Bloch Equation Simulations for bSSFP, Spin Echo, and SPGR Sequences When Using Hyperpolarized Carbon-13

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Introduction: Pulse sequence design for the imaging of hyperpolarized nuclei is extremely important because of the short time span available to image due to the rapid decay to thermal equilibrium of hyperpolarized nuclei. Spoiled gradient echo sequences (SPGR) have been used for ^{13}C spectroscopic imaging [1] because of their relative simplicity, robustness, and multi-spectral performance. However, because the remaining magnetization is spoiled at the end of each TR, the sequence is relatively inefficient when considering the total signal generated from the available magnetization. Because of this, balanced steady state free precession (bSSFP) [2, 3] and spin echo (SE) [4] sequences have been used in order to preserve the available transverse magnetization past a single TR as in bSSFP, or to preserve the transverse magnetization with spin echoes in order to utilize long T_2 times for SE sequences. It should be noted that with the exception of Svensson's work, all other works referenced here solely use a 180° RF pulse, in which case the bSSFP sequence becomes very similar to a fast spin echo sequence, with the exception of RF phase and initial flipdown timings [5], and therefore does not suffer from typical bSSFP banding. Henceforth low flip angle <180° bSSFP will be termed bSSFP, and high flip angle (180°) bSSFP will be termed 180° bSSFP to distinguish the two. This work studies the signal properties of SPGR, bSSFP, and SE sequences in order to determine the conditions in which each sequence would best be utilized. It is assumed that for the bSSFP and SE sequences, a flipback is performed [2].

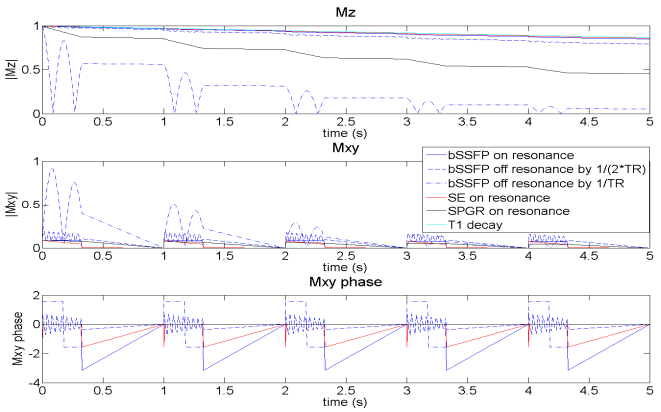

Figure 1: Multi-frequency bSSFP and on-resonance SE and SPGR. For an on-resonance species, the bSSFP sequence supplies the best signal combined with a very low magnetization usage, however if the species is off-resonance, signal and phase fluctuations increase as the off-resonance increases. Note that off-resonance SE and SPGR are omitted for simplicity and their more consistent response.

Methods: All pulse sequences were simulated by using Bloch equations [6] to determine the magnetization utilization for the duration of a scan. All sequences have 34 RF pulses with a TR of 10 ms, each repeated every second which mimics a real carbon imaging experiment (**Fig. 1**). The T_1 and T_2 values were 35 s and 0.5 s respectively, which are close to previously reported values [1]. **Table 1** shows the RF excitation angles for each sequence. The base excitation angle (α) was 5 °. For both bSSFP and SE sequences, the modulation of α was done to increase the stability and to maximize the magnetization recovery of the flipback pulse. For the SE sequence, α_b was calculated with Eq. 1 where t is the time since the previous α pulse, and for the bSSFP sequence α_{sb} is calculated from Eq. 1 with t equal to TR. Eq. 1 simply calculates the shift in the magnetization angle due to T_1 and T_2 effects. The bSSFP sequence uses a similar calculation Eq. 2 to calculate the pseudo steady state (a true steady state is never achieved for hyperpolarized media) flip angle α_s, which removes fluctuations from the on-resonance frequency by accounting for the magnetization phase angle change due to T_1 and T_2 after the initial RF pulse.

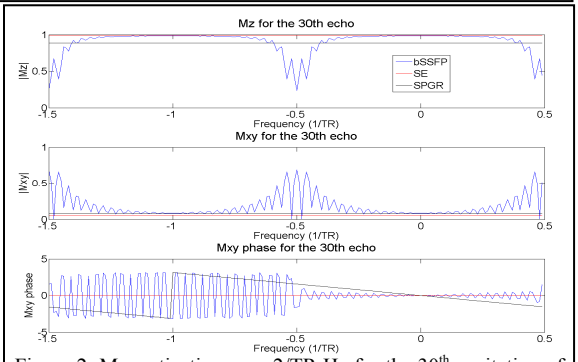

Figure 2: Magnetization over 2/TR Hz for the 30th excitation of the first set. Note that the absolute phase is of little importance, the change in phase is more important. The bSSFP phase alternates between 0 and π radians for successive passbands; one repetition of this cycle is shown here.

Results and Discussion: Fig. 1 shows the performance of the sequences for on and off resonance species. The on resonance bSSFP sequence has a very gradual net magnetization usage, on the order of normal T_1 decay. The SE sequence has very minimal magnetization decay compared to T_1, but the transverse magnetization decays at a rate of T_2, which results in more signal decay than either the on resonance bSSFP or SPGR sequences. The SPGR sequence has relatively consistent transverse magnetization, however due to the spoiled nature of the sequence, the longitudinal magnetization decays very quickly, leaving little for imaging after a relatively short imaging period. However, for off resonance species, bSSFP deteriorates significantly as the distance from the on resonance frequency increases. For non-hyperpolarized media, this is the manifestation of dark bands in the image at off resonance frequencies of π/2 relative to the center of the bSSFP pass band as shown at 0.5, -0.5, and -1.5 (1/TR Hz) in **Fig. 2**. These stopbands are the manifestation of spin saturation at the off resonance frequency. When imaging with hyperpolarized media, if these bands encroach on a resonance frequency, the signal will be quickly depolarized by the spin saturation. This depolarization can be avoided to some extent with short TR times, however this may not be an option for spectral imaging due to long TE demands for methods such as multi-echo spatial spectral encoding, or IDEAL [7]. Methods such as LCSSFP [8] or ATR-SSFP [9] could be used, however with 3 or more resonances, it becomes difficult to correctly select a center frequency which places all the resonances safely in passbands.

Sequence	1st RF	2nd to (N-1)th RF	Nth RF
SPGR	α	α	α
bSSFP	α	$\pm\alpha_s$	$-\alpha_{sb}$
SE	α	±180	$-\alpha_b$

Table 1: Flip angles for each RF pulse in the 34 RF pulse set for all sequences.

$$\beta = \alpha e^{t\left(\frac{1}{T_1}-\frac{1}{T_2}\right)} \quad (1)$$

$$\alpha_s = \alpha + \arctan\left(\tan(\alpha)e^{\left(TR\left(\frac{1}{T_1}-\frac{1}{T_2}\right)\right)}\right) \quad (2)$$

Conclusion: For multi-spectral imaging with 3 or more frequencies of interest, it becomes difficult to use a bSSFP sequence to its maximum effect due to the varying spectral Mxy and Mz response function. For this reason, low flip angle bSSFP sequences have been used with success for single resonance ^{13}C compounds [2], but not for ^{13}C pyruvate. However, the 180° bSSFP, as proposed by Svensson, which is similar to the SE discussed in this abstract, has been used in several studies of both ^{13}C pyruvate [3] and other compounds [2]. For double resonance applications such as pyruvate and pyruvate hydrate, a LCSSFP or FEMR type approach could be put to good use provided the peak locations and widths are well known before the beginning of the scan. Therefore, the most reliable and efficient sequence is the SE sequence, or the 180° bSSFP, both of which display none of the off resonance signal and phase modulations of the low flip angle bSSFP sequence. The SPGR sequence, while robust, provides low magnetization efficiency, and should be used in cases where the T_2 of the SE sequence is too low to make efficient use of the spin echo magnetization.

References: [1] Golman, K., et al., Magn Reson Med, 2008. **59**(5). [2] Svensson, J., et al., Magn Reson Med, 2003. **50**(2). [3] Leupold, J., et al., Magma, 2009. **22**(4). [4] Chen, A.P., et al., Magn Reson Med, 2007. **58**(6). [5] Le Roux, P., J Magn Reson, 2003. **163**(1). [6] Bloch, F., Physical Review, 1946. **70**(7-8). [7] Reeder, S.B., et al., Magn Reson Med, 2005. **54**(3). [8] Vasanawala, S.S., et al., Magn Reson Med, 2000. **43**(1). [9] Nayak, K.S., et al., Magn Reson Med, 2007. **58**(5).

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