Requirements for Optimal B_0 Shimming for a Spectroscopy Voxel in the Frontal Cortex at Ultra-High Fields

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INTRODUCTION

Magnetic Resonance Spectroscopy (MRS) is a powerful tool with a wide range of applications in diagnostics and research and the transition to ultra-high fields promises major advantages with respect to SNR and spectral resolution. For reliable results, however, a very homogeneous B_0 field is required, but the B_0 inhomogeneity induced by the subject itself increases in amplitude with increasing field strengths. Excellent B_0 shimming is therefore of outermost importance to yield improvements of the effective spectral resolution at ultra-high fields. To this end conventional MRI scanners are equipped with a set of shim coils, which produce spherical harmonic shaped fields of up to 3rd-order, and a variety of algorithms is used to determine optimal B_0 shim parameters[1-4]. Naturally, the produced amplitudes of the shim fields are limited by the specifications of the used hardware. However, an optimal B_0 inhomogeneity compensation might not be possible within these hardware constraints, especially for regions with large inhomogeneities, such as the frontal cortex. **THIS WORK** investigates the hardware requirements for optimal B_0 inhomogeneity compensation and the effect of shim hardware constraints on B_0 shimming for a spectroscopy voxel in the frontal cortex.

MATERIALS AND METHODS

B_0 maps (20 slices, 2×2×2mm^3, TE/TR = 3.1ms/6.86ms, ΔTE = 1ms) of the brains of 17 volunteers were acquired at a 7T scanner (Philips Healthcare, Cleveland, USA) with a volume transmit/receive coil for transmission and a 32-element receive coil for reception (Nova medical, Wilmington, USA). B_0 shim sets were calculated using an IDL-based (Exelis, Inc., Boulder, USA) Shim Tool[4], which applies Multiple Starting Values (MSV) for the fitting procedure. The shim volume was chosen equal to a typical spectroscopy voxel (20×20×20mm^3) in the bilateral grey matter of the frontal cortex. A set of 3rd-order shim parameters was calculated from each B_0 map using an unconstrained fit algorithm (**U**), in order to determine the required shim field amplitudes of the different spherical harmonic fields for the problem at hand. Additionally a set of shim parameters was generated by clipping the results from the unconstrained fit to the hardware constraints (**UCL**), which is a typical procedure in vendor pre-implemented algorithms, and another set of shim parameters was calculated using a constrained fit algorithm (**C**). Corrected B_0 maps were simulated using the different shim sets using in-house written scripts in MATLAB (Mathworks, Natick, USA). The standard deviation of frequencies (σ_ω) within the shim volume was determined from each simulated B_0 map which translates roughly into half of the expected spectral line width.

RESULTS AND DISCUSSION

Table 1 displays the maximum required shim field amplitudes for each shim channel as calculated for a spectroscopy voxel in the frontal cortex of all 17 volunteers, as well as the mean of the calculated shim field amplitudes. For ideal compensation of the strong inhomogeneities induced by the sinus cavities, the amplitude of the Z3 term would, in single cases, have to be 326.4 mT/m^3, which is 105 times as strong as the hardware limitations of the used setup allow for. Even average shim field amplitudes required for ideal inhomogeneity compensation for 2nd and 3rd-order shim terms range between 1.5 times to up to 33 times of the maximum shim field that can be produced by the employed setup.

Figure 1 compares field distributions within the spectroscopy voxel, simulated with the three different sets of shim parameters. An unconstrained shim (**U**), i.e. a B_0 shim without any hardware limitations would obviously lead to the best inhomogeneity compensation. However, this result is in practice of little use. By clipping the parameters obtained from an unconstrained fit, to the hardware limitations (**UCL**), heavy field distortions result, which would most likely even prevent proper localization for a spectral acquisition. By constraining the parameter space for the fit (**C**), the resulting field distribution within a 20×20×20 mm^3 voxel, would render a spectral acquisition feasible, however severe line broadening is to be expected that might lead to an effective resolution that is worse than at 3T. The histograms in figure 2 and the standard deviation of frequencies, σ_ω, from simulated field distributions for all volunteers in table 2 also display, that shim sets derived by clipping the results from an unconstrained algorithm to the hardware limitations (**UCL**) does not lead to sufficient B_0 shim quality.

In **CONCLUSION** this work demonstrates that B_0 shim hardware limitations do severely restrict the meaningful application of ultra-high field magnetic resonance spectroscopy in regions that suffer from strong B_0 inhomogeneities, such as the frontal cortex. Considering constraints of the maximal shim fields during the B_0 shim optimization procedure is mandatory to yield acceptable results.

Shim Term	F_{max} mT/m^n	SF_{mean} mT/m^n	SF_{max} mT/m^n
X	0.99	0.76 (0.44)	1.67
Y	0.99	0.35 (0.24)	0.95
Z	0.99	0.67 (0.65)	2.41
Z^2	4.63	25.26 (18.24)	66.71
ZX	7.88	16.34 (16.18)	55.92
ZY	7.75	12.37 (14.57)	54.40
X^2-Y^2	7.52	9.25 (12.06)	41.69
XY	7.35	4.61 (3.82)	15.14
Z^3	2.82	103.70 (105.33)	326.35
Z^2X	3.76	100.24 (82.01)	320.93
Z^2Y	3.76	35.98 (48.63)	156.68
$Z(X^2$-$Y^2)$	23.72	211.80 (212.57)	689.97
ZXY	23.25	110.17 (98.04)	358.00
X^3	10.57	73.68 (94.96)	281.62
Y^3	10.33	35.03 (28.67)	100.11

Table 1: Comparison of the maximum available shim field amplitudes (F_{max}) per shim channel and the mean (SF_{mean}) and maximum (SF_{max}) shim field amplitudes per channel required for optimal B_0 inhomogeneity compensation for a spectroscopy voxel in the frontal cortex. Values are given in mT/m^n, where n denotes the shim order of the respective shim term.

	σ_ω [Hz]
NS	29.50 (10.23)
C	8.26 (6.38)
U	5.57 (4.60)
UCL	155.03 (85.12)

*Table 2: Comparison of the mean standard deviations of frequencies (σ_ω) within a spectroscopy voxel in the frontal cortex derived from the simulated B_0 field distributions with the constrained (**C**), the unconstrained (**U**) and the clipped (**UCL**) shim sets, and from the unshimmed B_0 map (**NS**). σ_ω translates roughly into half of the expected spectral line width.*

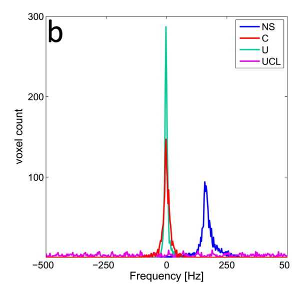

*Figure 2: Histogram of the frequency distribution within a spectroscopy voxel in the frontal cortex of a volunteer's brain without shimming (**NS**), and from simulated B_0 maps corrected using a constrained (**C**), an unconstrained (**U**), and a clipped (**UCL**) shim set.*

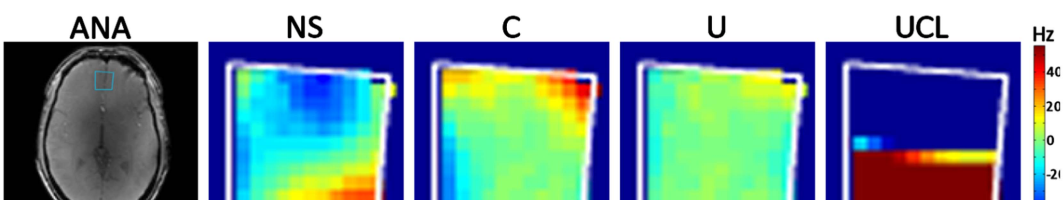

*Figure 1: B_0 maps of a spectroscopy voxel in the bilateral grey matter in the frontal cortex of a volunteer's brain, acquired without any shim (**NS**), and simulated B_0 maps corrected with a constrained (**C**), an unconstrained (**U**), and a clipped (**UCL**) shim set. For display purposes the unshimmed B_0 map is shown with a frequency offset. For comparison, the spectroscopy voxel (blue) is overlaid with an anatomical image (ANA).*

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