Expected Homogeneity Gain and Hardware Requirements for Slice-Wise 3rd Order Dynamic Shim Updating for fMRI

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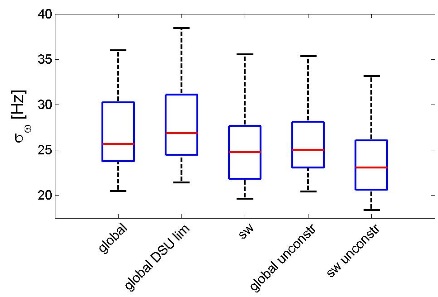
INTRODUCTION

In order to diagnose and understand neurological and psychological disorders functional Magnetic Resonance Imaging (fMRI) becomes an increasingly important tool. Echo Planar Imaging (EPI) allows for very fast acquisition, and therefore high temporal resolution of signal changes, and is, hence, the "work horse" of conventional fMRI. EPI, however, is intrinsically sensitive to B_0 inhomogeneities, which leads to signal drop-outs and image distortions, especially at high and ultra-high field strengths. Therefore, in order to exploit the full advantage of applying ultra-high field strengths to fMRI, sophisticated B_0 shim strategies are required. Since local B_0 shimming has proven advantageous[1,2] compared to global shimming, an auspicious approach for improving B_0 homogeneity is Dynamic Shim Updating (DSU)[3], in which the B_0 shim settings are updated dynamically during the sequence. As fast switching of shim currents gives rise to eddy-currents in the shim coils themselves and the surrounding conducting structures, a careful pre-emphasis calibration is necessary. Successful implementations and pre-emphasis calibrations[4,5,6,7] as well as the application of 3rd-order DSU to fMRI[8] have been demonstrated. However, the application of pre-emphasis requires the limitation of the applicable shim field amplitudes[8], which in turn limits the homogeneity gain that can be expected from DSU. **THIS WORK** compares the expected homogeneity gain from a global and a slice-wise DSU shim approach and, furthermore, investigates the hardware requirements for optimal slice-wise dynamic shimming.

MATERIALS AND METHODS

The application of pre-emphasis for eddy-current compensation requires overshooting of the shim current beyond the nominal value. Hence, in order to avoid exceeding the maximum output current of the shim amplifiers and risking failure or damage, the maximum applicable nominal shim currents need to be reduced for the application of DSU with respect to the maximum shim currents available for a static B_0 shim approach[8]. This limitation is dependent on the applied pre-emphasis calibration, i.e. the amplitude of the current overshoot that is required to compensate for induced eddy-currents.

B_0 maps (25 slices, voxel size = 2×2×2mm^3, ΔTE = 1ms) of the brains of 14 volunteers were acquired at a 7T whole body (Philips, Achieva, Cleveland, OH) system, using a T/R head coil in combination with a 16 channel receive array (both, NOVA medical, Wilmington, MA), without any B_0 shimming applied. These B_0 maps served as a basis for the calculation of five different sets of shim parameters: 1) a global shim set considering the hardware constraints of the system (**global**), 2) a global shim set with reduced maximum shim fields according to the calibrated pre-emphasis settings (**global DSUlim**), 3) a slice-wise optimized shim set constrained to DSU limits (**sw**), 4) a global shim set optimized without any constraints (**global unconstr**), and 5) a slice-wise optimized shim set without any constraints (**sw unconstr**). The calculations were performed using an IDL (Exelis, Inc., Boulder, CO)-based Shimtool[9], which was modified to allow slice-wise shim optimization. Corrected B_0 distributions were then simulated from the B_0 maps and the different shim sets in MATLAB (Mathworks, Natick, MA) and the standard deviation of frequencies, σ_ω, of the simulated B_0 field maps was determined in order to evaluate the expected homogeneity from each calculated set of shim parameters. Additionally, the mean and maximum field amplitudes for each shim channel, that would be required for an optimal B_0 inhomogeneity compensation, were extracted from the shim sets calculated without considering any constraints and the required shim current output per channel to allow for these shim field amplitudes were derived.



Standard deviation of frequencies σ_ω of B_0 distributions simulated using a global shim set considering the hardware constraints (global), a global and a slice-wise optimized shim set with reduced maximum shim field amplitudes according to the required pre-emphasis settings (global DSU lim, sw) and a global and a slice-wise optimized shim set calculated without any constraints (global unconstr, sw unconstr). The boxes extend from the 25th to 75th percentiles of all 14 volunteers and the median value is indicated by the red mark.

RESULTS AND DISCUSSION

Figure 1 displays a boxplot of σ_ω within the B_0 distributions simulated using the different shim sets that were calculated for each volunteer. It can be seen, that the application of slice-wise dynamic shimming leads to a reduction of σ_ω compared to static global shimming, as long as the same shim field constraints are employed in both cases. However, slice-wise dynamic shimming (**sw**), including the necessary reduction of applicable shim amplitudes, does only yield a moderate gain in B_0 homogeneity over global static shimming (**global**), when the maximum shim fields can be employed for the global shim. It is also visible, that B_0 homogeneity could be further improved by slice-wise DSU over global shimming of the same shim order, if higher shim amplitudes would be applicable.

The mean and maximum required shim field amplitudes for each channel were calculated with an unconstrained fit, and are shown in table 1. It can be seen, that the required maximum shim amplitudes of the 2nd-order shims are within the range of applicable shim amplitudes for dynamic shimming. The maximum shim amplitudes of most 3rd-order shim terms required for optimal slice-wise dynamic shimming, however, mostly exceed the applicable shim fields (red shading in table 1). The last column of table 1 displays the maximum shim currents, which would be required to produce the maximum calculated shim fields for slice-wise DSU including pre-emphasis for the vendor implemented shim coils and their respective sensitivities. The currently used shim amplifiers only allow for a maximum current output of 10A per channel, which is about an order of magnitude too little for the Z^3 and Z^2X channels. It is also questionable whether the employed shim coils could withstand such high currents without damage.

Shim Term	$F_{max,\ static}$ mT/m^n	$F_{max,\ DSUlim}$ mT/m^n	SF_{mean} mT/m^n	SF_{max} mT/m^n	$SC_{max,\ dyn}$ A
Z^2	4.51	4.10	0.64 (0.44)	2.88	6.97
ZX	7.43	5.46	0.82 (0.65)	3.18	5.40
ZY	7.53	5.57	0.36 (0.34)	1.72	2.87
X^2-Y^2	7.36	5.93	0.30 (0.23)	1.17	1.90
XY	7.25	5.80	0.09 (0.10)	0.60	1.00
Z^3	3.08	1.39	7.04 (5.25)	27.39	137.92
Z^2X	3.85	1.71	3.32 (2.76)	16.58	67.03
Z^2Y	3.71	1.64	1.15 (0.91)	3.79	15.92
$Z(X^2$-$Y^2)$	22.84	12.30	10.17 (7.00)	33.84	21.65
ZXY	22.97	10.05	3.60 (3.08)	16.24	11.05
X^3	10.21	4.86	1.07 (0.91)	5.08	7.58
Y^3	9.91	4.53	0.51 (0.44)	2.60	4.04

Table 1: Maximum available shim field amplitude per channel for static shimming ($F_{max,\ static}$) and according to pre-emphasis requirements reduced amplitudes for the dynamic shimming ($F_{max,\ DSUlim}$), as well as the mean (SF_{mean}) and maximum (SF_{max}) required shim field amplitudes for optimal slice-wise dynamic B_0 shimming. All shim amplitudes are given in mT/m^n, where n denotes the shim order. Additionally the maximum shim current ($SC_{max,\ dyn}$), required to produce SF_{max} as nominal field amplitude and enabling shim pre-emphasis, is given in A.

In **CONCLUSION** this work demonstrates, that a gain in homogeneity by slice-wise dynamic shim updating compared to a static global B_0 shim approach is theoretically possible. However, especially for 3rd-order terms, higher shim field amplitudes are required, for which stronger amplifiers and probably considerations about the shim coil design are necessary.

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