Improved Phase-Based Transmitter Calibration for Hyperpolarized-Gas MRI using Shinnar-Le Roux RF Pulses

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Background: Several variants of a phase-based method for B1 mapping or transmitter calibration have been proposed for hyperpolarized-gas (HPG) lung imaging [1-3]. For transmitter calibration, the signal is typically integrated over a thick slice through the lung, and thus robust performance in the presence of a range of resonance offsets is more critical than for B1 mapping. In addition, peak B1 is typically limited because broadband amplifiers on clinical MR scanners deliver much less power than their proton counterparts. Thus, for transmitter calibration, the method must be relatively insensitive to off-resonance effects and be accurate even for low peak B1 values. Nonetheless, the accuracy of previous methods proposed for HPG imaging suffers in the presence of off-resonance effects and limited peak B1 [4].

Although not recognized in the original formulations, previous HPG methods are based on the Bloch-Siegert shift associated with off-resonance RF pulses [5]. Viewing previous HPG methods in light of the formalism presented by Sacolick et al [5] reveals that the sidelobe behavior of the off-resonance portion of the calibration pulse is critical for maintaining accuracy in the presence of off-resonance signals, especially when the prepulse portion of the calibration pulse has a low flip angle, as dictated by peak B1 limitations. In particular, because signals are integrated over a range of off-resonance values for transmitter calibration, it is critical that both the phase and amplitude responses of the calibration RF pulse are fairly uniform across the range of off-resonance frequencies of interest. Therefore, the goal of the current work was to evaluate phase-based transmitter calibration based on Shinnar-Le Roux (SLR) RF pulses, optimized for the off-resonance and peak B1 constraints of HPG lung imaging.

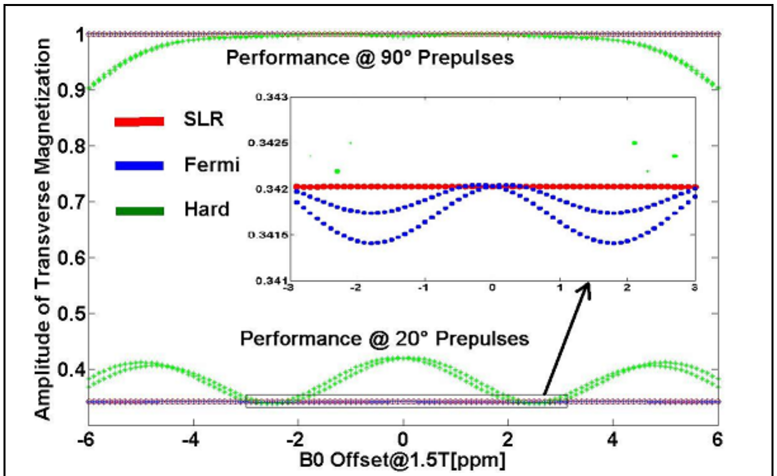

Fig.1. Performance of the three calibration pulses for B0 offset between -6 and 6 ppm.

Methods: We compared three phase-based calibration methods. Method 1 uses a hard RF pulse for both the prepulse and off-resonance components, as described in previous studies [3,4], and Method 2 uses a Fermi waveform for both the prepulse and off-resonance components [5]. Finally, for Method 3, we designed SLR pulses using MATPULSE (Gerald B. Matson) for the prepulse and off-resonance components. To provide a fair comparison of the three methods, we chose pulse durations and off-resonance frequencies that yield similar sensitivity. These were: Method 1, 3 ms and 7.5 kHz; Method 2, 5 ms and 3 kHz; and Method 3, 6 ms and 1.5 kHz. Simulations were implemented in the MATLAB (© The Math Works, Inc) platform to evaluate the performance of the three methods. For experimental evaluation, the phase-based method using SLR pulses was integrated with an amplitude-based method [6] that we use routinely for He3 transmitter calibration in human lung imaging studies. Thus, one calibration dose (~50 ml) of hyperpolarized He3 yielded both phase-based and amplitude-based results. This sequence was used to compare the two methods in 7 human subjects. Informed written consent was obtained from all subjects prior to imaging.

Theoretical Results: **Fig.1** illustrates the influence of off-resonance frequency (-6 to 6 ppm @ 1.5T) on the amplitude of the transverse magnetization obtained after transmitter calibration pulses with both positive and negative frequency offsets. For a 90º prepulse, both Fermi and SLR pulses perform well as indicated by the overlapping lines at the top of the graph; even the hard pulse has an acceptable performance for about -4 to 4 ppm. For a 20º prepulse, which might be the maximum flip angle suitable for an HPG application, the SLR pulse still performs well, as indicated by the flat red line in the zoomed-in region, compared to the slightly oscillating performance of Fermi pulses (blue curves). The phase variations for this case (not shown) are less than 3º for all three methods, and the Fermi pulse has a minor advantage in phase-shift consistency over the SLR and hard pulses. However, this advantage does not outweigh the Fermi's disadvantage in amplitude uniformity compared with the SLR pulse, and thus the SLR pulse performs better when the signal is integrated over a range off-resonance values such as for transmitter calibration. **Fig. 2** shows a simulation result of such a situation. We assume the flip angle is uniform but there is a normal distribution of off-resonance frequencies (to simulate B_0 inhomogeneity). The normal distributions were truncated at twice the full width at half maximum (FWHM) value. FWHM values for the frequency distributions (FR_fwhm) of 3 and 5 ppm were considered; the FR_fwhm = 3 ppm case is shown in **Fig.2**. As shown, the SLR pulses are predicted to have much less error than the Fermi pulse, especially at low peak B1, while the hard pulse gives substantial error even for peak B1 values as high as 10 µT. The SLR pulse also provides good performance for the FR_fwhm = 5 ppm case, with relative error values less than 0.1 (10%), while the Fermi and hard pulses have much higher error.

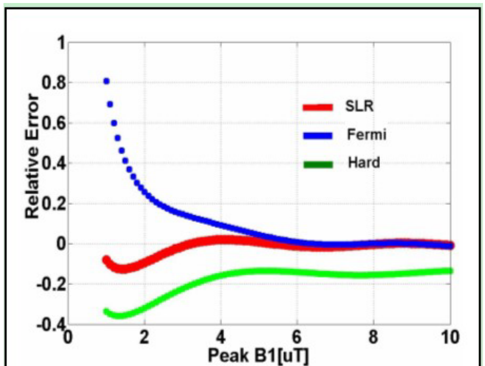

Fig. 2. Performance of the three calibration methods in the presence of B_0 inhomogeneity for FR_fwhm = 3 ppm.

Experimental Results: **Fig. 3** compares the phase-based and amplitude-based methods in 7 human subjects. The two methods yielded comparable results. The largest difference was for subject number 4 (10%), while the difference was less than 7% for all other subjects.

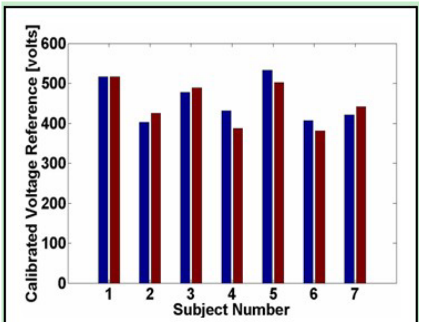

Fig. 3. Transmitter calibration results from human subjects. Blue bars indicate results from the amplitude-based method and red bars represent results from the phase-based method.

Conclusions: Use of an SLR pulse for phase-based transmitter calibration is predicted to provide more accurate results than those from hard or Fermi pulses, especially for a range of off-resonance values and relatively low peak B1. For transmitter calibration prior to hyperpolarized He3 lung imaging, this approach showed good agreement with an established amplitude-based method. In contrast to the amplitude-based method, the phase-based method uses only a small fraction of the available hyperpolarized magnetization and requires less than 100 ms, and thus could be prepended to a lung-imaging pulse sequence, obviating the need for a dedicated calibration.

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) Qing K et al. ISMRM 18 (2010);2574. (5) Sacolick LI et al. Magn Reson Med 2010; 63:1315. (6) Miller GW et al. ISMRM 15 (2007);1268. **Acknowledgements:** This work was supported in part by NIH R01 HL079077 and Siemens Medical Solutions.