Zero- to Third-Order Dynamic Shim Updating of the Human Brain at 7 Tesla

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INTRODUCTION: Dynamic shim updating (DSU) of the zero- to second-order spherical harmonic field terms has previously been shown to improve the magnetic homogeneity in the human brain at 4 Tesla [1]. The increased magnetic field inhomogeneity at 7 Tesla can benefit from inclusion of third-order shims during DSU. However, pulsed higher-order shims can generate a multitude of temporally varying magnetic fields arising from eddy-currents that can strongly degrade the magnetic field homogeneity.

Here we present DSU of the human brain at 7 Tesla using all zero- to third-order shims with full preemphasis and B_0 compensation between all shim orders.

METHODS: Experiments were done on a 7 Tesla Varian MR scanner (model 7T 68cm AS) that is equipped with a SGRAD MKIII 650/420 gradient and shim coil system. Gradients were driven with a Copley gradient amplifier model 282; the shim amplifier (model MXH-14) and the DSU unit used in this study were built by Resonance Research. Temporal shim-to-shim interactions were measured for each of the 16 zero- to third-order shim coils along 1D column projections on a spherical phantom. The decomposition into up to 3 exponentials allowed full preemphasis and B_0 compensation of all 16 shims covering 60 potential shim-to-shim interactions. The field homogeneity after slice-specific DSU with preemphasis and B_0 compensation was compared on 5 volunteers (two women, three men) to regular static, zero- to third-order shimming that was optimized over the whole brain. Field maps were calculated from five single-echo GE images (field-of-view 192 x 192 x 117 mm^3, matrix 64 x 64 x 39, echo time delays 0 / 0.2 / 0.5 / 1.5 / 3.0 ms). The homogeneity of the magnetic field after shimming was assessed by the standard deviation and the full width at half maximum of the frequency distribution, as well as the span that included 80%, 85%, 90%, 95%, 98% and 99% of the frequency values. All field map processing and analysis were done with custom-written software.

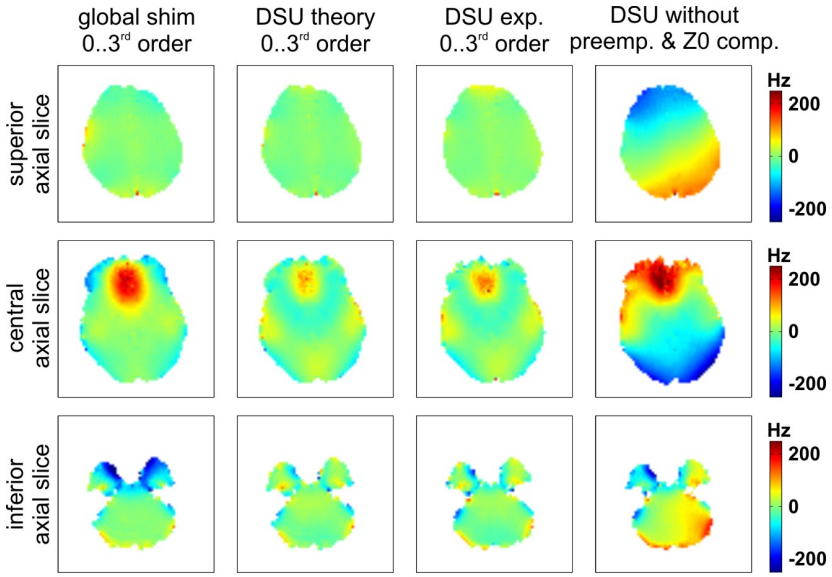

Fig. 1

RESULTS: Global zero- to third-order shimming provided good field homogeneity in superior parts of the brain, but considerable field variations remained in central and inferior areas (Fig. 1, first column). The theoretical, slice-specific removal of zero- to third-order terms largely improved the magnetic field homogeneity in the central and inferior axial slices (Fig. 1, second column). Field maps that were acquired with DSU closely resembled the theoretical predictions (Fig. 1, third column). Deactivation of the preemphasis and the B_0 compensation while applying the same DSU settings led to strong magnetic field inhomogeneity (Fig. 1, forth column). The artifact patterns were dependent on the shim settings of the previous slices and varied considerably over the subjects and slices. In many slices DSU without preemphasis provided worse homogeneity than static shims, indicating that preemphasis is a crucial aspect for the successful implementation of higher-order DSU. The application of zero- to third-order DSU with full preemphasis and B_0 compensation on the 5 subjects reduced the mean of all the above quality measures by 32% compared to global zero- to third-order shimming. Notably, zero- to second-order DSU reduced the mean of the field homogeneity measures by 14% compared to global zero- to third-order shimming. Depending on the application, data analysis can be changed to minimize different measures of magnetic field homogeneity.

DISCUSSION: The first realization of full zero- to third-order DSU with full preemphasis and B_0 compensation enabled improved shimming of the human brain at 7 Tesla not only in comparison with global (i.e. static) shimming, but also when compared to state-of-the-art zero- to second-order DSU. A thorough characterization of the shim system is considered key for the determination of all 16 zero- to third-order terms for all DSU slices from a single reference field map, i.e. multiple iterations were not necessary. The magnetic field homogeneity is still not perfect even with zero- to third-order DSU due to the shallowness of the low order spherical harmonics. However, DSU maximizes the usefulness of conventional shim coil systems and provides magnetic field homogeneity that is adequate for a wide range of applications.

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