Hyperpolarized Steady-State Free Precession with variable flip angles (bSSFP-VFA)

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Introduction: The most commonly used pulse sequence for imaging of hyperpolarized (HP) nuclei is the Spoiled Gradient Echo (SPGR) sequence, using either a small constant flip angle (CFA) or an increasing variable flip angle (VFA) [1]. The latter provides a constant transverse magnetization, which leads to a relatively high signal-to-noise ratio (SNR) compared to SPGR-CFA, and reduces image blurring due to *k*-space filtering. Another alternative is provided by balanced Steady State Free Precession (bSSFP) sequences, which are known to yield higher SNR than SPGR because they recycle transverse magnetization instead of spoiling it [2]. Typically, bSSFP is used with a constant flip angle; for ^{1}H imaging different varying flip angle schedules have been proposed with different goals, including modification of contrast [3], reduction of SAR [4] and minimization of *k*-space apodization [5]. All of these methods used either empirical estimation or complex numerical optimization to obtain the flip angle schedule. The present work derives iterative, analytical expressions for flip angle schedules for bSSFP-VFA of HP nuclei which maintain a constant transverse magnetization. Minimization of *k*-space apodization is demonstrated experimentally with HP ^{3}He.

Theory: Unlike SPGR-VFA [1], relaxation cannot be neglected in the treatment of bSSFP-VFA when determining the flip angle schedule, because coherence is retained between RF pulses. From the well-known matrix formulation of bSSFP (see e.g. [2]), the iterative expressions in Eqs. (1) and (2) can be derived by solving for the case of a constant transverse magnetization.

$$(1)\quad M_{z,n} = -E_1E_2M_y\sin\theta_n + E_1{}^2M_{z,n-1}\cos\theta_n$$

$$(2)\quad \theta_n = -\left[\arcsin\left(\frac{1}{E_2}\cdot\frac{M_y}{\sqrt{E_1{}^2M_{z,n-1}{}^2+E_2{}^2M_y{}^2}}\right)+\arcsin\left(E_2\cdot\frac{M_y}{\sqrt{E_1{}^2M_{z,n-1}{}^2+E_2{}^2M_y{}^2}}\right)\right]$$

Here, M_z and M_y are the longitudinal and transverse magnetization respectively, θ_n is the flip angle (about the x axis) at the n^{th} RF pulse, and E_1 and E_2 are the relaxation parameters exp($-TE/T_1$) and exp($-TE/T_2$) respectively, with $TE = TR/2$. Phase cycling by π is assumed, which manifests itself in the minus sign in Eq. (2). Eqs. (1) and (2) can thus be used to iteratively calculate flip angle schedules for bSSFP-VFA. The flip angle progression is fully determined by the magnetization components M_y and $M_{z,1}$ after an initial preparation phase, e.g. a linearly increasing flip angle series (ramp) [6] or a single θ/2-*TR*/2 start-up phase [7]. A larger transverse magnetization after the preparation phase leads to more signal, but an upper limit is imposed by the second term in Eq. (2), which starts to diverge for later RF pulses if M_y is chosen too large (see Results). In this case there is not enough longitudinal magnetization left to compensate for the loss in transverse magnetization by T_2 decay beyond a certain point because the sample has been depolarized.

Materials and Methods: Experiments were performed on a GE 1.5T HDx scanner (GE, Milwaukee), using a modified bSSFP (FIESTA) sequence. ^{3}He was hyperpolarized to ~12% using a Helispin polarizer (GE, Milwaukee). A 40 ml spherical phantom was filled with pure ^{3}He. A home-built ^{3}He birdcage coil of 15 cm diameter was used. Sequence parameters were FOV 48 cm, 10 cm slice, TE/TR = 1.8/3.6 ms, 128 × 128 matrix. Phase encode gradients were switched off to directly measure the imposed *k*-space filter in the phase encode direction. A single θ/2-*TR*/2 phase was used to catalyze the magnetization. Flip angle schedules were calculated from Eq. (1) and (2) with T_1 = 1200 s and T_2 = 0.1 s. The effective transverse relaxation time $T_{2,\text{eff}}$ = 19.3 ms was determined from the read gradient *b*-value, assuming a diffusion coefficient of $D = 2.0$ cm^{2}s^{-1} [2].

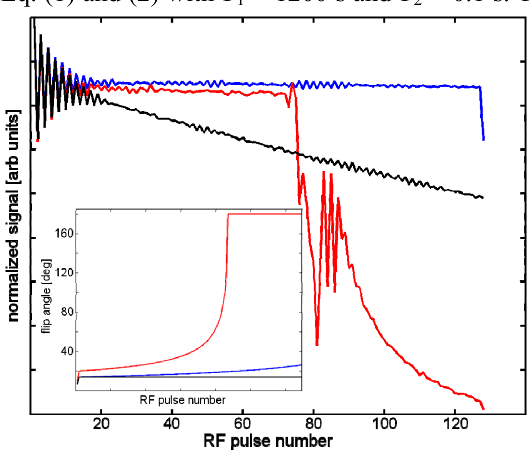

Figure 1: Measured signal for bSSFP-VFA with θ_1 = 7° (blue) and θ_1 = 10° (red), compared to bSSFP with constant flip angle 14° (black). Inset shows the flip angle schedules used.

Results and Discussion: The inset of Fig. 1 shows the flip angle schedules derived from Eq. (1) and (2) for startup flip angles θ_1 = 7° (blue) and θ_1 = 10° (red). The constant flip angle schedule for θ_1 = 7° (corresponding to a constant imaging flip angle of 14°) is shown in black. The measured *k*-space filters are shown in Fig. 1. The bSSFP-VFA curve with θ_1 = 7° (blue) represents the best *k*-space filter, yielding constant signal for the most part of the experiment. In comparison, the curve for constant flip angle SSFP (black) corresponds to an apodized *k*-space, leading to increased image blurring. The case of bSSFP-VFA with θ_1 = 10° (red) highlights what happens if the initial flip angle θ_1 is chosen too large. The loss in transverse magnetization cannot be compensated by higher flip angles for later RF pulses, as longitudinal magnetization runs out, resulting in an unacceptable signal drop for later RF pulses. All three curves exhibit initial oscillations due to residual off-resonance spins after the startup phase. These could potentially be reduced by employing an improved startup scheme. These results demonstrate the possibility of using flip angle schedules derived from Eq. (1) and (2) for minimizing k-space apodization and thus image blurring in bSSFP imaging of hyperpolarized nuclei.

References: [1] Zhao et al., J. Magn. Reson. B 113, 179-183 (1996) [2] Wild et al., J. Magn. Reson. 183, 13-24 (2006) [3] Paul et al., Magn. Reson. Med. 56, 82-93 (2006) [4] Paul and Zaitsev, Magn. Reson. Imag. 27, 933-941 (2009) [5] Smith et al., Proc. ISMRM 17, 2661 (2009) [6] Nishimura and Vasanawala, Proc. ISMRM 8, 301 (2000) [7] Deimling and Heid, Proc. SMR 2, 495 (1994)

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