Matrix gradient system: concept and performance evaluation

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Target audience: Developers of innovative hardware and novel spatial encoding strategies for MRI.

Purpose: Encoding with nonlinear encoding fields (SEMs) has raised increasing interest in the past few years [1-4]. Matrix coils appear to offer a high flexibility in generating customized SEMs [5, 6] and are particularly promising for localized high resolution imaging applications such as PatLoc [7] or ExLoc [8]. However, up to now, it is still an open question of how to assess the performance of such matrix coils. In this work we propose a new performance measure that is oriented towards optimal local encoding. An optimization problem is formulated that results in high-performance cylindrical matrix coil designs with a high number of elements. The results are tested and the analysis reveals novel features of matrix coil designs.

Methods: Figure 1 shows a schematic representation of a 8x17 cylindrical matrix coil. The outer surface of the coil is shown as semi-transparent. The grid on the inner surface corresponds to the areas allocated to individual elements. An element at z=0 is shown in 3D as a single-turn closed loop. The other 135 elements are not

Figure 1: Schematic representation of an 8x17 cylindrical matrix coil.

depicted to preserve clarity. In the ultimate matrix implementation the active loop elements will be tightly packed. The available space inside the loop packages may eventually be used for cooling and delivery of power. The focus in the design of the coil is to define the ultimate requirements to the number of elements in radial and longitudinal dimensions rather than to generate a viable coil construction.
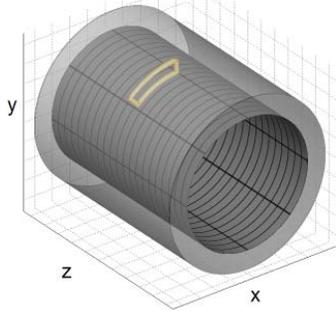
In order to be usable for imaging the matrix coil has to be able to generate strong local gradients at every location within the target imaging region by setting an appropriate combination of currents through the individual elements. For 3D imaging three strong local gradients at every location are required, which have to be non-collinear (ideally orthogonal). We hypothesize that upon a selection of an appropriate encoding strategy the combinations of currents for generating such gradients can be considered independently for different spatial locations. In order to obtain the required encoding fields in a ROI, the optimization problem was chosen as

$$\max_{I_{i,j}} F, \quad F = \sum_{k=1}^{n} \det\left(\frac{\partial \Psi(\mathbf{x}_k, I_{i,j})}{\partial \mathbf{x}}\right), \text{ subject to } I_{min} \leq I_{i,j} \leq I_{max} \text{ and } \sum_{i,j} l_j I_{i,j}^2 \leq P_{max}, \tag{1}$$

where $\Psi = (B_1, B_2, B_3)$ is a vector with three z-components of three encoding magnetic fields, $\mathbf{x}_k = (x_k, y_k, z_k)$, k=1, …, n, denote the coordinate vectors of n test points in a ROI, $I_{i,j}$ denotes current flowing through the j-th coil element which generates the magnetic field B_i, i = 1,...,3, j = 1,…,m (i.e. $B_i = \sum_j b_j I_{i,j}$), where b_j is the sensitivity of the j-th coil element calculated using Biot-Savart's law and m is the total number of coil elements. In the second constraint in (1), l_j denotes the length of the j-th coil element, thus this sets a limitation of the dissipated power in the entire coil. The selected objective function resembles the volumetric correction factor $|\det(\partial \Psi/\partial \mathbf{x})|^{-1}$ in [2], which is proportional to the local resolution in PatLoc imaging. Furthermore, Littin et al. [9] have defined the orthogonality of three encoding fields is as $|(\nabla B_1 \times \nabla B_2) \cdot \nabla B_3|/(|\nabla B_1||\nabla B_2||\nabla B_3|)$ which is equal to $|\det(\partial \Psi/\partial \mathbf{x})|^{-1}/(|\nabla B_1||\nabla B_2||\nabla B_3|)$. Therefore, optimizing (1) enhances both image resolution and local orthogonality. The optimization problem was solved with the function fmincon in the optimization toolbox of MATLAB (The MathWorks. Natick, USA) subject to $I_{max} = -I_{min} = 100$ A to obtain optimal current flows through the matrix coil elements for a collection of local spherical sub-ROI (r=2.5cm) within the target volume. A cylindrical matrix coil was considered with dimensions similar to those of whole-body gradients (inner diameter (ID): 68cm, outer diameter (OD): 88cm, len.: 120cm) with a variable number of elements in circumferential (4 to16 step of 2) and 49 elements in longitudinal directions. Each element consisted of a gradient-generating arc segment and two short radial segments (Fig. 2a). The x- and y-coordinates of the sub-ROI centers were chosen from the interval [0, 20]cm with step = 4 cm. For each of the sub-ROIs local orthogonality was calculated as in [9]. A performance parameter r_{orth} was defined as a maximum radius of a cylinder fitting into the region with the orthogonality ≥0.9 (Fig 2b).

Results and Discussion: Figure 2(b) depicts the local orthogonality of three optimal encoding fields in the z = 0 plane for the 4x49 matrix coil. Figure 2(c) shows r_{orth} values for the 4x49, 6x49, …, 16x49 matrix coils when different values of P_{max} are used. As shown in Figure 2(c), r_{orth} increases and variation of r_{orth} due to the change of P_{max} decreases when the number of elements (NE) increases. Figure 2(d) and 2(e) show the change of objective function values upon the increase of the number of elements with and without gaps and ¼ turns respectively when $P_{max} = 5.6e5$. As shown in Figure 2(d) and 2(e), the presence of gaps and turns has a contribution to the change of tendencies of objective values with respect to the number of elements. Objective values tend to decrease (NE >8) with gaps and turns while those without gaps and turns tend to increase. These results can help the determination of NE according to the practical application of a matrix coil.

In order to compare the performance of the 8x49 matrix coil considered in this work with that of Juchem et al. [6], the latter was scaled to similar size, (i.e. ID=68cm). For the coil of Juchem et al., the values of r_{orth} are 15.95cm and 8.9cm for z = 0cm and z = 10.67cm respectively (which corresponds to the alignment to the coil element edge vs. coil element centre). For this 8x49 coil, $r_{orth} = 23.63$ cm for both planes. This demonstrates the ability of the 8x49 matrix coil to generate locally orthogonal encoding fields in a wider region than a previous matrix coil from literature. The performance of a realistic design of the 8x49 coil in comparison with a conventional gradient set has to be assessed in the near future.

Conclusion: We present an optimization method and a principle design a novel matrix coil for spatial encoding in MRI. We propose using the objective function in Equation (1) and the local orthogonality analysis as measures to assess and compare performance of various matrix coil topologies. The next step will be the development of a feasible design for a matrix coil based on these considerations and construction of a prototype.
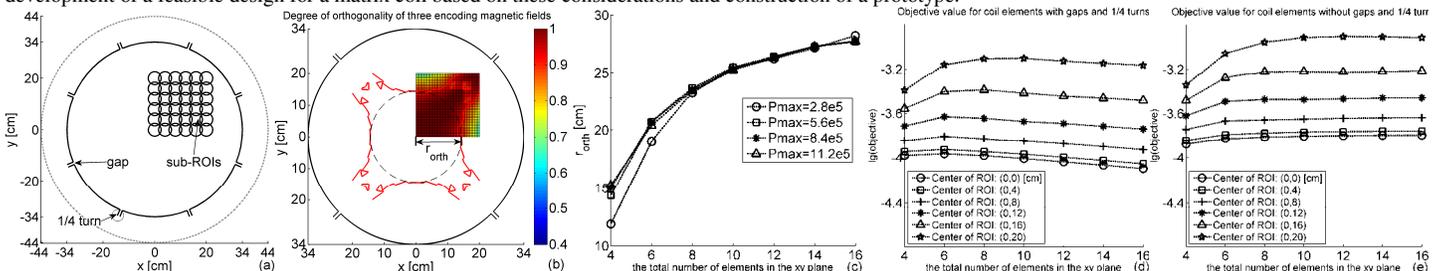

Figure 2: (a) Unshielded matrix coil elements in the xy plane. (b) Local orthogonality of three encoding fields as explained in the main text. (c) r_{orth} for different matrix coils. (d) and (e) Objective values in different ROIs with and without gaps and turns respectively when the center of ROI is at z=0 plane and $P_{max} = 5.6e5$.

References: [1] Stockmann et al., MRM 2010, 64:447; [2] Schultz et al., MRM 2010, 64:1390; [3] Gallichan et al., MRM 2011, 65:702; [4] Lin et al., MRM 2012, 68:1145; [5] Wintzheimer et al., Proc. ISMRM 2010, #3937; [6] Juchem et al., MRM 2011, 66:893; [7] Hennig et al., MAGMA 2008;21:5; [8] Weber et al., MRM 2012, doi: 10.1002/mrm.24364; [9] Littin et al., Proc. ISMRM 2012, #698;