Performance of Three Transmitter Calibration Methods for Hyperpolarized Gas MRI in the Presence of B0 and B1 Inhomogeneity

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Introduction: Due to the non-equilibrium nature of hyperpolarized magnetization, methods suitable for calibrating the transmitter voltage (or, equivalently, mapping the transmit B_1 field) are inherently different than those for proton MRI. Mugler et al presented a low-flip-angle, phase-based method for calibrating the transmitter voltage [1,2], which was extended by Santoro et al to provide low power deposition for the same sensitivity [3]. For transmitter calibration, the measurement typical integrates over a slice or volume of interest, and thus effects of B_0 and B_1 inhomogeneities are important. The goal of this work was to introduce a trajectory optimization for the phase-based methods and to evaluate their performance in the presence of B_0 and B_1 inhomogeneities compared to an amplitude-based method [4].

Theory: The original phase-based method used two composite RF pulses that rotated the magnetization in opposite directions along square trajectories, wherein the difference of the final signal phases is proportional to flip angle [1,2]. An improvement in sensitivity is obtained by replacing the square trajectory with a circular one. As illustrated in Fig. 1, this yields about a 20% sensitivity increase for the circular trajectory ("Method 1") compared to the original method. Figure 1 also illustrates the performance when the pre-pulse concept ("Method 2"), developed by Santoro et al [3] to improve sensitivity by causing the rotation to occur with respect to a tilted axis, is combined with a circular trajectory. Method 2 shows a several-fold sensitivity enhancement compared to Method 1 for the same number of trajectory cycles. The power deposition advantage of Method 2 is obtained by decreasing the number of cycles, and thus pulse duration, to yield similar sensitivity to Method 1. Therefore, we compared Method 1 with 10.3 trajectory cycles, Method 2 with 2 trajectory cycles and a pre-pulse of 0.1625 times the flip angle, and the amplitude-based method ("Method 3"), which measures the decay of the NMR signal as a function of RF pulse number for a series of constant, low-flip-angle excitation RF pulses [4].

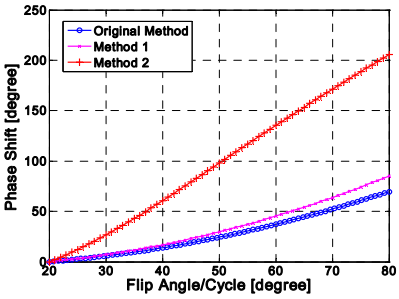

Fig.1. Flip angle/cycle vs. phase shift for original method (square trajectory, c=10.5), Method 1 (circular trajectory, c=10.3) and Method 2 (circular trajectory, c=10, pre-pulse=0.1625*flip angle). c = number of trajectory cycles.

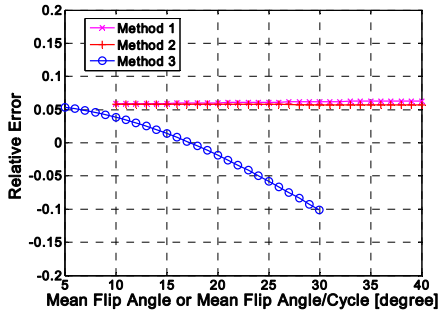

Fig.2. Performance of the three calibration methods in the presence of B_1 inhomogeneity for FA_fwhm = 50% of FA_mean.

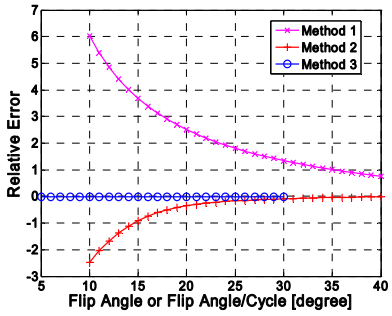

Fig. 3 Performance of the three calibration methods in the presence of B_0 inhomogeneity for FR_fwhm = 5 ppm.

Methods: To evaluate the performance of the three methods, simulations were implemented in the MATLAB(© The Math Works, Inc) platform. The flip angle estimated by each method was calculated for two cases: (1) assuming a normal distribution of flip angles (to simulate B_1 inhomogeneity), and (2) assuming the flip angle is uniform but there is either a normal distribution, or half of a normal distribution (i.e., 0 to some value, which is closer to the actual B_0 distribution we have observed in the lung), of off-resonance frequencies (to simulate B_0 inhomogeneity). The normal distributions were truncated at twice the full width at half maximum (FWHM) value. For B_1 inhomogeneity evaluations, the mean flip angle (FA_mean) for the distribution was varied between 10° and 40° per cycle for Methods 1 and 2, and between 5° and 30° for Method 3. (These values were chosen based on reasonable operating conditions for human imaging.) FWHM values for the flip-angle distributions (FA_fwhm) of 10%, 50% and 100% of FA_mean were considered. For B_0 inhomogeneity evaluations, FWHM values for the frequency distributions (FR_fwhm) of 1, 3 and 5 ppm were considered. Methods 1 and 2 used an RF-pulse duration of 400 µs per cycle; Method 3 used a pulse duration of 500 µs.

Results & Discussion: ***B_1* inhomogeneity:** The accuracy of all three methods is affected by significant B_1 inhomogeneity (FA_fwhm values of 50% or 100% of FA_mean). While the error for Methods 1 and 2 is approximately constant versus FA_mean (Fig. 2), that for Method 3 varies roughly linearly with FA_mean (Fig. 3), with a minimum at about 17°. The errors for FA_fwhm = 100% of FA_mean are about three (Method 3) to four (Methods 1 and 2) times larger than those shown in Fig. 3. ***B_0* inhomogeneity:** The amplitude-based method (Method 3) is robust to B_0 inhomogeneity, indicated by nearly zero error for all off-resonance conditions considered (Figs. 3, 4). In contrast, Method 1 is very sensitive to B_0 inhomogeneity, particularly for relatively low values of the flip angle per cycle (Figs. 3, 4). The off-resonance performance of Method 2 is better than that for Method 1, but Method 2 still shows substantial errors for relatively low values of the flip angle per cycle (Figs. 3, 4). The high sensitivity of Method 1 to off-resonance likely occurs because the rotation of the magnetization is with respect to the origin (z axis). Thus, when the off-resonance frequency is large enough Mxy, from which the phase information is extracted, experiences a sudden 180° phase change when the final Mxy lies in Quadrant 1 vs. Quadrant 3. Signals corresponding to certain off-resonance frequencies are affected by this phase jump, shifting the integrated phase value away from that corresponding to resonance. Method 2 does not exhibit the 180° phase jumps in its response, but the measured phase shift nonetheless varies with off-resonant frequency.

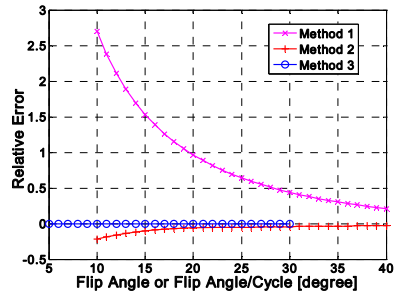

Fig. 4 Performance of the three calibration methods in the presence of B_0 inhomogeneity for the positive half of the frequency distribution used for Fig. 3.

Conclusions: In the presence B_1 inhomogeneity, the behavior of the phase-based methods is better than that for the amplitude-based method since the former yield approximately constant error regardless of the mean flip angle, and the error is relatively small unless the B_1 inhomogeneity is quite large. In contrast, the amplitude-based method is largely immune to B_0 inhomogeneity, while both phase-based methods show a high sensitivity to B_0 inhomogeneity, particularly at low flip angles. We are currently investigating modifications to the phase-based methods to decrease their sensitivity to off-resonance effects, to develop a method that is robust to both B_0 and B_1 inhomogeneity.

References: (1) Mugler JP et al. ISMRM 13 (2005);789. (2) Mugler JP et al. ISMRM 15 (2007);351. (3) Santoro D et al. ISMRM 17 (2009); 2611. (4) Miller GW et al. ISMRM 15 (2007); 1268

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