An algorithm for designing passive shim sets compensating for anatomically specific B0 inhomogeneities

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Introduction: Magnetic field inhomogeneity artifacts caused by susceptibility differences at air-tissue boundaries in the inferior frontal and temporal brain regions are an issue for brain imaging, especially for high field MRI. In current practice, active shimming effectively compensates for first-order B_0 inhomogeneity components. Higher-order components remain difficult to compensate for even with strong shim current supplies. This work demonstrates a synergetic shimming strategy that utilizes passive shimming to compensate for high order B_0 inhomogeneities and active shimming to compensate for linear components.

Methods: The design goal of the synergetic shimming strategy is to determine the optimal configuration (sizes R, susceptibility values $\Delta\chi$ and spatial locations) of a set of discrete shimming spheres within the magnet bore that minimize the B_0 field inhomogeneities of a given ROI. The proposed shimming method consists of an iterative optimization algorithm illustrated in figure 1. The initial ΔB_0 distribution in the ROI was calculated using an in-house ΔB_0 calculation program [1]. An N-by-4 matrix, A, was constructed where N denotes the total number of voxels in the ROI and 4 accounts for the 0th order and the three 1st order shim gradients in x, y and z directions. A given number of spheres were initialized around the ROI and served as the passive shimming material set. During each iteration, the spheres were first allowed to vary their radii, susceptibilities and spatial locations. The effects of the shim spheres on ΔB_0 were then approximated using analytical solutions [2] with Lorentz correction followed by linear superposition onto the calculated ΔB_0 field. First-order active shimming was performed using the Moore-Penrose pseudo-inverse. Finally, B_0 inhomogeneity was computed by taking the sum of squares of all the residual field inhomogeneities (ΔB_0^{Res}) in the ROI. The optimization algorithm looped until a minimum was found or a stopping criterion was reached. Constraints in the optimization procedure ensured reasonable solutions, e.g. the spheres would not be within the subject's head. The optimization routine was implemented in Matlab (The MathWorks, Inc., Natick, MA) and performed locally on a 6 mm thick axial human head slice with 2 mm resolution, and globally on a human head volume with 5 mm resolution. EPI images of the human head slice were simulated using a Bloch-based MRI simulator [3] to visualize the improvement in image quality due to synergetic shimming.

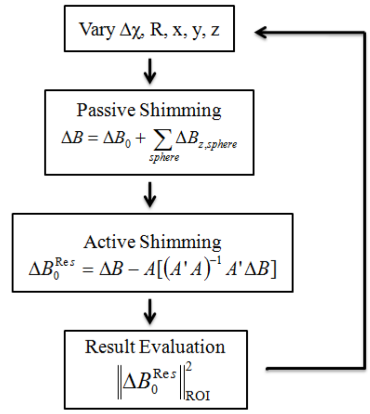

Figure 1. The iterative optimization algorithm for optimal parameters for the shim spheres.

Results: Figure 2 shows the effect of our synergetic shimming strategy on ΔB_0 distributions of the human head slice. The B_0 inhomogeneities in the inferior frontal and temporal lobes are reduced by more than 50%. Figure 3 (middle) demonstrates that the MRI simulator can successfully reproduce signal loss and geometric distortion artifacts common to EPI scanning. Figure 3 (right) demonstrates the reduction of these artifacts after synergetic shimming. Figure 4 displays the physical layout of the shim spheres for global shimming of the whole brain volume. Figure 5 displays a histogram of ΔB_0 over the whole brain without and with synergetic shimming, with significant improvement after shimming.

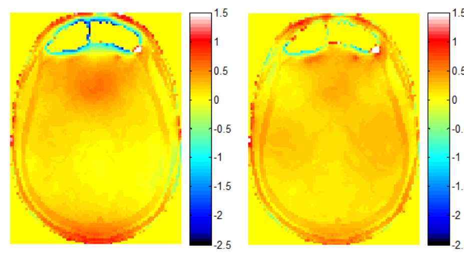

Figure 2. ΔB_0 maps (in ppm) of a 6 mm thick axial slice 2 cm from the base of the frontal lobe without (left) and with passive shimming (right).

Discussion: Previous implementations of passive shimming were investigated without synergistically incorporating active shimming. A passive shim configuration that could successfully reduce local B_0 gradients while preserving B_0 uniformity in the rest of brain region proved challenging to determine. Conversely, active shimming can achieve whole brain B_0 uniformity but is unable to compensate for localized, non-linear B_0 gradients. Application of synergetic shimming has successfully reduced local B_0 inhomogeneities inside the simulated human brain. The simulation routines utilized have been validated extensively in prior work, and are capable of physically realistic simulations. This work demonstrates the feasibility of synergetic shimming, and will be useful in implementation of this method *in-vivo*.

Several practical concerns need to be addressed. This study considered a range of shim material susceptibilities that may exceed the values found in typical materials. Perturbations to the B_0 field from shim spheres and human tissue are assumed to sum linearly, and the magnetic fields of the shim spheres are calculated with an analytical far field approximation rather than with a numerical computation method [4]. Future work includes refining simulation results and constructing a practically useful passive shimming frame to validate the simulation results *in-vivo*.

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References:
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[3] Cao *et al*., ISMRM 2009 Parallel Imaging Workshop
[4] Koch *et al*., J Magn Reson 182 (2006) 66–74

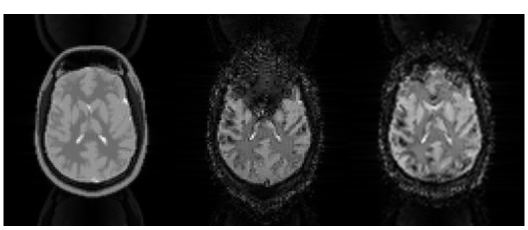

Figure 3. Simulated EPI images of the human head slice in figure 2. The simulation conditions are: (left) without realistic ΔB_0, (middle) with realistic ΔB_0 and active shimming, and (right) with realistic ΔB_0 and proposed active and passive shimming strategy.

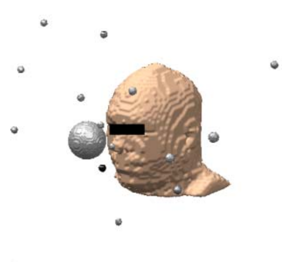

Figure 4. The approximate sizes and positions of one possible arrangement of 16 shim spheres in relation to the subject's head in 3D.

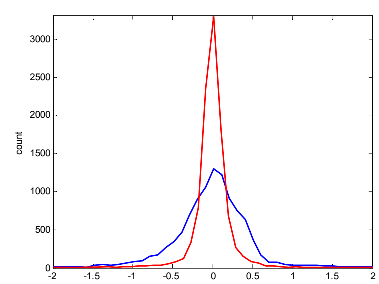

Figure 5. Histogram of the B_0 field inhomogeneity of the whole brain without (blue) and with (red) passive shimming spheres.