Advances in Software Compensation of Eddy Current Fields in Multislice Higher Order Dynamic Shimming.

S. Sengupta[1,2], M. Avison[2,3], J. Gore[2,3], and E. B. Welch[2,3]
[1]Biomedical Engineering, Vanderbilt University, Nashville, Tennessee, United States, [2]Vanderbilt University Institute of Imaging Science, Nashville, United States, [3]Radiology and Radiological Sciences, Vanderbilt University, Nashville, United States

INTRODUCTION

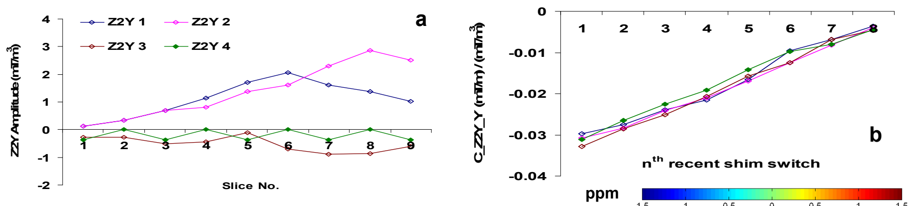
Dynamic B_0 shimming (DS) can produce better field homogeneity than static global shimming by dynamically updating slicewise shim values in a multislice acquisition [1, 2]. The performance of DS however may be limited by eddy current fields produced by the switching of 2nd and 3rd order unshielded shims. These time varying eddy fields can cause field deviations leading to distortion, signal losses, and ghosting, especially in single shot echo planar imaging (SSEPI). A software based prospective method of eddy current compensation (ECC) applied to higher order shim induced eddy currents in multislice DS has been proposed previously [4]. This method does not require shim shielding, hardware ECC or subject specific preparation scans and is based on an assumption of reaching an eddy field steady state during a DS experiment. We present extensions of the previous work to include static interaction terms, corrections in SSEPI and steps towards generalization with repetition time.

THEORY AND METHODS

This method assumes that in a multi slice DS scan, the eddy fields reach a steady state in which their magnitudes do not change from shot to shot for the same slice. Further, it assumes that that the fields produced depend on the history of the shim switches. Therefore, in an *n* slice DS experiment,

$$\begin{bmatrix} Ge_1 \\ Ge_2 \\ \cdot \\ Ge_n \end{bmatrix} = \begin{bmatrix} \Delta G_{1n} & \Delta G_{n,n-1} & \cdot & \Delta G_{3,2} \\ \Delta G_{2,1} & \Delta G_{1,n} & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \Delta G_{n,n-1} & \cdot & \cdot & \Delta G_{2,1} \end{bmatrix} \begin{bmatrix} C_1 \\ C_2 \\ \cdot \\ C_n \end{bmatrix}$$

$$Ge = \Delta G.C \quad \& \quad [(\Delta G^T \Delta G)^{-1} \Delta G^T].G_e = C$$



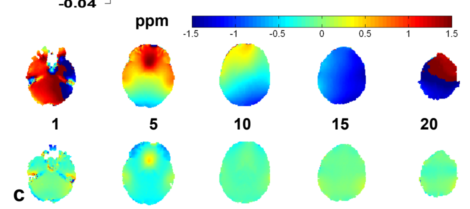


Figure 1 (a): Z2Y shim switching, 1-3 head phantom; 4 spherical phantom (b) ***C_Z2Y_Y*** showing invariability. (c) 3rd order DS invivo fieldmaps. Large gradients and offsets due to eddy fields (uncorrected maps; top row) are corrected (bottom row)

Ge is the *nx1* vector of slice wise eddy fields. **Δ*G*** is a $n \times n\text{-}1$ matrix of the slice wise shim differences such that $\Delta G_{ij} = G_i - G_j$ where G_i is the shim setting for slice *i* and ***C*** is a vector of '*correction factors*' which gives the contribution of the *n-1* recent shim switches to the eddy field prevailing during acquisition of any slice. ***C*** is estimated for the eddy interaction between any pair of shims by a calibration scan. ***C*** remains invariant with varying shim switching patterns, amplitudes and imaged object, for a fixed time between shim switches, Δt_{ss}. Then for a particular Δt_{ss}, ***C*** is used to prospectively compensate for the eddy fields. A complete one time calibration for 16 shims in a particular multislice experiment yields an *n-1 x 16 x 16* ***C*** matrix, which can compensate for all eddy fields without the use of any hardware ECC. Figure 1 shows previous results demonstrating invariability of ***C*** and correction of eddy field gradients and offsets in 3rd order DS.

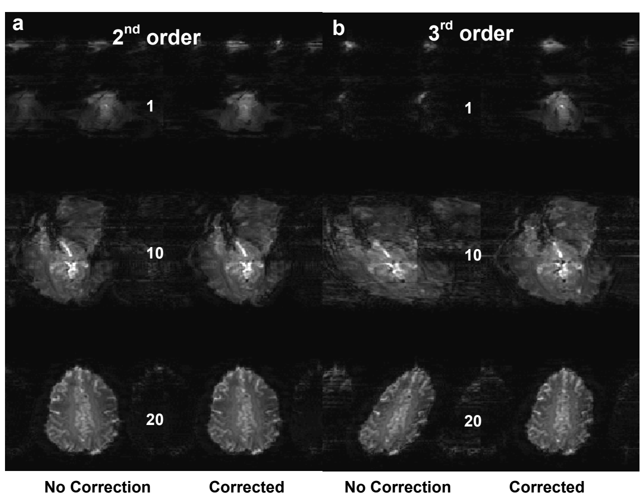
All studies were performed on a 7 Tesla Achieva scanner (Philips Healthcare, Cleveland OH, USA). For DS, a hardware module (MXH 14R Real Time Shim 'RTS', Resonance Research Inc, MA, USA), was employed.

Inclusion of static interaction: It was observed that when ***C*** was obtained using an $n \times n\text{-}1$ **Δ*G*** matrix, the estimated ***Ge***$_i$***'*** had a constant slicewise offset equaling the slicewise mean of the switched shim ***G*** multiplied by the *static* interaction factor between the shims ***G*** and ***Ge.*** This static interaction effect was included in the above model by adding a unity column in the **Δ*G*** matrix making it *n x 16 x16*, yielding a modified *n* element ***C*** vector. This vector therefore accounted for both the eddy and the static interactions in the system.

Experiments: SSEPI scans were performed on a subject with a Δt_{ss} of 110 ms (25 axial slices, TR/TE = 2765/27 ms, no SENSE acceleration, 10 dummy scans) with 2nd and 3rd order DS, with and without the steady state field corrections. The scans without the corrections included the static cross term corrections while the ***C*** vectors employed for the human correction scans were derived solely from phantom calibrations at Δt_{ss} of 18.7 ms. Offline reconstruction was performed by established methods [5] to eliminate N/2 ghost artifacts, most likely caused due to short time constant eddy currents distorting *k*-space sampling. For testing the influence of Δt_{ss} on ***C***, 9 slice calibration scans were performed on a spherical phantom with Δt_{ss} ranging from 18ms to 4444 ms. ***C_Z2_Z0*** vectors were derived as described above.

RESULTS AND DISCUSSION

The SSEPI images show large improvements with steady state field corrections in both 2nd and 3rd order DS. Uncorrected 2nd order DS images show bulk shifts in the left-right direction that are corrected by the method, indicating compensation of Z0 eddy fields. The 3rd order DS images without correction show very poor quality with distortions, bulk shifts, signal losses (signal is lost completely in slice 1) and ghosting that indicate large field gradients. The proposed method corrects for these effects leading to greatly improved image quality. Figure 2c shows that ***C_Z2_Z0*** remains invariant up to a Δt_{ss} of ~222 ms, which is much larger than those employed in most imaging experiments including fMRI



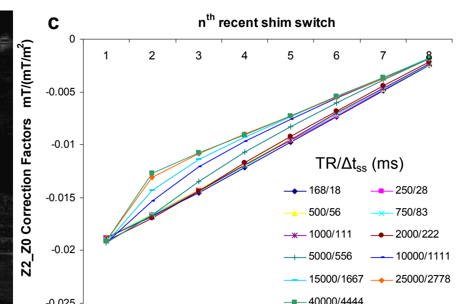


Figure 2 (a, b) SSEPI results in 2nd and 3rd order DS, bulk shifts, distortions, signal losses and ghosting are corrected by the technique. (c) Influence of Δt_{ss} on ***C_Z2_Z0***. ***C*** remains invariant upto Δt_{ss} of ~222 ms.

CONCLUSIONS

Advances in a promising new method for compensation of eddy fields produced by shim switching have been described. Inclusion of the static interaction factor characterizes the complete long term steady state behavior of the shim system. SSEPI results confirm the general applicability of the technique as does the invariability of ***C*** over a large range of Δt_{ss} .The method requires no additional hardware and has the potential to greatly reduce eddy current related field perturbations in DS.

REFERENCES

[1] Blamire AM, MRM. 36, 159 [2] Zhao Y, JMR, 173, 10 [3] Morich MA, IEEE TMI, 7, 247 [4] Sengupta S, Proc ISMRM 2010, p.1564 [5] Hu X,MRM,36,166.