Transient Balanced SSFP Imaging with Increased Signal by Variable Flip Angles

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INTRODUCTION: Often in balanced steady state free precession (bSSFP) acquisitions, physiological motion or use of contrast preparation mechanisms limit the acquisition block length. Therefore, acquisition occurs intermittently and during the transient (as opposed to steady state). This work presents a method for calculating **variable flip angles for bSSFP acquisition to generate echoes at predefined amplitudes**. The main advantage is to allow transient stage imaging with minimal artifacts and with increased signal. Higher signal can be gained by fully utilizing the magnetization (Figure 1). The idea is similar to variable-angle uniform signal excitation (VUSE) [1], which was implemented with RF-spoiled gradient echo (SPGR) for time-of-flight angiography and other applications [2,3].

This work aims to demonstrate the VUSE method for bSSFP to create temporally uniform echo amplitudes. The bSSFP VUSE algorithm considers longitudinal and transverse magnetization at each TR, producing a flip angle series that provides echo amplitude Mtarget (e.g., $0.28M_0$ in Figure 1), if such a target is achievable. The algorithm can be repeated: increasing Mtarget if a solution is found, or decreasing Mtarget if no solution is found. This iterative scheme typically takes fewer than 14 iterations. A non-contrast enhanced MR angiography acquisition, In-Flow Inversion Recovery (IFIR) bSSFP [4], was used to demonstrate the VUSE bSSFP method.

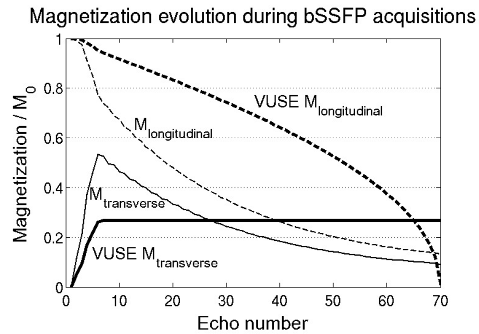

Figure 1: In a standard bSSFP acquisition that occurs intermittently, the magnetization ($M_{transverse}$ and $M_{longitudinal}$) never reaches steady state. A temporally uniform echo signal (VUSE $M_{transverse}$, bold solid line) can be achieved by calculating a flip angle series (e.g., VUSE, bold line, in Figure 2C) that "uses up" all of $M_{longitudinal}$ by the end of the acquisition block.

METHODS AND RESULTS: All studies were performed using a 1.5T MRI scanner (GE Healthcare) following IRB approval. A 3D bSSFP pulse sequence with Kaiser-filtered ramp (5 RF pulses) catalyzation (to minimize off-resonance artifacts from oscillations) [5] was modified to perform VUSE calculations on-the-fly. Linear-ramp pulses or the α/2-TR/2 pulse can be used [6], but a Kaiser-ramp provides the optimal response.

Simulation: Numerical Bloch simulations were used to verify the VUSE method and investigate its off-resonance behavior. As shown in Figure 2, VUSE bSSFP produces a uniform on-resonance signal profile, and has a similar, well-behaved off-resonance response to constant flip angle bSSFP.

Phantom acquisition: A birdcage head coil was used to image a spherical agar phantom (T_1/T_2 = 907/50 ms). The acquisition matrix (no phase encoding) was 256×64×10 (readout×echoes×slice), with 64 echoes per acquisition block. Echoes from the center slice were measured to avoid errors from imperfect slice excitation. Figure 3 shows the expected decaying and uniform echoes from constant flips and VUSE bSSFP.

Volunteer acquisition: IFIR bSSFP was modified to acquire axial 3D renal angiograms of one volunteer using the VUSE method. An 8-channel phased array coil was used. Common parameters between constant flips and VUSE bSSFP were: matrix = 256×77×50; FOV = 33×20 cm; slice thickness = 1.6 mm; TI = 1.1 s; with linear phase encode ordering, fat-selective IR and respiratory triggering. 77 phase encodes (i.e., one complete *kz* plane) were acquired per acquisition block. The TR was slightly higher in VUSE bSSFP (5.6 ms versus 4.6 ms) to accommodate the high flip angles. VUSE angiograms have higher signal, and improved small vessel depiction (Figure 4), attributed to the higher echo amplitude at *k*-space center, and higher integral of the echo amplitude versus time curve. Fat suppression is poorer in VUSE, perhaps due to the increased TR resulting in sub-optimal fat nulling with the fat-selective IR, which can be mitigated by changing the phase encode acquisition ordering.

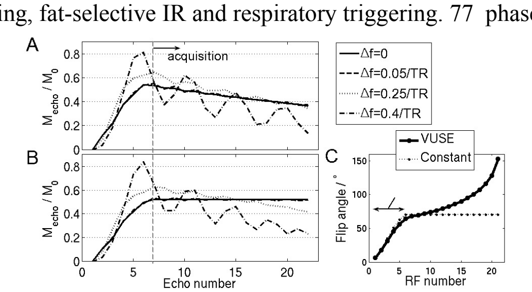

Figure 2: Echo amplitudes from simulations of on- and off-resonant spins for (A) constant flips and (B) VUSE bSSFP (Δf = off-resonance frequency). A flat echo profile is achieved in VUSE on-resonance. The flip angle schemes used are shown in (C). Both acquisitions have minimal oscillations when off-resonant owing to the Kaiser-ramp catalyzation.

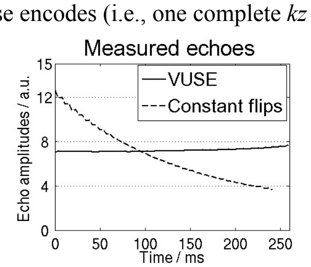

Figure 3: Plots of MRI signal (in arbitrary units) versus time for the constant (70°) and VUSE flip angle schemes. VUSE bSSFP took more time than constant flips bSSFP due to an increased TR (due to SAR restrictions).

DISCUSSION: VUSE bSSFP provides a method for increasing signal in a transient bSSFP imaging acquisition. Other advantages from the uniform echo signal may include improved resolution and SNR efficiency.

Limitations of VUSE include increased TR and B_1 sensitivity due to the high flip angles used (Figure 2C), which can be avoided by simply limiting the maximum flip angle in the algorithm. Also, the calculation is optimized for a specific T_1/T_2 (that of blood in the case here), therefore other tissue species will have a different (smoothly increasing or decreasing) echo profile.

The algorithm can also provide any arbitrary sequence of echo amplitudes such as ramped or windowed profiles that may improve other applications.

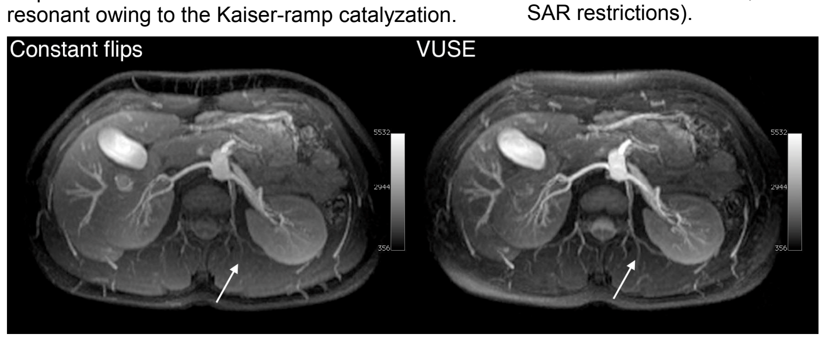

Figure 4: Axial MIP renal angiograms from IFIR acquisitions using constant flips (60°) and VUSE bSSFP. VUSE has higher signal and improved small vessel depiction (white arrows). The images are displayed at the same window and level.

CONCLUSION: Modulating echo profiles by calculating a scheme of flip angles can improve signal in bSSFP transient imaging and improves small vessel depiction in IFIR angiography.

ACKNOWLEDGEMENTS: GE Healthcare.

REFERENCES: [1] Priatna A & Paschal CB. JMRI 5:421-427, 1995. [2] Wang SJ et al. MRM 17:244-251, 1991. [3] Mugler JP et al. MRM 28:165-185, 1992. [4] Young P et al. ISMRM p1870, 2009. [5] Le Roux P. JMR 163:23-37, 2003. [6] Deimling M & Heid O. SMRM p495, 1994.