B_1 mapping by Bloch-Siegert shift

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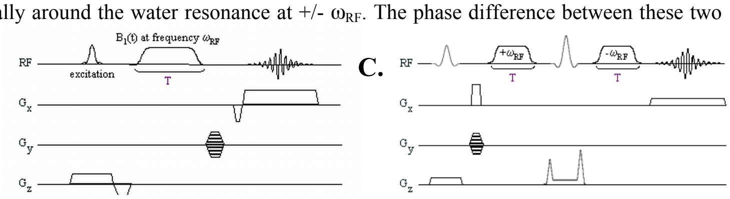
INTRODUCTION: A wide variety of B_1 mapping methods have been developed to date, but problems with scanning time, accuracy over only a narrow range of B_1, and sensitivity to B_0, T_1, and TR have prevented any one method from becoming dominant. Here, we present a novel fast B_1 mapping method based on the Bloch-Siegert shift. The term Bloch-Siegert shift describes the effect where spin precession frequency shifts in response to an off-resonance RF pulse (1). This frequency shift is proportional to the square of the B_1^+ field and to the frequency difference between the RF pulse and resonance. An RF pulse at off-resonance frequency ω_{RF} is placed into an imaging sequence following excitation. The Bloch-Siegert frequency shift ω_{BS} results in a B_1^2-dependent phase φ_{BS}. Two images are acquired: with the pulse applied symmetrically around the water resonance at +/- ω_{RF}. The phase difference between these two images is proportional to the square of the B_1 magnitude.

A.

$$\varphi_{BS} = \int_0^T \omega_{BS}(t) = \int_0^T \frac{(\gamma B_1(t))^2}{2\omega_{RF}(t)}$$

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

B. **C.**



D.

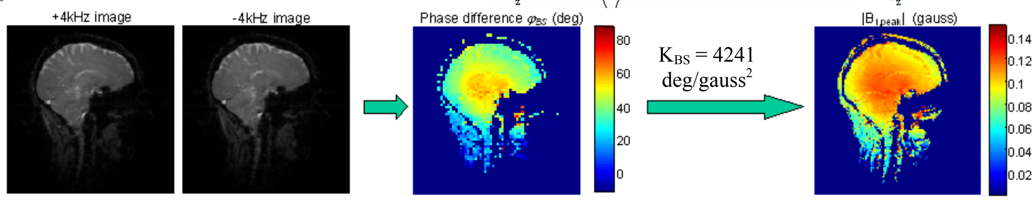
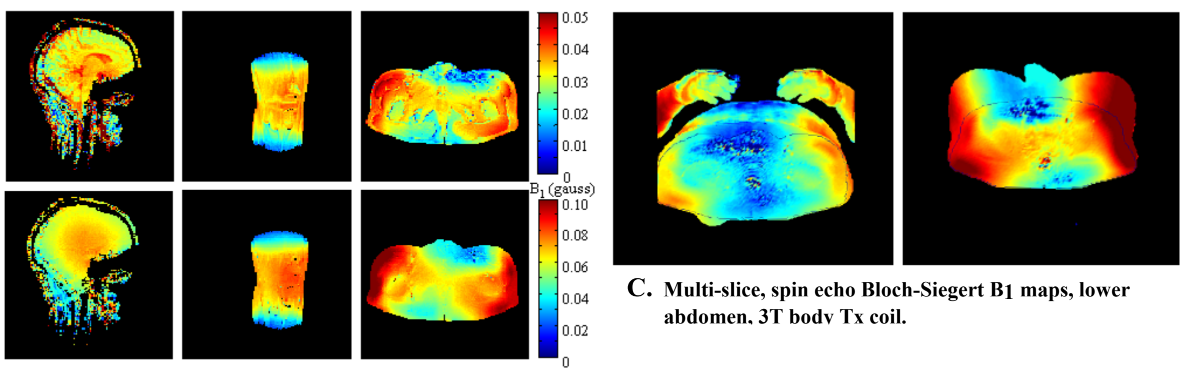


Figure 1a. Bloch Siegert phase shift φ_{BS} for an RF pulse with normalized pulse shape $B_{1,\ normalized}$, and maximum $B_{1,peak}$, length T, and off-resonance frequency ω_{RF}. K_{BS} is the relationship between Bloch-Siegert phase shift and B_1 magnitude (degrees/gauss^2) **b.** Gradient and **c.** Spin echo sequence incorporating off-resonance Fermi RF pulses. **d.** Two images acquired with the sequence in **b.**, the phase difference, and calculated B_1 map. 128x128 resolution, 0.5cm slice thickness, TE/TR = 13/50 msec, scan time = 12.8 sec.

METHODS/RESULTS: The gradient and spin echo Bloch-Siegert sequences were implemented on 3T GE Signa Excite HD and DVMR systems. The off-resonant RF pulses used in these sequences were 8 msec (grad. echo) and 6 msec (spin echo) Fermi pulses, 4 kHz off-resonance. These pulses produce Bloch-Siegert phase shifts of 4241 (8 msec) and 3180 (6 msec) degrees/gauss^2. Two images were acquired with the Fermi pulses having opposite +/- ω_{RF} frequencies. The phase difference is then 2x the Bloch-Siegert phase shift, removing transmit, B_0, receive, and other sequence related phases that are the same in both scans.

A. Double angle 13 min.

B. Bloch-Siegert 25.6 sec



C. Multi-slice, spin echo Bloch-Siegert B1 maps, lower abdomen, 3T body Tx coil.

Figure 2a. 128x128 double angle B_1 maps, 45°, 90° average flip angles over the slice, TR = 3 sec. **b.** 128x128 Bloch-Siegert maps (brain, knee: grad. echo sequence, TE/TR = 12/100 ms), abdomen: spin echo sequence, TE/TR = 28/100 msec. **c.** 3D rendering of two multi-slice lower abdomen B_1 maps from a whole-body Tx coil. Slices were acquired interleaved, with 128x128 in plane resolution, 30 slices (left) and 18 slices (right) of 1 cm thickness. TE = 28, TR = 3sec (left), 1.8 sec (right).

DISCUSSION: The Bloch-Siegert shift has long been overlooked outside of decoupling in spectroscopy (2) and multi-band RF pulse design (3). The B_1-dependence of this effect gives a fast, accurate, robust, and conceptually straightforward method for measuring B_1 maps. This B_1 mapping method is insensitive to T_1, TR, chemical shift, inhomogeneous B_0, and magnetization transfer. While the Bloch-Siegert shift is B_0 dependent, the phase difference between two scans with the RF applied symmetrically around resonance is independent of B_0, for B_0 offset << ω_{RF}. The Fermi pulse used here is often used similarly in magnetization transfer sequences. Magnetization transfer is observed as a magnitude difference between scans with and without the pulse. No phase contribution from magnetization transfer is evident in the in-vivo scans or in milk phantom experiments or has been reported. The 8 msec, 4 kHz pulse demonstrated here provides easily detectable phase shift over a wide range of B_1. The upper bound on B_1 amplitude that can be detected is 0.21 gauss- where phase wrapping begins for this particular RF pulse. At the lower bound, the Bloch-Siegert phase shift falls within the level of image phase noise. In the in-vivo experiments shown here we found a lower limit of approximately 0.03 gauss. However, the lower bound depends on the SNR of the base images and the phase stability of the transmit RF chain. Scan time in most cases is limited at low field by a tradeoff between scan acceleration and image SNR, and at high field (≥ 3 Tesla) by clinical SAR limits. All B_1 mapping demonstrated here falls well within the SAR limits as measured by conventional power monitoring. This method is compatible with EPI, spiral readout, or other imaging acceleration methods, which can additionally reduce scan time and/or SAR.

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