SNR Analysis of Adiabatic Bloch-Sigert 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 faster B-S B_1^+ mapping within approved SAR limits. In this work, we present an analytical expression for ABS angle to noise ratio (ANR) and investigate it in a series of phantom experiments as well as an in-vivo study. We also compared the ANR of the ABS method with the recently introduced DREAM method [3]. Both DREAM and ABS offer fast volumetric B_1^+ mapping and can provide B_1^+ mapping of the whole brain in a few seconds per channel, which makes them good candidates for parallel transmit applications. Our analysis predicts that the quality of the resulting B_1^+ maps will be highest for the ABS method.

Theory: Using the minimum variance estimator, the B-S phase shift of a phase array coil with N_c channels is given by Eq. 1, where $\Delta\phi_{BSi}$ is the B-S phase shift measured by the ith channel, R_i is the receive sensitivity of the ith channel and the noise standard deviation of the ith channel is given by $K_i\sigma$. We assume that the noise between channels is uncorrelated. Assuming a normal distribution for $\Delta\phi_{BSi}$ [4], the maximum image signal to noise ratio is given by Eq. 2 and the standard deviation of $\Delta\phi_{BS}$ is given by Eq. 3 where the excitation flip angle is set to the Ernst angle, $E_1=\exp(-TR/T_1)$ and $E_2=\exp(-TE/T_2^*)$. Eq. 4 gives the ANR of ABS. In order to compare the ABS method with others that measure flip angle rather than B_1^+, we have re-written Eq. 4 in Eq. 5, where K_{EX} is the constant conversion factor between B_1^+ and flip angle. Similarly the ANR of DREAM is computed using the flip angle standard deviation [3] and is given by Eq. 6.

$$(1)\ \Delta\phi_{BS}=\frac{\sum_{i=1}^{N_c}\frac{|R_i|^2}{K_i^2}\Delta\phi_{BS_i}}{\sum_{j=1}^{N_c}\frac{|R_j|^2}{K_j^2}} \qquad (2)\ SNR=M_0\sqrt{\frac{1}{N_c}\sum_{i=1}^{N_c}\frac{|R_i|^2}{K_i^2\sigma^2}}$$

$$(3)\ \sigma_{\Delta\phi_{BS}}=\sqrt{2\frac{1+E_1}{1-E_1}}\cdot\frac{1}{E_2 SNR}$$

$$(4)\ ANR_{ABS}=\sqrt{2\frac{1-E_1}{1+E_1}}E_2B_1^2K_{BS}SNR$$

$$(5)\ ANR_{ABS}=\sqrt{2\frac{1-E_1}{1+E_1}}E_2\frac{\alpha^2}{K_{EX}^2}K_{BS}SNR$$

$$(6)\ ANR_{DREAM}=\frac{\alpha\sin(\beta)SNR}{\sqrt{\cot^2\alpha+\tan^2\alpha/4}}$$

Methods: Phantom experiments were performed to measure the ABS method's ANR. The B_1^+ maps in a silicon oil phantom on a 7T scanner (GE-Healthcare, Waukesha WI) were measured with a Nova 32ch Head coil (Nova Medical, Wilmington, MA) and a conventional gradient echo based ABS method using a 6ms B-S pulse with amplitude set between 1-6μT. The scan parameters were set as follows: TR=34ms, TE=9.7ms, FA=30deg, matrix=64×64, bandwidth ±32kHz and slice thickness=5 mm. Each experiment was repeated 20 times and B-S phase standard deviation and ANR maps were generated. In order to compare ABS with DREAM, we choose ABS with single shot spiral readout, which generates B_1^+ maps in scan times comparable to DREAM. We used TR=1.2s, TE=9.9ms, FA=60deg, 4096 points / 1 arm, bandwidth ±83.3kHz, 25 slices with slice thickness=5mm, effective resolution=4.6mm using a 6ms ABS pulse with pulse amplitude of 6.3μT and K_{BS}=440 rad/G^2. Total scan time for whole brain B_1^+ mapping was 4s. To determine the K_{EX} value, we matched the optimal flip angle of DREAM method i.e. α=55° [4] to optimal B-S pulse amplitude in the prescribed single-shot spiral ABS i.e. $|B_1^+|$=6.3μT and therefore K_{EX}=55/6.3 deg/μT. This sequence was used for head B_1^+ mapping in a volunteer on a 7T scanner (GE-Healthcare, Waukesha WI) using a Nova 32ch head coil, repeated 20 times to obtain ANR maps. To calculate ANR, we assumed T_1=1.8s and T_2^*=25ms [5] and we assumed β=15deg for DREAM [3].

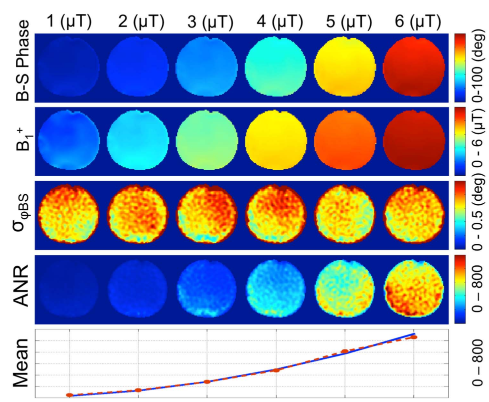

Fig 1: Measuring ANR of ABS method using silicon oil at 7T with 1-6μT ABS pulse amps. The ANR (red dots) increases quadratically with ABS pulse amplitude (blue line).

Results: Fig. 2 shows the ratio of ABS B_1^+ mapping ANR to DREAM method's ANR. The ABS method benefits from high SNR phase maps compared to DREAM and generates more than 3 times higher ANR maps compared to DREAM. Fig. 1 shows the ANR maps of the ABS method in a silicon oil phantom with different ABS pulse amplitude. Higher ABS pulse amplitudes generate more B-S phase shift as is shown in the first row. The B-S phase standard deviation is shown in the 3rd row and as expected is in the same range for all experiments (ref Eq. 3). The last two rows show the ABS method's ANR and its mean value over the phantom and, as expected, the mean ANR increases quadratically with ABS pulse amplitude (ref Eq. 4). Fig. 3 shows the ANR map of ABS method with spiral readout in a volunteer head at 7T. ANR is greater than 200 for most of the brain; however it depends on the coil sensitivity, excitation flip angle, T_1 and T_2^* as it is shown by Eq. 4.

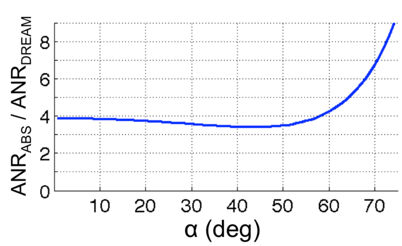

Fig 2: Angle to noise ratio comparison between ABS and DREAM methods.

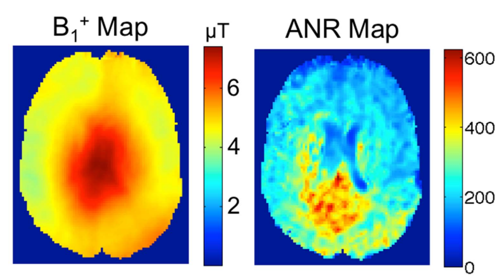

Fig 3: In vivo B_1^+ map and ANR map by ABS B_1^+ mapping using 6ms ABS pulse at 7T.

Discussion: The ANR equation for ABS method has been derived including effects of relaxation. Phantom and volunteer experiments have been performed to show the high ANR maps achieved by ABS. An analytical comparison shows more than 3-fold gain in ANR for ABS compared to DREAM in similar or shorter scan times.

References: [1]Khalighi et al., ISMRM 2012, p607. [2]Sacolick et al., MRM 63:1315-1322, 2010. [3]Nehrke et al., MRM 68:1517-1526, 2012. [4]Gudbjartsson et al., MRM 34:910-914, 1995. [5]Yacoub et al., MRM 45:588-594:2001.

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