Flexible spatial encoding strategies using rotating multipolar fields for unconventional MRI applications

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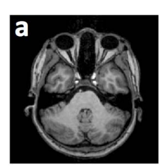
TARGET AUDIENCE: Researchers interested in quadratic spatial encoding and reconstruction

PURPOSE: Our goal is to perform flexible MR imaging with rotating nonlinear spatial encoding magnetic (SEM) fields, removing constraints on hardware design, and reducing the cost, complexity, and weight of imaging systems. By shifting the burden away from hardware performance and toward computer power in the form of generalized reconstruction algorithms, we open the door to unconventional MR imaging systems for applications where spatially-varying resolution can be tolerated. Several encoding strategies using quadratic and nonlinear SEMs have recently been proposed as a way to accelerate parallel imaging and reduce peripheral nerve stimulation during field switching [1-3]. Common to all higher-order encoding methods is the problem of aliasing due to redundant frequency contours (causing a non-bijective mapping), which can be resolved using additional spatial encoding from local RF receive coils. Another issue is the flatness of higher-order SEMs at the center of the FOV, where encoding can only be achieved through the addition of linear SEMs. The present work builds on these approaches by assessing the encoding of a rotating SEM (wrt the object), with and without parallel imaging and a spatial offset between the axis of rotation and the axis of field symmetry, breaking the symmetry of the SEM within the FOV.

METHODS: We simulate imaging performance with a nonlinear SEM comprised primarily of second-order spherical harmonics with some additional higher-order terms (Fig. 1). To break the symmetry of the field by shifting it off-center, we also simulate the SEM with the addition of a linear field component (2000 Hz/cm or 3000 Hz/cm). We further simulate the use of multi-channel RF receive coils to remove aliasing. Approximate RF coil sensitivities for an 8-channel loop array are calculated using the Biot-Savart law (Fig. 2). Field maps of the SEM at each rotation angle as well as the coil sensitivities are used to build the encoding matrix. A GRE transverse brain slice acquired on a 3T scanner is used to generate the simulated data. The simulated readout duration is 7 ms with a 36 kHz bandwidth (Nyquist sampled). Reconstruction is performed using the algebraic reconstruction technique (ART) [4], which cycles through the encoding matrix one row at a time, back-projecting the data point corresponding to each row (Fig. 3). The algorithm iterates until convergence is achieved.

RESULTS: The spatially-varying resolution of the two SEMs can be visualized by looking at overlaid frequency isocontours of each SEM as it is rotated over the range of encoding angles (Fig. 4). Even with the non-ideal encoding fields used here, much of the detail in the object is retained in the reconstructions (Fig. 5). As expected, a linear offset SEM recovers resolution, though some detail is still lost at the center. Surface coils are effective in reducing aliasing artifacts and also in improving resolution, particularly when no field offset is used.

DISCUSSION: All SEMs can be approximated with linear combinations of spherical harmonics. The geometric similarity of a multipolar harmonic implies that unique projections of the object can be obtained using only a limited range of rotation angles [1]. For SEMs without a significant linear term, the range of rotation angles is 180°/N, where N is the order of the dominant SEM. For the multipolar SEM case considered here, the dominant components are the second-order harmonics XY and X^2-Y^2, hence the SEM is rotated over 90°. However, when the multipolar symmetry of the field is broken by the addition of a linear term, unique projections of the object can be acquired over 360°, similar to O-Space imaging. The linear term shifts the symmetry point away from the rotation axis, improving image resolution near the center of the FOV, as shown in Fig. 5.



CONCLUSION: Flexible reconstruction methods relax the need for a homogenous B_0 field and linear gradient fields, as illustrated here using a single rotated multipolar SEM. This permits unconventional encoding strategies and MR imaging systems in applications that do not require isotropic resolution. Performance gains are achieved by breaking the symmetry of SEMs using multiple receive coils and/or a linear field offset. Future work will generalize the approach to three dimensions, possibly through curvilinear slice selection [5]. A total generalized variation prior [6] will also be used to help suppress streaking artifacts for highly undersampled data.

REFERENCES: [1] Schultz G, TMI 2011. [2] Stockmann JP, MRM 2010. [3] Gallichan D, MRM 2011. [4] Kaczmarz S, Bull. Acad. Polon. Sci. Lett. A, 1937. [5] Weber, MRM 2012. [6] Knoll F, MRM 2012. **ACKNOWLEDGEMENTS**: Grant support DoD/USAMRRA W81XWH-11-2-0076 (DM09094).

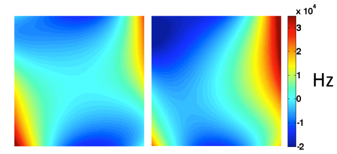


Fig. 1 Example SEM field dominated by second-order terms (left). In order to provide spatial encoding at the center of the FOV, the SEM is offset using a linear component (a 2000 Hz/cm offset is shown here).

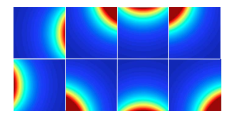
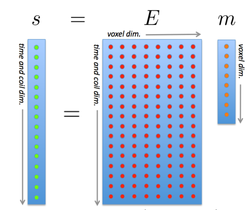


Fig. 2 Encircling array of 8 RF receive coils used to remove aliasing caused by the non-bijectivity of the multipolar SEM.



$$\hat{m}^{(n+1)} = \hat{m}^{(n)} + \lambda \frac{s_{i_n} - \left\langle E_{i_n}, \hat{m}^{(n)} \right\rangle}{\| E_{i_n} \|^2} E^*_{i_n}$$

Fig. 3 ART backprojects the i_nth row of encoding matrix E weighted so as to achieve consistency between data vector s and image m. The rate of convergence is controlled by λ.

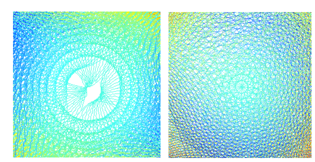


Fig. 4 Spatially-varying resolution illustrated qualitatively by the density of overlapping frequency isocontours from 16 rotations of the SEMs in Fig. 1. Isocontours are plotted with 1 kHz separation. The symmetric SEM (left) rotates over 90° while the offset SEM rotates over 360° and provides smaller voxel sizes in the center.

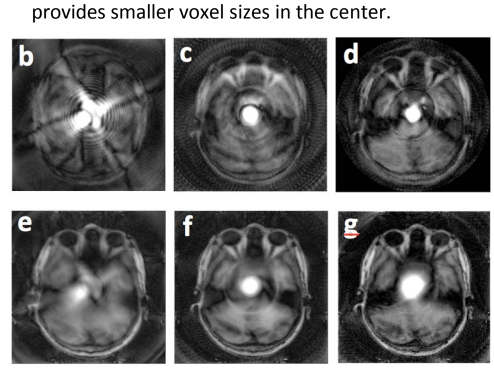


Fig. 5 Simulated 256×256 reconstructions of reference brain image (a) encoded using 128 projections by SEMs with no offset (a), 2000 Hz/cm offset (b), and 3000 Hz/cm (c) with no coil encoding. The offset removes most of the aliasing associated with the symmetry of the multipolar SEM and also recovers some resolution near the center. The addition of 8 receive coils for each case (e-g) improves resolution and removes aliasing, though resolution remains better near the periphery. FOV is 28 cm.