Rapid 3D Mapping of the B_1 Field Using a Low-Flip-Angle, Phase-Based Method with Improved Sensitivity

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Introduction: A low-flip-angle, phase-based method was recently described for calibrating the transmitter voltage (or, equivalently, mapping the transit B_1 field) when imaging hyperpolarized substances [1]. Since this method yields accurate calibration values even for low (< ~15°) flip angles, it should be possible to incorporate this method into a short-TR, gradient-echo sequence thus permitting rapid, three-dimensional mapping of the B_1 field for proton-MRI applications. In this work, we describe a modification of the previously described low-flip-angle, phase-based method that more than doubles its sensitivity, and demonstrate that the phase-based method can provide rapid and accurate three-dimensional mapping of the B_1 field for proton MRI.

Theory: The method described in [1] uses a composite RF pulse of the form $[\alpha_{0^\circ}, \alpha_{90^\circ}, \alpha_{180^\circ}, \alpha_{-90^\circ}]_n, \alpha_{0^\circ}, \alpha_{90^\circ}$ where n ranges between 5 and 20, and each α° segment is a rectangular RF pulse. For very small α, the 4-pulse portion of the composite pulse, which is repeated n times, moves the magnetization in a square pattern in the transverse plane that essentially returns to the origin. However, as α increases and non-linear behavior becomes important, the pattern deviates from a perfect square and the magnetization no longer returns to the origin. The result is that the phase of the transverse magnetization depends on the value of α, increasing as α and n increase [1]. The $\alpha_{0^\circ}, \alpha_{90^\circ}$ pulses at the end of the composite RF pulse reduce its sensitivity to off-resonance signals.

To account for background sources of phase shift, the original method collected data sets at two flip angles, $\alpha/3$ and α, and subtracted the corresponding phase measurements to eliminate phase shifts common to both. While this approach successfully eliminates background phase shifts, it results in reduced sensitivity (i.e., degree of phase shift per degree of flip angle) compared to that for a single acquisition with flip angle α. To provide improved sensitivity, we developed sequences of phase angles for the segments of the composite RF pulse that result in either a positive or negative phase for the transverse magnetization as a function of α. The resulting composite RF pulses are: $[\alpha_{-135^\circ}, \alpha_{-45^\circ}, \alpha_{45^\circ}, \alpha_{-135^\circ}]_n, \alpha_{-135^\circ}, \alpha_{-45^\circ}$ and $[\alpha_{-45^\circ}, \alpha_{-135^\circ}, \alpha_{135^\circ}, \alpha_{45^\circ}]_n, \alpha_{-45^\circ}, \alpha_{-135^\circ}$. By subtracting the phase measurements from these two pulses, background phase shifts are canceled and the phase shift per degree of flip angle is double that for a single acquisition with flip angle α, and thus more than double that for an $\alpha/3$, α measurement. The predicted phase shifts for n=10 as a function of α are plotted in Figure 1 for the original and proposed methods.

Methods: The predicted performance of our proposed modifications to the phase-based calibration method was verified by measuring the phase-shift versus flip-angle behavior in a water phantom. The flip angle was independently calibrated by determining the transmitter voltage required to produce an inversion (180°) RF pulse. The composite RF pulses were then incorporated into a 3D gradient-echo (FLASH) pulse sequence and used to generate maps of the transmit B_1 field in a 17-cm sphere filled with a non-conducting water solution (T1 = 300 ms). For comparison, field maps were also generated using the established signal-amplitude-based method wherein the flip angle is calculated based on the ratio of signal intensities from images acquired with flip angles θ and 2θ, and a long TR [2]. Parameters for the 3D-FLASH acquisition with composite RF pulses included: TR/TE, 15/4 ms; α, 15° (nominal value based on manufacturer's transmitter calibration); acquisition time, 2.0 minutes. Parameters for the long-TR acquisition with conventional RF pulses included: TR/TE, 1500/4 ms; θ, 60° (nominal value); acquisition time, 205 minutes (3.4 hours). Both acquisitions used: matrix, 64 x 64 x 64; FOV, 19.2 x 19.2 x 19.2 cm. The value of n was 10 for all composite RF pulses. Measurements were performed on a commercial 1.5-T scanner (Sonata, Siemens Medical Solutions) using the body coil as the transmitter. The field maps from the phase-based and amplitude-based methods were compared by calculating the root-mean-squared (RMS) value of the percent difference between methods over all signal-containing pixels.

Results: Figure 2 shows experimental verification of our proposed modification for improving the sensitivity of the phase-based method. For these measurements in a water phantom, the solid line is the theoretical behavior assuming that the independent transmitter calibration was accurate. There is excellent agreement between theoretical and experimental values. Figure 3 compares the B_1-field profiles obtained with the phase- and amplitude-based methods along 3 perpendicular axes through the center of the spherical phantom. The phase-based method shows excellent agreement with values from the established amplitude-based measurement. The RMS difference between the methods was 1.3% (97,300 pixels).

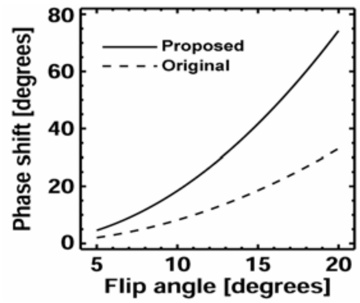

Fig. 1. Predicted phase shifts vs. flip angle for the original (dashed) and proposed (solid) composite RF-pulse configurations.

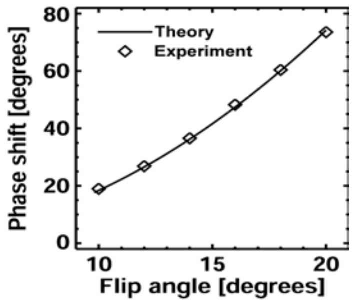

Fig. 2. Theoretical (lines) and experimental (diamonds) phase shifts vs. flip angle for the proposed composite RF-pulse configuration.

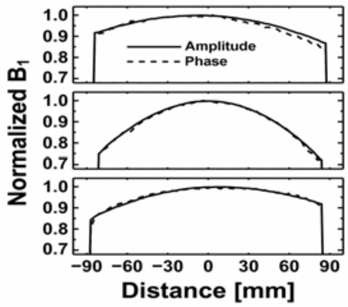

Fig. 3. B_1-field profiles through the center of a spherical phantom from the phase (dashed) and amplitude (solid) methods.

Conclusions: We have shown that the sensitivity of a previously described phase-based technique for transmitter calibration [1] is more than doubled by appropriate modification of the phase angles for the composite RF-pulses used in the method. We have also demonstrated that this phase-based method can be combined with a short-TR, gradient-echo acquisition to yield accurate mapping of the B_1 field in a small fraction (1%) of the time required for the established long-TR method, making high-resolution 3D mapping of the B_1 field practical. By using a more efficient scheme for sampling *k* space such as spiral imaging [3], the acquisition time for the phase-based method could be further reduced.

References: 1. Mugler JP et al. ISMRM 13 (2005); 789. **2.** Stollberger R et al. SMRM 7 (1988); 106. **3.** Cunningham CH et al. MRM 2006; 55:1326.

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