Design of a cylindrical passive shim insert for human brain imaging at high field

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Introduction: Local susceptibility-induced field variations can lead to inhomogeneities that cause artifacts such as image distortion and signal loss. In addition to active shimming, localized passive shimming has been used to reduce field deviations over desired regions of interest for high field MRI [1, 2]. For passive shimming, it is advantageous to position shim elements away from the subject to reduce discomfort. Positions for the shim elements can be computed using methods introduced by Romeo and Hoult [4]. Determining the correct magnetic susceptibility and dimensions for the shim pieces is essential for generation of the desired shim fields. In this work, we introduce a method to determine the requisite magnetic susceptibility and dimensions for the shim elements and verify the accuracy of our technique using simulation.

Theory: Following selection of shim element locations, one can evaluate the susceptibility χ and shim element dimensions required to produce a spherical harmonic field of order n and degree m with amplitude $A_{n,m}$ using Eq (1), which is adapted from Holt's work [3,4].

$$\chi = -4A_{n,m}.\pi / (\varepsilon_m B_0 \int_{\rho=R}^{R+t} \int_{z=z_1}^{z_1+\Delta z} \int_{\varphi}^{\varphi+\Delta\varphi} \sum_{i,j} \sum_{nm} \left(\frac{(n-m+2)!P_{n+2,m}(\cos\gamma_j)\cos(m\varphi_i)}{(n+m)!s_j^{n+3}} \right) dV_{ij} \qquad (1)$$

Here φ_i, γ_j and s_j are the azimuthal, polar and radial positions of the shim elements and ε_m is the Neumann factor (ε_m=1 if m=0; 2 otherwise). Assuming shim elements are very small compared to the dimensions of the shim coil, the thickness, width and height of the shim elements can be estimated from the integration limits. The least-squares optimal A_{nm} is given by

$$A_{nm} = [f(x_{ijk})^T . f(x_{ijk})]^{-1} . f(x_{ijk})^T . \Delta H_Z(x_{ijk}) \qquad (2)$$

where the columns of $f(x_{ijk})$ are the n^{th} order and m^{th} degree spherical harmonics evaluated at x_{ijk} and $\Delta H_Z(x_{ijk})$ is the measured inhomogeneous magnetic induction at position x_{ijk} (the -1 and T superscripts represent matrix inversion and transposition, respectively).

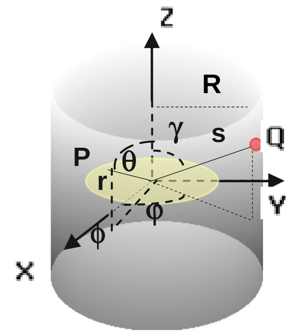

Figure 1 A ferromagnetic shim element of volume dV, susceptibility χ placed at point Q (s_i, γ_j, φ_i) on a cylindrical surface of radius R. The shim element in B_0 (**z**) gives rise to a magnetic induction at $P(r,\theta,\phi)$ according to Eq. 1 [4]. The fields produced from higher multipoles are small and neglected.

Methods: A 3D gradient-echo pulse sequence with modifications to reduce eddy currents was used to measure the uncompensated B_0 field of a volunteer's brain by comparing phase evolution between of two images acquired at two echo times (TE=5.25 or 7ms, TR=16ms, 10° flip, 256x256x256mm FOV, 128x64x64 matrix) on a 4T whole-body Varian INOVA imager. Phase-difference reconstruction was used to extract the B_0 magnetic field with 3D phase unwrapping as necessary. The measured, uncorrected field distribution was then projected into the 1st, 2nd and 3rd order spherical harmonic field basis functions (Eq. 2) to obtain the desired amplitudes A_{nm} for correction of the inhomogeneity. The positions of the shim elements for each harmonic component were then computed as in [4] with adaptations for cylindrical design. With the positions selected, the required susceptibility χ and shim element dimensions were determined according to Eq. (1).

Results: Fig. 2(a) shows the unshimmed B_0 field of the subject's brain at a center slice, which is decomposed as a sum of spherical harmonics fields in Fig 2(b). The simulated residual field map after introduction of the cylindrical passive shim insert is shown in Fig 2(c). These figures demonstrate that Eqs. (1) and (2) can be used to correctly estimate the χ and shim element dimensions needed to suppress the B_0 inhomogeneity.

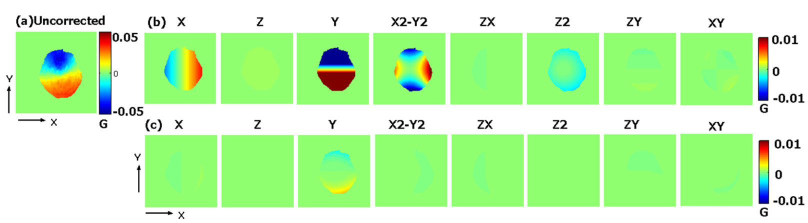

Figure 2 Axial slice of (a) the unshimmed B_0 field of the subject's brain (b) decomposed into 1st and 2nd order spherical harmonic fields. (c) Simulated residual magnetic field for a 1st and 2nd order cylindrical shim tube insert.

Discussion: We have used simulation to validate that our method can be used in the design of a cylindrical passive shim insert for brain imaging. Some field inhomogeneous may not be entirely suppressed due to the presence of higher order field contributions. This manifests in the Y B_0 map (i.e. H_{1-1} as seen in Fig. 2(c)), which retains some residual field. This suggests that a higher order shim tube design will be required. Using spherical harmonic decomposition, one can construct a passive coil with any desired order and degree. Although we present a 2nd order design, the technique for determining shim element susceptibility and dimensions easily scales to higher order designs. These preliminary results are based on measurements of a single subject; however we intend to design a shim coil based on an averaged B_0 field derived from multiple subjects. This is expected to improve the shimming process for all subjects by reducing overall B_0 inhomogeneity.

References: [1] C. Juchem et al., JMR 2006; 183:278-289; [2] J. L. Wilson et al., MRM 2002;48:906-914; [3] Hoult and Lee, Rev.Sci.Instrum.1985; 56:131-135; [4] Romeo and Hoult, MRM, 1984, 1, 44-65.