Improved Bloch-Siegert Based B_1 Mapping by Reducing Off-Resonance Shift

Qi Duan[1], Peter van Gelderen[1], and Jeff H. Duyn[1]
[1]*Advanced MRI section, LFMI, NINDS, National Institutes of Health, Bethesda, Maryland, United States*

Target Audience MR physicists, engineers.

Purpose

B_1 mapping methods based on the Bloch-Siegert (BS) effect[1] have traditionally used large frequency offsets ω_{RF} for the BS irradiation pulse to minimize sensitivity to off-resonance and direct excitation of magnetization by this pulse[1]. In addition, the use of large ω_{RF} facilitates B_1 calculation since it allows linear approximation of BS frequency shift as function of B_1^2. However, it may be possible to improve on B_1 mapping performance by reducing ω_{RF} and correcting for the negative side effects mentioned above. To investigate this, we performed theoretical analysis of the BS mapping technique without restricting ω_{RF}. Based on this, we demonstrate that with some sequence modifications, the BS-based sequence can be applied far beyond the regime of offsets original defined[1] to achieve lower RF power deposition and better SNR efficiency. Finally, for a gradient-echo (GRE) based BS mapping sequence, the effect of sequence parameters on SNR at a given SAR level is studied. The theoretical findings were then confirmed with studies of human brain at 7T.

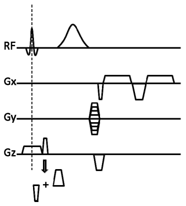


Fig. 1: Modified GRE based BS B_1 mapping sequence

Methods

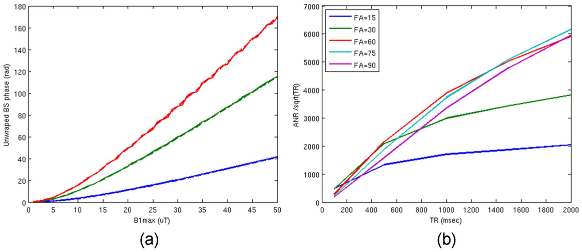
For the BS phase shift ϕ_{2BS} acquired with dual constant frequency offset $\pm\omega_{RF}$, under linear approximation ($|\gamma B_{1p}| << \omega_{RF}$)[1], it can be shown that $\phi_{2BS}/SAR \propto \gamma^2/\omega_{RF}$ and $SNR_{B1} \propto SNR_{image}\gamma^2 SAR/\omega_{RF}$. This suggests reducing ω_{RF} to increase the energy efficiency of BS methods. Three adverse effects of reducing ω_{RF} can be corrected with additional sequence modifications. Increased sensitivity to B_0 inhomogeneity can be corrected with integrated B_0 mapping (reproduced from the reference[2]) (Fig.1). The other two modifications are provided in the following.

Correcting Direct Excitation and Imaging Flip Angle (FA) Dependency:

Artifacts related to the direct excitation effect may be suppressed by *sufficient* crusher gradients, which should be optimized given the non-selective nature of the BS pulse. In addition, it can be derived from Bloch equations that with *sufficient* crushers, the BS shift does not depend on FA if FA>0. In other words, sufficient crusher pair reduces the sensitivity to actual slice profiles and steady state effects, and FA can be simply selected as Ernst angle, a very nice feature in practice.

Overdriving:

If the condition $|\gamma B_{1p}| << \omega_{RF}$ is lifted, mapping efficiency can be further improved. But the linear approximation is no longer valid. This makes derivation of analytical equations very hard. In the following, we will refer to this situation as "overdriven" BS mapping, or OBS mapping. Signal evolution during OBS mapping was studied by simulations of the Bloch equations. For our sequence (Fig. 1) Δf_{RF}=500Hz was used. Fig.2a shows how ϕ_{2BS} changes as a function of B_{1p} for the hard pulse (red), Fermi pulse[1] (green), and the optimized pulse (blue, "QDAPX")[2]. The figure shows that with sufficient crushers, over a large range of B_{1p}, ϕ_{2BS} continues to increase with B_{1p}, although at high B_{1p}, depending on the pulse shape, different degrees of oscillation can be observed. The QDAPX pulse was chosen for further optimizations given its robustness in B_1 estimation in the presence of noise in ϕ_{2BS}. To optimize the sequence parameters (such as imaging flip angle and repetition time TR) at a constant SAR level, both the SNR and the SAR level acquired in a volunteer study were used to calibrate the simulation parameters. In addition, for each simulation, the steady state magnetization level was computed (T_1 was assumed to be 1.5 seconds). Angle-to-Noise Ratio (ANR) efficiency, i.e. mapping sensitivity, was determined from the calculated ϕ_{2BS}, divided by the thermal noise level and the square root of the scan time. Simulation results for various imaging flip angles at a given SAR level (100%) (Fig.2b) show that for a specific SAR level, optimal ANR is achieved at long TR; furthermore, at a specific TR value, ANR is optimal when using imaging flip angles close to the Ernst angle.



(a) (b)

Fig. 2: Bloch-simulation results for Δf_{RF}=500Hz: (a) BS shift v.s. the peak B_1 value calculated from simulation (b) ANR efficiency versus TR at a constant SAR level at a range of imaging flip angles.

Results and Discussion

The effectiveness of the proposed sequence was demonstrated with IRB approved volunteer studies. All experiments were performed on a Siemens Magnetom 7T (Erlangen, Germany) scanner based on an Agilent 7T-830-AS (Oxford, UK) magnet, with a 32-channel head coil (Nova Medical Inc., Wilmington, MA, USA). Common imaging parameters were: FOV 256mm, imaging matrix 64x64, slice thickness=5mm, and BS pulse duration=8ms. The reference B_1 map was acquired with a ±8kHz Fermi pulse (nominal ϕ_{2BS}=70°, TR = 844ms, 10 averages). OBS B_1 mapping (Fig.3) with $\gamma B_{1p}/\omega_{RF}$=1.54 and $\gamma B_{1p}/\omega_{RF}$=0.37, TR=500ms, TE=[15,16]ms, 45° imaging flip angle, single repetition, and maximum allowable SAR level. The B_1 map acquired with OBS has an RMSE of 0.57% whereas the one acquired under linear assumption has a RMSE of 3.01%, comparable to that achieved in recent studies, but about 5-fold larger than the RMSE acquired under the overdriven condition. The ANR advantage of OBS is illustrated in Fig. 4. Comparison of an OBS sequence with a traditional BS sequence used at identical TR, TE, and imaging flip angle shows ANR efficiencies of 69.25 and 8.11 respectively (OBS: Δf_{RF}=500Hz, QDAPX pulse, 64% maximum SAR level, BS: Δf_{RF}=8kHz, Fermi pulse, 93% maximum SAR level). The OBS sequence achieved at least 8-fold improvement in ANR with 30% lower RF energy deposition than the BS mapping under conventional conditions. Even for the OBS sequence with much shorter TR (140ms rather than 1s) at 64% SAR, the average ANR efficiency is still about 25, three times higher than the traditional Fermi based sequence at 93% SAR.

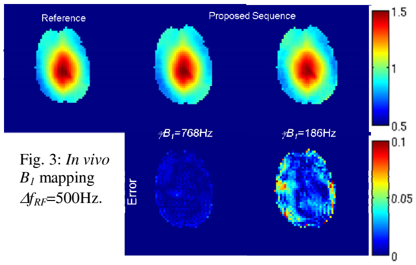


Fig. 3: *In vivo* B_1 mapping Δf_{RF}=500Hz.

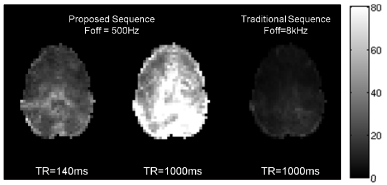


Fig. 4: Mapping efficiency (OBS vs Traditional)

Conclusion

Reducing the off-resonance frequency of the irradiation pulse in BS-based B_1 mapping allows improved mapping efficiency and speed. Potential detrimental effects of this approach on B_1 mapping accuracy can be mitigated by modifications to the acquisition technique and to the theoretical model used for the B_1 calculation. As a result, improved B_1 accuracy can be achieved for given scan time and SAR, as was demonstrated in human studies.

Reference

1. Sacolick LI, Wiesinger F, Hancu I, Vogel MW. B1 mapping by Bloch-Siegert shift. *Magn Reson Med.* May 2010;63(5):1315-1322.

2. Duan Q, van Gelderen P, Duyn J. Fast Simultaneous B0/B1 Mapping by Bloch-Siegert Shift with Improved Gradient Scheme and Pulse Design. *20th Annual Meeting & Exhibition of ISMRM.* Melbourne, Australia, 2012:2504.