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 $r=S_2/S_1; \alpha=\arccos[(r-1)/(r+1)]$. Typically, AFI is used with $TR_1=10-30$ ms, the factor $n=TR_1/TR_2=4-6$, and the nominal flip angle 50-70° (1). The phase of RF pulses is progressively incremented with the increment value $\alpha$, 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, spoiled RF pulses 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.

Measurements. 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 $\alpha$ on the phase increment $\phi_0$ were recorded in a range 0-180° with the step 3° 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 $\psi_s$ and $\psi_w$ as follows:

$$P_n = \exp[-(\psi_s - \psi_w)^2/4D\Delta_t^2 + i(1/2)(\psi_s + \psi_w) - (1/12)(\psi_s^3 + \psi_w^3)].$$

where $\Delta_t=TR_1$ or $TR_2$ and $\psi_0$ is the time when a gradient is turned on. The propagator [1] describes the Gaussian probability of magnetization exchange between isochromat pairs 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 $\alpha$ and $\phi_0$. 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.

Fig. 2. Simulating behavior of the AFI sequence in the weak (a) $TR_1/TR_2=15/75$ ms, $A_{G1}/A_{G2}=16/82.6$ mm$^2$/ms (strong) and (b) $TR_1/TR_2=15/75$ ms, $A_{G1}/A_{G2}=163/827$ mm$^2$/ms (strong) spoiled regimes. The independently measured actual $\alpha=58.8^\circ$. Top: Experimental signal measurements (points) are superimposed with simulations (lines). Bottom: Experimentally determined flip angles (black lines) are superimposed with simulations (red lines).

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°. Depending on the gradient echo sequence such symmetry occurs relative to the 180° point (2). The projection of the phase increment $\phi_0$ is opposite to the actual flip angle. However, such dependencies are smooth in a range of values and can be precisely determined from plots similar to those shown in Fig. 2b. Excellent agreement between experiments and simulations (Fig. 2) allows using the described theoretical model for sequence optimization.

Optimization of $B_1$ measurement accuracy. Theoretically, for any gradient configuration, the exact optimal $\phi_0$ depends on the actual flip angle. However, such dependencies are smooth in the strong spoiling regime, and an appropriate $\phi_0$ 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 consistency between 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 $A_{G1}/A_{G2}=200/1000$ mm$^2$/ms and $\phi_0=33-36^\circ$, highly non-uniform $B_1$ distributions ($\leq 50\%$ $B_1$ variations) can be mapped with relative errors $<2\%$.

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 high signal spoiling gradients and an optimal value of the RF phase increment. A reduced accuracy may limit AFI applications with ultra-short TR<10 ms, since the available hardware may not be used for sequence optimization (e.g. white matter in the brain). The optimal spoiling conditions are easily achievable on most commercial MR scanners.