Increased speed and image quality for single shot fast spin echo imaging in the pelvis via variable refocusing flip angles and full-Fourier acquisition

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Target Audience: Physicians seeking to increase speed and quality of pelvic MRI, and researchers studying variable refocusing flip angles in spin echo techniques.

Purpose: Single shot fast spin echo (SSFSE) sequences are often used in body MRI, especially when robustness to non-periodic motion such as irregular breathing or bowel peristalsis is important. In current implementations, the speed (minimum TR) of SSFSE acquisition is limited by specific absorption rate (SAR), and image quality is compromised by various factors including T2-decay related blurring and the half-Fourier acquisition. We developed a variable refocusing flip angle single shot technique and demonstrated it could speed pelvic MRI and improve image quality in a clinical setting.

Methods: A refocusing flip angle modulation algorithm similar to that used in 3D-FSE techniques [1] was utilized to create an SSFSE sequence with variable refocusing flip angles (vrfSSFSE). The variable flip angles in the echo train (Fig. 1) are smoothly modulated between 4 control points: α_{init} (initial flip angle), α_{min} (target angle for initial ramp down), α_{cent} (angle at the center of k-space), and α_{last} (ending flip angle). Simulation studies utilized an extended phase graph algorithm as previously described [2].

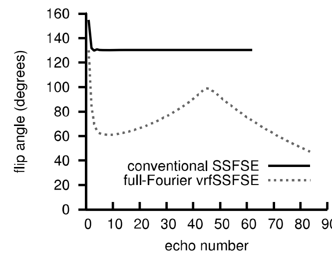

Fig 1: Flip angle train

With IRB approval and informed consent, we recruited 25 consecutive women referred for MRI evaluation of suspected fibroids. Subjects were scanned on a 3.0T MRI scanner (MR750, GE Healthcare, Waukesha, WI) with conventional SSFSE and vrfSSFSE with the following parameters: 32-channel torso coil, ARC parallel imaging factor 2 (sagittal) or 3 (coronal oblique), free-breathing, matrix 416 x 224, phase FOV 0.8 (sagittal) or 1 (coronal oblique), bandwidth ±125 kHz. SSFSE utilized a constant refocusing flip angle of 130° and half Fourier (half-NEX) k-space acquisition with homodyne reconstruction, vrfSSFSE utilized variable refocusing flip angles as described in results and full Fourier k-space acquisition. Field of view was optimized to each patient's anatomy (26-42 cm), but was identical between both sequences for a given subject. Paired sets of SSFSE/vrfSSFSE images were graded in random order and blinded fashion by two radiologists to judge if the images were equivalent (0 points), or if one of the pair was improved either without effecting diagnostic capability (1 point) or to the point of improving diagnostic capability (2 points). Scores were then transposed to a -2 to 2 scale with positive numbers indicating improved vrfSSFSE quality. Subjective image quality parameters assessed were noise, contrast, sharpness, and artifacts. The ability to evaluate the endometrium, junctional zone, myometrium, ovaries, and musculoskeletal structures were similarly assessed. The null hypothesis of no significant difference in score between sequences was assessed with a Wilcoxon signed rank test, with two-tailed $p<0.05$ considered significant, with the Holm–Bonferroni method used to correct for multiple comparisons.

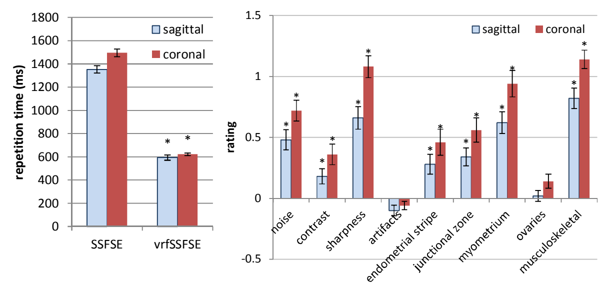

Fig 2a: Shorter TR with vrfSSFSE. **2b:** Grading, positive values favor vrfSSFSE. * indicates significant difference. Error bars are SEM.

Results/Discussion: Via a combination of simulation and volunteer studies, the flip angle parameters for vrfSSFSE were chosen as: α_{init} 130°, α_{min} 60°, α_{cent} 100°, and α_{end} 45° (Fig 1). Image quality was most dependent on α_{min}; lowering this led to reduced SAR and relative prolongation of T2-decay reducing blurring. However, lower flip angles lead to a greater dependence on longer refocusing pathways in the echo train, creating longer time periods over which phase shifts from motion can accumulate and result in signal loss [3]. Setting α_{min} to 60° was a compromise, yielding no perceptible tendency to motion induced signal loss for structures in the pelvis, and allowing sufficient T2-decay prolongation that full-Fourier k-space aquisition could be performed while still achieving clinically relevant echo times. The parameter α_{end} led to little perceivable changes in image quality, and was set to 45° to reduce SAR. The parameters α_{init} and α_{cent} were set based on prior work and not reevaluated here [2].

Clinical acquisition times were reduced by >50% (Fig 2a). Median echo times were 120/125 ms and 131/138 ms for sagittal/coronal SSFSE and vrfSSFSE, respectively. Gradings of vrfSSFSE were statistically significantly improved for noise, contrast, sharpness, endometrial stripe evaluation, junctional zone evaluation, myometrial evaluation, and musculoskeletal evaluation for both coronal and sagittal acquisitions (Fig 2b, representative images in Fig 3). Reflected in the results, and as might be expected from the T2-decay prolongation and the full-Fourier technique of vrfSSFSE, improvements were most apparent for structures with relatively short T2 times (myometrium/fibroids, muscle, bone). Improvements were greater for coronal acquisitions; this was felt to reflect a larger relative improvement to SNR for the full-Fourier technique when utilized with higher acceleration factors (ARC 3).

SSFSE: TR 1567ms TE 127ms **vrfSSFSE**: TR 638ms TE 130ms

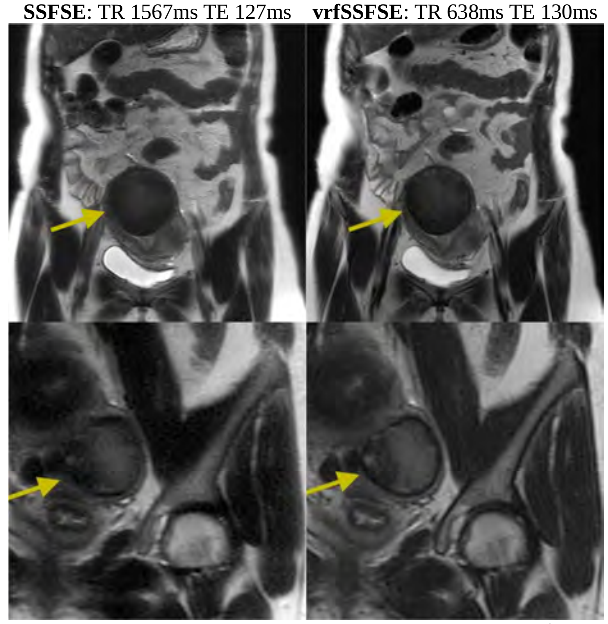

Fig 3: Representative images showing two large partially calcified fibroids (yellow arrows). Note decreased noise with vrfSSFSE, as well as the better delineation of species with short T2-decay times particularly in the phase encoding direction (right-left) such as the rim of the fibroid.

Conclusion: vrfSSFSE gives a 2-fold speed increase and permits full-Fourier k-space acquisition, yielding a significant improvement in subjective image quality metrics.

References: [1] Busse RF, Brau AC, Vu A, et al. Effects of refocusing flip angle modulation and view ordering in 3D fast spin echo. Magn Reson Med. 2008 Sep;60(3):640-9. [2] Saranathan M, Loening AM, Litwiller DV, *et al.*, Optimized refocusing flip angles for efficient single-shot fast spin echo imaging. ISMRM, Milan, 2014, #2175. [3] Litwiller DV, Holmes JH, Saranathan M, *et al.*, Sensitivity of modulated refocusing flip angle single-shot fast spin echo to impulsive cardiac-like motion. ISMRM, Milan, 2014, #1613.