A Low Power Imaging Alternative to bSSFP

W. R. Witschey[1], A. Borthakur[2], M. Elliott[2], E. L. McArdle[2], and R. Reddy[2]

[1]Biochemistry and Molecular Biophysics, University of Pennsylvania, Philadelphia, PA, United States, [2]Radiology, University of Pennsylvania, Philadelphia, PA, United States

Introduction: Balanced steady-state free precession (bSSFP) imaging offers a very high signal-to-noise ratio (SNR) and T2/T1-weighted image contrast useful for bright-blood MRI and fast imaging applications (1). The sequence requires a very short TR to reduce steady-state artifacts originating from the heterogeneity of the static magnetic field, but may consequently result in prohibitively high tissue specific absorption rate (SAR), although some applications have been demonstrated at ultra high field (2). Recently, a spin locked steady-state free precession (slSSFP) sequence was introduced (3), which does not flip the magnetization in the usual way, but locks it parallel to the effective field in the rotating frame (also see abstract 1261 for details of the pulse sequence design). It was hypothesized that reducing RF pulse power would have little effect on signal, allowing one to reduce power low enough to scan safely, but still sufficient to overcome field variation artifacts. The purpose of this investigation was to determine if RF pulse power could be reduced without changing the steady-state signal in $MnCl_2$ phantoms and *in vivo* knee joint imaging.

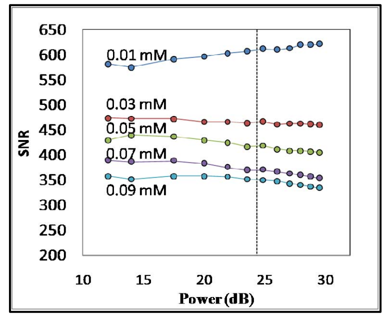

Figure 1: The slSSFP signal is independent of RF pulse power. By comparison, the power required for a similar bSSFP acquisition is moderately higher (vertical line).

Materials and Methods: ***Simulations.*** α/2-prepared, phase-alternated bSSFP (4) and α-prepared slSSFP steady-state signals were simulated using the Bloch equations with an ODE solver based on an explicit Runge-Kutta formula, the Dormand-Prince pair (TE/TR = 2.5/5 ms, τ_{pulse} = 1 ms, T1/T2 = 800/50 ms, α = 0-180°). ***MRI.*** A five compartment phantom was prepared containing 0.01-0.09 mM $MnCl_2$ in distilled water. $MnCl_2$ phantom T1 and T2 relaxation times were measured by inversion recovery-prepared fast spin echo (TI = 50- 3200 ms, TR = 10 s) and cmpg spin echo (TE = 25-250 ms, TR = 10 s). A single healthy human volunteered for axial knee scans. Scanning was performed on a 1.5 T Siemens MRI systems equipped with 40 mT/m gradients and a cp knee coil (1.5 T). Acquisition parameters were TE/TR/τ_{pulse} = 3.6/7.2/0.4 ms, 2α = 50°, matrix = 128 x 128 x 64, FOV = 130 x 130 x 320 mm^3, BW = 500 Hz/pixel. Separately, a knee study was performed at 7T in a single human volunteer to measure the available contrast-to-noise (CNR) for cartilage imaging applications. ***Data Analysis.*** Circular regions-of-interest (ROIs) were drawn manually in phantoms and in the medial patellar cartilage compartment, plantaris muscle and synovium of the knee joint from which the signal was measured; noise measurements were measured from an ROI containing no tissue signal. Signal variation in slSSFP scans was measured by least-squares estimation of the percent change in signal with power ($\Delta S(\%)/\Delta dB$).

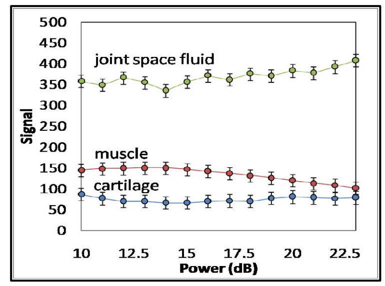

Figure 2: The slSSFP signal is independent of pulse power in knee joint space fluid, muscle and cartilage.

Results: Several experiments were performed to validate the independence of the steady-state signal in response to RF pulse power adjustment. The signal from each of the 5 $MnCl_2$ samples was found to vary less than 1% per dB of RF pulse power over a wide range of pulse power 10-30 dB (ν_1 = 71-710 Hz) (Figure 1). The percent change in signal for each of the phantoms was 0.47 (0.01 mM), 0.17 (0.03 mM), 0.47 (0.01 mM), 0.56 (0.07 mM) and 0.34 (0.09 mM) %/dB. These were extraordinarily small changes relative to changes observed with modulation of the effective field (Figure 3), which was as much as 30.4% (0.01 mM) between slSSFP acquisitions at α = 30 and 70°. It was important to shim well, since RF pulse power much less than 10 dB (71 Hz) suffered signal nonuniformity owing to variations in the static field. For reference, the amplitude of an identical RF pulse used during bSSFP which would achieve the same signal is drawn as a vertical line, which illustrates that a spin locked steady-state could be maintained with nearly 14 dB lower power and a 24-fold reduction in SAR. To further test the signal independence, *in vivo* knee imaging was performed and the signal from joint space fluid, muscle and cartilage signal was determined also to be independent of pulse power (Figure 2 – NB: the required bSSFP power was approximately 25 dB (347 Hz) and does not appear on this scale). It was predicted that it should still be possible to modulate the slSSFP signal in a flip angle-dependent way by rotating the direction of the effective field and varying the flip angle of the preparatory α-pulse. In this way, it was found during simulations that it was possible to mimic the well-known bSSFP flip angle signal dependence (Figure 3, left). This was found experimentally in $MnCl_2$ samples, which demonstrated flip angle-dependent signal which was identical to bSSFP (Figure 3, right). The phase alternated bSSFP flip angle was maximized for $\cos(\alpha) = (T1/T2-1)/(T1/T2+1)$ (4), which for each sample was calculated to be 64.9, 54.3, 48.2, 44.6 and 42.7°, in close agreement with the observed maximum and, notably, the slSSFP signal maximum was nearly identical (Figure 3, right). Representative axial knee images are shown in Figure 4 and demonstrate a 5 dB reducing in power without changing contrast (B and C).

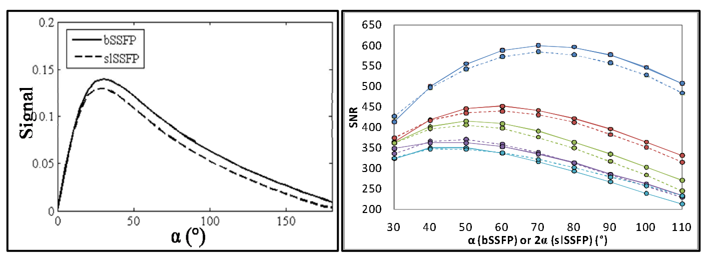

Figure 3: Simulated (left) and experimentally determined (right) slSSFP signal dependence is nearly identical to bSSFP and could be adjusted with the direction of the effective field and preparatory flip angle.

Discussion: We demonstrated that slSSFP imaging can be performed over a range of RF pulse power without modifying the steady-state signal. This result seems counterintuitive since most spin locking applications are SAR intensive and require high power and long duration RF irradiation, however, it was shown experimentally (Figure 1) that for liquid samples under extreme motional narrowing, the RF power can be lowered significantly without directly changing the contrast. The near signal equivalence over a wide range of flip angles presupposes that, at least for liquid samples, it should be possible to extrapolate analytical solutions for phase-alternated bSSFP to slSSFP. In spin systems which exhibit low frequency relaxation dispersion, it is probable that the signal will vary with locking power, although it is unclear to what extent this occurs in muscle or cartilage (Figure 2). The use of very long locking pulses may also allow for long repetition times which were previously unavailable because of static field variation.

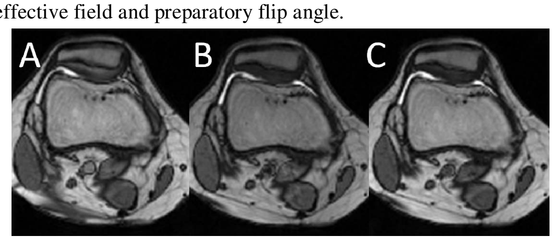

Figure 4: slSSFP axial knee images at 1.5 T acquired at two effective field orientations (A) α = 15° and (B,C) α = 30°. Note particularly the difference in cartilage contrast between (A) and (B,C), where, instead, the power was adjusted to (B) 15 dB and (C) 20 dB.

Conclusion: slSSFP is a promising fast imaging imaging technique with very high SNR efficiency and a signal dependence which can be manipulated in such a way as to mimic bSSFP, but using significantly lower power. One very promising application of this technique is for ultra high field applications which require a very short TR, but for which SAR is excessive.

References: (1) Oppelt, et al. *Electromedica*. (1986) (2) Krug, et al. *Magn Reson Med.* (2007) (3) Witschey, et al. *ISMRM Workshop: High Field Systems and Applications*. Rome (2008). (4) Haake, et al. *MRI: Physical Principles and Sequence Design* (1999).