First-to-fourth order spherical harmonics shimming with a grid of circular electrical coils

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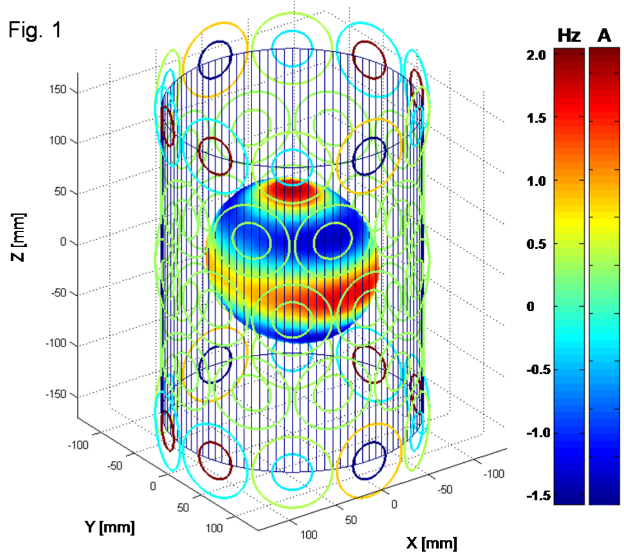
INTRODUCTION: The quality of all kinds of NMR experiments critically relies upon the homogeneity of the magnetic field within the volume-of-interest. In order to improve its homogeneity the field distribution is typically measured and decomposed into low-order ($n \leq 4$) spherical harmonic functions. MR scanners have specialized built-in electrical coils, each of which can create one spherical harmonic field term. By driving the coils with currents that were derived from the analysis of the measured field map, the distortions can largely be compensated. In practice, however, the set of available spherical harmonic terms is limited due to space, current or cost restrictions. In particular, higher order terms, which become increasingly important for high field applications, are difficult to generate at sufficient strength [1]. Here we propose the use of a grid of 100 local coils to generate spherical harmonic fields in a flexible manner instead of one spherical harmonic term per coil. Based on field simulations we show that by placing the coils around the head of the subject all 15 first-to-fourth order spherical harmonic terms can be generated.

METHODS: Magnetic fields were simulated for a 237x237x165 mm^3 FOV at isotropic 3 mm resolution. Circular coils of 100 turns and diameters of 35/70 mm were grouped to 5 nested lines and spread over a cylinder surface (diameter 23 cm, length 30 cm). The dimensioning is similar to a birdcage RF coil and allows the placement of a human head inside the cylinder. The best set of coil currents was determined for each spherical harmonic term assuming a 1 A limit per channel. The optimization was restricted to a centered ellipsoidal ROI of 14x17x14 cm^3 axis diameters, which exceeds normal-sized human brains and covers some potential head displacement. Figure 1 illustrates the coil placement as well as the current requirements for the generation of a Z4 term at 0.001 Hz/cm^4. Realistic coil currents were calculated based on first-to-forth order requirements for whole brain shimming of 10 adult brains at 4 Tesla. All data processing, simulations and analysis were done with customized software.

Fig. 1



RESULTS: For all 15 first-to-forth order spherical harmonic terms very similar fields could be generated. The required total currents necessary for the generation of single terms were largely dependent on the desired field accuracy. Average deviations of the generated multi-coil field from the targeted spherical harmonic term were adjusted to be <3% with $1-R^2$ values below 0.06 [2]. Amongst others, spherical harmonic fields of >500 Hz/cm/A for the linear terms, 200 $Hz/cm^2/A$ for Z2, 2 $Hz/cm^3/A$ for Z3 and 0.02 $Hz/cm^4/A$ for Z4 were derived. For comparison, shim fields of 39 Hz/cm/A, 2.1 $Hz/cm^2/A$, 0.066 $Hz/cm^3/A$ and 0.0041 $Hz/cm^4/A$, respectively, can be generated with our Magnex SGRAD 930/670/PS gradient and shim system. First-to-fourth order shimming of 10 adult human brains with the 100 coil approach at 4 Tesla required a current summed over all channels of 8.7±3.6A (mean ± std). The sum of the magnitude currents of the individual shim terms was multiple times higher (23.1±7.5 A).

DISCUSSION: Field simulations were used to show that spherical harmonic fields can be generated by a 3-dimensional matrix of simple, circular coils and not only by dedicated coils. The currents needed for the generation of first-to-forth order terms were found to be multiple times smaller than the requirements of the bore-sized gradient and shim coils, mostly due to the much closer coil positioning. When multiple spherical harmonic terms were generated together as is the case for brain shimming, cancellation of coil currents further reduced the total current requirement. Care had to be taken as not to exceed the total current limitations for particular channels, as current requirements might also add up constructively. Since the shapes of the fields were determined by weighted superposition of multiple coil fields (rather than the shapes of single, dedicated coils), the method remained very flexible at all times. For instance, a trade of minor shim field degradation for further reduction of coil currents was always possible. The best experimental realization of the multi-coil setup might be achieved by integrating it into the RF coil. The ability to flexibly generate strong, high order shim fields is of particular interest for dynamic shimming and the distance of the coil setup from the magnet will minimize the generation of eddy currents when shims are pulsed. Since the setup doesn't rely on spherical harmonic functions, it can also be directly used for non-spherical harmonic field optimization. Other applications might include the generation of linear or shaped field gradients for imaging applications [3].

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