The Steady State Properties of Actual Flip Angle Imaging (AFI)

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Introduction

Recently, a fast B_1 mapping technique dubbed AFI (actual flip angle imaging, [1]) has been introduced, potentially allowing the in-vivo acquisition of 3D flip angle maps. This approach assumes that all transverse coherencies are completely spoiled for the two interleaved gradient echoes of the specific non-equidistant pulse sequence. Therefore, conventional RF spoiling as introduced for equidistant pulse sequences [2] was applied.

In the present work, it is shown that such a spoiling scheme may prevent the AFI sequence from reaching a proper steady state. Moreover, an adapted RF and gradient spoiling regime is derived and its improved steady-state properties are experimentally validated.

Methods

Theory:

The AFI sequence may be regarded as a conventional spoiled gradient echo sequence, where an additional time delay ΔT is inserted every second *TR*, resulting in effective repetition times TR_1 and $TR_2 \geq TR_1$, respectively (Fig.1, top). However, an equivalent representation as an equidistant gradient echo sequence consisting of real and dummy RF pulses is possible (Fig.1, bottom), if two conditions are satisfied: firstly, the intervals TR_1 and TR_2 have to be commensurate (i.e. their ratio is rational), which does not present a practical limitation. Secondly, the ratio of the gradient areas has to be adjusted according to Eq.1 to allow a concerted impact of unbalanced gradients and static field inhomogeneities on the phase evolution of the sequence. Then, it is evident that the RF phase cycling scheme derived for equidistant pulse sequences (Eq. 2) has to be applied to each real or dummy RF pulse. For the original AFI sequence, this corresponds to a phase cycling scheme according to Eqs. 3a,b, which preserves the quadratic increase of the spoil phase over time. Please note that even and odd *k's* refer to RF pulses immediately before and after the short TR interval, respectively. In contrast, direct application of Eq. 2 on the AFI sequence will result in a violation of the steady-state condition given in [2].

$$\mathbf{k}_2 = \mathbf{k}_1(TR_2/TR_1) \quad , \quad \mathbf{k}_1 = \gamma\int_0^{TR_1}\mathbf{G}(t)dt \qquad [1]$$

$$\varphi_k - \varphi_{k-1} = k\varphi \qquad [2]$$

$$\varphi_k - \varphi_{k-1} = k\varphi \ \text{ for even k} \qquad [3a]$$

$$\varphi_k - \varphi_{k-1} = \mathrm{TR}_1/\mathrm{TR}_2 \cdot k\varphi \ \text{ for odd k} \qquad [3b]$$

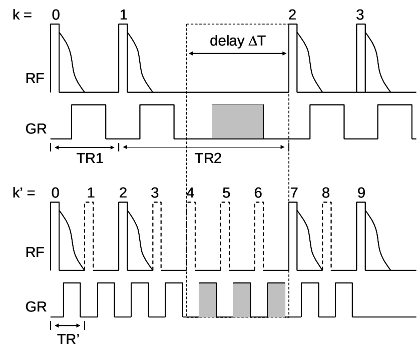

FIG. 1: Timing diagram of the AFI sequence. Two equivalent representations are shown (top: non-equidistant pulse sequence, bottom: equidistant pulse sequence). The dashed bars represent dummy pulses with zero flip angle. The gray-shaded areas indicate the adjusted gradients according to Eq. [1]. For this particular example, a ratio TR2/TR1=5/2 was chosen.

Experiments:

Phantom experiments have been performed on a clinical 1.5 T MR scanner (Philips Medical Systems, Best, The Netherlands). The AFI sequence was used to acquire 2D images of a spherical water phantom (128×128×1 scan matrix, 256×256×20 mm³ FOV, flip angle α=60°, spoil phase shift increment φ=120°, TR_1=10 ms, TR_2=20 ms). For comparison, experiments with conventional (cf. Eq.2) and with adapted phase cycling schemes (cf. Eqs.3a,b) were performed. To study the impact of the spoiler gradient adjustment (Eq. 1), additional experiments (128×128×1 scan matrix, 256×256×20 mm³ FOV, flip angle α=60°, spoil phase shift increment φ=120°, TR_1=10 ms, TR_2=50 ms) were performed with equal gradients in the two intervals TR_1 and TR_2 for deliberate violation of Eq. 1.

Results

Fig. 2 shows selected AFI images acquired with the two investigated spoiling schemes. The conventional phase cycling scheme resulted in strong ghosting artifacts, while proper images were observed for the adapted scheme. In Fig. 3, the influence of the spoiler gradient adjustment is shown for selected AFI images. Without adjustment, banding artifacts related to off-resonance are observed as a result of the asynchronous phase evolution. These artifacts disappear in the presence of properly adjusted gradients according to Eq. 1. These results are in accordance with the results of the theory section.

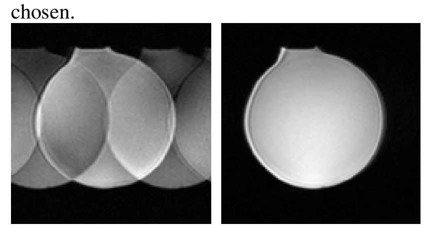

FIG. 2: **Steady State Formation**. AFI images acquired with conventional (left) and adapted phase cycling scheme (right), respectively. The latter improves the steady state formation of the sequence.

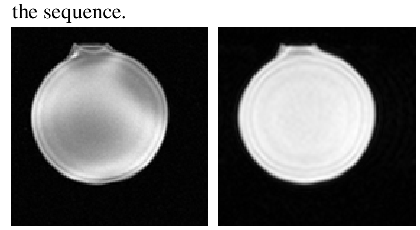

FIG. 3: **Off resonance sensitivity**. AFI images acquired without (left) and with (right) spoiler gradient adjustment. The latter improves the off-resonance robustness of the sequence.

Discussion

The AFI approach estimates the actual flip angle from the ratio of the signals acquired in the intervals TR_1 and TR_2, respectively. Hence, image artifacts will have adverse impact on the accuracy of the approach. Therefore, the improved spoiling regime presented in this work will potentially increase the robustness of the technique. However, the improved spoiling regime will solely ensure the formation of a proper state, but by no means guarantee complete spoiling. This may be achieved by optimizing the spoil phase shift increment ϕ and the diffusion sensitivity resulting from the spoiler gradients.

References

1. Yarnykh VL. Magn Reson Med. 2007 Jan;57(1):192-200.
2. Zur Y, Wood ML, Neuringer J. Magn Reson Med 1991;21:251–263.