Comparison between RF spoiling schemes in the Actual Flip-angle Imaging (AFI) sequence for fast B_1 mapping

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Introduction. Fast methods for B_1 measurements recently gained popularity due to the advent of high-field clinical and research scanners operating at 3T and higher field strengths. One of such methods, actual flip-angle imaging (AFI) (1) allows utilization of a short sequence repetition time and provides fast single-scan 3D acquisition of B_1 field maps. Incomplete spoiling in AFI was recently identified as a cause of B_1 measurement errors, and the combination of diffusion-based gradient and RF spoiling mechanisms was shown to considerably improve accuracy of this method (2,3). Two RF spoiling techniques were proposed for AFI: the standard scheme where the RF phase φ_j is incremented between cycles of the sequence with a constant value of the phase increment φ_0: $\varphi_j = \varphi_{j-1}+(j-1)\varphi_0$ (1,2), similar to a regular RF spoiled gradient echo sequence (4); and the modified scheme (3) where a new value of the phase increment φ_n depends on the ratio n=TR$_2$/TR$_1$, $\varphi_n=\varphi_0(n+1)/2$, and two phase increments, φ_n and $n\varphi_n$, are intermittently applied after delays TR$_1$ and TR$_2$ instead of φ_0. The purpose of this study was to compare the spoiling behavior of the AFI sequence and accuracy of B_1 measurements between the above RF spoiling schemes.

Methods. ***Experiments.*** Measurements were conducted on a 3T Philips Achieva whole-body scanner using a phantom with T_1/T_2=784/662 ms and diffusion coefficient D=2.2x10^{-3} mm^2/s (0.2 mM Gd-DTPA solution). Dependences of signals S_1 and S_2 generated by the AFI sequence and actual flip angle α (α=arccos[(rn-1)/(n-r)], where n=TR$_2$/TR$_1$ and r=S_2/S_1) on the phase increment φ_0 were recorded in a range 0-180º for various spoiling gradient areas A_{G1} and A_{G2} applied on TR$_1$ and TR$_2$.

Simulations. Simulations were performed using a combined isochromat summation and diffusion propagator model (2,5), where a distribution of isochromats after each RF pulse is convolved with the propagator of the Bloch-Torrey equation. Evolution of a single isochromat with the spatially dependent phase ψ_l on jth TR interval is described as follows:

$$\mathbf{m}^-_{j+1}(\psi_l) = \sum_{q=l-N}^{l+N} P^{[1,2]}(\psi_l - \psi_q)\mathbf{E}^{[1,2]}(\psi_l + \psi_q)\mathbf{m}^+_j(\psi_q) + (1-E_1^{[1,2]})\mathbf{m}_0,$$

where the summation is performed over N isochromats, the upper signs "-" and "+" indicate states before and after an RF pulse, the upper indexes [1,2] denote delays TR$_1$ and TR$_2$ with corresponding spoiler gradient areas A_{G1} and A_{G2}, the Gaussian probability of diffusion for a pair of isochromats is calculated as

$$P^{[1,2]}(\psi_l - \psi_q) = 2\pi N^{-1}(4\pi D\mathrm{TR}_{1,2})^{-1/2}(\gamma A_{G1,2})^{-1}\exp(-(\psi_l - \psi_q)^2 \big/ 4D\mathrm{TR}_{1,2}\gamma^2 A^2_{G1,2}),$$

where D is the diffusion coefficient, and the combined evolution matrix is given by

$$\mathbf{E}^{[1,2]}(\psi_l + \psi_q) = \begin{bmatrix} E_D^{[1,2]}E_2^{[1,2]}\cos((\psi_l+\psi_q)/2) & E_D^{[1,2]}E_2^{[1,2]}\sin((\psi_l+\psi_q)/2) & 0 \\ -E_D^{[1,2]}E_2^{[1,2]}\sin((\psi_l+\psi_q)/2) & E_D^{[1,2]}E_2^{[1,2]}\cos((\psi_l+\psi_q)/2) & 0 \\ 0 & 0 & E_1^{[1,2]} \end{bmatrix},$$

where $E_{1,2}^{[1,2]}$=exp(-TR$_{1,2}$/$T_{1,2}$) are the relaxation terms, and $E_D^{[1,2]}$=exp(-1/12$\gamma^2 A_{G1,2}^2 t_{G1,2} D$) are the diffusion terms for delays TR$_1$ and TR$_2$ with corresponding spoiler gradient durations t_{G1} and t_{G2}. RF pulses are described by the standard rotation matrix defined by the phase calculated for a particular incrementing scheme (2,3) and flip angle. The computational procedure is iterated until the total magnetization (vector sum of isochromats) achieves the steady state.

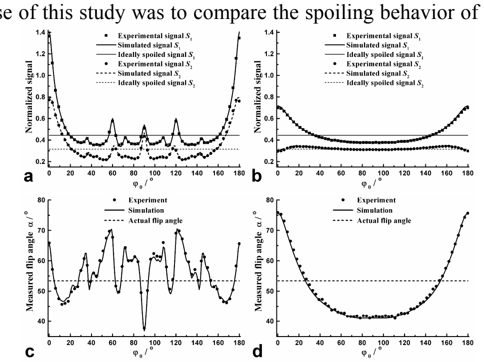

Fig. 1. Spoiling behavior of the AFI signals S_1 and S_2 (**a,b**) and measured flip angle (**c,d**) in the weak (**a,c:** A_{G1}/A_{G2}=11.7/55 mT·ms/m) and strong (**b,d:** A_{G1}/A_{G2}=110.8/552.7 mT·ms/m) spoiling regimes. Sequence parameters: TR$_1$/TR$_2$=10/50 ms, actual α=58.8° (independently measured). Experimental data (points) are superimposed with simulations (lines).

Results. Accuracy of simulations was confirmed by comparison with experimental data (Fig. 1). In agreement with previous reports (2,3), weak and strong spoiling regimes were observed depending on the gradient areas (Fig. 1). Simulations comparing the spoiling behavior of both schemes are presented in Figs. 2 and 3. The general distinction between the schemes is that the modified scheme has the periodicity of 360°/(n+1) (for example, 60° period if n=5, Figs. 2 and 3a,b), whereas the period for the standard scheme is 180° regardless of n. Another distinction is that in the weak spoiling regime at certain φ_0 values the signal S_2 exceeds the signal S_1 for the modified scheme (Fig. 2b). This translates into multiple discontinuities of the measured flip angle (Fig. 3a), since the argument of the arccosine function in the flip angle calculation formula (α=arccos[(rn-1)/(n-r)]) becomes >1. In the strong spoiling regime, an almost similar range of spoiling-related variations of signals (Figs. 2c,d) and measured flip angles (Figs. 3b-d) can be achieved for both schemes at different n, if the total spoiling gradient area (A_{G1}+A_{G2}) is maintained constant across the sequence repetition period (TR$_1$+TR$_2$). Correspondingly, both schemes enable identical B_1 measurement accuracy, though each scheme requires its own optimal φ_0, as seen in Fig. 3. Periodic properties of the modified scheme should be taken into account, if the AFI sequence is applied with different n (Fig. 3). The spoiling profiles for the standard scheme are very similar at different n, though they are not completely identical, and optimal φ_0 may slightly vary (in ranges ~32-38° and 148-142°). This translates into very minor (<2%) potential variability of measured flip angles, if φ_0 found for a specific n is applied to a protocol with different n. Accordingly, a single φ_0 value (e.g. 36° as suggested previously (2)) can be used for the standard scheme regardless of n in combination with sufficiently strong spoiling gradients. However, in the modified scheme (3), optimal φ_0 is specifically determined by n. Based on periodicity properties, a simple rule can be suggested to recalculate an optimal φ_0 found for the standard scheme into the modified scheme:

$$\varphi_0^{\mathrm{mod}} = 2\varphi_0^{\mathrm{stand}}/(n+1),$$

where $\varphi_0^{\mathrm{stand}}$ and φ_0^{mod} are the optimal phase increments for the standard and modified schemes, respectively, defined on the first half-period of a spoiling profile (0°-90° for the standard or 0°-180°/(n+1) for the modified scheme).

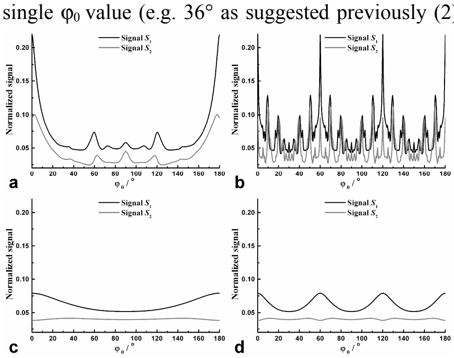

Fig. 2. Simulated dependences of signals S_1 (black) and S_2 (gray) on the phase increment φ_0 for the standard (1,2) (**a,c**) and modified (3) (**b,d**) RF phase incrementing schemes in the weak (**a,b**) and strong (**c,d**) spoiling regimes (A_{G1}/A_{G2}=17/85 and 170/850 mT·ms/m, respectively). Other simulation parameters were T_1/T_2=2000/2000 ms, D=2.2x10^{-3} mm^2/s, TR$_1$/TR$_2$=20/100 ms (n=5), and α=60°.

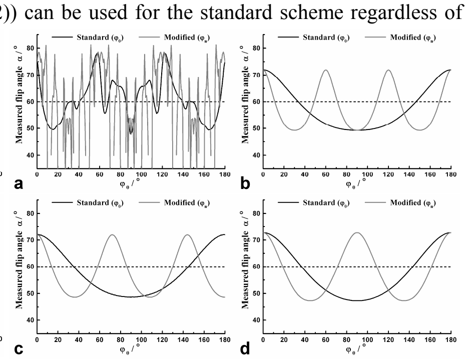

Fig. 3. Simulated dependences of the measured flip angle on φ_0 in the weak (**a**) and strong (**b-d**) spoiling regimes for n=5 (**a,b:** parameters from **Fig. 2**); n=4 (**c:** TR$_1$/TR$_2$=20/80 ms, A_{G1}/A_{G2}= 204/816 mT·ms/m); and n=3 (**d:** TR$_1$/TR$_2$=20/60 ms, A_{G1}/A_{G2}=255/765 mT·ms/m). Black and gray lines correspond to the standard (1,2) and modified (3) RF spoiling schemes. For plots (**b-d**), the constant spoiler area is maintained through the AFI repetition period, A_{G1}+A_{G2}=1020 mT·ms/m.

Discussion and Conclusions. Strong spoiling regime is required for accurate B_1 measurements using the AFI method with both RF phase incrementing schemes. Optimal φ_0 values in the AFI sequence are specific for the implemented RF phase incrementing scheme. While both the standard (1,2) and modified (3) schemes can provide equivalent accuracy in the strong spoiling regime, the modified scheme requires readjustment of optimal φ_0 depending on the actual n=TR$_2$/TR$_1$ value.

References: (1) Yarnykh VL. MRM 2007;57:192. (2) Yarnykh VL. ISMRM'08, p.3090. (3) Nehrke K. MRM 2009;61:84. (4) Zur Y, et al. MRM 1991;21:251. (5) Yarnykh VL. ISMRM'08, p.234.