

Coded Spatial Localization using Rotating Nonlinear Sets of Gradient Fields and Continuous Readout

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Introduction: Recent work in PatLoc, Ospace, and Null Space imaging has generated interest in the use of nonlinear gradients for spatial encoding. Such gradients introduce a new degree of freedom in pulse sequence design and open up new strategies for spatial encoding. In this work we introduce a series of rotating gradient waveforms (the linear x and y gradients, and second order terms Z^2 and X^2-Y^2) in order to code each voxel in an image with a unique phasor. By rotating the gradients in a periodic but nonuniform manner it is possible to generate a unique gradient-time series for each voxel such that each voxel will have a unique code. It is also possible when rotating a gradient set comprised of these terms to a) perform the rotations smoothly thereby reducing dB/dt and scanner acoustic noise and b) to repeatedly refocus spins thereby providing very high SNR signals throughout the data acquisition.

Methods: For coded spatial localization with rotating nonlinear gradients 4096 readout data points were used with a continuous readout strategy. Two design strategies were employed for the rotating gradients (to be precise only the linear x & y gradients and the X²-Y² gradients were rotated while at max amplitude, while the Z² gradient amplitude was oscillated over the range +/- maximum amplitude). In the first design strategy the gradients were rotated at different and changing (accelerating) rates of rotation such that any particular combination of rotations of the 3 gradient terms was never repeated. An example showing 3 time points for the rotating gradient shapes and the resultant 3 readout time points is shown in Figure 1 below. The second strategy for coded spatial localization is to divide the readout into sections and within each section rotate the gradients at random multiples of a complete cycle such that spins are often refocused both within the cycles as the multiple phases come together and at the end of each cycle. This approach provides a continuous readout strategy with no need for a dephase lobe prior to readout.

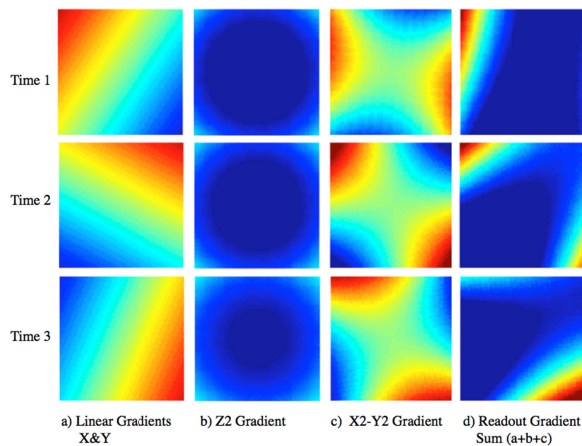


Figure 1: Rotating linear (a), oscillating Z² (b), and rotating X²-Y² gradients (c), are summed to yield a dynamic readout gradient (d,) shown at 3 slightly different time points (rows). Each gradient term is oscillated at a different frequency to encode each voxel in the image with a unique phasor.

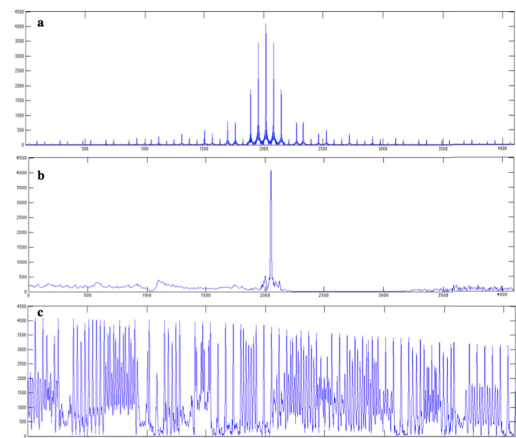


Figure 2: Resultant echoes from: a) conventional blipped EPI, b) a coded nonlinear gradient acquisition with no overlapping periodicity, and c) coded nonlinear gradient acquisition with each rotating gradient a random multiple of the other. The latter approach leads to a high SNR continuous readout.

Results and Discussions: All results are compared to a conventional blipped EPI acquisition with 64 echoes and 64 phase encoding steps to yield 4096 data points as shown in Figure 2a below (the magnitude of the echo signals are all concatenated in this figure). Using the first strategy for calculating a set of 4096 gradient terms with each term containing a different and changing rotation rate 4096 gradient shapes were obtained, the first half of which was time reversed and multiplied by -1 in order to use as a dephase lobe prior to a long readout with 4096 data acquisition points while the 4096 gradients are run leading to a complete refocusing of all the spins at the center of the readout as shown in Figure 2b. This approach however requires a long dephase gradient (half-the length of the readout) and there is little signal at the ends of the readout due to rapid dephasing of the spins with the rotating gradients. However because there are no redundancies in the phasors created with this approach the encoding matrix has full rank and thus may be directly inverted to reconstruct the image. The second strategy for generating a set of gradient shapes for coded localization yields many refocused intervals and much higher SNR for the data as shown in Figure 2c where it is obvious that throughout the readout gradient spins are being refocused as the gradients complete different cycles of their rotations, each of which is a multiple of the other gradients. This approach provides much higher SNR but a lower rank for the encoding matrix and thus the reconstruction is not as straight forward and requires an iterative algebraic approach. In summary this oscillating nonlinear gradient encoding during a continuous readout provides each voxel with a unique gradient-by-time signature allowing for efficient spatial localization, potentially lower acoustic noise, lower dB/dt rates, and higher SNR than conventional EPI.