Optimum RF Pulse Width for Adiabatic Bloch-Siegert B_1^+ Mapping

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Purpose: The Adiabatic Bloch-Siegert (ABS) B_1^+ mapping method [1] addresses the long TE and high RF power deposition (SAR) problems of conventional B-S pulses [2] by introducing short frequency-swept ABS pulses with maximum sensitivity, which in turn allows for much faster B-S B_1^+ mapping within approved SAR limits. However, it is still not clear how to design the optimal ABS pulse for a given pulse sequence; by optimal, we mean the highest Angle to Noise Ratio (ANR) in the resulting B_1^+ maps. In this work we present a method to optimize ABS pulse design; we first optimize the analytically designed ABS pulse and then we extend this theory to numerically optimized ABS pulses.

Theory: The ABS pulse that produces maximum Bloch-Siegert phase shift ($\Delta\phi_{BS}$) with a given pulse width (T) and peak amplitude (B_{1p}) is defined by Eq. (1-3), where K (adiabatic factor) is a design parameter which determines the in-band excitation tolerance [1]. In a special case where there is no B0 inhomogeneity, the B-S shift is given by Eq. (4). Assuming large K values and relatively short pulses and using a Taylor expansion of Eq. (4), the B-S phase shift can be approximated by Eq. (5). Assuming that the sequence is always run with maximum allowable SAR in order to get highest ANR, the amplitude of the ABS pulse is given by Eq. (6), where K_s is a constant factor. In order to compare ABS pulses with different pulse widths, we define ABS pulse efficiency, Γ, as the ABS phase shift adjusted by the SNR hit due to T_2^* signal decay caused by the echo time increase that results from the insertion of the ABS pulse into the pulse sequence. Combining Eqs. (5) and (6), Γ is given by Eq. (7), where K_Γ are all the terms in $\Delta\phi_{BS}$ which are independent of ABS pulse width, T. By setting $d\Gamma/dT=0$ the optimum pulse width which maximizes Γ is found in Eq. (8), which is equal to $\frac{3}{4}T_2^*$.

(1) $B_1(t)=\Pi\left(\frac{t-T/2}{T}\right)e^{i\Delta\omega(t)t}$

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

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

(4) $\Delta\phi_{BS}=4K(\psi_0-\sin\psi_0)$

(5) $\Delta\phi_{BS}\approx\frac{2}{3}\frac{(\gamma B_{1p}T)^{3/2}}{K^{1/2}}$

(6) $B_{1p}=\sqrt{\frac{K_s TR}{T}}$

(7) $\Gamma=\Delta\phi_{BS}e^{-T/T_2^*}=K_\Gamma T^{3/4}e^{-T/T_2^*}$

(8) $T_{opt}=\frac{3}{4}T_2^*$

Methods: A numerically optimized ABS pulse was designed with -40 dB in-band attenuation assuming ±500 Hz on-resonance bandwidth. The ABS pulse was inserted into a spiral sequence for B-S B_1^+ mapping. The spiral sequence parameters were selected as minimum TE, minimum TR, 2048 points, 2 arms, bandwidth ±83.3kHz, FOV 24cm, slice thickness 5mm, flip angle 30deg and 25 contiguous slices. The sequence was used on a 7T GE scanner (GE Healthcare, Waukesha, WI) using a 32ch Nova Head coil (Nova Medical, Wilmington, MA). Based on the SAR limit, the peak amplitude (B_{1p}) values for 27 different ABS pulses with various pulse widths T in the range 1-14ms with 0.5 ms step were calculated for minimum TR. The B-S phase shift of each pulse was calculated using a Bloch simulation and the efficiency of each pulse was obtained from Eq. (7) for T_2^* values over the range of [1 30] ms. A subject was scanned and the B_1^+ map was acquired using 2, 4 and 6ms ABS pulses. The scan was repeated 20 times for each pulse and ANR maps were generated.

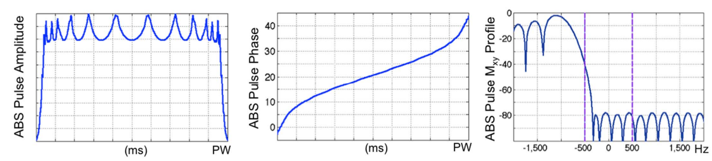

Fig. 1: ABS pulse amplitude and phase along with transverse magnetization profile for the 4ms ABS pulse.

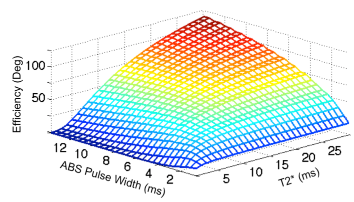

Fig. 2: ABS pulse efficiency of numerically designed ABS pulses with different T_2^* value.

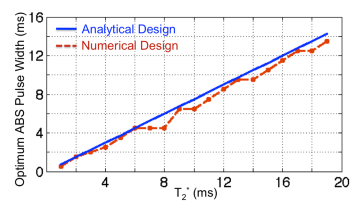

Fig 3: Optimum ABS pulse width with different T_2^* values using numerical & analytical methods.

Results: Fig. 1 shows the ABS pulse amplitude and phase modulation profiles along with the transverse magnetization frequency response, which is plotted for the 4ms numerically optimized ABS pulse. Fig. 2 shows the B-S pulse efficiency plotted as a function of T and T_2^* showing how the pulse efficiency decreases as T_2^* decreases. The efficiency of longer ABS pulses decreases faster due to the longer echo time. The pulses that create the maximum efficiency for each T_2^* value were picked from Fig. 2 and those optimal pulse widths vs. T_2^* are plotted in Fig. 3. For comparison the optimum pulse width for the analytical design (Eq. 8) is also plotted (blue line) and a good match with the numerically designed ABS pulse width vs. T_2^* behavior is observed, with slope equal to ¾. As T_2^* is variable around the brain, 2, 4 and 6ms pulses were chosen for ANR comparison in head at 7T. Fig. 4 compares the ANR obtained by these 3 pulses. It shows that the 6ms ABS pulse is the most efficient under the same scan-time and SAR constraint.

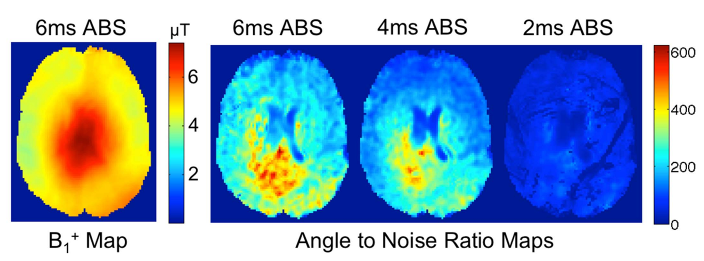

Fig 4: ANR maps of brain B_1^+ map (left) acquired with ABS using 2, 4 and 6ms pulse widths.

Discussion: For maximum B-S B_1^+ mapping efficiency, we designed ABS pulses with minimum TR achievable by the spiral sequence and showed high quality B_1^+ maps at 7T for head. The optimum ABS pulse width depends on T_2^*. We showed that in head at 7T, 6ms ABS pulse generates very high quality B_1^+ maps.

References: [1]Khalighi et al., MRM DOI 10.1002/mrm.24507. [2]Sacolick et al., MRM 63:1315-1322, 2010.

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