

Performance Analysis of Multi-Coil Magnetic Field Modeling

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INTRODUCTION: Multi-coil (MC) modeling enables the flexible and accurate generation of magnetic fields from generic basis fields. To date, the MC concept has been applied to synthesize zero to fourth order spherical harmonic (SH) functions [1,2] and field shapes for magnetic field homogenization (i.e. shimming) in the mouse and the human brain [3,4]. Any magnetic field generated with the MC approach is the result of a scaled superposition of unspecific basis fields from individual coils which is conceptually different from driving a dedicated wire pattern with a single current to produce a predefined and coil-specific shape. The MC method furthermore stands out by its unique ability to flexibly trade volume-of-interest, field accuracy and generation efficiency for the specific experimental conditions at hand [2]. After the introduction of the MC concept and first applications, here we present the characterization of the fundamental abilities and limitations of MC magnetic field shaping. The results are compared to conventional imaging and shim coils that resemble the shapes of SH functions.

METHODS: MC magnetic field modeling and the generation of SH terms with dedicated wire patterns were analyzed with respect to accuracy and efficiency for the generation of magnetic fields relevant for MR imaging and shimming. MC configurations and SH wire patterns were defined on the same cylindrical surface with a 30 mm diameter and fields were calculated on an $83 \times 83 \times 83$ matrix over a $20.75 \times 20.75 \times 20.75$ mm³ field-of-view using Biot-Savart's law. Field accuracy was determined as the mean deviation from the ideal, targeted field distribution normalized by the maximum field amplitude.

Efficiency was defined as the field amplitude that could be realized per unit current and wire length. Multiple MC configurations were studied and a 48-coil example consisting of 6 rings with 8 coils per ring similar to [2] is considered here (Fig 1, left). The MC performance was analyzed for imaging and shim fields in centered, spherical volumes-of-interest with diameters ranging from one third (Fig. 1, center) to two thirds of the cylinder diameter and over stacks of circular horizontally (Fig. 1, right, center example) and vertically oriented slices with one third to two thirds of the cylinder extension. The performance was compared to the characteristics of first to third order SH wire patterns taken from literature [5] or courtesy of Dan Green, Agilent Inc. (Fig. 1, center/right).

RESULTS: MC magnetic field modeling allowed to accurately resemble all considered SH shapes over all volumes-of-interest. The MC performance analysis for the generation of a linear X gradient is given in figure 2 (green) when generated over a stack of horizontal, circular slices at a third of the cylinder diameter. The generation efficiency (Fig. 2, right) is shown as a function of slice position for a chosen 1% error level (Fig. 2, left). Notably, the generation of even higher precision field shapes was possible in all cases. For comparison, the conventional SH coil from [5] showed excellent field accuracy within a -5.5 mm range (corresponding to its optimized range) along with high efficiency (Fig. 2, red). Outside this range fields quickly deteriorated whereas accurate MC fields could be generated far outside the cylinder center. In general, the MC efficiency for the generation of individual first order SH terms was found to be somewhat reduced compared to dedicated SH coils. However, MC efficiencies exceeded those of SH wire patterns for individual higher order terms (e.g. by a factor of 1.2 for the X2-Y2 term) and this effect became more pronounced the higher the SH order. The overall efficiency of the MC setup was found to exceed that of SH coil systems for the synthesis of magnetic fields that required more than one SH term. For instance, the effective efficiency for the creation of an XY gradient is inherently reduced to $1/\sqrt{2}=71\%$ when generated indirectly by combination of dedicated X and Y terms, whereas the direct XY synthesized with the MC approach was possible without efficiency penalty. The gains in MC efficiency were found to be further enhanced for more complex field shapes, i.e. when additional SH terms were included. As such, the MC efficiency for global, static shimming of the mouse brain (from [3]) to the homogeneity levels achievable with second and third order SH shimming were 1.6 and 3.4 times higher, respectively, than for SH coil systems.

DISCUSSION: The analysis of fundamental performance properties of MC magnetic field modeling has been presented. Methods were developed for the characterization of MC systems and applied to study the effects of coil number, diameter, shape and positioning on the shaping ability and efficiency (with only a single example shown here). The knowledge and methodology derived in this work lay the foundation for performance comparisons with other wire patterns (e.g. state-of-the-art gradient coils) and allow the optimization of future MC designs. Note that the relationship of field efficiency and cylinder size is the same for all coil systems and wire patterns and, therefore relative efficiencies are independent of the specific cylinder dimensions chosen in this study. MC shimming has been shown previously to outperform SH approaches due to improved field shaping [3,4]. Along with the efficiency gains of MC shimming shown here, the MC concept has the potential to replace conventional shim systems based on sets of SH coils.

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[1] Proc ISMRM 2009, p. 3081; [2] JMR 204:281-289 (2010); [3] MRM 66:893-900 (2011); [4] JMR 212:280-288 (2011); [5] MRM 1:44-65 (1984).

