Adjustable Subject-Specific Passive Shims using Optimized Distributions of Bismuth and Zirconium

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Introduction Existing spherical harmonic shim coil technology has limited capabilities globally compensating in-vivo subject-specific static field inhomogeneity. When modeling global inhomogeneity in the human or animal brain, regions near the auditory and sinus cavities exhibit induced field gradients far higher in order than are available with any commercial shim system. Subject-targeted passive shims are one approach to mediate this problem [1][2]. Here, we present the optimization and construction of subject-specific passive shims using a combination of highly diamagnetic and paramagnetic magnetic materials. Materials are utilized of magnetic susceptibility large enough to induce significant fields, but small enough that no measurable torques are experienced at high field. A procedure is described, whereby optimal distributions of these shim materials are determined through linear response theory. Given the speed of the optimization computation and the ease of working with these materials in a magnet, such a method could be used to construct optimal passive shims on a single-subject specific fashion. Utilizing this optimization protocol, a prototype passive shim was successfully constructed to globally homogenize the brain of C-57 BL mice.

Methods Rapid induced field simulation protocols [3][4] utilize a small magnetic susceptibility approximation (χ < 1000 ppm) to derive numerical solutions through Fourier transformations of the sample susceptibility distribution. Within this approximation scheme, the external field induced by an object placed in a vacuum is linear in the object's magnetic susceptibility. This linear response can be used to optimize the placement of passive shim material in a fast and accurate manner.

This approach was used to optimize global homogeneity in C-57 BL mouse brains using zirconium (Zi, χ ~120ppm) and bismuth (Bi, χ~-260ppm) metals. Pure Zi foil (0.025 cm thick) was acquired from ESPI (http://www.espi-metals.com) and pure elongated Bi pieces (~0.5 g) were acquired from Sigma Aldrich (http://www.sigmaaldrich.com). Experiments were performed on a 9.4 T Bruker small animal magnet using a custom-built volume coil. Basis elements 1.00 x 0.500 x 0.025 cm of Zi and 1.0 x 0.500 x 0.100 cm of Bi were used in the optimization. Element locations were identified on a 50 mL polyethylene Falcon centrifuge tube. Figure 1 is an illustration of the element locations, which were placed octagonally in three rings on the tube. Responses for the Bi element at each position were then measured with an asymmetric gradient echo field mapping sequence. 32 0.5 mm slices were acquired with 64 x 64 pixels over 3.2 x 3.2 cm , TE=4 ms, TR = 480 ms, and echo delays of 0, 0.5, 1.0, and 4.0 ms. The target field was measured with identical experimental parameters on a living mouse. Software in Matlab was written to construct the linear optimization problem, select the region of interest (which for this demonstration was the entire brain), and solve the system using a minimum norm inversion scheme. The resulting coefficients were optimal fractional responses of the single-element Bi response. Once the responses for the system were measured and processed (which only needed to be done once), the actual time requirement for the optimization calculation was less than 2 seconds on a 2.6GHz processor workstation.

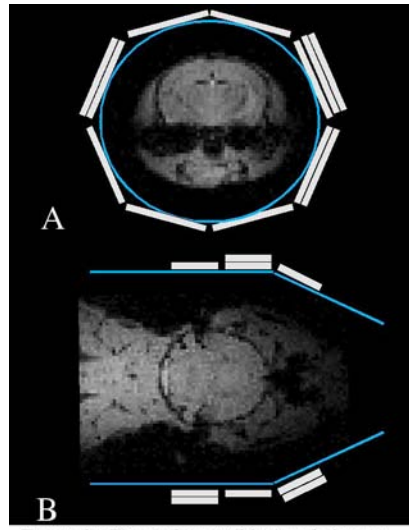

Figure 1: Plastic former (blue) and element positions (white) for passive shim optimization on mouse brain in axial (A) and coronal (B) directions

Optimal fractional Bi responses varied from 1.7 to -1.9. Approximate effective responses at each position were accomplished by stacking Bi and Zi elements. Given the thin nature of the Zi elements, they were not only used to build the negative response coefficients, but also for reduction or 'tuning' of the Bi response. Correct numbers of Zi and Bi elements were determined through experimental calibrations.

High resolution field maps were acquired with and without the passive shim in place across 48 0.33mm slices with 96x64 pixels over 3.2 x 2.1 cm resolution using 5 echo delays of 0.0, 0.5, 1.0, 2.5, and 5.0 ms with TE = 4 ms and TR= 720 ms .

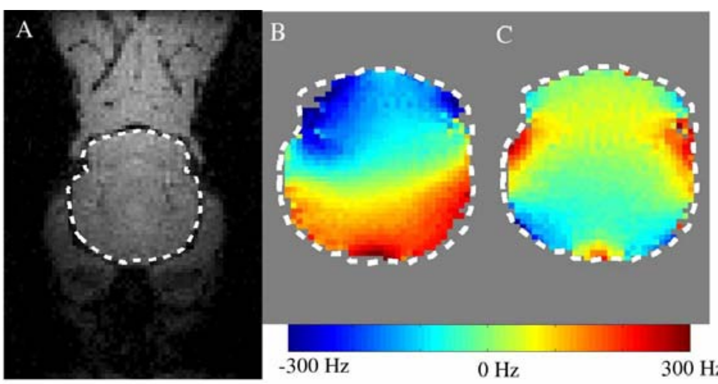

Figure 2: A) Coronal slice from MRI in the vicinity of sinus and auditory cavitie (arrows) with brain region outlined, B) field map of brain without passive shim, and C) field map with passive shim. White outlines on the maps indicate signal loss when the shim is not used.

Results and Discussion
Figure 2 demonstrates the improvement in global homogeneity using the passive shim. The overall field distribution across the displayed slice is significantly flattened when the shim is used. Residual inhomogeneity directly adjacent to the sinus and auditory cavities can be removed through another iteration of the optimization procedure over a finer material distribution grid.

The procedure outlined here measured element responses empirically through image-based field maps. Since this optimization scheme operates under a small susceptibility approximation, field simulation methods [3] [4] could also be used to generate element responses. Such an approach would require accurate knowledge of the material susceptibilities. Given this information and its utilization in the simulation protocols, element responses and calibrations could be performed in a more rapid, and accurate fashion.

Through careful positioning of the animals, homogeneity variation between individual C-57 BL mice was found to be insignificant. Therefore, a single passive shim is sufficient for all studies. Such a passive shim could remove the need for time-consuming spherical harmonic shim optimization and increase animal throughput. In addition, recent parallel acquisition strategies using multiple-animals [5] could benefit from sets of shims optimized for each animal position in the apparatus.

Extension of this method to human studies, where inter-subject variation is a significant factor, will require a more extensive set of basis shims covering a wide range of head sizes and shapes. Alternatively, given the extremely fast numerics of the optimization procedure and the ease of working with the Bi and Zi elements at high field, a system could be developed to optimize element distributions on an individual basis. Such a system would require only a few minutes for field map acquisitions and optimum element placement.

Acknowledgments and References

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