Localization by Nonlinear Phase Preparation and K-Space Trajectory Design (GradLoc)

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Introduction: A technique is presented using nonlinear magnetic field gradients for target volume localization. This technique shifts the localization burden from the RF pulse to the nonlinear magnetic field rendering it unnecessary to modulate the RF pulse amplitude or phase. There are obvious advantages to gradient pulse localization: no additional RF energy is required using shaped RF pulses and, if a sufficiently strong nonlinear gradient is delivered, localization may be performed in a much shorter time than multidimensional RF pulse excitation would allow. An important development is the use of local k-space theory to identify a spatial encoding trajectory to localize the desired target volume. Finally, we show localization of target volumes *in vivo* using 3D spoiled gradient echo and 2D spin echo acquisitions.

Theory: The signal in a MRI experiment after general nonlinear phase modulation is given by $S(t) = \int_V \rho(x) e^{i\phi(x,t)} e^{i(k(t)\cdot x)} dx$, where *ρ(x)* is the spin density function, *φ(x,t)* is the phase modulation function, a time and spatially varying phase that is imparted on the object and ***k*** is the usual spatial encoding function or trajectory. The phase modulation function redistributes the local spatial frequencies in the Fourier domain. From another perspective, gradient echoes from different spatial locations are not refocused at the same time, but instead are shifted by the shift vector $k_S(x,t) = \nabla\phi(x,t)$. ***Quadrupolar Coils:*** The fields shown in Fig. 1 each generate a 1:1 mapping of position to spatial frequency in the Fourier domain. For a combination of linear magnetic fields and 2 quadrupolar fields the phase preparation function is defined as fields, the shift vector is $k(x,t) = \begin{bmatrix} q2 \\ q3 \end{bmatrix} + 2\begin{bmatrix} x \\ y \end{bmatrix}\begin{bmatrix} q5 & q4 \\ q4 & -q5 \end{bmatrix}$, where $q_{2,3}$ are linear and $q_{4,5}$ are quadratic gradient moments. Choosing $q_{2,3,4}$=0, a target square volume can be selected through the relationship $x_{window} = k_{xmax}/q_5$, where x_{window} is the window width.

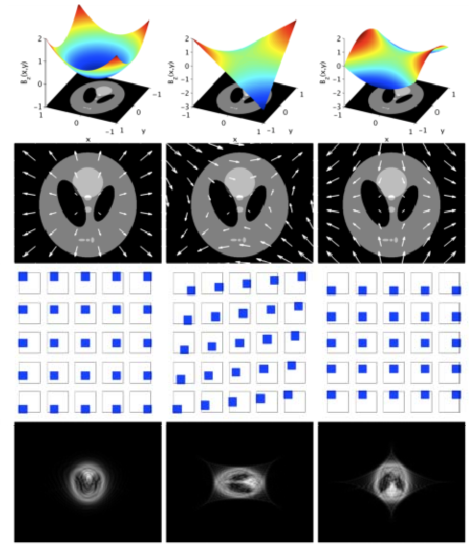

Figure 1: (Row 1) Quadrupolar magnetic fields for localization. (R2) The k-space shift vector is superimposed on the object and its magnitude and orientation determines the location of the gradient echo arising from a position. (R3) Local k-space plots of the spatial frequencies encoded at each position x in the object. (R4) K-space signals are 1:1 mappings of the object to the spatial frequency domain and enable localization.

Methods: ***Hardware.*** Experiments were performed on a 3 T clinical MRI device (TIM Trio Model, Siemens Healthcare, Erlangen, Germany, Trio Model) equipped with two custom quadrupolar, pulsed magnetic field inserts (2). Each magnetic field could be driven at a maximum of 80 A (≈ 2.5 mT/m²/A) with a maximum slew rate 400 A/ms. A birdcage RF transmit and 8-channel receive coils were positioned inside the custom fields for signal reception. ***MRI.*** Spoiled gradient echo and fast spin echo imaging sequences (Fig. 1) were programmed in a pulse sequence programming environment (Siemens). The spoiled gradient echo imaging parameters were the following: matrix = 256 x 256, FOV = 120 mm, TE/TR = 10/100 ms, flip angle = 20°, total acquisition time = 5.5 minutes. The parameters used for the gradient insert were: target size = 100 mm², Spin echo imaging parameters were: matrix = 256 x 256, FOV = 250 mm, TF = 3, echo spacing = 12 ms, TR = 3 s, total acquisition time = 1.4 minutes. Tukey window filtering (=0.05) was applied to suppress Gibb's artifacts. 2 volunteers gave informed consent prior to participating in a protocol approved by the IRB of the University Medical Center Freiburg.

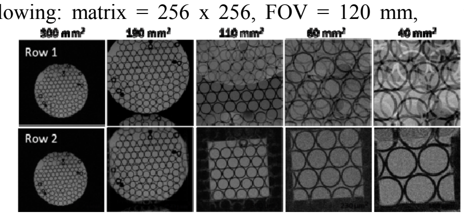

Figure 2: Target localization performed using quadrupolar gradients on a selected region within a large phantom. (R1) In a typical Cartesian acquisition, significant aliasing occurs when the FOV is much smaller than the volume. Using a matched Cartesian k-space trajectory and quadrupolar gradients, a small target volume can be localized without aliasing.

Results: Figure 2 demonstrates the use of the phase preparation module to acquire reduced FOV images. These images were encoded such that the spatial resolution and matrix size would cause significant aliasing in the absence of the phase preparation pulses (Figure 2, first row). In the second row, sufficient phase preparation was applied to suppress the signal from regions outside the desired encoded region. To demonstrate *in vivo* localization for neuroimaging applications, T1-weighted 3D gradient echo images were acquired from a cortex subvolume (Fig. 3). In this implementation, a region of interest is chosen from which to perform reduced FOV imaging. The quadrupolar gradients apply sufficient phase dispersion to eliminate signal outside the target region.

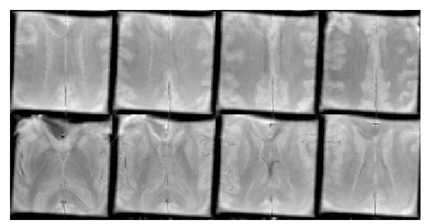

Figure 3: 3D T2*-weighted spoiled gradient echo human brain images. Localized imaging was achieved using quadrupolar fields (in-plane) and slab-selection (through-plane). Approximately 2-fold acceleration was achieved for the target volume for the same resolution with identical contrast to a scan without quadrupolar localization.

Discussion: These methods were introduced by early work performed using topical magnetic resonance (1), surface coil spoiling (3,4), and quadratic encoding (5,6). Unlike these previous investigations, the local k-space framework determined the design of an appropriate spatial encoding strategy to localize an arbitrary target volume in multiple dimensions. Although, in principle, localization could be achieved using nonselective excitation and any nonlinear magnetic field design, a particularly useful nonlinear magnetic field is a quadratic field, because there is a 1:1 correspondence between the image domain and the signal domain. There are two important limitations to target localization with nonlinear gradients. First, the resolution of the target pattern must be sufficiently larger than the resolution of the final reconstructed image. In practice, however, useful localization patterns take a shape corresponding to the boundaries of the object, such as squares or ellipses. Second, it is necessary to apply a windowing filter at the edges of the sampling trajectory to reduce Gibbs ringing, especially when echoes refocus near the boundaries of the sampling trajectory. An undesirable feature is the spatial variation in echo time, which for multiecho imaging sequences like EPI or FSE may be considered unacceptable. For 1D quadratic encoding in EPI, a special sequence, called RASER, was developed to overcome temporal variations in echo time (7).

Conclusion: Multidimensional nonlinear localization strategies could be a highly beneficial alternative strategy to shaped RF pulse localization. Theoretical and experimental results demonstrate that localization can be achieved without significant high spatial frequency aliasing of signals. There may be possible advantages for steady-state MRI applications like cardiac or body imaging

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