Adiabatic pulse design for Bloch-Siegert B_1^+ Mapping

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Purpose: The Bloch-Siegert (B-S) B_1^+ mapping method [1] is accurate and efficient, and largely insensitive to tissue properties such as T_1 and T_2. However, it suffers from long TE and high RF power deposition (SAR) due to the long high-amplitude B-S RF pulse, which is typically played out at constant off-resonant frequency and is used to create the measured B-S phase shift. The off-resonant B-S pulse should have negligible on-resonant excitation, while at the same time coming as close as possible to the on-resonant frequency band in order to create enough Bloch-Siegert phase shift for adequate B-S B_1^+ map quality. Thus we sought to optimize the design of short B-S pulses by *adiabatically sweeping* the resonant frequency offset toward and then away from the water resonance frequency; the closest approach to resonance serves to maximize B_1^+ sensitivity while the adiabatic characteristic serves to limit unwanted on-resonant excitation.

Theory: Our fundamental concept is to modulate the frequency offset of the B-S pulse in such a way as to bring it as close as possible to the resonance band adiabatically, then symmetrically returned to the starting offset, such that the transverse magnetization magnitude is not perturbed while generating maximum B-S phase shift (which is proportional to the squared magnitude of $|B_1^+|$). Let's assume B_1 is an adiabatic RF pulse with time varying resonance offset $\Delta\omega(t)$ given by Eq. 1. Eq. 2 gives the effective B_1 in the rotating frame and the adiabatic condition is shown in Eq. 3. In order to fulfill the adiabatic condition, we assume K>>1. Maximizing the B-S phase shift (φ_{BS}), given by Eq. 4 in order to get the best ANR maps, will lead to analytical solutions for optimized $\Delta\omega(t)$ and $A(t)$, given by Eq. 5-8. K is a key pulse design parameter. A higher K value results in a more strongly adiabatic RF pulse and therefore smaller in-band excitation, but also leads to lower B-S phase shift. In order to further optimize the adiabatic B-S RF pulse, we used the quadratic programming utility in MATLAB (The Mathworks, Natick, MA) similar to [2] and [3] to maximize B-S phase shift subject to an in-band excitation constraint. The numerical optimization algorithm differs from the analytical solution in that the former does not assume a constant K.

$$(1) \quad B_1(t) = A(t)e^{i\Delta\omega(t)t}$$

$$(2) \quad |B_{eff}| = \sqrt{A^2(t) + (\Delta\omega(t)/\gamma)^2}$$

$$(3) \quad K = \frac{\gamma|B_{eff}|}{|d\psi/dt|} >> 1$$

$$(4) \quad \phi_{BS} = \int_0^T \left(\gamma|B_{eff}| - \Delta\omega(t)\right)dt$$

$$(5) \quad \psi(t) = \cos^{-1}\left(1 - \frac{\gamma B_{1p}}{K}t\right)$$

$$(6) \quad \psi_0 = \cos^{-1}\left(1 - \frac{\gamma B_{1p}T}{2K}\right)$$

$$(7) \quad \Delta\omega(t) = \begin{cases} \gamma B_{1p}\cot\psi & 0 < t < \frac{T}{2} \\ \gamma B_{1p}\cot(2\psi_0 - \psi) & \frac{T}{2} < t < T \end{cases}$$

$$(8) \quad A(t) = \Pi\left(\frac{t - T/2}{T}\right)$$

Methods: Two short adiabatic B-S pulses were designed with pulse widths of 1 and 2 ms using both analytical and numerical methods. The transverse magnetization frequency responses of the 2ms adiabatic B-S pulse designed by analytical and numerical methods were computed by Bloch simulation. The 1ms and 2ms adiabatic B-S pulses were compared to the conventional 6ms Fermi pulse [1] on a 7T scanner (GE Healthcare, Waukesha, WI) scanner using a head-neck phantom filled with cupper sulfate. A conventional GRE sequence modified with B-S pulse insertion [1-2] was used with TR=100ms, FOV=24cm, BW=15.63kHz, matrix=64×64, slice thickness=5mm. TE was 4.7, 5.7 and 9.7 ms for 1ms, 2ms and 6ms B-S pulse respectively. The scan was repeated 20 times, from which mean and SNR of the B_1^+ maps were calculated. The 1ms and 2ms adiabatic B-S pulses were also used on a 3T scanner (GE Healthcare, Waukesha, WI) system to acquire B_1^+ maps of brain on a volunteer. The same modified GRE sequence was used with TR=425ms, FOV=20cm, BW=15.63kHz, matrix=64×64, and 40 slices with 5mm thickness to cover the entire brain. TE was 4.7 and 5.7 ms for 1ms and 2ms adiabatic B-S pulses respectively.

Results: The analytical and numerical adiabatic B-S pulses with 1ms and 2ms pulse widths are shown in Fig 1. Fig 2 shows the frequency profile of the transverse magnetization of analytical and numerical designs for the 2ms pulse with the amplitude of 20μT. The numerical design shows 20dB less in-band excitation with 27% less energy while it produces the same B-S phase shift as the analytical design. Fig 3 shows the mean B_1^+ maps of the head-neck phantom using the 6ms Fermi and numerically-designed 1ms and 2ms adiabatic B-S pulses. The difference between B_1^+ maps generated by adiabatic B-S pulses and 6ms Fermi pulse is less than 2% in high SNR areas and less than 10% everywhere. The SNR maps show that the 2ms adiabatic B-S pulse creates higher ANR maps compared to the 6ms Fermi pulse. Fig 4 shows the whole brain B_1^+ maps of a volunteer on a 3T scanner using numerically designed 1ms and 2ms adiabatic B-S pulses. As expected the 2ms pulse generates higher ANR maps compared to the 1ms pulse, but both produced high-quality B_1^+ maps across the brain, in short total scan time and within SAR limits.

Discussion: We have shown here for the first time that short (<2ms) *adiabatic* B-S pulses generate high ANR B_1^+ maps and address the long TE and high SAR problems of conventional B-S pulses. The shorter TE achieved by the adiabatic B-S design concept will be especially useful in areas with high B_0 inhomogeneity, such as in the forebrain and near other susceptibility boundaries. The low SAR property of these pulses allows shorter TR and therefore shorter scan times. The 2ms adiabatic B-S pulse for instance, is 4ms shorter than 6ms Fermi pulse and assuming the same amplitude it generates 2.9 times less SAR. The B-S phase shift created by this pulse is 28% less than that created by the 6ms Fermi pulse, but assuming $T_2^* = 20$ ms in the brain, it generates only 13% less ANR compared to 6ms Fermi pulse.

References: [1]Sacolick et al., MRM 63:1315-1322, 2010. [2]Khalighi et al., MRM in press, 2011. [3]Khalighi et al., ISMRM p4342, 2011.
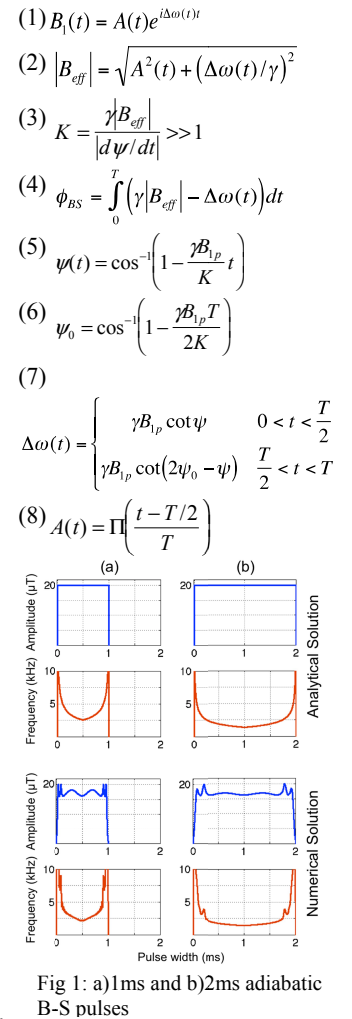
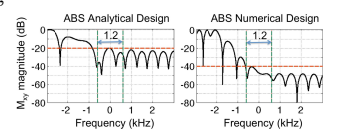Fig 1: a)1ms and b)2ms adiabatic B-S pulses

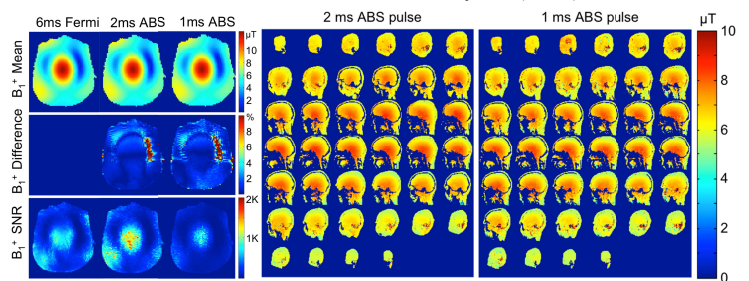Fig 2: M_{xy} frequency profile of a 20 μT 2ms adiabatic B-S pulse with analytical (K=60) and numerical

Fig 3: Comparing 6ms Fermi with 1ms & 2ms ABS pulses.

Fig 4: Whole brain B_1^+ mapping at 3T with 1ms and 2ms adiabatic B-S pulses.