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Multi-coil magnetic field modeling

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ABSTRACT

The performance of multi-coil (MC) magnetic field modeling is compared to dedicated wire patterns for the generation of spherical harmonic (SH) shapes as these are the workhorse for spatial encoding and magnetic field homogenization in MR imaging and spectroscopy. To this end, an example 48 channel MC setup is analyzed and shown to be capable of generating all first through fourth order SH shapes over small and large regions-of-interest relevant for MR investigations. The MC efficiency for the generation of linear gradient fields shares the same order of magnitude with classic and state-of-the-art SH gradient coils. MC field modeling becomes progressively more efficient with the synthesis of more complex field shapes that require the combination of multiple SH terms. The possibility of a region-specific optimization of both magnetic field shapes and generation performance with the MC approach are discussed with emphasis on the possible trade-off between the field accuracy and generation efficiency.

MC shimming has been shown previously to outperform current SH shimming. Along with the efficiency gains of MC shimming shown here, the MC concept has the potential to (1) replace conventional shim systems that are based on sets of dedicated SH coils and (2) allow optimal object-specific shim solutions similar to object-specific RF coils.

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1. Introduction

1.1. Generation of magnetic field shapes with dedicated coils

To date, magnetic field shapes resembling spherical harmonic (SH) functions are the workhorse for MR and specialized wire patterns are used for their generation with dedicated single [1–3] or composite coils [4]. X, Y and Z gradients, corresponding to first order SH functions, are employed for spatial encoding and complemented by higher order SH terms for the homogenization of magnetic field distributions, so-called magnetic field shimming. Gradient coil design aims at the generation of accurate field distributions at maximal strength and efficiency while minimizing the coil's inductance to allow fast current switching, i.e. maximum slew rates. Although variable shape gradient systems have been presented for special applications [5–7], gradient systems are typically constructed on a cylindrical surface to surround the subject and the RF coil(s). Methods like the target field approach [8] and improvements of the gradient coil design such as self-shielding [9] or 3D current geometries [10] replaced the earlier relatively simple Golay-type gradient systems [2,3,11,12] with advanced designs. The coil patterns for the generation of higher order SH fields are still dominated by the designs described by Romeo and Hoult [2] and only minor modifications have been applied to account for the limited radial space in MR scanners [13].

Conventional coil systems are optimized over a predefined spatial range, e.g. a 'diameter spherical volume' (DSV), that is chosen large enough to cover the range of targeted subject sizes and potential placement variations. Once built, the magnetic field amplitude generated by an SH coil is a linear function of the applied coil current and independent of the considered region-of-interest (ROI) within the DSV. Magnetic field shapes to be generated, e.g. for shimming, are approximated by the available SH terms and generated by a weighted superposition of SH coil fields. The orthogonality of the employed basis fields played an important role in the early days of MR as, in principle, the serial optimization of individual terms is possible. However, SH functions are only strictly orthogonal in centered, spherical volumes which rarely coincide with anatomical, clinical or functional areas-of-interest. In addition, SH field shapes generated by SH coils commonly contain imperfections, i.e. deviations from their exact, theoretical shape which impacts their orthogonality and renders the serial adjustment of individual terms difficult. To date, magnetic field imperfections are therefore typically mapped either in 3 dimensions with MRI methods or along selected projections (FASTMAP [14] and its derivatives) and converted to shim fields via least-squares optimization. These analytical approaches can be fully automated to provide robust and user-independent magnetic field homogeneity.

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1.2. Magnetic field generation with a set of small, generic coils

It has been shown recently that small, generic coils can form a magnetic field modeling system capable of generating simple and complex magnetic field shapes in a flexible and experiment-specific fashion [15]. Romeo and Hoult achieved magnetic field modeling with orthogonal basis shapes [2]. The multi-coil (MC) approach demonstrated that successful field modeling is possible even without orthogonal basis functions when least-squares methods are applied to decompose a desired magnetic field into the set of available basis shapes. No generic DSV needs to be predefined and performance parameters such as field accuracy or generation efficiency can be chosen and optimized for specific ROIs on a subject- or MR application-specific basis. Magnetic fields can even be synthesized and optimized on a per-slice-basis, thereby allowing the minimization of the necessary MC currents [15] or the application of slice-specific correction fields for dynamic shimming [16–18]. The limited susceptibility to the details of the MC geometry such as the number of individual basis coils or their placement has been used in previous MC designs to minimize [17] or avoid [16,18] interactions with the RF system.

1.3. Performance assessment of multi-coil magnetic field modeling

SH-shaped magnetic fields are applied for decades by the MR community and the generation of individual SH terms by dedicated wire patterns is well-established. The MC approach for magnetic field modeling is still in its infancy. To date, a comprehensive description of its performance characteristics is lacking and so is the comparison to conventional coil systems that are based on dedicated wire patterns. The current work sets out to fill this gap.

The first MC publication introduced the methodological, i.e. theoretical and experimental, framework of the MC approach and described the basic concepts [15]. The following work demonstrated the benefits of static and dynamically updated MC fields for magnetic field shimming in the mouse [16], the rat [18] and the human brain [17]. The current publication builds on previous work by evaluating the capabilities and limitations of the MC magnetic field synthesis in more detail. The analysis of the characteristics of the magnetic field generation with the MC technique is provided for an example MC setup and compared to conventional coil systems that apply dedicated wire patterns. Emphasis is placed on the trade-off between the efficiency of the field generation and the achievable field accuracy.

Preliminary results of this work have been published in abstract form [19].

2. Methods

The evaluation of the performance of a field modeling system requires the definition of magnetic field shapes to be produced. In this study, the decision was made to analyze the properties of the MC approach for the generation of individual SH terms (or combinations thereof) due to their key role in MR and to allow the comparison of performance measures with dedicated SH coils. Note that typical MR experiments apply multiple SH shapes together. The consideration of individual performances is therefore somewhat hypothetical and must not be overstated. The properties of MC and SH coil systems were subsequently analyzed for the generation of shim fields in the mouse brain, i.e. a real-world MR problem.

More specifically, the selected MC setup (Fig. 1B) was compared to two types of conventional coil SH systems: The basic SH wire patterns described by Romeo and Hoult ([2], Fig. 1A), hereafter referred to as 'conventional', and a set of state-of-the-art SH wire patterns [20]. The conventional wire patterns were included as they set the standard of SH coil design for several decades and as similar coils are still used in today's MR scanners for the generation of higher SH order shim fields. Furthermore, the Romeo and Hoult designs are in the public domain, whereas the details of most modern designs are proprietary. As such, conventional SH wire patterns can serve as a performance reference for the indirect comparison of the chosen MC design with any other coil system. In addition, an example comparison has been done with selected, modern X and Z gradient coil designs as described in [20].

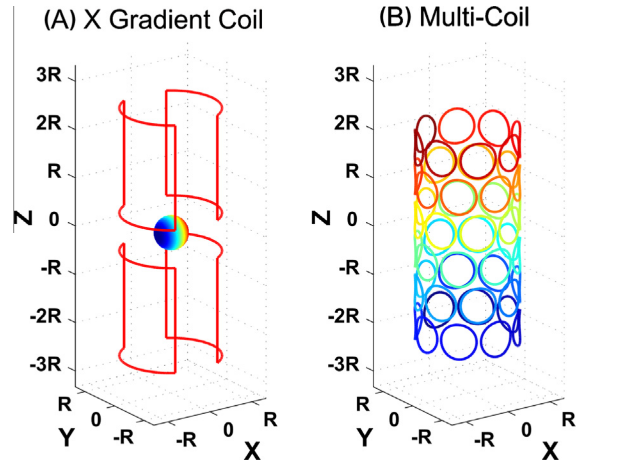

Fig. 1. Coil setups for the generation of magnetic fields compared in this study. (A) Conventional SH coils consist of dedicated wire patterns for the generation of magnetic field shapes resembling SH functions (X gradient (N = 1, M = 1), from [1]). The radius of the sphere inside the coil corresponds to 1/3 of the wire patterns' cylinder radius (compare Fig. 2, case I). (B) Non-orthogonal basis fields generated from individual, generic coils are combined with the MC approach to synthesize the desired field shape. An example MC setup consisting of 6 rows of 8 coils, i.e. 48 coils total, has been analyzed in this study and its field modeling properties have been compared to the performances of conventional SH wire patterns.

2.1. Performance analysis: Field accuracy and generation efficiency

Magnetic fields were calculated on a 83 × 83 × 83 grid at 250 μm isotropic resolution for dedicated SH wire patterns and individual MC basis fields by integration of Biot-Savart's law. The accuracy of the field distributions generated by dedicated SH coils or the MC approach was quantified over specific ROIs with respect to shape through the $1 - R^2$ value [21] and in absolute terms as average deviation (in %) of the generated field from the target field, normalized by the maximal amplitude within the chosen ROI [15]. Frequency offsets were removed before the analysis as they could be considered as simple frequency shifts in the MR sequence. Notably, magnetic field offsets can readily be provided by the MC approach which has been demonstrated for dynamic MC shimming [16–18].

Coils and coil systems for the generation of magnetic fields are typically characterized by a series of technical and performance parameters. These include, among many others, the size of the coil (diameter and length), the shape of the wire pattern, the wire length and the concomitant conductor mass, the resulting inductance and the resistance. The most relevant performance characteristics are the accuracy of the synthesized field shape over a given ROI, the achievable switching time (or alternatively its slew rate) and the coils' efficiency in generating a given magnetic field. Coil efficiency and field generation efficiency are interchangeably used for SH coil systems, since every SH term is generated by a dedicated, fixed (single or composite) coil. However, this concept does not apply to the MC approach, since more than one field

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