Fast RF Flip Angle Calibration by Bloch-Siegert Shift

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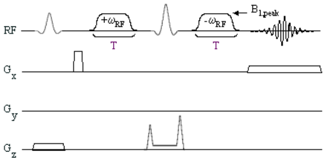
INTRODUCTION: The relationship between RF amplifier output to the transmit coil and B_1^+ field is dependent on the size, orientation, geometry, and composition of the subject. This relationship is typically determined in an automated pre-scan. One measures the magnitude of the B_1 transmit field over the imaging volume for one or more starting gain levels, and calculates the adjustment necessary to produce an RF pulse of a desired flip angle. This B_1^+ measurement is similar to spatially resolved B_1 mapping, except here one would determine the average B_1 field over a sample volume. That sample volume could be an imaging slice or slab, or a spectroscopy volume. Recently we have presented a novel method for phase-based B_1 mapping based on the Bloch-Siegert shift (1). This was shown to be highly robust to TR, T_1 relaxation, chemical shift, B_0 inhomogeneity, and magnetization transfer. Unlike signal magnitude based methods there are no degeneracies or flip angle ranges where this method inherently fails. Here we demonstrate applying this Bloch-Siegert B_1 method to RF flip angle calibration. A robust implementation of this is demonstrated with a scanning time of 1.6 seconds.

The Bloch-Siegert shift is an effect where spin precession frequency shifts in response to an off-resonance RF pulse (2,3). This frequency shift is proportional to the square of the B_1 field and to the frequency difference between the RF pulse and resonance. A spin echo sequence was modified to include two off-resonance 6 msec Fermi shaped RF pulses applied symmetrically around a refocusing pulse. This results in a $B_{1,peak}^2$-dependent phase shift φ_{BS} in the acquired signal (Eqn. 1). Two measurements are acquired- one with the Fermi pulses at ω_{RF} = +4kHz, -4kHz; and one with the opposite frequencies: -4kHz, +4kHz. The phase difference between these two acquisitions is proportional to the square of the B_1 magnitude $B_{1,peak}$ of the Fermi pulses. A 6 msec, 4kHz off-resonance Fermi pulse gives K_{BS} of 55.3 radians/gauss, and the total phase shift from the two Fermi pulses in this sequence is K_{BS} = 110.6 radians/gauss^2.

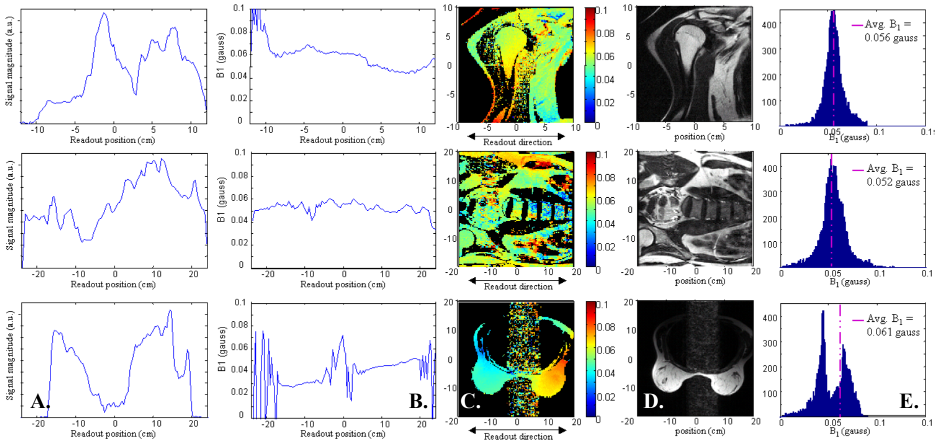
$$\varphi_{BS} = \int_0^T \omega_{BS}(t) = \int_0^T \frac{(\gamma B_1(t))^2}{2\omega_{RF}(t)}, \quad \varphi_{BS} = B_{1,peak}{}^2 \int_0^T \frac{(\gamma B_{1,normalized}(t))^2}{2\omega_{RF}(t)} dt, \quad \varphi_{BS} = B_{1,peak}{}^2 \times K_{BS}$$



Signal was spatially resolved in two dimensions- by slice selection, and by a 15kHz bandwidth readout gradient. An average value for the B_1 over the volume was calculated by the signal-weighted average along the readout dimension. Any off-resonance signal excited by the Fermi pulses was cancelled by adding together two acquisitions with the Fermi pulses phase cycled. The sequence was run with a pre-determined starting gain appropriate for the transmit coil. The B_1 in a 5 mm thick slice was measured, and used to calculate the transmit gain needed to produce an average B_1 field of 0.0732 gauss over the slice. This corresponds to the peak B_1 needed for the 3.2 msec sinc excitation pulse to give a 90° flip angle. The Fermi pulses were scaled to have the same $B_{1,peak}$ as the excitation pulse. The measurement was then repeated once more with the resulting transmit gain for improved SNR. A total of 2 dummy scans + 4 acquisitions (1st pass) + 4 acquisitions (2nd pass) were used for a full B_1 measurement protocol.

METHODS/RESULTS: This sequence was implemented on a 3T GE DVMR scanner (GE Healthcare, USA) with TE/TR = 28/200 msec. The flip angle calibration was performed in 16 human subjects: head, wrist, shoulder, breast, and abdomen, with local Tx/Rx birdcage coils for the head and wrist and a whole body Tx/Rx coil otherwise. Transmit gain ($TG_{predicted}$, dB units) was calculated to give an average of 0.0732 gauss B_1 field ($B_{1,desired}$) over the slice by the Bloch-Siegert method for the starting transmit gain ($TG_{starting}$) and measured B_1 ($B_{1,starting}$). This transmit gain was compared to a conventional calibration. The signal magnitude over the slice from a spin echo sequence was measured with the same pre-determined starting transmit gain. This acquisition was repeated with a TR of 2s, incrementing the transmit gain by 0.1 dB. The integrated signal magnitude was fit to a $\sin^3(\alpha)$ curve, where α is the excitation pulse flip angle, and the maximum was assumed to be α = 90°, or B_1 = 0.0732 gauss.

$$TG_{predicted}{}' = TG_{starting} - 20 \times \log \frac{B_{1,starting}}{B_{1,desired}}$$



Location	*N*	TG difference (dB)
Abdomen	8	0.33±0.28
Shoulder	4	0.35±0.22
Wrist	1	0.26
Head	1	0.23
Breast	2	0.65

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Figure 1: a. Signal magnitude along the readout (128 points, 15.6 kHz bandwidth). **b.** B_1 calculated by Bloch-Siegert shift along the readout. **c.** Bloch-Siegert B_1 map of the slice. Same sequence, with phase encoding (1). **d.** One of the two spin echo images used for the B_1 maps (+4 kHz). **e.** Histogram of the B_1 field in the 128x128 pixels of the B_1 maps. The signal magnitude-weighted average B_1 calculated from a. and b. is displayed on the histogram. **f.** Difference in transmit gain calculated by our Bloch-Siegert and conventional spin echo signal maximum, mean ± s.d, acquired for *N* volunteers per location.

DISCUSSION: The transmit gain predicted by the Bloch-Siegert and conventional methods agreed to within 0.37 ± 0.24 dB over all locations, corresponding to a flip angle error of 3.7° ± 2.5° for a 90°, 3.2 msec sinc excitation pulse. The Bloch-Siegert method is sensitive to heart motion and flow, as can be seen in the phase encoded direction in line with the heart and in the greater variability in the flip angle calibration in the breast. This, however can be suppressed by increasing gradient flow crushing, and/or fitting to remove data along the readout with discontinuous phase. Insignificant (<0.4 dB) variation was found to come from breathing motion in free-breathing vs. breath-held calibration scans. Overall, the Bloch-Siegert shift provides a highly robust and fast method for flip angle calibration. This approach translates easily to flip angle calibration for spectroscopy volumes as well.

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