Software Compensation of Eddy Current Fields in Higher Order Dynamic Shimming

S. Sengupta[1,2], B. E. Welch[1,3], A. Anderson[1,4], J. Gore[1,4], and M. J. Avison[1,4]

[1]Vanderbilt University Institute of Imaging Science, Nashville, Tennessee, United States, [2]Biomedical Engineering, Vanderbilt University, Nashville, Tennessee, United States, [3]Philips Healthcare, Cleveland, Ohio, United States, [4]Radiology and Radiological Sciences, Vanderbilt University, Nashville, Tennessee, United States

Introduction

Dynamic Shimming (DS) is a technique for obtaining optimal B_0 field homogeneity over a volume by updating the shim coil currents for every slice in a multislice acquisition in real time [1, 2]. While DS can theoretically produce better B_0 homogeneity for each imaging subvolume than static, global volume shimming methods, its performance may be limited by eddy current fields produced by the switching of 2nd and 3rd order unshielded shims, especially at ultra-high fields. These time varying eddy fields (which include 'self' as well as other spatial harmonics) can cause severe field deviations leading to signal losses, distortion and ghosting in imaging. Traditionally, compensation of eddy currents produced by linear gradients has been achieved using shaped current waveforms, which requires special hardware that is typically not available for higher order shims [3]. In this work, we present a novel method of eddy current compensation (ECC) applied to higher order shim induced eddy currents in a multislice DS experiment. This method does not require the use of extra hardware for ECC and is based on an assumption of reaching an eddy field steady state during an FFE (fast field echo) acquisition.

Theory

For our method of ECC, we make three assumptions. First, we assume that in a multi slice DS FFE experiment, the time varying eddy fields reach a steady state in which the magnitudes of these fields do not change from shot to shot for the same slice. Secondly, we ignore any change in eddy field magnitude during the FFE data readout window. Thirdly, we assume that the eddy fields produced depend not only on the most recent switch of higher order shim but also on the previous switches. It follows then, that in an n slice DS experiment we can write:

$$\begin{bmatrix} Ge_1 \\ Ge_2 \\ . \\ Ge_n \end{bmatrix} = \begin{bmatrix} \Delta G_{1n} & \Delta G_{n,n-1} & . & \Delta G_{3,2} \\ \Delta G_{2,1} & \Delta G_{1,n} & . & . \\ . & . & . & . \\ \Delta G_{n,n-1} & . & . & \Delta G_{2,1} \end{bmatrix} \begin{bmatrix} C_1 \\ C_2 \\ . \\ C_n \end{bmatrix} \quad Or \quad \begin{matrix} \boldsymbol{Ge} = \boldsymbol{\Delta G.C} \\ \& \\ [(\Delta G^T \Delta G)^{-1} \Delta G^T].Ge = C \end{matrix}$$

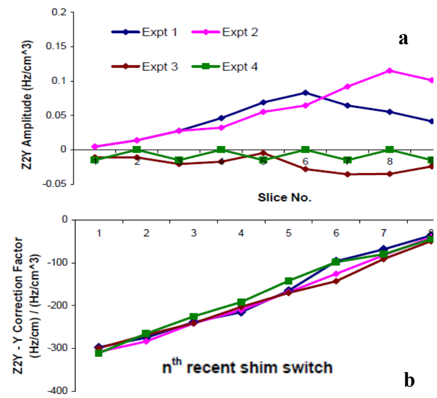

Fig1 (a): Switching of Z2Y shim, Experiment 1-3 Head phantom; Experiment 4 Spherical phantom (b) Z2YtoY correction factors.

Here, ***Ge*** is the $n\times 1$ vector of slice wise eddy fields produced. $\boldsymbol{\Delta G}$ 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*** can be estimated for the eddy interaction between any pair of shims by using a calibration scan, for example, the time varying Z0 field produced by Z2 shim switching yields a vector C^{Z2_Z0}, which we hypothesize 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*** can be used to prospectively compensate for the expected eddy fields, assuming the metallic structures in the magnet in which the eddy currents flow remain the same. A complete one time calibration of all the shim eddy interactions for a particular multislice experiment therefore yields a set of ***C*** vectors, which can compensate for all eddy fields without the use of any hardware eddy current compensation.

Methods

All studies were performed on a Philips 7 Tesla Achieva whole body MR scanner (Philips Healthcare, Cleveland OH, USA) with a Resonance Research Inc shim power supply (RRI Inc, MA, USA MXH 10A). For higher order DS, a hardware module (MXH 14R Real Time Shim System, RRI Inc), was employed, enabling switching of shims in real time. The real time shim switching hardware module had no built-in ECC mechanisms. In order to calculate the correction factor vectors ***C*** for all eddy interactions and demonstrate their invariability, calibration scans were performed where the higher order shims were switched individually in random patterns (Fig 1a). The calibration scans were performed on different days with two different phantoms (head-shaped saline-filled and 17 cm spherical gel) and phantom positions. The resulting fieldmaps were measured using a dual echo FFE sequence (9 slices, TR/TE = 168/4.4ms, 25 slices, TR/TE = 466/4.4ms, Δt_{ss} = 18.6 ms, ΔTE = 0.1ms). A reference fieldmap with no shims applied was subtracted from the dynamically-shimmed fieldmaps. Shim decomposition was performed to identify the harmonics that correlated strongly with the switched shim pattern (cutoff r^2 = 0.9), and the entire correction factor matrix for the whole shim system was populated. For validation of the correction, 9 and 25 slice DS FFE experiments were performed employing shims up to the 3rd order, both in phantoms and in humans, with and without the steady state shim eddy corrections. The Δt_{ss} was the same as the calibration scans. These corrections were added in addition to static cross terms describing the interaction between shims in the absence of dynamic switching.

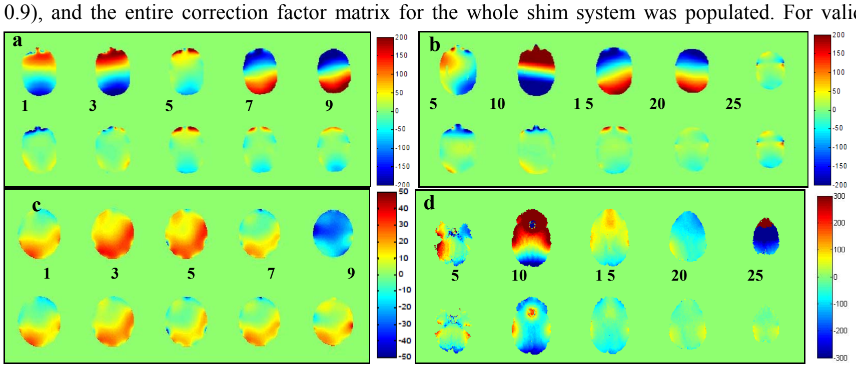

Fig 2. Fieldmaps in Hz before (top row) and after (bottom row) correction. (a,b) : Slices from 9 & 25 slice head phantom scans (c) Slices from 9 slice spherical phantom scan showing Z0 correction. (d) Slices from a 25 slice human scan. Slice 25 shows large field wrap corrected. Slice numbers shown in between.

Results and Discussion

Figure 1b shows the Z2Y to Y shim correction factors obtained from four different Z2Y shim switching patterns showing high reproducibility. Fig2 shows selected slice fieldmaps collected in multislice 3rd order DS FFE experiments, with and without the corrections for different number of slices and imaged objects, including a human head. In all cases, the severe field gradients were corrected using this method, without any hardware ECC or individual prescanning.

The invariability of the correction factors across different types of imaged objects and across different applied shim patterns translates into a characterization of the eddy current behavior of the shims and the magnet. We have described this behavior for one Δt_{ss}. This can potentially be extended to different number of slices and varying Δt_{ss} to yield a complete description of the shim eddy fields, which may be then used for automatic software ECC. To compensate for self eddy fields, a recursive approach may be needed, as adding corrections in that case would change the causative shim itself.

Conclusions

A promising new method for compensation of eddy fields produced by shim switching has been described and demonstrated. The method requires no additional hardware and has the potential to greatly reduce eddy current related field perturbations in DS. Further work is needed to completely characterize the behavior of these fields and robustness of the technique with respect to varying experimental conditions.

References

[1] Blamire AM et al, MRM. 36:159, 1996.[2] Zhao Y et al, JMR, 173, 10-22.[3] Morich MA et al, IEEE Trans Med Imag, 7, 247-254,1988