SNR behavior of SSFP: Dependence on TR, Bandwidth & Gradient Performance Optimization

D. A. Herzka[1], S. B. Reeder[2], E. R. McVeigh[3]

[1]Department of Biomedical Engineering, Johns Hopkins University School of Medicine, Baltimore, MD, United States, [2]Department of Radiology, Stanford University Medical Center, Stanford, CA, United States, [3]Laboratory of Cardiac Energetics, NHLBI, National Institutes of Health, DHHS, Bethesda, MD, United States

Synopsis: The SNR behavior of SSFP was studied with respect to TR and receiver BW. Optimum imaging flip angle and the maximum signal are shown to be independent of TR and BW. Therefore, SNR is independent of TR and BW for a constant scan time and depends only on T_1, T_2, voxel size, and pulse sequence efficiency. Maximum gradient amplitude and slew rate are critical to optimize SNR. Simulations show current gradient performance is well matched: no appreciable gain in efficiency or SNR is possible within current peripheral stimulation limits or without the development of gradient hardware concepts for reduced stimulation.

Introduction: Refocused Steady-state free precession (SSFP, TrueFISP, FIESTA, BFFE) [1,2], is a fast imaging technique that has recently gained acceptance due to its increased SNR with respect to other gradient echo sequences. The short TRs and high efficiency available with SSFP have lead to a diverse set of applications including ultrafast imaging (low resolution≈128x96matrix), cardiac cine imaging (normal resolution≈256x192 matrix), and musculo-skeletal (MSK) imaging (high resolution≈512x256 matrix), among many others. It can be shown that when TR is short (TR<< T_2,T_1), the maximum signal intensity (S_0) (Eq [1] from ref [1], $E_1=\exp(-TR/T_1)$, $E_2=\exp(-TR/T_2)$) and α_{OPT} (Eq [2]) are functions only of T_1 and T_2 and independent of TR and receiver bandwidth (BW). As shown by Eqn. [3], SNR for a constant scan time becomes independent of TR and BW and is dependent only on relaxation parameters, voxel size and pulse sequence efficiency (η = total readout time/TR). Hence, optimization of gradient hardware performance in the form of max amplitude and slew rate (SR) becomes critical for optimization of both SNR and η.

$$[1]: S_0 \approx M_0\sqrt{\frac{1-E_1}{(1+E_1)(1-E_2^2)}} \approx \frac{1}{2}\sqrt{\frac{T_1}{T_2}}$$

$$[2]: \cos(\alpha_{OPT}) \approx \frac{T_1-T_2}{T_1+T_2}$$

$$[3]: SNR \propto S_0\cdot\Delta V\cdot\sqrt{\eta}\cdot\sqrt{T_s}$$

Materials & Methods: *Phantom Experiments:* To confirm the relationship between SNR and TR & BW, three stationary agar/$CuS0_4$ phantoms with varying T_1/T_2 characteristics were imaged in a Sonata 1.5T (Siemens, Erlangen, Germany) scanner with a standard head coil using a product SSFP (TrueFISP) sequence. BW was varied from 1500 to 100 Hz/pix leading to TRs from 2.9 to 11.3 ms. To ensure steady-state, imaging was repeated 30 times consecutively and results from ROI analysis from the last 10 repetitions were averaged to obtain signal, SNR and normalized SNR measurements.

Gradient Optimization Simulations: Simulations were written in MATLAB (Natick, MA) to explore the relationship between TR, efficiency, and gradient performance. For each gradient amplitude and SR, the TR and efficiency were calculated for a SSFP pulse sequence designed using the hardware optimized waveform algorithms as implemented in [4] and described in [5]. The optimum gradient hardware operating point, defined as the matched gradient amplitude/slew rate pair at which an increase in gradient amplitude provided no increase in η, was determined for each of six imaging scenarios:

(a) Low Resolution SSFP
(b) Normal Resolution SSFP
(c) High Resolution SSFP
(d) Low Resolution, 3-echo EPI-SSFP
(e) Normal Resolution, 3-echo EPI-SSFP
(f) Low Resolution ,5-echo EPI-SSFP

Simulation parameters for the low/normal/high resolutions were: 128x96/256x192/512x256 matrix sizes; FOV 40/36/16cm; BW ±200/±120/±120 kHz; slice thickness 10/6.0/3.0 mm, respectively.

Results: Phantom experiments confirmed the above equations. Signal intensity and SNR normalized by sampling time (Fig 1) are independent of TR or BW. Fig 2 shows the relationship between gradient performance and η for 3 of the 6 imaging settings described above (a-c). Maximum slew rates are limited by restrictions to avoid peripheral nerve stimulation; therefore, the optimum gradient performance (dotted lines) is defined as the point for each slew rate at which increases in gradient amplitude do not yield any increases in efficiency. For low resolution imaging (i.e. ultrafast imaging), including 3-echo and 5-echo EPI-SSFP (results not shown), the optimal gradient operating point is well below the maximum gradient amplitude hardware capabilities of current scanners. Similarly, for normal resolutions (i.e. cine imaging) gradient amplitude performance is adequate. However, optimum performance is never reached for high resolution imaging. The use of EPI-SSFP greatly increases efficiency and benefits from increased slew rates.

Discussion: When imaging at α_{OPT}, the maximum signal available with an SSFP sequence is independent of TR and BW. Therefore, SNR for a constant scan time is also independent of TR and BW, making pulse sequence efficiency the major determinant of SNR. This indicates that SSFP should be run with the highest allowed slew rates and high bandwidths since decreases in TR are not detrimental to SNR *as long as efficiency is not decreased significantly*. Pulse sequence efficiency depends mostly of on gradient hardware performance, indicating that the matching of max amplitude and slew rate becomes particularly important for SSFP. Simulations show that current gradient operating points (Amp. = 40mT/m, SR = 150 mT/m/s) provide more than adequate performance for low resolution imaging and are well matched for cardiac cine imaging. These results indicate that for future improvements in SSFP pulse sequence efficiency (and therefore SNR efficiency) must come from either easing of current peripheral stimulation restrictions or the design and development of new gradient hardware concepts for reduced stimulation. For high resolution imaging, maximum gradient amplitude needs to be increased to better match available slew rates.

References: [1] Sekihara K. IEEE TMI 6:157–164 (1987). [2] Oppelt A, et al. *Electromedica* 54:15–18 (1986).
[3] Herzka DA, et al. *MRM* 47:655–664 (2002). [4] Derbyshire JA, et al. *10th ISMRM* pp. 2359 (2002).
[5] Atalar, E et al. *MRM* 32(6):773-7 (1994).

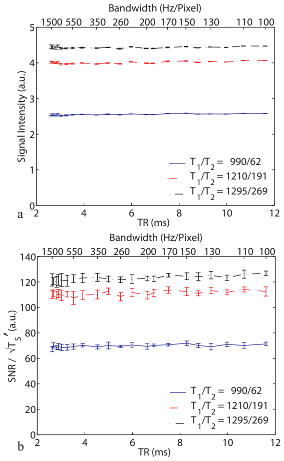

Figure 1: (a) Signal and (b) SNR normalized by sampling time ($T_s'=\eta\cdot T_s$) are independent of TR and BW for stationary phantoms, making pulse sequence efficiency the primary factor in determining SNR.

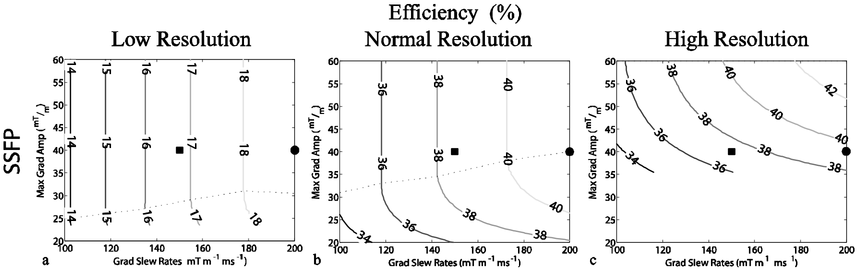

Figure 2: Contours demonstrating the relationship between gradient performance and pulse sequence efficiency (η) for the 3 of the 6 different imaging settings described above (a-c). Optimum gradient performance (dotted lines) is defined as the point for each slew rate at which increases in gradient amplitude do not yield any increases in efficiency. The current operating points for clinical and high performance 1.5T systems are denoted by (■) and by (●) respectively. Note that for low resolution imaging, gradient performance is more than adequate as indicated by the fact that the optimum gradient performance line falls below current operating points. For normal resolution scans (i.e. cardiac cine imaging) gradient performance is well matched though increases in pulse sequence efficiency must be derived from increases in both maximum gradient amplitudes and slew rates. For high resolution imaging, the optimum gradient performance curve is much higher than current maximum gradient amplitudes (~80mT/m).