Optimal spoiling of the transverse magnetization in the Actual Flip-angle Imaging (AFI) sequence for fast B_1 field 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. The theoretical description of the AFI method (1) is based on the ideal spoiling approximation, and therefore does not take into account the possibility of errors caused by transverse interference. The purposes of this study were to optimize conditions required for sufficient spoiling of the transverse magnetization in the AFI sequence and to describe possible errors in B_1 measurements caused by incomplete spoiling.

Methods. ***Pulse sequence.*** The AFI sequence (Fig. 1) acquires two signals, S_1 and S_2, which allow calculation of the actual flip angle from their ratio $r=S_2/S_1$: $\alpha=\arccos[(rn-1)/(n-r)]$. Typically, AFI is used with TR_1=10-30 ms, the factor $n=TR_2/TR_1$=4-6, and the nominal flip angle 50-70° (1). The phase of RF pulses is progressively incremented with the increment value φ_0, similar to a spoiled gradient echo sequence (2). The spoiling gradients are applied during delays TR_1 and TR_2 with areas proportional to delay durations. The last condition makes uniform any phase evolution, independent of the cause (external gradient or B_0 non-uniformity). In the considered design, spoilers are simultaneously applied along slice-select and readout directions with on-axis areas A_{G1} and A_{G2}.

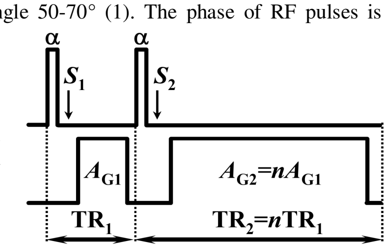

Fig. 1. Diagram of the AFI sequence with RF pulses and spoiler gradients shown.

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 $D=2.2\times10^{-3}$ mm^2/s (0.2 mM Gd-DTPA solution). Dependences of S_1, S_2, and measured α on the phase increment φ_0 were recorded in a range 0-180º with the step 3º for various TR_1/TR_2 and A_{G1}/A_{G2}.

Simulations. Simulations were performed using a combined isochromat summation and diffusion propagator model (3,4). To describe magnetization evolution during delays TR_1 and TR_2, a distribution of isochromats after each RF pulse is multiplied by relaxation terms and convolved with the propagator of the Bloch-Torrey equation, which can be written for a pair of isochromats with spatially dependent phases ψ_j and ψ_k as follows:

$$P_{jk} = (4\pi Dt_D)^{-1/2}(\gamma A_G)^{-1}\exp[-(\psi_j-\psi_k)^2\big/(4Dt_D\gamma^2A_G^2)+i(1/2)(\psi_j+\psi_k)-(1/12)\gamma^2A_G^2t_GD)] \quad , \quad [1]$$

where $t_D=TR_1$ or TR_2 and t_G is the time when a gradient is turned on. The propagator [1] describes the Gaussian probability of magnetization exchange between isochromats caused by diffusion assuming the free diffusion case (first term), average phase shift in the gradient field (second term), and irreversible signal loss due to diffusion in the presence of the gradient (third term). RF pulses are described by the standard rotation matrix dependent on α and φ_0. Similar to the traditional isochromat summation technique, the computational procedure is iterated until the total magnetization (vector sum of isochromats) achieves the steady state. The algorithm was implemented in a custom-written C program.

Results. ***Spoiling behavior of the AFI sequence.*** The spoiling behavior of AFI is different from that of a regular gradient echo sequence (2). Particularly, the spoiling dependence on the phase increment is symmetric relative to 90°, whereas for the gradient echo sequence such symmetry occurs relative to the 180º point (2). Depending on the gradient areas and TRs, the spoiling patterns of the AFI sequence can be classified into two regimes: weak spoiling and strong spoiling. The examples are shown in Fig. 2. In the weak spoiling regime (Fig. 2a), signals S_1 and S_2 have multi-peak dependence on the phase increment, and flip angle measurements also have a complex dependence on φ_0. Although optimal spoiling (i.e. correct B_1 measurement) is possible at multiple φ_0, the dependences are steep and their shape is subjected to rapid changes when the flip angle, gradient areas, or the diffusion coefficient are varied. If sufficiently large spoiling gradients are used, the strong spoiling regime (Fig. 2b) occurs, where the dependence of the measured flip angle on φ_0 has a smooth shape with the single minimum at 90°. There are two optimal φ_0 values producing correct measurements. They are positioned in ranges 20-40° and 140-160° and can be precisely determined from plots similar to that shown in Fig. 2b. Excellent agreement between experiments and simulations (Fig.2) allows using the described theoretical model for sequence optimization.

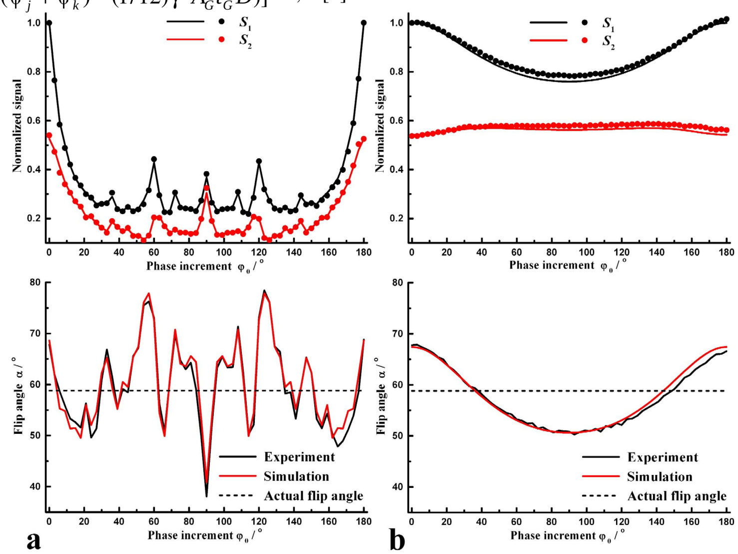

Fig. 2. Spoiling behavior of the AFI sequence in the weak (**a:** TR_1/TR_2=10/50 ms, A_{G1}/A_{G2}=16.7/82.6 mT*ms/m) and strong (**b:** TR_1/TR_2=15/75 ms, A_{G1}/A_{G2}=163/827 mT*ms/m) spoiling regimes. The independently measured actual α=58.8°. **Top:** Experimental signal measurements (points) are superimposed with simulations (lines). **Bottom:** Experimentally determined flip angles (black lines) are superimposed with simulations (red lines).

Optimization of B_1 measurement accuracy. Theoretically, for any gradient configuration, the exact optimal φ_0 depends on the actual flip angle. However, such dependencies are smooth in the strong spoiling regime, and an appropriate φ_0 value can be determined for a particular gradient configuration and timing to maximize the accuracy of B_1 measurements within a specified range of B_1 non-uniformities. Fig. 3 shows simulated relative B_1 measurement errors for the three parameter settings of the AFI sequence assuming that the relaxation and diffusion properties of the object are similar to the brain white matter. Note that T_1 and T_2 do not affect the accuracy of measurements in the strong spoiling regime, but the D value is important. For slower diffusion (low D), the spoiling effect is weaker. For in vivo applications, the tissue with the lowest D should be used for sequence optimization (e.g. white matter in the brain). The combinations of gradient areas and TRs shown in Fig. 3 are easy to achieve on most clinical MR scanners permitting 20-25 mT/m gradient strength. With A_{G1}/A_{G2}>200/1000 mT*ms/m and φ_0=33-36°, highly non-uniform B_1 distributions (~50% B_1 variations) can be mapped with relative errors <2%.

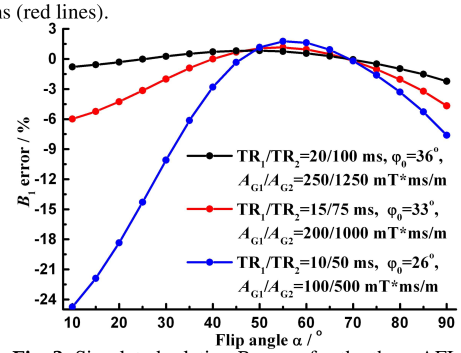

Fig. 3. Simulated relative B_1 error for the three AFI timing and gradient combinations with their corresponding optimal φ_0 in the strong spoiling regime. T_1/T_2=700/80 ms and $D=0.8\times10^{-3}$ mm^2/s.

Discussion and Conclusions. The strong spoiling regime is preferable for B_1 measurements using the AFI method. Accurate B_1 measurements require the use of sufficiently high spoiling gradients and an optimal value of the RF phase increment. A reduced accuracy may limit AFI applications with ultra-short TR_1<10 ms, since the available hardware may not allow sufficient gradient strength to reach the strong spoiling regime. For TR_1=15-25 ms, optimal spoiling conditions are easily achievable on most commercial MR scanners.

References: (1) Yarnykh VL. MRM 2007;57:192. (2) Zur Y, et al. *MRM* 1991; 21:251. (3) Gudbjartsson H, Patz S. MRM 1995;34:567. (4) Kiselev VG. JMR 2003; 164:205.