B1-Mapping with the Transient Phase of SSFP

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Introduction: The ability to perform fast and accurate B1-mapping is a relevant precondition in various situations, such as quantitative imaging (e.g. T1-mapping) or RF-pulse design (e.g. high-field imaging, parallel transmission). Current methods rely on steady-state properties and utilize either the signal magnitude (based on alternating TR (AFI), variable flip angles, stimulated echoes, etc.) or phase (2α–α excitation, adiabatic pulses, Bloch-Siegert shift, etc.). All of these techniques have their specific pros and cons, the latter of which comprise accuracy problems (e.g. dependence on T1, T2, B0 or a limited B1 range) and methodological restrictions (long acquisition times, high SAR, etc.). Consequently, the choice of the proper method usually depends on specific requirements or simply accessibility.
It is well known that the transient phase of rapid SSFP sequences, i.e. the decay toward the dynamical equilibrium from some initial state, typically consists of a smooth decay and a superimposed damped oscillation. Recent theoretical studies (1) for the FID signal of unbalanced SSFP (FISP, FFE, GRASS, etc.) showed that the frequency of the latter is closely connected to the actual flip angle α and depends only weakly on tissue parameters. In this work, we show that fast and accurate B1-mapping, based on a frequency analysis of the transient phase of SSFP, can be implemented in a conceptually simple and flexible manner.

Theory: From RF-pulse to RF-pulse, the damped complex oscillatory component of the deviation from steady-state is observed to rotate with some constant phase Ω in the yz-plane, cf. Fig. 1 (magnitude signal). Theoretically, this can be explained with a pole singularity of the z-transform of the transient phase (1). For short TR, i.e. $\delta = TR/T2 << 1$, it can be shown that - up to corrections of order $O(\delta^2)$ - the phase Ω and the flip angle α are essentially equivalent:

$$\alpha \approx \Omega \qquad [1]$$

Measurement of Ω thus yields an estimate for α.

Methods: Based on an implementation of the configuration model, simulated transient phase data were calculated in Matlab 7.10 (The Mathworks, Inc., Natick, MA), allowing for freely adjustable noise corruption. For sufficient repetitive deviation from steady-state in the dynamical 3D MRI measurements (Achieva 1.5T, Best, The Netherlands), synthetic triggers were applied to alternate trains of SSFP blocks (CINE phases) with idle periods (standard product sequence). Data were exported for offline post-processing. The matrix-pencil method (2) was used to extract the phase Ω from the recorded data (simulated and measured).

Results: Fig. 1 shows the simulated oscillatory decay toward dynamic equilibrium for $\alpha = 40°$, with a period of $2\pi/\Omega \approx 9$ TR cycles, in accordance with Eq. [1]. The overall bias without noise, exemplarily shown in Fig. 2, remains small (< 1% in this example) for all relevant combinations of T1 and T2. Initial irregularities, caused by a subtle delayed response effect (1), can be avoided by adding a small number of dummy cycles, as done in Fig. 2. The overall bias can be further reduced considerably by extending the duration of the idle (= recovery) period, which also improves SNR. Fig. 3 shows an *in vivo* example of an effective flip angle measurement (not optimized for speed yet).

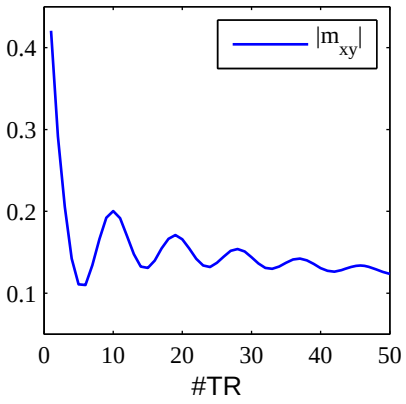

Fig. 1: The approach toward dynamic equilibrium is associated with superimposed oscillations. Shown is the simulated magnitude over 50 TR cycles (T1/T2/TR = 150/15/1, $\alpha = 40°$), with intermittent idle periods of duration 100.

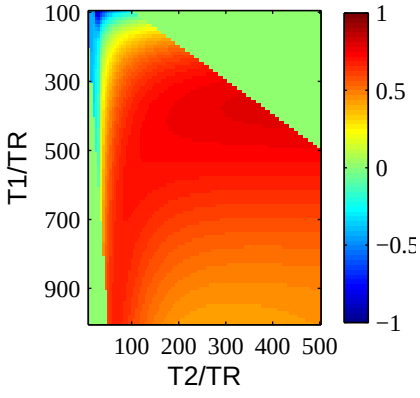

Fig. 2: The relative difference (in percent) between α and the numerically determined Ω, for $0.05 < T2/T1 < 1$ (simulated, without noise). Sequence parameters as in Fig. 1. The first 3 echoes were excluded from the calculation of Ω (see text).

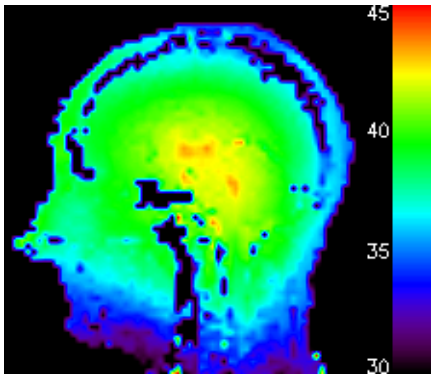

Fig. 3: Effective flip angle in a sagittal plane of a volunteers head. Parameters of the 3D measurement were: $\alpha = 40°$, TR = 2.35 ms, 64 echoes (first 5 excluded), resolution = 4mm (isotropic), trigger interval = 1 sec. As expected, the tissue dependence is negligible.

Discussion and Conclusion: For TR << T2, the transient phase of unbalanced SSFP can be used for rapid and accurate B1-mapping. Only little dependence on tissue parameters is observed and - as long as the oscillations remain sufficiently observable - a good robustness against noise (simulation results, not shown). The spoiler gradients, inherent in unbalanced SSFP, have the same effect as for the steady-state: Sensitivity to rapid motion (e.g. signal loss in pulsatile liquor), insensitivity to B0 inhomogeneities.
In summary, B1-mapping with transient phase SSFP seems to be a promising alternative to steady-state techniques, particularly with respect to robustness, accuracy and ease of implementation.

References: (1) Ganter C., MRM 2009; 62:149, (2) Lin YY et. al., JMR 1997; 128:30