Rapid B_1 mapping in the presence of B_0 variations

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Introduction: Accurate calibration of the radio frequency (RF) magnetic field (B_1) is important for many applications, including quantitative MRI. This is particularly true at high fields (≥3T), where large B_1 variations can cause flip angle variations that confound quantitative results. The most widely used "B_1 mapping" method is the double angle method (DAM) [1]. While DAM is straight-forward to implement, it is inherently inefficient due to a need to set $TR \geq 5T_1$. Recently, saturation-recovery DAM (SDAM) was developed to increase the data acquisition efficiency at the expense of signal-to-noise ratio [2]. An alternative approach is to perform a series of RF-prepared ultra-fast gradient echo (TurboFLASH) imaging and use the Bloch equation to calculate for the local "B_1" [3]. However, both these methods directly measure the local flip angle rather than the local B_1 field itself, because they do not measure the corresponding local static magnetic field (B_0) field, which can also lead to changes in the flip angle, and thus the signal intensity. A separate additional B_0 measurement may be required to calculate the B_1. The purpose of this study was to modify the RF-prepared TurboFLASH imaging approach to include B_0 correction for rapid B_1 mapping and to evaluate its accuracy against SDAM.

Methods: Compared with the conventional RF-prepared TurboFLASH imaging method, which used a non-selective RF pulse with fixed duration and variable amplitude, our method (Pre) is based on three different pulse durations (τ=0.4, 1, 20ms) with fixed nominal flip angle (α^{nom}) of 70°. This design was theoretically determined based on expected B_1 and B_0 variations within different organs at 3T. After each preconditioning pulse with spoiler gradients, a TurboFLASH imaging acquisition with centric k-space reordering was immediately applied (i.e., near zero M_z recovery) to image the residual longitudinal magnetization (M_z) [4]. For the calculations of the B_1 and ΔB_0 maps, the dependences of the observed magnetization can be separated into two parts, related to the normalized B_1 scaling factor ($\kappa = B_1^{act} / B_1^{nom}$) and $\Delta\omega_0 = \gamma\Delta B_0$, respectively, using an optimization procedure to fit the measured magnetizations, which can be derived from the Bloch equations in the off-resonant rotating frame [5]. Note that our method can also estimate the magnitude of ΔB_0 map, due to the quadratic term in the equation.

The three image acquisitions with different pulse durations were performed with a wait time to allow for full M_z recovery between image acquisitions. In addition, proton-density weighted (PDW) image acquisition was performed with 4° of flip angle and without the preconditioning pulse, for signal normalization. The pulse sequence was implemented on a whole-body 3T MR scanner (Tim Trio; Siemens). All experiments were performed using a body coil for RF transmission and a 12-channel phased array head coil for signal reception. Imaging parameters include: FOV = 300×225 mm^2, acquisition matrix = 64×48 , in-plane resolution = 4.69×4.69 mm^2, slice thickness = 8mm, TE/TR =1.29/2.56ms, flip angle = 10° , and bandwidth = 750Hz/pixel. The total image acquisition time (including the wait time and PDW image acquisition time) was approximately 10s for the phantom and 28s for the brain (i.e., T_1 of brain matter ~2s).

A spherical oil phantom (T_1 = 530ms) was imaged in a coronal plane, with a shim field along the x-direction modified to generate a linearly increasing B_0 variation (see Fig. 1). Six volunteers were imaged in all three orthogonal planes of the brain. We also performed the SDAM and a standard double-echo phase difference B_0 technique [6], in order to validate our method. For image analysis, the preconditioned images were divided by the PDW image on a pixel-by-pixel basis, and the result was multiplied by the factor sin(4°)/sin(10°), in order to account for the different flip angles. The relative accuracy of κ and $|\Delta\omega_0|$ maps was evaluated against the reference methods using Bland-Altman analysis.

Results: Figure 1 shows the PDW image, the κ and $|\Delta\omega_0|$ maps from Pre and SDAM, and their corresponding vertical and horizontal profiles. The patterns of the κ maps and $|\Delta\omega_0|$ maps between Pre and the reference methods showed good overall agreements (Fig. 1), where the mean absolute differences for the κ map and $|\Delta\omega_0|$ map were 0.021 (95% intervals were 0.009 and 0.033) and 3.2Hz (95% intervals were -1.7Hz and 8.1Hz), respectively. Figure 2 shows representative brain images in the sagittal plane. The results also showed good agreement. The mean absolute differences for the κ map and $|\Delta\omega_0|$ map were 0.019 (95% intervals were -0.016 and 0.037) and 7.997Hz (95% intervals were -15.249Hz and 31.242Hz), respectively.

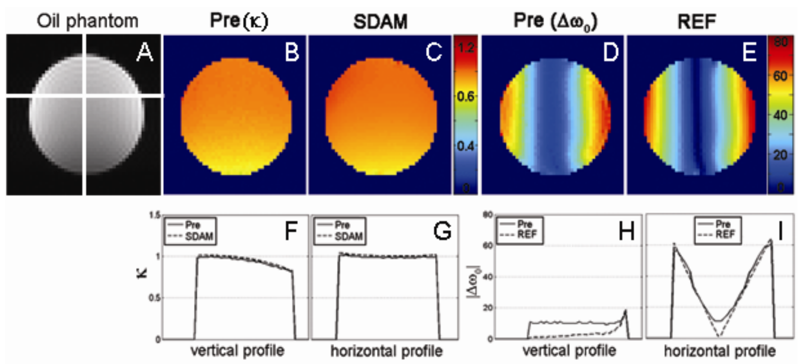

FIG. 1. (A) PDW image. The κ maps of **(B)** Pre and **(C)** SDAM are displayed in dimensionless units of 0-1.3. The $|\Delta\omega_0|$ maps of **(D)** Pre and **(E)** the reference method are displayed in 0-80 Hz. **(F-I)** The corresponding vertical and horizontal profiles.

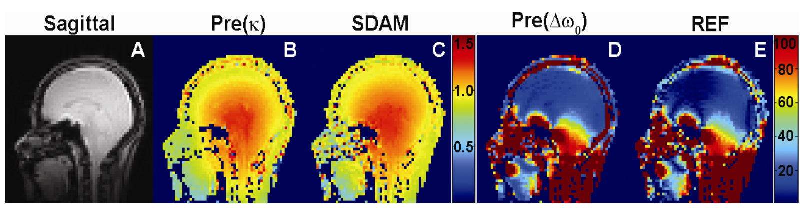

FIG. 2. Brain data: **(A)** PDW image. The κ maps of **(B)** Pre and **(C)** SDAM are displayed in dimensionless units of 0-1.5. The $|\Delta\omega_0|$ maps of **(D)** Pre and **(E)** the reference method are displayed in 0-100Hz.

Discussion: We developed a new strategy to perform fast B_1 mapping using a modified RF-prepared rapid imaging approach with B_0 correction. This method can be used for various quantitative MRI applications that require B_1 calibration. In addition to its fast performance, this method can also correct for B_0 variations that exist at high field MRI. Conventional "B_1 mapping" methods assume that the B_1 has a linear relationship with the flip angle. This assumption may be acceptable when using a large B_1 pulse (i.e, short pulse duration <1ms) in the presence of relatively homogeneous B_0 field. However, B_0 effects may not be negligible at high fields (≥3T), particularly within the heart [7]. Future work may include the use of a saturation pulse prior to the pulse sequence (i.e. similar to SDAM), in order to accelerate the acquisition and optimizing the sequence for 7T imaging.

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