Measurement and Automatic Correction of High-Order B0 Inhomogeneity in the Rat Brain at 11.7 Tesla

J. Shen[1], S. S. Li[2], Z. Chen[1], J. Yang[1], D. Letizia[1]
[1]Molecular Imaging Branch, NIMH, Bethesda, MD, United States, [2]Spectroscopy Core, NIMH, Bethesda, MD, United States

Introduction

It has been of considerable interest to quantitatively measure and automatically correct high order B_0 distortions in rodents in vivo at very high field strength over a large brain region to facilitate studies using imaging methods which are susceptible to T_2* effects. Since in vivo B_0 inhomogeneity often cannot be modeled accurately using a few orders of spherical harmonic terms here we modify the FLATNESS method (1) by the use of denser radial sampling of B_0 inhomogeneity within the selected slices. The measured high-order B_0 inhomogeneity in the rat brain should provide useful criteria for efficient shim design. The effectiveness of the slice shimming routine was demonstrated using in vivo phase mapping, SE and asymmetric SE EPI and localized ^{1}H spectroscopy of the rat brain at 11.7 Tesla.

Methods

All experiments were performed on a Bruker microimaging spectrometer interfaced to an 11.7 Tesla 89-mm bore vertical magnet equipped with 28 widebore room temperature shims but with no eddy current or B_0 shift compensation. Male Sprague-Dawley rats (160-200 g, n = 4) were measured. The modified FLATNESS slice shimming method uses six evenly spaced linear columns of 1.5-mm x 1.5-mm thickness per slice. The phase maps were analyzed using polynomial regression to calculate shim corrections based on eq. [1] and the pre-calibrated shim strengths. A total of 18 columns were used to determine the corresponding spherical harmonic terms in coronal, axial and sagittal slices. Of the 2n+1 nth order shims, only n+1 in-slice shims have non-zero interception with a slice perpendicular to one of the three principal axes. The in-slice B_0 inhomogeneity of the *j*th *n*th-order spherical harmonic term c_j^n is then determined using Gaussian elimination on the n+1 independent non-orthogonal linear equations given by $\sum_i^m \sum_j^{n+1} a_{ij}^n a_{ik}^n c_j^n = \sum_i^m a_{ik}^n p_i^n$ with k = 1, …, n+1 and m = 6 [1] (ref. 1). p_i^n is the *n*th order polynomial coefficient determined from the *i*th column with a normalized spherical harmonic angular function of a_{ij}^n.

Results and Discussion

Fig. 1 shows 2D phantom phase maps (first row), SE EPI (TE = 26.5 ms, second row), asymmetric SE EPI (asymmetric delay = 7.5 ms). FOV = 30 mm. With progressive first- (column a), second- (column b), third (column c) and fourth- (column d) order shimming, the quality of the images improves with dramatic reduction in geometrical distortion in EPI achieved after third-order shimming. The third order distortion shown in Fig. 1 is intrinsic to our magnet. Fig 2 shows corresponding results from in vivo axial (y) slice shimming. All parameters are the same as in Fig. 1 except FOV = 20 mm. With only first-order shimming (column a), no significant geometrical distortion of the intracranial region was seen in the SE EPI due to the much smaller slice area and stronger PE gradients as compared to Fig. 1, but significant loss of signal was found in the asymmetric SE EPI. Dramatic improvement of the phase map was achieved after correcting both the first- and the second-order in-slice shims accompanied by moderate reduction in EPI signal loss and ghosting (column b). Compared to the effect of second order shimming, only minor improvements were seen in the phase map after fully correcting the third-order in-slice shims (column c). However, further significant improvements were seen in the reduction of signal loss in the asymmetric SE EPI image after third order shimming was performed (column c, third row). No correction of the fourth-order shims was attempted due to the limited shim currents available. A 3D localized proton spectrum (Fig. 3) was acquired from a 4.5 mm x 2.5 mm x 4.5 mm voxel using a fully adiabatic PRESS sequence. In this case, only the first- and second-order shims were fully corrected. The z^3, z^2x and x^3 of the third order shims were partially corrected with the rest of the shims set to zero so as to operate under the shim current limitations. LB = 2 Hz with no resolution-enhancing window functions or baseline correction applied. The creatine methylene protons at 3.92 ppm and those of phosphocreatine at 3.93 ppm are clearly resolved. The spectral region down field from water was not shown which is dominated by residual water because of the significantly large uncompensated B_0 shifts and eddy currents on our system. Table 1 lists in vivo B_0 inhomogeneity in terms of spherical harmonic terms. The basal B_0 inhomogeneity measured from a perfect spherical phantom was subtracted from brain values.

References

1. J Shen, *NMR Biomed.*, 14:177-183 (2001).

Table 1. High-order B_0 inhomogeneity in units of Hz/mm^n measured in the rat brain (n = 4)

Coronal slice

B_0	x	y	z^2	x^2-y^2	xy	z^2x	z^2y	x^3	y^3	z^4	$z^2(x^2$-$y^2)$	z^2xy
Mean	1.0	16.3	-0.6	-2.1	0.2	-0.02	0.4	0.05	-0.04	0.06	0.1	0.06
SD	3.8	2.4	3.1	0.2	0.4	0.2	0.5	0.3	0.4	0.3	0.2	0.02

Axial slice

B_0	z	x	z^2	zx	x^2-y^2	z^3	z^2x	$z(x^2$-$y^2)$	x^3
Mean	34.3	2.3	-0.9	-0.06	-2.6	0.08	-0.01	0.3	0.02
SD	5.8	3.7	1.9	0.5	0.03	0.5	0.1	0.2	0.05

Sagittal slice

B_0	z	y	z^2	zy	x^2-y^2	z^3	z^2y	$z(x^2$-$y^2)$	y^3
Mean	35.5	13.4	-1.1	-5.8	-1.5	-0.2	0.1	0.01	0.1
SD	3.4	2.0	2.0	2.6	1.3	0.9	0.2	0.04	0.1

Fig. 1

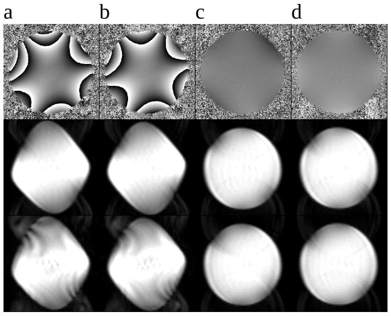

Fig. 2

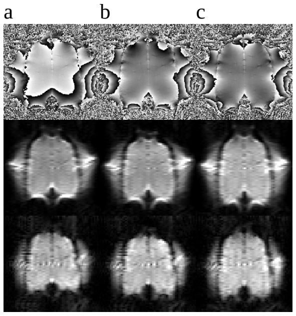

Fig. 3