Ultrafast Single Shot Imaging with Rotating Nonlinear Fields

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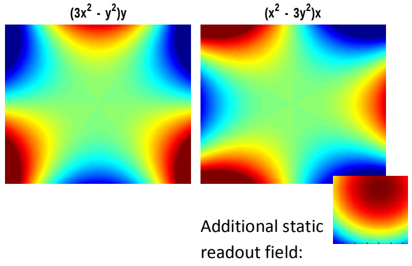
Target Audience: Ultrafast imaging, parallel imaging, and especially nonlinear gradient communities. MR physicists focused on fMRI modalities should be interested in this method as one that may provide extremely high temporal resolution.

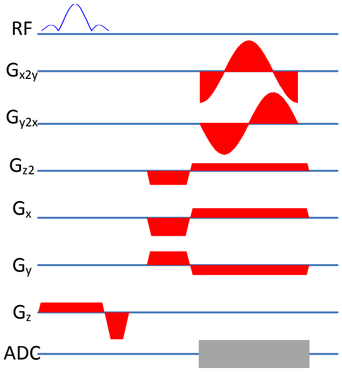
Purpose: While readouts with nonlinear gradient fields have been shown to reconstruct good images from highly undersampled datasets[1,2], here we present a very different approach whereby nonlinear gradient encoding can facilitate extremely fast imaging. We describe a trajectory that encodes the entire 2D image with a single rotation of a strong nonlinear field. Because this entails ramping through just one sine/cosine-shaped gradient pulse on each channel, the slew requirements of a single shot acquisition are minimal, and the acquisition can be compressed to a very short acquisition time without violating PNS limits. Our calculations show that the rotating gradient strategy could potentially allow us to acquire a full 20cm 64^2 image in as little as 2ms.

Figure 1: Nonlinear fields rotated for encoding



Methods: Images were encoded using rotating versions of the fields shown in Figure 1. This would be accomplished by applying linear combinations of fields shaped like the real spherical harmonic functions: $(3x^2-y^2)x$ and $(x^2-3y^2)x$. Readout was accompanied by static fields along $z^2-.5(x^2+y^2)$, x, and y (inset of Figure 1). Encoding was simulated in Matlab at a 64^2 matrix size and with 4% noise amplitude. The simulations used experimental receiver coil profiles from an 8 channel coil, and they also included terms to capture intravoxel dephasing expected at the edges of the FOV. Reconstruction was performed with a Kaczmarz algorithm with 5 iterations. The encoding matrix included both gradient and coil encoding, making this a true parallel imaging reconstruction.

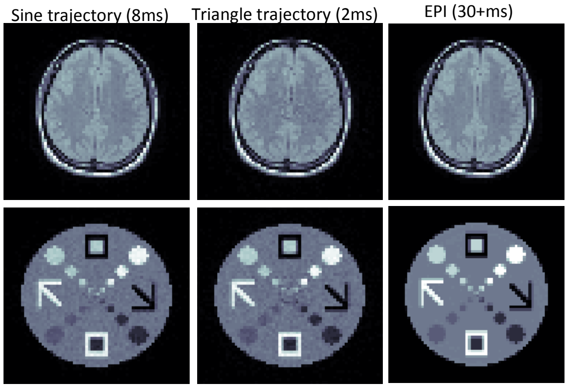
Figure 2: **Complete** pulse sequence diagram for **single shot** 2D imaging



Results: Figure 2 shows the pulse sequence diagram for an entire single shot image acquisition using a rotating gradient; this single sinusoid is equivalent to the 64 echoes of an EPI acquisition. Assuming that a maximum gradient amplitude of 2500Hz/cm^3 could be achieved, this acquisition could be compressed to an 8ms window and still have a maximum slew rate below 45T/s at the edge of the FOV. To further accelerate the acquisition, we also simulated trajectories that employ triangular approximations to the sine and cosine gradient waveforms for dynamically changing the gradient amplitude. This lowers the maximum slew such that with a maximum amplitude of 10kHz/cm^3 and a slew rate under 60T/s, the entire dataset could be collected in a single 2ms window.

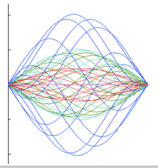
Figure 3 shows reconstructions of images simulated from acquisitions with both the sinusoidal and triangular trajectories described above. These are shown alongside a standard EPI acquisition, which would require an echo train of approximately 30ms or more. As expected, the EPI readout, with its longer acquisition time and lower bandwidth, shows better SNR.

Figure 3: Reconstructed Images



Conclusion: Compared to equivalent sequences using linear gradients (e.g., 64 echo EPI or a comparable spiral trajectory), the nonlinear rotating gradient trajectory is very smooth. Rather than acquiring the data in a series of echoes, this approach focuses on assigning each voxel a unique phase trajectory during readout. (Figure 4) Thus algebraic reconstruction is framed as an analog to GLM decomposition in fMRI, used to distinguish each spatial component by its unique timecourse. This inspired the design of a very smooth sequence that could be played at a very high bandwidth, which could reduce the encoding time of single shot images by an order of magnitude.

Figure 4: Phase trajectories of select voxels during readout



References: [1] Stockmann, MRM 2010. [2] Tam, MRM 2012. [3] Constable, Proc. ISMRM 2011.