A hexagonal spoiler gradient scheme improves the transition to steady state in spoiled gradient echo sequences

Aaron T Hess[1] and Matthew D Robson[1]

[1]*Oxford Centre for Clinical Magnetic Resonance Research (OCMR), Oxford, Ox, United Kingdom*

Target audience: MRI sequence developers, ultra-high field body imaging and those imaging with local transmit coils.

Purpose: Spoiling in a gradient echo acquisition should minimize the influence of unwanted echoes and produces a T1 dependent contrast. Spoiling is typically achieved with a combination of gradient and RF spoiling (1,2). Gradient spoiling reduces the total number of unwanted echoes refocused into the acquired k-space, and RF spoiling makes the phase of those echoes that are refocused incoherent from one another. However, as we show, at flip angles significantly larger than the Ernst angle the smooth transition to steady state required by some sequences and in fast imaging, does not occur, also see (3). We propose the use of a 3D six point (hexagonal) gradient spoiling strategy to reduce the number of refocused unwanted echoes and improve the transition to steady state for large flip angles. A smooth transition to the steady state is important in fast imaging where preparation pulses cannot be afforded, moreover as local transmit coils are used with 7T body imaging, large flip angles near the coil cannot be avoided.

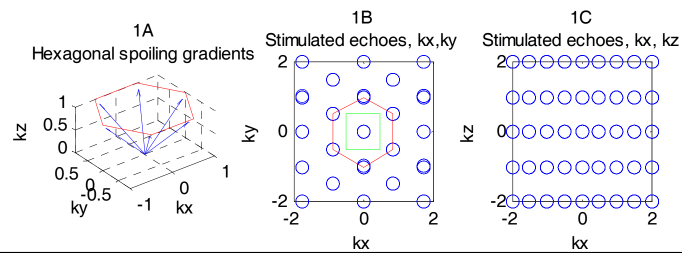

Figure 1: A. Hexagonal spoiler gradients proposed, red hexagon shows the order followed by the gradients. B and C are location of unwanted echoes when M =1 in k-space. Green square is the acquired k-space.

Methods: A novel hexagonal spoiling strategy is proposed where unwanted echoes are distributed in 3D k-space and are either refocused at the centre of k-space or lay outside the spatial frequencies of interest. This is important in order to take advantage of RF spoiling and minimize interference from the unwanted echoes. The hexagonal strategy employs six spoiling gradient moments defined in the three spatial axes of [PE, Read, Slice] = [M.cos(k*60°), M.sin(k*60°), M], where k is the repetition counter and M is the moment of a spoiling gradient. 60° is chosen as it ensures <u>all</u> unwanted echoes lie on a grid owing to the symmetry of the equilateral triangles and are either refocused or further than M from the k-space origin as shown in figure 1. With this strategy the first unwanted echoes are refocused only after the 6th RF pulse, compared to the 3rd RF pulse when using a constant spoiling gradient. We assess the phase coherence pathways in k-space to determine the total number of unwanted echoes produced compared the total number refocused for the hexagonal and constant gradient strategies. The method was implemented in a 2D gradient echo sequence where all gradient moments were balanced before the spoiler gradients were added. M was set to twice the highest spatial frequency in the readout direction. For comparison to a constant spoiling scheme, the sequence was modified to execute the following constant gradient [0, M, M], this ensure both sequences used the same magnitude spoiling gradient. RF spoiling used quadratic increments of 50° each repetition.

Phantom scans were performed with four different spoiling strategies on a peanut oil phantom at 7T (Siemens, Erlangen), with a T1 of 434 ms and T2 of 43 ms (4). The four strategies are, i) hexagonal gradient spoiling, ii) constant gradient spoiling, iii) hexagonal gradient spoiling with RF spoiling, iv) constant gradient with RF spoiling. Both the steady state reached and the approach to steady state are compared to that predicted by the well-known signal equations for a theoretically ideal spoiled gradient echo. In each experiment 512 repetitions, with no phase encoding, were acquired with a TR/TE of 10ms/4ms at flip angles of 1°, 3°, 5°, 7°, 9°, 10°, 11°, 12°, 13°, 14°, 15°, 16°,17°,18°,19°,20°,30°,40°, 50°, and 60°, readout bandwidth of 200 Hz/pixel with a single channel transmit/receive birdcage coil. The slice thickness was set to 250 mm, FOV of 300 mm with 256 readout points. The phantom was 20 x 20 x 40 mm^3.

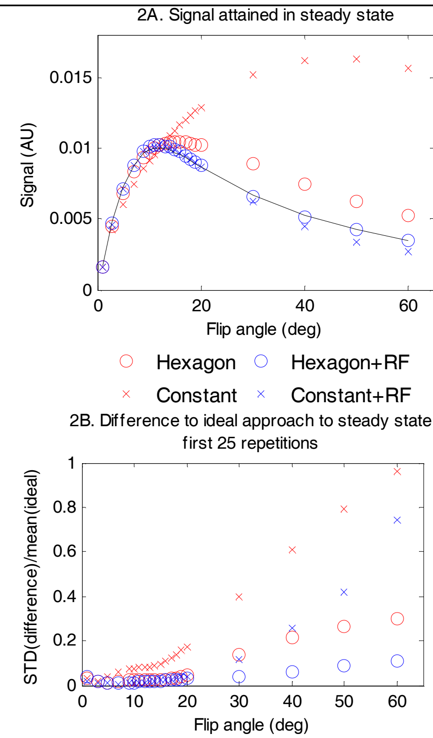

Figure 2. Results of phantom scan for A. steady state reached, and B. Difference from the ideal approach to steady state.

Results: The phase coherence analysis gave 848 and 25,652 refocused unwanted echoes out of a total of 177,147 unwanted echoes for hexagonal and constant spoilers respectively after 12 TRs. Figure 2A shows the steady state measured in the phantom after 500 TRs for each spoiling method, it shows the ideal line as calculated with the equation for the spoiled steady state and scaled to the magnitude of the measurement with constant gradient with RF spoiling at the Ernst angle. Figure 2B shows the standard deviation of the difference from the ideal approach to the steady state for each type of spoiling in the first 25 TRs. The greatest deviation from the ideal trajectory at high flip angles was when constant spoiling was used, and least for hexagonal spoilers with RF spoiling.

Discussion and Conclusion: This new hexagonal gradient spoiling method with RF spoiling is found to closely follow the ideal predicted steady state, and without RF spoiling it performs substantially better than a constant gradient spoiler. More importantly the hexagonal spoiler gradients with RF spoiling closely follow the ideal approach to steady state and provide a smoother transition. This is important when flip angles larger than the Ernst angle will be present, such as when using a surface coil in situations where a huge number of preparation pulses are not practical. In conclusion we have shown that using a hexagonal spoiling gradient scheme provides a smooth transition to the steady state at high flip angles, and closely follows the ideal spoiled signal at flip angles larger than the Ernst angle.

References: 1) Leupold J, Hennig J, Scheffler K. MRM 2008 60: 119-127 2) Zur Y, Wood ML, Neuringer LJ. MRM 1991 212: 251-263. 3) Epstein FH, Mugler JP, Brookeman JR, MRM 1996 35: 237-245 4) Jordan C et al. Eur J Radiol 2013 82(5):734-739.

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