Automated Single-Volume Shimming in the Presence of Shim Field Imperfections

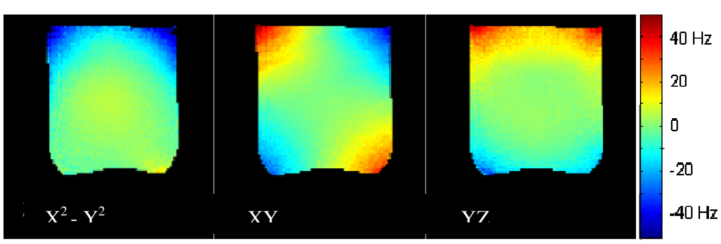
L. Sacolick[1], K. M. Koch[2], D. L. Rothman[3], and R. A. de Graaf[3]

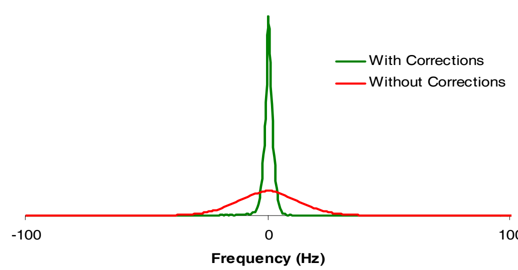
[1]Biomedical Engineering, Yale University, New Haven, CT, United States, [2]Physics, Yale University, New Haven, CT, United States, [3]Diagnostic Radiology, Yale University, New Haven, CT, United States

INTRODUCTION: In this work, a method is described to improve the off-center performance of the FASTMAP shimming method in the presence of imperfect room-temperature shims. FASTMAP provides an algorithm for the calculation of all first and second room-temperature (RT) shims (1). A common assumption underlying FASTMAP, as well as other shimming routines, is that the RT shims generate, besides the desired spherical harmonic field, only lower-order imperfections (e.g. a change in Z^2 is accompanied by a (smaller) change in Z and Z^0). However, depending on the geometry of the individual shim coil set, the second-order shims can generate a variety of higher-order fields. Close to the magnet isocenter, these higher order functions have an insignificant impact on the shim quality. However, outside the magnet isocenter the contribution of these higher-order imperfections increase rapidly with increasing distance and may significantly affect the magnetic field homogeneity that can be obtained. Here the higher order imperfections generated by second-order RT shims are characterized and position-dependent corrections are calculated and shown to greatly improve the magnetic field homogeneity obtainable with off-center FASTMAP.

METHODS: All experiments were carried out on a 4.0 T Magnex magnet interfaced to a Bruker Avance spectrometer. First and second-order shims were housed in a Magnex whole-body gradient system (ID = 72 cm). RF reception and transmission were carried out by a Bruker birdcage volume coil (ID = 26 cm). Gradient echo B_0 field maps were acquired from a 3L water bottle to calibrate the second-order RT shims over a 24x24x16 cm volume in the magnet center. Each shim (Z^2, X^2-Y^2, XY, XZ, YZ) was changed by ±30% of the maximum strength from a global shim setting and the resulting B_0 field maps were fit by first through fourth order spherical harmonic functions. Higher-order (n > 4) imperfections were found to be negligible. Over a small volume, the higher-order imperfections can be approximated as additional position-dependent corrections to the linear and second-order shims. Thus, during an off-center FASTMAP acquisition all eight RT shims are determined as previously described (1). The third- and fourth-order imperfections generated by the changes in the second-order shims are then calculated over the off-center volume-of-interest. A least-squares optimization fits this additional inhomogeneity to first and second-order spherical harmonic functions which are added to the already required shim corrections.

RESULTS: Fig. 1 shows B_0 maps of a water bottle following 30% shim changes to the X^2-Y^2, XY and YZ shims, respectively. The background magnetic field inhomogeneity, as well as all first and second-order spherical harmonic functions were removed by subtraction and least-squares curve fitting, respectively, leaving only higher-order imperfections. It follows that all second-order shims generated significant third -and fourth order imperfections (similar results were obtained for Z^2 and XZ shims). Even for small distances out of the isocenter, the imperfections can degrade the magnetic field homogeneity by 20-30 Hz. For example, the XY shim generated $Z(X^2$-$Y^2)$, ZXY (n = 3) and Z^2XY (n = 4) imperfections with amplitudes of $-1.6.10^{-3}$ Hz/cm^3, $+1.1.10^{-1}$ Hz/cm^3 and $+6.2.10^{-4}$ Hz/cm^4 for a XY shim change of 1 Hz/cm^2. While the imperfections have negligible contributions in the magnet isocenter, they becomes comparable to the XY shim several cm out of the isocenter. The other second-order shims generated different third- and fourth-order harmonics at similar amplitudes. Fig. 2 shows proton NMR spectra of water acquired from a 27 mL (3x3x3 cm) volume positioned 7 cm out of the isocenter in the y direction. The magnetic field homogeneity was optimized with FASTMAP. Without the correction for higher-order imperfections the spectrum is dominated by residual magnetic field inhomogeneity (FWHM ~ 35 Hz) despite the fact that FASTMAP converged. With the correction a greatly improved line is obtained (FWHM ~ 4 Hz) in one iteration.





DISCUSSION: A given room-temperature shim coil will generally generate a magnetic field corresponding to a specific spherical harmonic of order n and degree m together with imperfections from other orders and degrees. While most automatic shimming routines, like FASTMAP, take low-order imperfections into account during the shim calibration, the higher-order imperfections are typically ignored. Here it is shown that for particular shim coil assemblies, the higher-order imperfections can become a dominant contribution to the magnetic field homogeneity far out of the magnet isocenter. For small volumes, the proposed method eliminates the imperfections by approximating them as lower-order spherical harmonics, leading to greatly improved homogeneity (Fig. 2). For larger volumes, like 2D slices or whole brain, the proposed method does not work and the magnetic field homogeneity will be degraded. The correction protocol as outlined is especially important for applications where the volume-of-interest is far out of the isocenter, like MRS of the frontal cortex, or when multiple volumes at different locations are studied with dynamic shim updating (2).

ACKNOWLEDGEMENTS AND REFERENCES: This research was supported by NIH grant R21 CA118503.

1. Gruetter R. Automatic, localized *in vivo* adjustment of all first- and second-order shim coils. Magn Reson Med 1993;29:804-811.
2. Koch, K.M. et al, Dynamically-shimmed multi-voxel 1H MRS and multi-slice MRSI of the human brain. Magn. Reson. Med 2006; in press