Gradient Localized (GradLoc) parallel imaging using a 3-D magnetic encoding field with a quadratic-phase RF pulse to precompensate for through-slice dephasing

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INTRODUCTION: Spatial encoding magnetic fields (SEMs) with quadratic or hyperbolic shapes have been proposed for spatial encoding schemes [1,2], spectral localization [3], and RF excitation of curvilinear regions [4-6]. Quadratic SEM pulses have been applied prior to readout in Cartesian sequences to "phase scramble" the signal, permitting unaliased reconstructions with variable fields-of-view (FOVs) using the Fresnel transform [7-9].

GRADLOC: More recently, phase scrambling has also been shown to enable gradient localization ("GradLoc") of signals from a target region-of-interest (ROI) within the larger FOV [10]. Localization is achieved by using quadratic modulation prior to readout in a Cartesian pulse sequence to spoil signals outside the ROI. The gradient moment is chosen according to the relation [10] $G_{SEM}\tau = k_{max}/\Delta_{ROI}$, where Δ_{ROI} is the size of the desired localization window, τ is the pulse length, and G_{SEM} is the field strength. This SEM pulse convolves the object's spectrum with a quadratic kernel, causing the spectrum to resemble the object in a 1-to-1 mapping [10]. Seen another way, the phase-scrambling field is scanned across the ROI by the linear gradients, dephasing spins that reside outside this region. GradLoc permits either faster acquisition of the desired ROI, or higher-resolution acquisition of the ROI in equivalent time. Experimental GradLoc images have been shown using second-order hyperbolic fields that vary only in the axial plane.

EXTENSIONS OF GRADLOC: The primary goal of the present work is to extend the utility of GradLoc to 3-D fields such as the Z^2 spherical harmonic that vary in the through-slice direction: $G_{Z2}(x,y,z) = z^2 - ½\,(y^2+y^2)$. The Z^2 field has advantageous properties from a coil designer's perspective and has already found other applications for spatial encoding [11-12]. The quadratic in-plane variation of this SEM is also ideal for performing GradLoc. But because the SEM varies twice as strongly in the Z-direction as it does in-plane, image quality suffers from extensive through-plane dephasing, which seriously degrades the signal even for thin slices at small offsets (Fig. 1). We use the quadratic-phase RF pulse along with a conventional slice select Z-gradient to precompensate for the phase that the quadratic SEM applies along the Z-direction. As a secondary goal, we also investigate whether SENSE parallel imaging [14] can be combined with GradLoc to image target ROIs at high acceleration factors.

METHOD: A quadratic-phase RF pulse is designed using the low flip angle approximation. The target slice profile is assumed to be a rectangular slab with quadratic phase equivalent to that applied by the phase-scrambling SEM, but with opposite sign (Fig. 4). The Fourier transform is used to calculate an RF pulse that will produce approximately this desired slice profile. GradLoc images of target ROIs are acquired in the axial plane using a custom-built, 12 cm, Z^2 SEM coil [14] (Fig. 2). An 8-channel transmit-receive array is nested within the bore of the SEM insert coil. Coil profiles in the target ROI are obtained from fully-sampled GradLoc images using the adaptive method in [15] (Fig. 5). The GradLoc images are then undersampled in k-space and the resulting images are unaliased using SENSE.

RESULTS: GradLoc images with 4 mm slice thickness are successfully acquired (Fig. 4) using the Z^2 SEM along with the quadratic-phase RF pulse for slice-phase precompensation. SENSE reconstructions are successfully performed in a GradLoc ROI (Fig. 6) in one quarter of the original FOV, yielding a net acceleration factor of 2*R*, where *R* is the k-space undersampling factor. SENSE image quality degrades more quickly than would be expected based on the number of available receive RF coils. This is likely due to the fact that only 4 out of the 8 RF coils have significant spatial variation and B_1 sensitivity within the GradLoc ROI.

FUTURE WORK: This work shows that parallel imaging may be combined with GradLoc to image local ROIs with high net acceleration factors as compared with imaging the full FOV. We also show that GradLoc may be performed using 3-D SEMs if care is taken to compensate for through-plane dephasing using a tailored RF pulse. Future efforts will seek to refine the RF pulse to more closely match the phase from the Z^2 SEM. Alternatives will also be sought to the use of GradLoc images for obtaining coil profiles. Because it is auto-calibrated, GRAPPA may be a more suitable method. The Z^2 SEM will also be used to perform GradLoc in the sagittal and coronal planes, albeit with rectangular instead of square ROIs.

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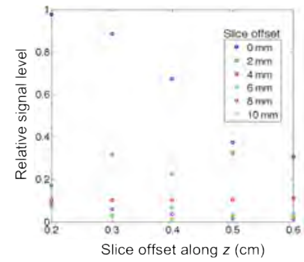

Fig. 1 Signal level as a function of slice offset and slice thickness. Dephasing in the through-slice direction causes severe signal loss at offsets of only 2 mm. The calculation assumes a phase-scrambling SEM sufficient to acquire signal from an ROI measuring ½ of the FOV in each dimension.

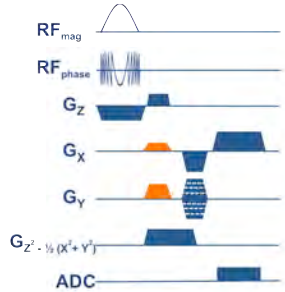

Fig. 2 GradLoc pulse sequence based on a Cartesian gradient echo sequence. A quadratic phase RF pulse is used to precompensate the through-slice phase applied by the Z^2 phase scrambling SEM. The GradLoc window size is determined by the quadratic SEM pulse moment, while the offset depends on the orange lobes of the linear SEMs.

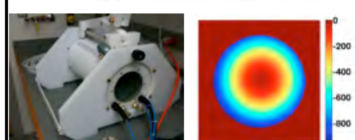

Fig. 3 Insert coil used to produce quadratic field for phase scrambling (left) along with field map (in Hz) acquired at 1% of peak SEM strength.

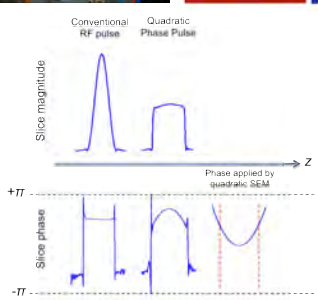

Fig. 4 Comparison of slice profiles acquired using a conventional RF pulse (left) and quadratic-phase RF pulse (center). The quadratic-phase pulse applies a through-plane phase (simulated at right) to precompensate the phase that will be applied by the Z^2 SEM prior to readout. Example shown is a 3 mm slice at *z*=0.

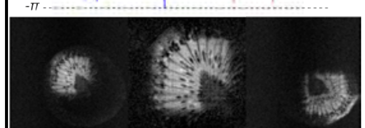

Fig. 4 GradLoc images of a kiwi with a 7 cm FOV (left), a 3.5 cm FOV with the same voxel size (center), and an offset ROI.

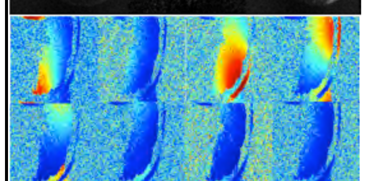

Fig. 5 Coil profiles are obtained from full-sampled GradLoc images in the 5 cm target ROI for an orange phantom. Some residual aliasing is present due to the highly variable flip angle of the TX/RX coil array used.

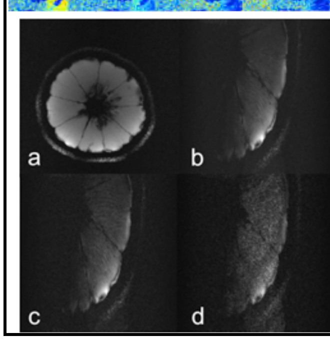

Fig. 6 Reference image of an orange (a) (256×256, 10 cm FOV) and fully sampled GradLoc image (b) (128×128, 5 cm FOV). SENSE parallel reconstructions of under-sampled GradLoc image are shown with *R*=2 (c) and *R*=4 images (d), for net acceleration factors of 4 and 8, respectively.