found, is highly dependent on the chosen starting values. To reduce the risk of the algorithm being trapped in a flat minimum, the fitting algorithm is applied six times to the shimming problem, each time with different starting values for every shim parameter (0, positive/negative maximum of the respective term, and 3x random generated numbers). The smallest of the determined sum of least squares values, and the corresponding parameters are then considered the best approximation for the problem. To avoid problems arising from large B_0 inhomogeneities in the vicinity of the ROI, the possibility to define a Region Of Less Interest (ROLI) is implemented. The ROLI can be defined by the user, and thus tailored to each individual shimming task. In case the field difference of the theoretically derived optimized field distribution within the ROLI would exceed a certain adjustable threshold, the weighting of the ROLI within the fit would be decreased, and thus the optimization of the ROI can be improved.

Measurements were performed on a 7T Philips Achieva whole body MR system (Philips Healthcare, Cleveland, USA), equipped with a full set of 3rd order shim coils. A B_0 map without any B_0 shimming is used as a basis for the calculation of the optimal shim by the modified ST. B_0 maps of 4 healthy volunteers were acquired, to which the determined shim sets were applied. Multi-slice single-shot EPIs (TE/TR = 28ms/1000ms, EPI factor = 99, voxel size = 2mm x 2mm x 2mm, 30 slices) were obtained to demonstrate the advantage of the improved B_0 shim approach for whole brain fMRI. For two volunteers also a resting state fMRI (rs-fMRI) scan (100 dynamics, TE/TR = 28ms/6000ms, other parameters as above) was performed, to assess the effect of B_0 shimming on the accessibility of the default mode network (DMN) [4] at 7T. All results obtained using a ST shim set, are compared to measurements using a vendor preimplemented FASTERMAP routine with a spiral read out (FM). For analysis of the B_0 maps and EPIs, in-house build MATLAB (Mathworks, Natick, USA) routines were employed. The rs-fMRI data were analyzed using the SPM8 (Wellcome Trust Center for Neuroimaging, England) based toolbox DPARSF (Yan Chao-Gan, State Key Laboratory of Cognitive Neuroscience and Learning, China) and followed a standard protocol [5]. In order to avoid any additional influence of normalization on functional connectivity due to differences in EPI distortion, the results are shown overlaid on the unprocessed functional images.

volunteer	no shim	FM shim		ST shim	
	std [in Hz]	std [in Hz]	red [in %]	std [in Hz]	red [in %]
1	120.54	68.29	43.35	62.29	48.32
2	70.55	54.61	22.59	45.04	36.15
3	58.66	46.87	20.10	45.05	23.20
4	38.07	29.65	22.13	20.32	46.62

***Table 1:** Standard deviations (std) of frequencies derived from ROIs in B_0 maps with different shim settings in Hz and reduction (red) of std by shimming in %, compared to the not shimmed case.*

RESULTS AND DISCUSSION

Fig. (1) and (2) display B_0 maps and EPIs of three different slices throughout a volunteers brain, acquired with an applied FM and ST shim. The ROI and the ROLI that have been used for the calculation of the ST shim parameters and from which the standard deviations (table 1) are obtained, are overlaid the B_0 maps. For the ST shim both figures demonstrate an improvement of B_0 homogeneity over a large area of the brain compared to the FM shim. Especially for the lower slices and frontal brain regions signal dropouts and distortions in the EPIs are clearly reduced. Even the shape of the eyes and the brain structure between them can be recognized in the EPI acquired with a global ST shim set (fig. (2), green arrows). The qualitative improvement of B_0 homogeneity is also illustrated for the different shim settings by the histograms over the ROI (fig. (3)). A considerable reduced width of the histogram for the ST shim is visible. Fig. (4) shows the results of a rs-fMRI analysis, acquired using the different shim settings, projected on two orthogonal planes through the brain. Correlations of a spherical seed region of interest with a diameter of 10mm, created in the bilateral posterior cingulate cortex (PCC) as a major hub of the DMN, to areas in the medioprefrontal cortex (MPFC) are clearly visible. However, in the case of the FM shim a large part of the frontal cortex (FC) is suffering from distortions and signal dropouts, and therefore yields weaker and spatially distorted DMN-related resting-state BOLD signal correlations. The ST shim is able to restore most of the signal in the FC, which allows for an acceptable data quality of fMRI data in the FC. In **CONCLUSION,** an improved global B_0 shimming routine is presented that allows for whole-brain functional MRI at 7T based on EPI readout.

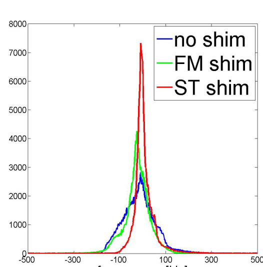

***Figure 3:** Histograms over the ROI (volunteer 2) for a not shimmed (blue), a FM shimmed (green) and a ST shimmed (red) B0 map.*

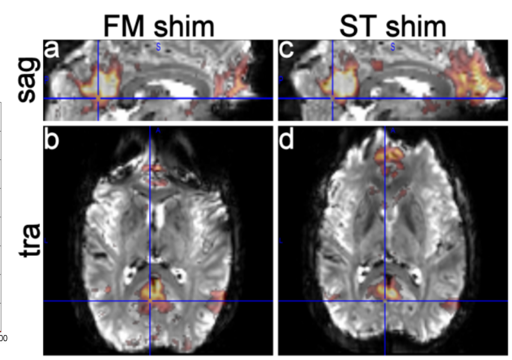

***Figure 4:** Resting State fMRI activations projected on the unprocessed functional images (volunteer 2), acquired with a FM shim (a,b) and with an ST shim (c,d). The comparison especially of the sagital images (a,c) demonstrates the ability of the ST shim, to restore signal in the FC area.*

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