A k-space approach to designing multi-dimensional frequency modulated pulses for spatiotemporal MRI

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Introduction: Two-dimensional (2D) RF pulses have gained widespread utility in many areas of MRI and MRS. 2D amplitude-modulated (AM) pulses are usually designed using the low-tip angle approximation[1]. Using this approach, a one-dimensional (1D) adiabatic pulse was expanded to achieve square-shaped 2D selectivity[2] utilizing separable k-space excitation in which an EPI trajectory was traversed using amplitude modulation in one orthogonal direction and frequency modulation in the other. Recently, Dumez et al[3] described the theoretical concepts leading to frequency-modulated (FM) 2D pulses for spatiotemporal encoding[4,5]. Building on this, we introduce a new class of 2D FM pulse that excites a cylindrical-shaped volume by sweeping the resonance region during the pulse along a spiral trajectory. The 2D profile produced by these new 2D FM pulses maintains its spatial-selectivity despite frequency offsets arising from chemical shift and/or B_0 inhomogeneity.

Principle: The quadratic phase of a 1D FM pulse (such as the chirp or HS1 pulse) excites spins sequentially in the presence of a constant gradient and induces a spatially dependent quadratic phase along the slice select direction[6,7]. We extend this principle to two dimensions by sampling a spiral k-space trajectory with radial symmetry. If we sample the RF and gradient tables such that, in the radial direction, k-space is equivalent to the 1D k-space produced by the 1D FM pulses (chirp and HS1), we excite a spatially selective cylindrical disc with a chirp or HS1 radial slice profile. Analogous to the 1D case, the spins excite sequentially, but in a 2D excitation space. The 2D k-space amplitude and phase of the chirp pulse and its 2D counterclockwise sequential spiral excitation obtained from simulations are shown in Fig 1A and B, respectively.

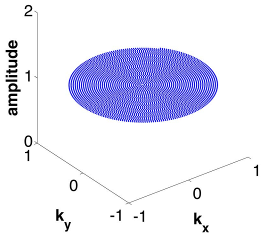

FIG 1A

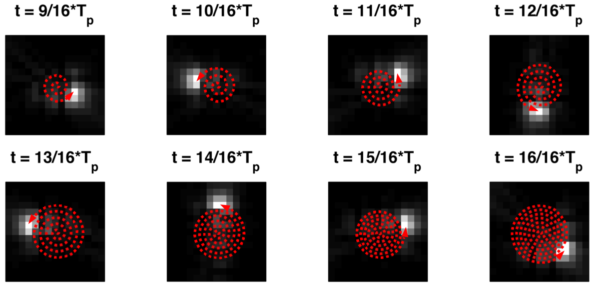

FIG 1B

FIG 1A: Amplitude and phase of spiral 2D k-space for chirp. **B:** Bloch simulation using 10 isochromats to voxel average at different time points. Dotted curves depict sequential excitation spiraling outwards, counterclockwise.

Methods: Constant gradient amplitude equivalent uniform sampling was used in defining 2D spiral k-space to generate 2D FM pulses. An increase in the angular velocity when sampling near the center of k-space results in unrealistic slew rates. This practical issue was addressed by modulating the gradient, ensuring equivalent k-space profile while meeting gradient slew rate constraints. Bloch simulations confirmed both pulses produced equivalent excitation profiles. Experimental verification was carried out by employing the pulse as an excitation pulse for a GRE sequence and tested on a 16.4T scanner (Varian) to image a cylindrical water phantom.

Results and Discussion: The gradient modulated 2D HS1 pulse with k-space dependent time-bandwidth product (R_k) equal to 28 (Fig 2A) was used for Bloch simulation and generated the disc profile shown in Fig 2B. Applying an offset of +250Hz (the approximate chemical shift of fat at 1.5T) increased the radial width of the excited cylinder, whereas the shape of the cylindrical excitation profile was unchanged (Fig 2C). This chemical shift induced 2D spatial shift can be minimized using a higher R_k-value, which also benefits in a sharper disc excitation profile. This is relatively easy to achieve independent of pulse width when using FM pulses if gradient strength is not limiting. Fig 3A is an image of the 3cm diameter cylindrical water phantom used in the experiment. Fig 3B is the image acquired using our pulse for GRE excitation. It is clear that the pulse selectively excites a disc. Fig 3D is the horizontal slice profile take at center. We suspect that the non-uniform excitation is due to k-space sampling error and correcting this should produce a more uniform excitation, similar to that obtained in the simulation. Fig 3C is the same GRE excitation but with a +250Hz frequency offset applied. In agreement with Bloch simulations, the radius of excitation increased while the overall profile was maintained.

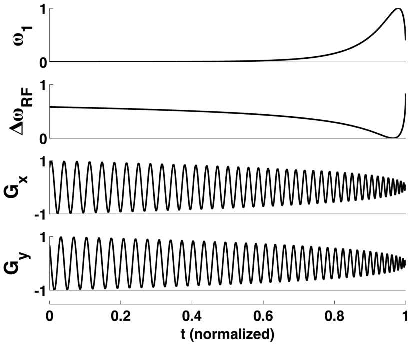

FIG 2A

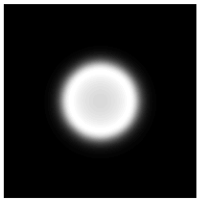

FIG 2B

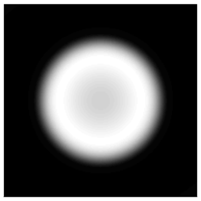

FIG 2C

FIG 2A: 2D HS1 pulse diagram (T_p = 20.48ms and R = 28). **B**: Simulation results show that disc excitation. **C**: Applying frequency offset of +250Hz increases excitation radius.

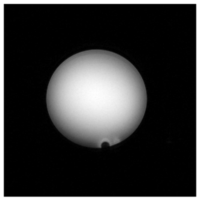

FIG 3A

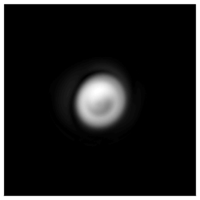

FIG 3B

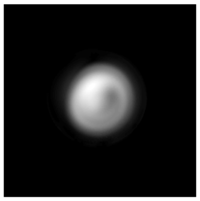

FIG 3C

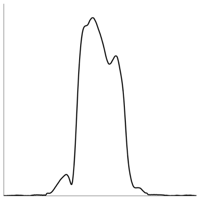

FIG 3D

FIG 3A: Image of cylindrical water phantom. **B**: Using 2D HS1 as GRE excitation pulse shows spatially selective disc. **C**: Offset of +250Hz increases excitation radius, consistent with simulation. **D**: On resonance horizontal slice profile taken at center.

Conclusion: 2D FM pulses using a spiral k-space trajectory were designed, simulated and experimentally verified. Analogous to the one-dimensional counterpart, Bloch simulations showed that sequential excitation occurred in two dimensions. It was demonstrated that spatially selective cylindrical volume excitation was achievable and that off-resonance behavior resulted in an increase in excitation disc radius, which can be minimized using high bandwidth.

References: [1] Pauly J, *JMR* 1988, **81**:43-56, [2] Conolly S, *MRM* 1992, **24**:302-313, [3] Dumez JN, *JMR* 2013, **226**:22-34, [4] Shrot Y, *JMR* 2005, **172**:179-190, [5] Snyder A, *MRM* 2013, doi: 10.1002/mrm.24888, [6] Pipe J, *MRM* 1995, **33**:24-33, [7] Park JY, *MRM* 2006, **55**:848-857.

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