**Fast RF Flip Angle Calibration by Bloch-Siegert Shift**

L. Sacolick1, L. Sun2, M. W. Vogel1, and I. Hancu3

1GE Global Research, Garching b. Munchen, Germany, 2GE Healthcare, Waukesha, WI, United States, 3GE Global Research, Niskayuna, NY, United States

**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 pulses applied symmetrically around a refocusing pulse. This results in a $B_1\text{peak}^2$-dependent phase shift $\varphi_{BS}$ in the acquired signal (Eqn. 1). Two measurements are acquired - one with the Fermi pulses at $\omega_{BS} = +4kHz$, $-4kHz$; 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 $B_{1,\text{peak}}$ 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.

![Diagram of signal magnitude along the readout](image)

**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 (TGpred, dB units) was calculated to give an average of 0.0732 gauss $B_1$ field ($B_1\text{desired}$) over the slice by 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 (TGpred, dB units) was calculated to give an average of 0.0732 gauss $B_1$ field ($B_1\text{desired}$) over the slice by 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 (TGpred, dB units) was calculated to give an average of 0.0732 gauss $B_1$ field ($B_1\text{desired}$) over the slice by
gain= \frac{t B_{1,\text{peak}}}{t B_{1,\text{desired}}} \int 2 B_{1,\text{peak}} \varphi_{BS} d\alpha

Signal was spatially resolved in two dimensions- 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 $B_{1,\text{peak}}$ 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.

**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 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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