Construction and optimization of local 3rd order passive shim system for human brain imaging at 4T MRI

M. L. Jayatilake[1,2], J. Storrs[1,3], J. Osterhage[1], and J-H. Lee[1,4]
[1]Center for Imaging Research, University of Cincinnati, Cincinnati, OH, United States, [2]Department of Physics, University of Cincinnati, Cincinnati, OH, United States, [3]Department of Psychiatry and Behavioural Neuroscience, University of Cincinnati, Cincinnati, OH, United States, [4]School of Energy, Environmental, Biological, and Medical Engineering, University of Cincinnati, Cincinnati, OH, United States

Introduction: The optimal MRI quality relies on a homogeneous magnetic field. However, local susceptibility variations within human brain can lead to field inhomogeneity that causes artifacts such as image distortion and signal drop-out, which become worse with increasing magnetic field strength. Many evidences showed that high order shims (i.e. > 2nd order) are required for optimal MRI at field greater than 3T [1, 2]. However, due to limited space, many MRI systems provide only up to second order active shims. In this work, we introduce a 3rd order local passive shimming along with the active 1st and 2nd order shimming to improve field homogeneity within the human brain for a group of subjects.

Theory: By careful selection of azimuthal, γ_j and polar φ_i angles independently, a passive shim coil can be designed with desired 3rd order spherical harmonics by using Equations (1) and (2) [3, 4]. Here, *i* and *j* represent the location of shim element in γ and φ angles; *n* and *m* are the order and the degree of spherical harmonics and *R* is the radius of the cylinder (see Fig 1).

$$dH_z \propto \int_{-\Delta\varphi/2}^{\Delta\varphi/2} d\varphi_i \cdot \cos(m(\phi-\varphi_i)) \qquad (1)$$

$$dH_z \propto \sum_j \sin^{(n+3)}(\gamma_j)\cdot P_{(n+2,m)}\cos(\gamma_j)/R^{(n+3)} \qquad (2)$$

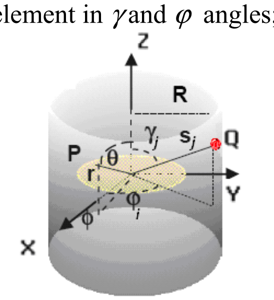

Figure 1 A ferromagnetic shim element of volume dV, susceptibility χ placed at point Q (s_i,γ_j,φ_i). The shim element in $B_0(z)$ gives rise to a magnetic induction at $P(r,\theta,\phi)$ [3].

Following the selection of shim element locations, the susceptibility and the dimensions of shim pieces can be evaluated to produce a magnetic field with an optimal 3rd order passive shim coefficients ($\beta_{n,m}$) for the sub population using Eq. (3) [4]

$$\chi = -4\pi\cdot\beta_{n,m.}/(\varepsilon_m\cdot B_0\int_{V_{ij}}\sum_{i,j}\sum_{n,m}\left((n-m+2)!P_{n+2,m}(\cos\gamma_j)\cdot\cos(m\varphi_i)/(n+m)!s_j^{\,n+3}\right)\cdot dV_{ij} \qquad (3)$$

Here s_j is the radial positions of the shim elements and ε_m is the Neumann factor (ε_m = 1, if m = 0; otherwise, ε_m = 2). Assuming shim elements are very small compared to the dimension of the shim coil, the thickness, width and height of the shim elements can be estimated from the integration limits. The $\beta_{n,m}$ is given in Eq (4).

$$\beta_{n,m} = [g(x_{ijk,n'})^T\cdot g(x_{ijk,n'})]^{-1}\cdot g(x_{ijk,n'})^T\cdot\Delta F_Z(x_{ijk,n'}) \qquad (4)$$

where the columns of g($x_{ijk,n'}$) are subject dependent 1st, 2nd and the averaged 3rd order spherical harmonics evaluated at $x_{ijk,n'}$ of the n'^{th} subject and ΔF_Z ($x_{ijk,n'}$) is the measured inhomogeneous magnetic induction at position x_{ijk}. The denotes -1 and T represent inverse and transpose, respectively.

Methods: A 3D gradient-echo pulse sequence was modified to reduce sensitivity to eddy currents and used to obtain field maps of 4 subjects' brains at a 4T Varian INOVA system. Measured field maps were used to evaluate the subject dependent 3rd order spherical harmonic coefficients of the passive shim (Eq. 4). The optimized positions (Eq.1, 2), the required susceptibility and dimensions (Eq.3) of shim elements were evaluated on a cylindrical surface to generate the desired magnetic field that can optimize the field variation over the entire human brain. A ferromagnetic material of Ni (77%)-Fe (16%)-Cu (5%)-Cr (2%) was used to construct the 3rd order passive shim system. Then the constructed 3rd order passive shim tube (36.5 cm OD and 35.5 cm in length) (Fig 2A) was mounted surrounding the RF coil. The adjustable 1st and 2nd order active shimming was applied following introduction of the desired 3rd order passive shim fields.

Results: Fig 2(A) shows the cylindrical passive shim system with ferromagnetic shim pieces for generating the Z(X2 – Y2) (green), YZ2 (blue), and Y3 (red) 3rd order passive shim field. Fig 2(B) shows the measured field maps within the subject's brain (a) following active shimming only and (b) following both active and 3rd order, Z(X2 – Y2); YZ2 and Y3 passive shimming. The whole brain field histogram line width (Fig 2C) 135.2 Hz (blue) was reduced to 107.8 Hz (red) when using both active and the 3rd order passive shimming as comparing to using the active shimming only.

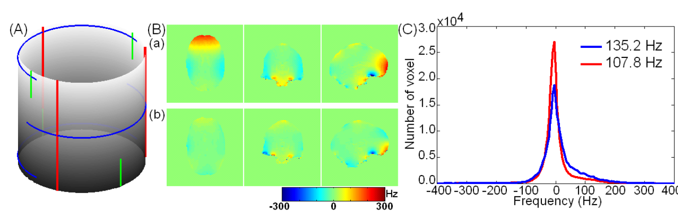

Figure 2(A) The 3D configuration of shim inserts on the surface of the cylinder to generate the 3rd order passive shim field. (B) Measured brain field maps (a) with active only and (b) with both active and passive shimming. (C) Histogram of frequency distribution within the brain corresponding to Fig 1B (a) and (b).

Discussion: This study shows that the introduction of both active and the 3rd order passive shimming the field homogeneity over the entire brain particularly in the regions of prefrontal lobe and the hippocampus regions is improved significantly, which is clearly noticeable in the field map shown in Fig. 2B(b). Additionally, it is also noticeable that the slight improvement in the B_0 homogeneity within the top of the parietal and occipital lobe as revealed by the comparison of the sagittal field maps of Fig 2B (a) and (b).This technique will greatly benefit studies of the prefrontal lobe (MRI/MRS) at high field. The average brain field map can be used to construct any higher order passive shim system to improve the field homogeneity over the human brain for a group of subjects. This work demonstrated that a 3rd order local passive shimming is effective and easy to construct.

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