Resting-State fMRI with 3rd-Order Dynamic Shim Updating (DSU) and Dynamic F_0 Determination

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INTRODUCTION

Functional Magnetic Resonance Imaging (fMRI) becomes increasingly important in basic science, neurological and psychological disorders. The "work horse" of fMRI is Echo Planar Imaging (EPI), as it allows for very fast acquisition, and therefore high temporal resolution of signal changes. EPI is, however, sensitive to B_0 inhomogeneities, especially at high- and ultra-high fields, which leads to signal drop-outs and image distortions. At 7T or higher fields, these artifacts make fMRI in regions as e.g. the frontal cortex difficult, or even impossible. Therefore sophisticated B_0 shim strategies are required in order to exploit the full potential of the application of ultra-high fields to fMRI. Instead of applying a global B_0 shim set, earlier work suggested updating the B_0 shim settings dynamically (Dynamic Shim Updating, DSU) during the sequence[1], to achieve improved local B_0 shim quality. However, due to the velocity of the acquisition and the sensitivity of EPI to residual field distortions, the application of DSU to EPI and fMRI requires very fast settling times of eddy currents, induced into shim coils and neighboring conductive structures during switching of shim currents. Previous pre-emphasis calibration methods[2,3,4] did result in settling times of 50 ms to 200 ms, which is insufficient for the application to EPI. Our group recently developed an iterative pre-emphasis calibration method based on spatio-temporal field monitoring[5,6] for precise eddy current compensation (ECC), which allows for switching shim currents only 2 ms before excitation. **THIS WORK** presents the first report of slice-wise (sw) 3rd-order dynamic shim updated (DSU) resting-state fMRI (rs-fMRI) data, acquired at 7T based on the before mentioned DSU implementation and calibration approach[5,6] combined with an optimized slice wise B_0 shim optimization routine[7] and automatic slice wise F_0 determination.

MATERIALS AND METHODS

All measurements were performed at a 7T Achieva system (Philips Healthcare, Cleveland, USA) equipped with a full set of 3rd-order spherical-harmonic shim coils and a 32-channel receive/volume transmit head coil (NOVA medical, Wilmington, USA). The higher-order shim amplifiers were directly controlled by a DSU Load & Go Unit (Resonance Research Inc., Billerica, USA) and an in-house build gradient offset driver was used, which sums up the linear shim voltages, and the driving voltages for the gradient amplifiers[5]. As fast switching of shim fields leads to long lasting eddy currents within the shim coils and the surrounding conducting structures, a very accurate pre-emphasis calibration for ECC is required, especially for the application to fast techniques such as fMRI. This was implemented for eddy currents that produce field components same as the respective shim term, and Z_0 field components, using iterative spatio-temporal field monitoring with a 3rd-order field camera[8], as previously reported[5,6]. However, eddy current cross terms between different shim terms, other than between a higher order term and Z_0, could not be addressed with the current setup. Three 3rd-order shim terms (Z^3, Z^2X and Z^2Y), which induce large eddy currents to the linear shim terms, were therefore not used in this study. Furthermore, in order to stay within the shim systems specifications, the maximum 2nd and 3rd-order shim field amplitudes needed to be reduced to 73% to 90% and 43% to 53% of their original value (DSU limits), respectively, as ECC requires a short but strong overshoot of the shim currents[5]. Since the application of different B_0 shim sets results in different static Z_0 offsets, a dynamic F_0 determination was implemented to determine the excitation frequency dependent on each slice specific B_0 shim set. The excitation frequency was then dynamically updated during the sequence, 5 ms prior to the excitation, when the shim settings are updated as well.

Multi-slice single-shot EPIs were acquired from two healthy volunteers (20 slices, voxel size: $2\times2\times2$ mm^3, TE/TR = 26.6 ms/63.24 ms, EPI factor = 99) with 3 different B_0 shim settings applied (fig. 1): 1) slice-wise DSU without a dynamic F_0 determination (sw dyn w/o F0); 2) slice-wise DSU with dynamic F_0 determination (sw dyn); and 3) a slice-wise shim, applied statically (sw stat). All B_0 shim sets were calculated by a modified version of an IDL (Excelis, Inc., Boulder, USA) based B_0 Shimming Tool[7,9]. To overcome the problem of shim term degeneration for slice-wise shim sets, information of neighboring slices is taken into account for the optimization.

Additionally rs-fMRI data sets were obtained from two volunteers (200 dynamics, 25 slices, voxel size: $3\times3\times3$ mm^3, TE/TR = 16.39 ms/150 ms, EPI factor = 73), applying slice-wise DSU and a dynamic F_0 determination. Analysis was performed using the SPM8 (Wellcome Trust Center, London, UK) based toolbox DPARSF (State Key Laboratory, China) and a standard protocol for post processing was followed[10]. The results are shown overlaid on the unprocessed functional images (fig. 2), in order to avoid any additional influence of normalization on functional connectivity.

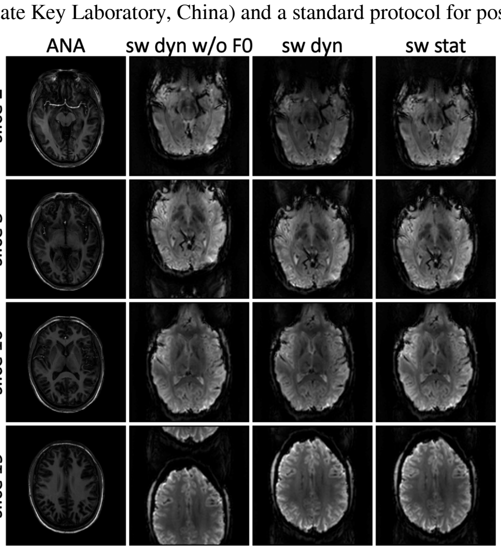

Figure 1: EPIs of four slice-wise B_0 shimmed slices of a volunteers' brain acquired with different settings: 1) dynamically updated without a dynamic F_0 determination (sw dyn w/o F0, 2nd column); 2) dynamically updated with a dynamic F_0 determination (sw dyn, 3rd column); and 3) a statically with slice-wise shim setting (sw stat, 4th column), for comparison with the slice-wise dynamic shim. An anatomical image (ANA, 1st column) is shown for comparison.

RESULTS AND DISCUSSION

Fig. 1 compares four different slices of EPIs acquired with different shim sets. Due to the implemented accurate pre-emphasis calibration for ECC, there are almost no visible remaining artifacts from residual eddy currents, as can be seen from the comparison of the slice-wise shim settings applied statically (sw stat) and dynamically (sw dyn). Furthermore, it is demonstrated, that a dynamic F_0 determination is necessary, as Z_0 offsets, induced by different B_0 shim settings, lead to image shifts (sw dyn w/o F0), and could in a worst case scenario result in a failing localization.

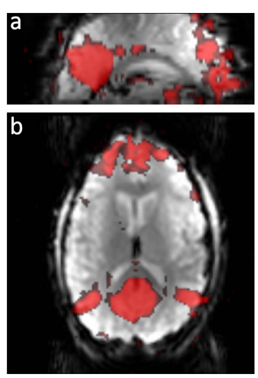

Figure 2: Resting-state fMRI activations projected on the sagittal (a) and transversal (b) unprocessed EPIs, acquired with a slice-wise dynamic updated B_0 shim with a dynamic F_0 determination.

Transversal (b) and sagittal (a) projections of the results of an rs-fMRI analysis of the dynamically shimmed data set can be seen in fig. 2. A spherical seed region of interest with a diameter of 10 mm was created in the bilateral posterior cingulate cortex as a major hub of the default mode network[11]. Correlations of this region of interest, to areas in the medioprefrontal cortex, depicting the default mode network, are clearly visible. It is demonstrated, that the accurate pre-emphasis calibration for ECC enables the fast switching of B_0 shim settings during a sequence, just 2 ms before the excitation, over 200 dynamics, without induction of artifacts due to long lasting eddy currents, and therefore enables the application to fMRI.

In **CONCLUSION** this work demonstrates that the application of dynamic shim updating based on an accurate iterative pre-emphasis calibration for eddy current compensation in combination with dynamic F_0 determination and updating is feasible for application to fast and demanding techniques, such as fMRI. In fact, this work presents the first dynamically shimmed fMRI data.

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