Echo Planar Imaging at 7T with 3rd Order Slice-Wise Dynamic Shim Update (DSU) and Full Eddy-Current Compensation (ECC)

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INTRODUCTION

As the use of ultra-high static field strength in functional MRI (fMRI) promises major advantages such as increased SNR and stronger BOLD effects, concepts for the solution of problems arising with higher field strengths, as for example B_0 and B_1 inhomogeneities, are demanded. A very promising idea to address the increasing B_0 inhomogeneities is higher-order slice-wise or regional dynamic shim update (DSU) [1]. However this approach has its challenges, as suitable hardware and an exact calibration of eddy-current compensation are essential [2], [3]. **THIS WORK** represents the first report of fast 3rd order DSU with full eddy-current compensation for multi-slice Echo-Planar Imaging (EPI), the basis for fMRI at 7T. Compared to global shim settings, determined by a FASTERMAP routine with a spiral read out (FM), which is considered the gold standard for higher-order shimming, we achieve a significant gain in image quality.

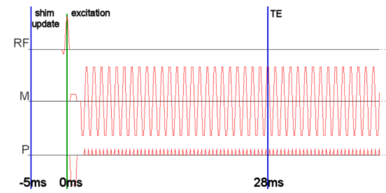

***Figure 1:** Sequence diagram for DSU EPI acquisition. The shim is updated 5ms before excitation and 6.9ms before start of the acquisition. TE = 28ms.*

MATERIALS AND METHODS

All 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, shim amplifiers (Resonance Research Inc., Billerica, USA) and a DSU Load & Go unit (Resonance Research Inc., Billerica, USA). The shim amplifiers for the higher order shim terms are driven directly by the DSU Load & Go unit, whereas the linear shims are driven by the gradient amplifiers, which could not be directly accessed by the DSU Load & Go unit. Therefore an in-house built gradient offset driver box has been constructed, which sums up the voltages from the DSU Load & Go unit to the driving voltages for the gradient amplifiers.

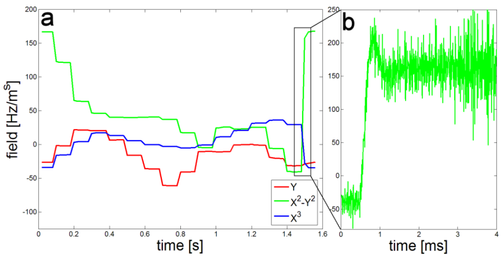

***Figure 2:** (a) Spatio-temporal B field evolution of the Y (red), X^2-Y^2 (green) and X^3 shim terms (blue), for a 15 slice EPI scan with shim sets as used for volunteer 1 (b) X^2-Y^2 shim stabilizes after a major shim step in 2ms. Data is scaled to Hz/m^s, where s = shim order*

Due to fast switching of driving currents in the shim coils, eddy-currents arise in the shim coils themselves and in surrounding conductive structures. Eddy-currents occurring in the cold structures of the cryostat can last up to several seconds and lead to field distortions that can cause image artifacts even more severe than those stemming from the static B_0 inhomogeneities [2,3]. Therefore a careful pre-emphasis calibration is required to gain image quality by DSU. This was performed using higher-order spatio-temporal field monitoring in an iterative approach as presented previously [2]. This way optimized, the temporal field evolution of the shim fields deviates less than 2% of the step size from the desired rectangular shape, after 2ms (fig. (2b)). In order to actively compensate short term eddy-currents the pre-emphasis overshoots the nominal driving voltage for a shim setting on a short time scale. Hence a reduction of the shim strength of 2nd and 3rd order shim terms to 73% to 90% and 43% to 53% of their maximum values, respectively, was required to maintain the functionality of the shim system. The set of shim values was determined separately for each slice using a modified version of an IDL (Exelis, Inc., Boulder, USA) based Localized Shimming Tool [4]. To overcome the problem of degeneration of some shim terms, due to a lack of data points in the according direction in case of thin slices [5], initial B_0 fields of neighboring slices are taken into account during the shim optimization.

To assess the gain in image quality, *in vivo* multi-slice single-shot EPIs of the brain (TE/TR = 28ms/3000ms, EPI factor = 99) were acquired in two healthy volunteers (fig. (3)), once using a FM shim over the considered region and once using a slice-wise dynamically updated shim, which was set 5ms before excitation of each individual slice (fig. (1)).

To monitor the field evolution for such a dynamically updated shim during an EPI sequence, a 3rd order field camera, containing 16 NMR probes equally distributed on a sphere with a diameter of 20cm as described in [6] was employed.

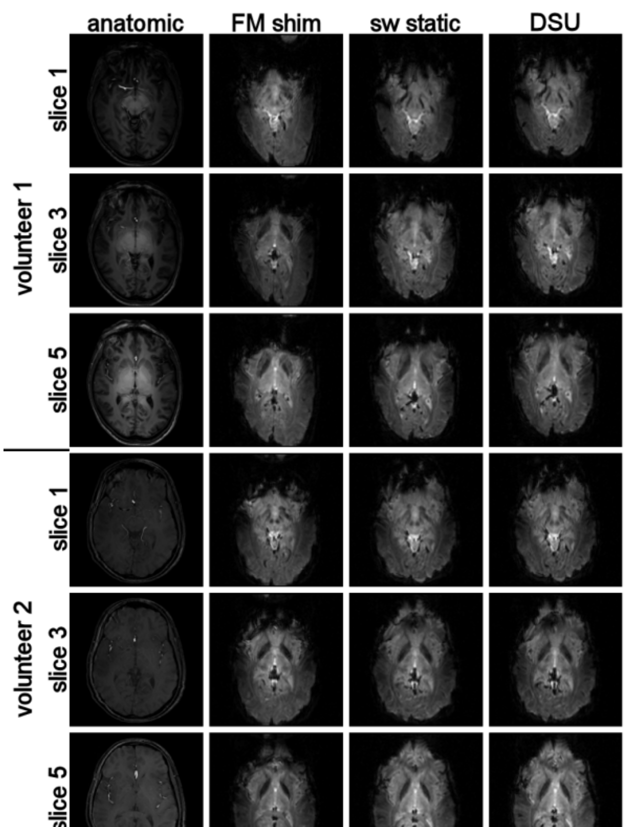

***Figure 3:** EPIs of three slices of two volunteers' brains acquired with a FM shim (2nd column) and a dynamic updated shim (4th column) with reduced shim strengths. Additionally an T_1 weighted FFE anatomic reference image (1st column) and an EPI acquired with a slice-wise (sw) static shim (3rd column) of the respective slices are shown for comparison.*

RESULTS AND DISCUSSION

The accuracy of the pre-emphasis calibration method used [2] allowed for updating the shim setting only 5ms before excitation and 6.9ms before the start of the acquisition (fig.(1)), contrary to more than 60ms before excitation, as reported in earlier publications [3,7]. This enables the employment of DSU for very fast acquisition techniques, such as EPI, without extension of the scan time, and therefore the application to fMRI. In fig. (2a) the temporal field evolution of 3 shim terms for a 15-slice EPI sequence with DSU is displayed. Although the field-monitoring data gets noisy in a very high time resolution (fig(2b)), it can be observed that the field is stabilizing within less than 2ms, even after the largest shim term switch. Fig. (3) shows the comparison of EPIs of three different slices of two volunteers' brains acquired with a global FM shim, and a dynamically updated shim with reduced shim strengths. As can be seen in the anatomical reference images the positioning of the slices has been chosen to be rather low in the brain, where especially T_2* weighted images, such as EPIs, suffer from the B_0 inhomogeneities induced by the sinuses. It is clearly visible that distortions and signal dropouts in frontal brain areas are significantly reduced by the application of DSU, even though the maximum shim strengths of 2nd and 3rd order terms were notably reduced in comparison to the global FM shim. By comparison of EPIs employing slice-wise static shims with dynamically shimmed EPIs no significant loss in image quality due to residual eddy currents can be observed.

In **CONCLUSION** this work demonstrates the feasibility of very fast slice-wise DSU for reduction of B_0 inhomogeneities and gaining image quality in gradient echo EPI, after iterative calibration of the eddy-current pre-emphasis settings for all shim terms by spatio-temporal field monitoring.

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