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 B0 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.