Signal to Noise Ratio Analysis of Bloch-Siegert B_1^+ Mapping

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Introduction: B_1^+ mapping is important in a variety of new MR applications, including the design of RF pulses in parallel transmit systems and flip angle calibration for T_1 mapping. The Bloch-Siegert (BS) B_1^+ mapping method has been recently introduced as a fast, accurate and robust technique for B_1 mapping [1]. In order to compare the quality of B_1^+ maps acquired with the BS method to other methods, we derived analytical expressions for SNR in B_1^+ maps generated by the BS, AFI [2] and "classical" long-TR double angle (DA) methods. We then compared B_1^+ SNR between these methods, using both theoretical and experimental approaches.

Theory: In the BS B_1^+ mapping technique, the B_1^+ map is calculated from the BS-pulse-induced phase shift (φ_{BS}), which depends on the BS pulse amplitude, shape/duration, and off resonant frequency, according to Bloch-Siegert theory [1][3]. The resulting phase images are then processed according to Eq. (1) to produce a map of the excitation pulse flip angle, where K_{BS} (radians/Gauss^2) is a constant that depends on the BS pulse characteristics and K_{EX} (radians/Gauss) is a constant relating flip angle to $B_{1,peak}$ for the excitation pulse. By using a first order Taylor series approximation of Eq. (1), we can show that the signal to noise ratio in the BS-derived transmit flip angle maps (which we term ANR for alpha-to-noise ratio) is given by Eq. (2). This equation shows that the BS ANR is proportional to the product of SNR, the signal-to-noise ratio in the acquired gradient echo magnitude images, and the square of the actual flip angle α. A key advantage of the BS method is that we can transmit on all channels simultaneously, adding the BS pulse to one channel at a time, thereby maximizing the SNR in the acquired magnitude images while encoding the single-channel B_1^+ information in the image phase. We also analyzed the AFI and DA methods in the same way, which yielded the ANR relationships given in Eq. (4) for AFI, and Eq. (6) for DA.

$$(1) \quad \alpha_{BS} = K_{EX}\left|B_{1,peak}\right| = K_{EX}\sqrt{(\varphi_{BS,+4kHz} - \varphi_{BS,-4kHz})/(2K_{BS})}$$

$$(2) \quad ANR_{BS} = \frac{2K_{BS}}{K_{EX}^2}\ \alpha^2\ \ SNR$$

$$(3) \quad \alpha_{AFI} = \arccos\left(\frac{rn-1}{n-r}\right)$$

$$(4) \quad ANR_{AFI} = \frac{(n^2-1)}{(n^2+1)(1+\cos^2\alpha)+4n\cos\alpha}\ \ \alpha\sin^2\alpha\ \ SNR$$

$$(5) \quad \alpha_{DA} = \arccos\left(\frac{S_2}{2S_1}\right)$$

$$(6) \quad ANR_{DA} = \frac{2}{1+4\cos^2\alpha}\ \ \alpha\sin^2\alpha\ \ SNR$$

Methods: We used BS pulse sequence proposed in [1] with an 8 ms Fermi shaped BS off resonance pulse for which K_{BS}=74.02 radians/Gauss^2. BS pulses were applied at +4 kHz and -4 kHz off resonant frequencies. We assumed an RF excitation pulse with TBW=4 and K_{EX} = 21.4 radians/Gauss. Experiments were performed on a whole-body research 7T system (GE Healthcare, Waukesha, WI), equipped with 2-ch parallel transmit hardware, using a 2-ch T/R birdcage head coil (Nova Medical Inc., Wilmington MA). We measured a magnitude image SNR of approximately 200 from our GRE images; this SNR value was therefore used in our simulations. To validate our simulation results, we performed experimental comparisons between BS and DA transmit flip angle mapping on the 7T system, using phantoms and normal volunteers. For phantom experiments, an 18cm diameter saline-filled sphere was used. The phantom scans was repeated 7 times in succession to permit ANR estimation from these multiple repeats. The sequence parameters were TE 11.6 ms, TR 150 ms, FOV 24 cm, matrix 128 x 128, slice thickness 10 mm, flip angle 90°, and BS off-resonant frequency +4 kHz. The sequence was then repeated with BS off-resonant frequency set to -4 kHz. The total scan time was 46 seconds. For the DA method we used conventional GRE with the same parameters as for BS, with the exception of the following: TE 5 ms, TR 5 s, and flip angles of 60° / 120°. The total scan time was 22 minutes. We also acquired single in vivo transmit flip angle maps in a normal volunteer, using both DA and BS methods. For the in vivo measurements, we changed the acquisition matrix to 32 x 32. The total scan time was 16 s for BS and 330 s for DA.

Results: Fig. 1 shows the result of the ANR simulations. The BS ANR (green) exceeds that of both DA (blue) and AFI (red) over the low flip angle range. Fig. 2 shows mean and standard deviation maps computed across the 7 repeated flip angle maps derived from the BS and DA acquisitions. The BS method shows lower noise in regions of low flip angles, despite the 33-fold shorter scan time compared to the DA method. Fig. 3 compares in vivo BS and DS flip angle maps. In areas of low transmit flip angle, the DA method fails to produce a valid result, and large "holes" are present in the flip angle map, which are not so evident in the BS maps. The DA method is known to perform poorly for low flip angles [4], and our results demonstrate this problem in the context of 7T transmit sensitivity mapping.

Conclusion: The BS method is a better candidate than the DA method for transmit flip angle mapping on parallel transmit systems, particularly in regions of low flip angle or where there is high B_1^+ non-uniformity, such as exists at 7T. One reason that the BS method performs well is the fact that all channels can be used simultaneously for excitation, with the BS pulse selectively applied only to the single channel being mapped. Other methods require that only one channel at a time be used for excitation, which can be problematic for transmit elements that produce highly non-uniform excitation across the object, such as is the case for most multi-transmit arrays.

References: **[1]** Sacolick et al, MRM 2009, In Press, [**2**] Yarnykh et al. MRM 2007;57:192-200, **[3]** Ramsey NF. Phys Rev 1955;100:1191-1194, **[4]** Wade et al. PISMRM 2009;120.
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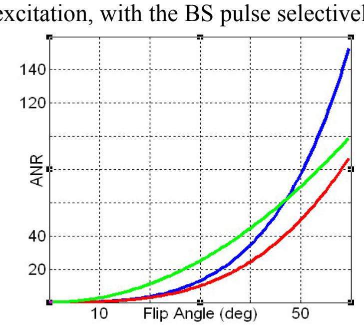

Fig 1: ANR Comparison between BS (green), AFI (red), and DA (blue) methods

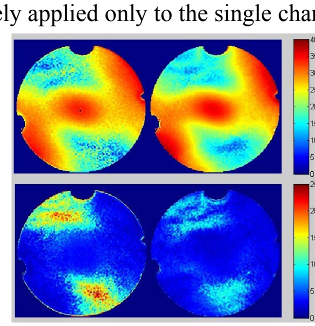
Fig 2: Comparison of DA (left) and BS (right) - mean (Top), std (bottom)

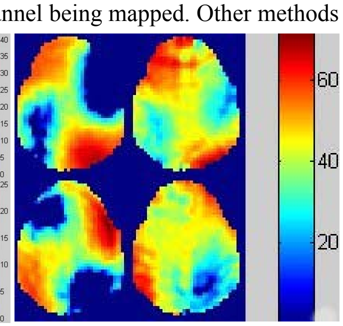

Fig 3: In vivo comparison of DA (left) and BS (right) on a 7T 2-channel pTx system