Silent slice-wise shimming with a multi-coil setup at ultrahigh-field MRI

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Synopsis

Multi-Coil shimming is advantageous because of its ease of use for effective local and slice-wise shimming. Shim coils are constructed of current-carrying conductor wires and undergo Lorenz force while placed in the magnet. Currents alteration in slice-wise shimming changes the magnitude and direction of force and imposes mechanical vibrations and noise. Here we propose three strategies to control degree of inter-slice shims current change. The proposed strategies show that inter-slice current change can be appropriately reduced without degrading shimming performance by including a minor change in shimming routine.

Introduction

Inhomogeneity of static magnetic field, B0, increases at ultrahigh-field (UHF) MRI because of an induced magnetic field from susceptibility differences which is a linear function of B0 strength. One remedy is increasing number of shims when possible. In the human brain, inhomogeneity spots are local and steep, formed around air-tissues interfaces. Shimming using a Multi-Coil (MC) setup[1,2] is advantageous because of its architecture where employing small local coils allows targeting local inhomogeneities and increasing the number of shim channels.

B0 shimming problem is usually an overdetermined system of linear equations; hence, shimming of reduced ROI is expected to yield an improved homogeneity[3]. In a reduced ROI, the target field can be better approximated with a fixed number of shim coils. Slice-wise shimming takes advantage of this notion by calculating optimal shim current per slice in advance and performing dynamic shim update (DSU) during acquisition.

A current-carrying conductor in presence of a magnetic field experiences a so-called Lorenz force. At UHF where the field strength is higher and the desire is toward increasing shim current or coils with more turns, local shim coils undergo higher Lorenz force. DSU alters Lorenz force magnitude and/or direction and results in mechanical vibration and acoustic noise which can degrade data quality if not addressed properly, damage the setup in long-term, or discomfort subject since the setup is physically attached to RF head coil. In this work, we propose some tactics to tackle and reduce Lorenz force temporal fluctuations.

Methods

Simulation results are in figure 1.A depicts the root sum of square (RSS) of shims current change when moving from slice q to slice p for shimming of a target brain B0 map with a 16-channel multi-coil setup[4] (current limit = $\pm$3A). Figure 1.B represents RSS of shims current change for two common acquisition schemes, sequential and interleaved. Although B0 inhomogeneity in adjacent slices varies smoothly; however, figure 1 shows that it is not guaranteed that minor shims current change is sufficient to reach the most optimum solution. Here we propose the following approaches to control inter-slice shims current change:

1) covering both adjacent slices for slice-wise shimming is used to avoid shim degeneracy and improve orthogonality for shims basis sets[5]. However, this can be expanded to more than two adjacent slices. With more adjacent slices involved, more similarity in shims for consecutive slices is expected at the cost of lowering shimming efficiency. To recover efficiency loss, a Gaussian profile is applied to control the contribution of each slice (Figure 2.A). Thus, shimming optimization can be formulated as:

$$\tilde{c} = \arg\min_{c} ||Ac + \Delta B_0||_W^2 \qquad s.t.\ lb \le c \le ub$$

where **c** is currents to be calculated, **A** is shims basis set, and **W** is NxN (N=number of voxels) diagonal matrix containing weights from a Gaussian profile.

2) Schwerter et al.[6] proposed to add two additional regularization terms and dynamic constraints to dampen eddy-current in DSU. Here we employ a simplified form of that algorithm with one regularization to regulate inter-slice shims current change. Hence, the shimming problem can be reformulated as:

$$\tilde{c} = \arg\min_{c} ||Ac + \Delta B_0||_2^2 + \lambda ||c - \dot{c}||_2^2 \qquad s.t.\ lb \le c \le ub$$

where λ is regularization weighting parameter and ċ is the calculated shims current for preceding slice.

3) shims current is calculated per slice first. Then, slice acquisition order will be sorted in a way that overall inter-slice currents change reduces. A simple sort method is to pick a slice as starting and calculate RSS of shims current change with respect to every other slice and choose the one that gives the minimum value. This can be simply repeated for all slices in a loop. From optimization perspective, this is a form of linear assignment problem and can be effectively solved with methods like Hungarian algorithm.

Results and Discussions

Figure 2.B shows RSS of inter-slice currents change for sequential acquisition with different number of adjacent slices involved in shimming. Integral of RSS (iRSS) can be used as a metric to compare inter-slice current change reduction. iRRS is 257, 203, and 136 A for the case of including 0, 4, and 8 adjacent slices in shimming of a target slice, respectively. Figure 2.C depicts B0 maps before and after DSU, including different number of adjacent slices.

RSS of inter-slice currents change with different regularization weights to dampen inter-slice currents change is shown in Figure 3.A for a sequential acquisition order. As Expected, iRSS reduced with larger regularization weight; however, whole brain STD has not affected much (iRSS=257, 230, 111, and 34 and SD=5.89, 35.89, 35.93, 37.81 Hz for λ=0, 1e2, 1e4, and 1e6, respectively. SD before DSU=74Hz). Figure 3.B shows that a larger regularization weight can dampen RSS for any acquisition order.

Figure 4, compares RSS for sequential, basic, and Hungarian acquisition order sorting (iRSS=257, 236, and 215 for sequential, basic, and Hungarian, respectively). RSS increases moving to the end of acquisition for basic sorting since fewer slices are left to be chosen for minimum RSS. Unlike the two other approaches, basic and Hungarian sorting methods do not affect shimming performance as they only change chronological acquisition order.

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Figure1

A) root sum of square of inter-slice shims current change between a pair of slices for a whole human head. Diagonal values are zero as it represents shims current change from a slice to itself. A plot of any acquisition scheme can be extracted from this image. B) inter-slice shims current change plot for sequential and interleaved acquisition scheme, extracted from (A). In interleaved scheme, first, even slices are measured sequentially, then odd slices.

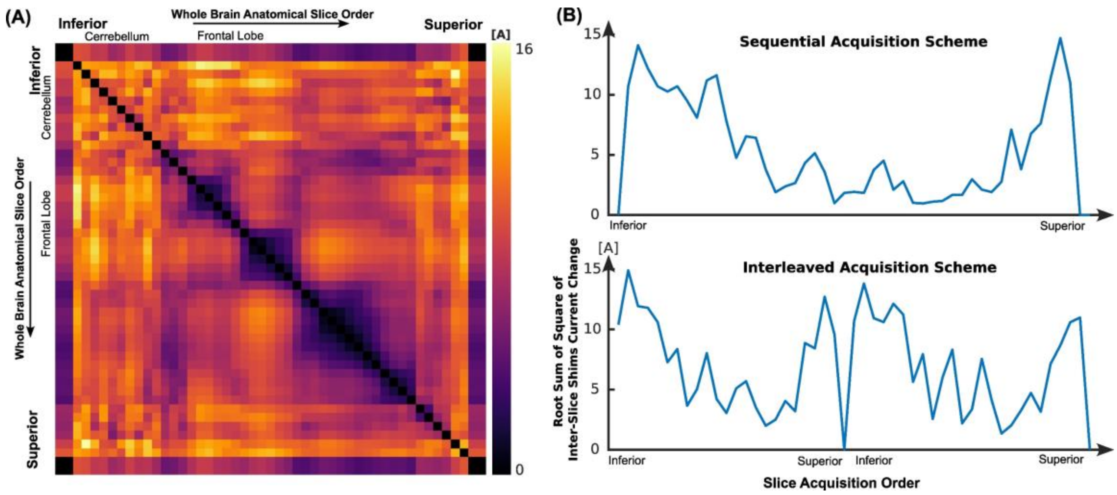

Figure 2

A) Gaussian weighting profile used to control the contribution of adjacent slices to shim slice number p. B) root sum of square of inter-slice shims current change for sequential acquisition scheme while 0, 4, and 8 adjacent slices are included in shimming. C) Simulated B0 map obtained after slice-wise shimming with a different number of adjacent slices involved in shimming.

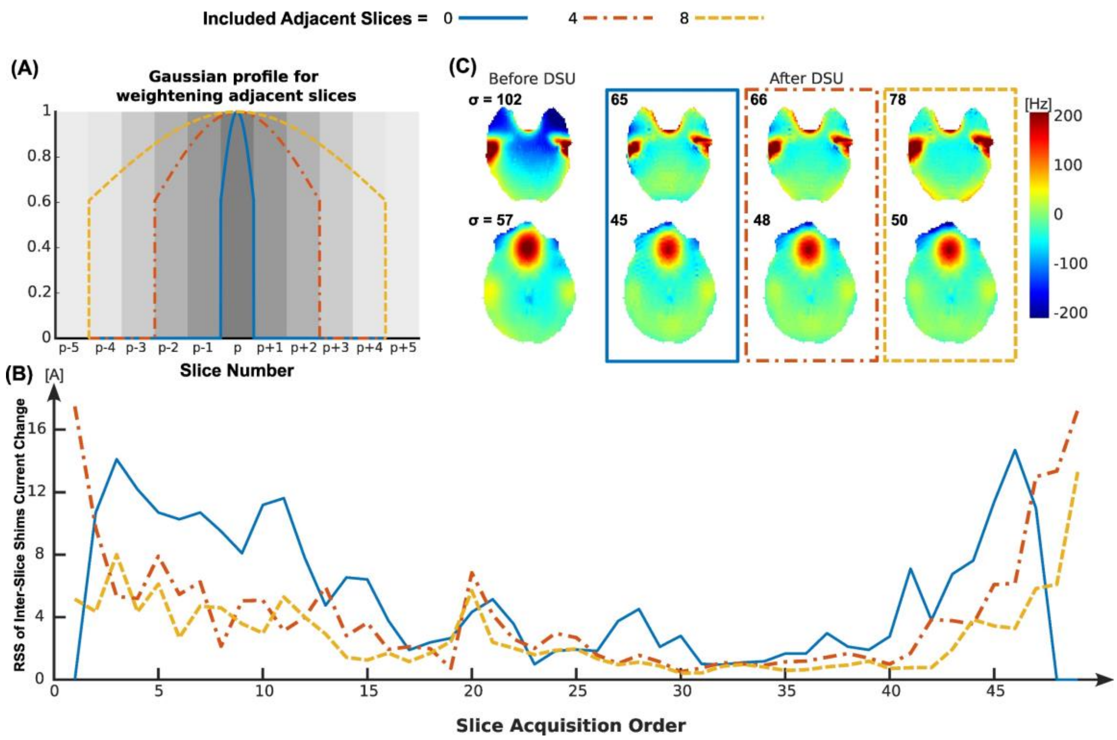

Figure 3

A) root sum of square of inter-slice shims current change when additional regularization term is added to shimming problem to reduce shims current change between two consecutive slices in sequential order. Parameter λ defines the weight for regularization. B) inter-slice shims current change between every two slices (49 slices in total).

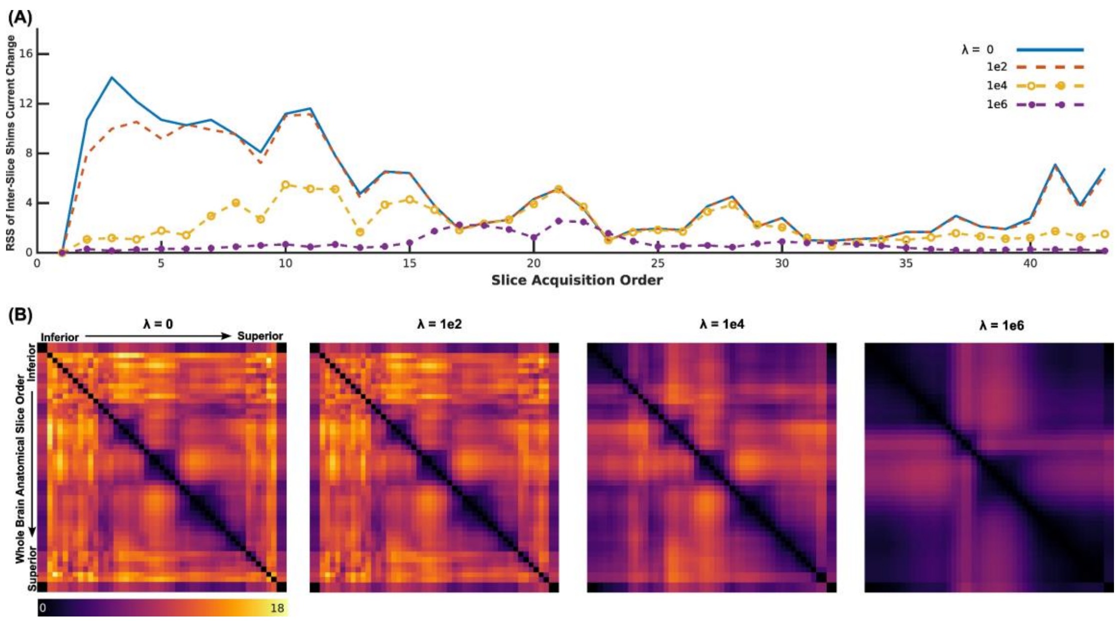

Figure 4

Slices acquisition is reordered in a way that overall shims current change reduces. In basic sorting slice Nr. 1 is selected optionally and the next slice with the minimum shims current change respect to slice Nr. 1 will be chosen as slice Nr. 2. This will be repeated for slice Nr. 2 to find slice Nr. 3 and so forth. Hungarian algorithm does not necessarily find the slices with the minimum shims current change; however, it tries to sort in a way that overall shims current change gets minimized