Design of a high power customized shim set insert for in vivo spectroscopy of deep brain structures in humans at 4T

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Introduction: High field magnetic resonance spectroscopy (MRS) places increasing demand on resistive shim systems. One of the major challenges in MRS is the characterization of the hippocampi deep inside the medial temporal lobes. Performing MRS at higher field strengths potentially allows for the acquisition of high quality, more easily quantifiable spectra from this region; however, this is obviously limited by field inhomogeneity, the impact of which increases with increasing field strength. The demands placed on the resistive shim systems by this application are beyond the capability of existing whole-body shim coil systems. We are investigating the development of an extremely high performance, high order, short, insertable shim set specifically designed for the medial temporal lobes of the human brain. A first goal was to determine how much improvement could possibly be achieved using such a shim set compared with the existing shims on our 4T whole-body system. A second goal was to identify what shim axes are most important for this application.

Methods: A region of interest was identified as a 6 cm diameter spherical volume (DSV) enclosing the medial temporal lobes, as shown in Fig. 1. Multi-echo 3D gradient echo images (96×96×96 matrix) of 10 normal human volunteer subjects' heads were collected using a 4T Varian MRI system. Field maps were derived from the image data using the RASTAMAP algorithm [1]. In order to obtain field maps for the unshimmed head, the effect of the normal system shims had to be removed. This was achieved by subtracting the applied field profiles of each shim, taking into account the known current used for each shim during the field-mapping experiment. This process results in a final field profile such as that shown in Fig. 1. This field profile was then used to design a special shim set customized to correction of field distortions over the specified DSV.

A Fourier series algorithm, which allowed for the design of finite length shim coils, was implemented. In this algorithm the current density was expanded as a general 3D Fourier series in cylindrical coordinates [2]. The coefficients of the expansion were solved for each shim axis such that power was minimized while maintaining a specified field over the desired DSV. The algorithm was implemented in MATLAB® (Mathworks) and applied to design the following 7 separate axes: XY, X^2-Y^2, YZ, XZ, Z^2, Z^3, Z^4. Linear (gradients) and B_0 shims were assumed to be those of the whole-body system. The entire shim set was designed to be used for human head shimming, and had the following dimensions: ID = 34.0 cm, OD = 38.2 cm, total length = 40 cm, distance from edge of coil to edge of DSV was 17 cm. These dimensions are similar to those for human head gradient coil designs reported previously [3].

Discrete wire patterns were derived for each axis. The total shim field as a function of the currents in each shim axis in three dimensions was fit to the unshimmed field map over the DSV to determine the optimal currents. The correction field was applied to the unshimmed data and a final field profile was calculated over the DSV.

The final field profiles achievable with the proposed customized shim set were compared to the best profiles attainable using the whole-body shims of the existing system. This was accomplished by generating histograms of the field inhomogeneity inside the DSV, as shown in Fig. 3. Lorentzians were fit to the histograms in order to determine the line width (full-width at half-maximum).

Results and Discussion: The profiles for the customized shim system across three slices through the DSV are shown in Fig. 2. For each slice, the customized shim set is expected to reduce the field inhomogeneity by a factor of approximately 2 as compared to that obtained using the whole-body shim system. The total field inhomogeneity over the entire DSV is predicted to be reduced by a factor of 2.5. Specifically for the 4T system, the line width for a voxel over the entire 6cm DSV would be expected to decrease from 6.2±0.2 Hz to 2.51±0.06 Hz (Fig. 3). The maximum current required in any single axis of the customized shim is predicted to be 32 A (XY axis). The maximum power for a single axis is 1.85 kW (Z^2 axis). The total power dissipated throughout the entire set in order to achieve the uniformity shown is calculated to be 2.7 kW. These results indicate that in order to achieve a significant improvement in shimming in the deep brain at high magnetic fields, insertable shim coils of dramatically increased power are necessary. Certainly this would not be practical in many applications; however, we hypothesize that for very high field spectroscopy research applications, this approach should be further investigated. The proposed shim coil set is essentially equivalent to an insert gradient coil in terms of size, weight, and power [3]; therefore it is not unreasonable to consider this approach for some of the highest-field applications.

References, Acknowledgements

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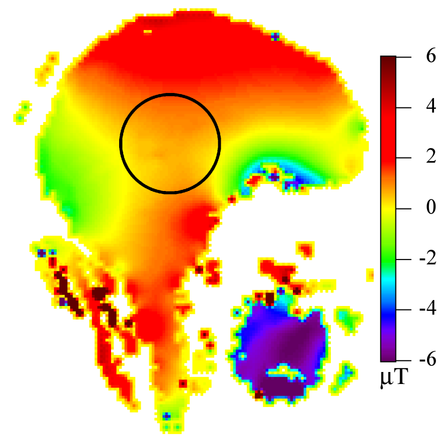

Fig.1 A saggital slice of the field inhomogeneity of the head. The circle shows the location of the DSV and encloses the medial temporal lobes.

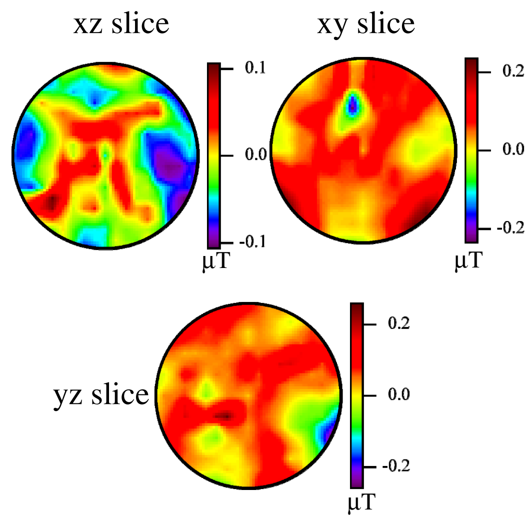

Fig.2 Planar slices of the field inhomogeneity through the centre of the DSV when our simulated shim set was used.

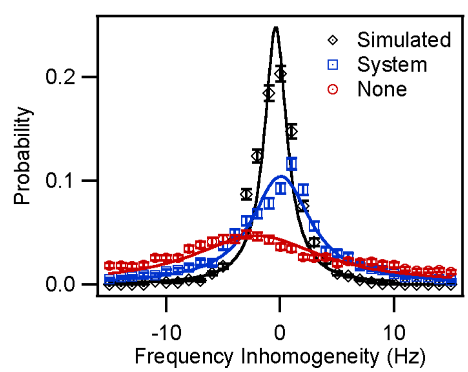

Fig.3 Histograms with Lorentzian fits of the field inhomogeneity inside the DSV when our simulated shims (◇), existing system's whole-body shims (□) and no shims (○) were used.