An RF Spoil Regime for Steady-State DREAM B_1^+ Mapping

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Introduction

In high field MRI, fast and robust in vivo B_1^+ mapping is an essential prerequisite for many quantitative or parallel-transmit-based applications (1-3). However, most B_1^+ mapping techniques are too slow for seamless integration into the clinical workflow. Recently, the DREAM (Dual Refocusing Echo Acquisition Mode) B_1^+ mapping approach has been introduced (4), allowing a 2D B_1^+ map to be acquired in only a short fraction of a second. Since STEAM preparation pulses are used for B_1^+ encoding, the sequence has to start from thermal equilibrium to guarantee the accuracy of the method. However, for applications such as parallel transmit coil sensitivity mapping (5) or motion-resolved B_1^+ mapping (6), a frequent re-acquisition of data from the same location may result in a steady-state formation, potentially degrading the accuracy of the method. In the present work, an efficient RF spoiling scheme is theoretically deduced for the DREAM sequence and investigated in simulations and phantom experiments.

Theory

The DREAM approach employs a STEAM magnetization preparation sequence consisting of two RF pulses of equal shape and flip angle α, followed by a low-angle imaging train, where both, the STE and the FID signals, are measured quasi-simultaneously as gradient-recalled echoes (Fig.1). Starting from thermal equilibrium M_0, the unknown flip angle α of the STEAM pulses is given by the ratio of the measured STE and FID signal magnitudes according to Eq.1. However, in case of a periodic repetition of the sequence, the two longitudinal magnetization components relevant for B_1^+ encoding are affected by previous shots, which can be described by a recurrence equation (Eq.2). Note that all transverse coherence pathways between successive shots have been neglected, assuming a T_2 much shorter than the shot interval T_i, which greatly simplifies the problem. Linear incrementation of the phase shift between the two RF pulses of the STEAM sequence according to Eq.[3] makes the matrix **R** independent of the index *n*, thus allowing the formation of a steady-state, which is in close analogy to RF spoiling for gradient echo sequences (7). Note that the steady-state may be described by an analytical formula (Eq.[4]) within the scope of the simple model. Thus, the accuracy of the flip angle estimation, which is potentially biased by the steady-state, may be trimmed by adjusting the value of the phase shift increment ϕ_0.

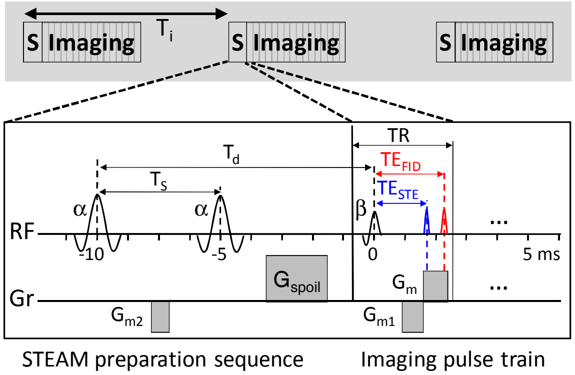

FIG. 1. **DREAM pulse sequence scheme,** here used as dynamic sequence with shot repetition time T_i. In the upper row, S denotes the STEAM preparation followed by the imaging readout.

$$\alpha = \arctan\sqrt{2M_{z,STE}/M_{z,FID}} = \arctan\sqrt{2I_{STE}/I_{FID}} \qquad [1]$$

$$\text{recurrence equation:} \quad \mathbf{M}_{n+1} = \mathbf{R}_{n+1}\left(E_1\mathbf{M}_n + (1-E_1)\mathbf{M}_0\right) \qquad [2]$$

$$\text{with} \quad \mathbf{M}_n = \begin{pmatrix} M_{z,STE} \\ M_{z,FID} \end{pmatrix}, \ \mathbf{M}_0 = \begin{pmatrix} 0 \\ M_0 \end{pmatrix}, \mathbf{R}_n = \begin{pmatrix} f_n\cos^2(\alpha) & -\sin^2(\alpha)/2 \\ -\mathrm{Re}(f_n)\sin^2(\alpha) & \cos^2(\alpha) \end{pmatrix},$$

$$E_1 = \exp(-\mathrm{T_i}/\mathrm{T_1}) \quad \text{and} \quad f_n = \exp\left(i\left(\Delta\phi_{n+1} - \Delta\phi_n\right)\right)$$

$$\text{linear phase shift increment:} \quad \Delta\phi_n = n\cdot\phi_0 \qquad [3]$$

$$\text{steady state:} \quad \mathbf{M}_{n\to\infty} = \mathbf{M} = (1-E_1)\left(\mathbf{R}^{-1} - E_1\mathbf{I}\right)^{-1}\mathbf{M}_0 \qquad [4]$$

Methods

Simulations based on Eqs.[1-4] have been performed, calculating the predicted flip angle as a function of the actual flip angle for different T_1 relaxation times, shot intervals and phase shift increments. In addition, experiments were performed on a clinical 3T MRI system (Achieva, Philips Healthcare, Best, The Netherlands) using a tap water phantom ($T_1 \approx 3$s). DREAM B_1^+ maps were acquired in 2D acquisition (slice width = 20 mm, FOV = 360×210mm², scan matrix = 96×58, imaging flip angle β = 10°, TR = 3.1ms, total scan duration = 0.2s). To achieve a steady-state, the sequence was played as a dynamic scan with 30 dummy shots before the actual acquisition of the B_1^+ map (T_i = 0.5 s). Experiments were performed for spoil phase shift increments of ϕ_0 = 0°, 90° and 180° in the STEAM flip angle range α = 0°-90°. For comparison and reference, additional experiments were performed, where DREAM maps were acquired after full relaxation. For a fixed pixel in the B_1^+ maps, the predicted flip angle was plotted against the actual angle, derived by the nominal angle chosen in the protocol and by a common global scale factor derived from the reference acquisition.

Results

Figure 2a shows simulations for the DREAM-predicted STEAM flip angle as a function of the actual flip angle for various spoil phase shift increments ϕ_0 and a short shot interval ($T_i = 0.1\ T_1$). For ϕ_0 = 0°, strong deviations from the ideal straight line are observed, where the angle is overestimated below 50° and underestimated above. With increasing ϕ_0, the deviations decrease and optimal accuracy is achieved for ϕ_0 = 90°, nearly approaching the ideal straight line. Above 90°, the deviations increase again, and ambiguities arise due to non-monotonous behaviour. The experimental results shown in Figure 2b are in very good agreement with the simulations. Accordingly, the accuracy is strongly improved for a spoil phase of 90° compared with the unspoiled acquisition. The slight residual flattening of the curve near 90° flip angle is most probably due to T_1 relaxation during the DREAM imaging train, which was not accounted for in the simulations.

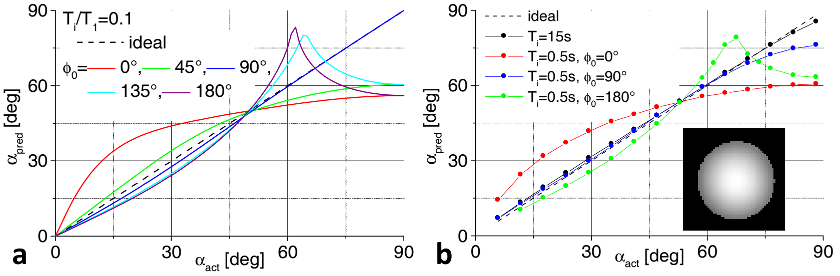

FIG. 2. **RF-spoiled DREAM B_1^+ mapping.** Simulations (a) and experimental results (b) are shown. The STEAM flip angle α predicted by the DREAM approach is plotted against the actual flip angle for different RF spoil phase shift increments ϕ_0, and a short repetition interval T_i, resulting in a strong steady-state. In addition, a reference series was measured after full relaxation (b: T_i = 15s, black symbols). For illustration, an underlying B_1^+ map is shown as an inset in b.

Discussion

The proposed RF spoiling scheme could be useful for a variety of parallel transmit applications based on DREAM B_1^+ mapping, such as real-time B_1^+ mapping for motion-resolved RF shimming, the monitoring of transient phenomena like changes of tissue conductivity, interactions between the RF system and surgical devices, or a fast multi-channel calibration scan. Furthermore, it could be used for other STEAM-based sequences to reduce sensitivity to short sequence repetition intervals.

References

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