

Fast 3D B1+ mapping using an optimized, asymmetric Bloch-Siegert method

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Purpose: B₁⁺ mapping is important in a number of high-field imaging applications including multi-transmit rf pulse design and accurate MR relaxometry. The recently proposed Bloch-Siegert (BS) B₁⁺ mapping method [1] circumvents spoiling and saturation issues faced by magnitude-based methods such as Actual Flip-angle Imaging (AFI) [2] and the Double Angle Method [3] and its variants. While the BS method is relatively fast due to its T₁ insensitivity, its accuracy depends on the power of the BS pulse, which is SAR limiting, especially at 7T. This SAR limit can prolong acquisition times, especially for multiple transmit channel B₁⁺ mapping applications. We propose a novel, fast whole brain 3D Bloch-Siegert B₁⁺ mapping method that is optimized for very short scan times and/or low SAR and demonstrate isotropic whole human brain B₁⁺ mapping in scan times on the order of 30 seconds at 3T and less than a minute at 7T.

Theory: The SNR of the BS method is proportional to the SNR of the magnitude image [4]. Hence, we developed a 3D BS technique benefitting from the SNR advantage over conventional multi-slice 2D imaging [1]. We accelerated our 3D method by: (a) confining the acquisition to an elliptical region in k_y-k_z space (30% savings) (b) using a new, optimized 4ms BS pulse with minimal stop band ripple that reduced TR as well as SAR and improved sensitivity due to the smaller offset of the BS off-resonance frequency.

At 7T, where the BS method is severely SAR limited due to the high rf power of the BS pulses, we used a novel scheme which helped reduce SAR and further reduce scan time. The two-sided BS technique [1] applies off-resonant rf pulses at $\pm\Delta\omega_{BS}$ and generates B₁⁺ maps from the resulting phase difference image. This eliminates coil, sequence, and local B₀ inhomogeneity-related phase errors. By acquiring the second BS acquisition with the BS pulse turned off and using its phase instead of the $-\Delta\omega_{BS}$ phase image (as in [1]) to generate the B₁⁺ map, SAR can be reduced by up to a factor of 2 or can be traded off for shorter TR. We refer to this as the asymmetric BS scheme (ABS). Note that this "reference" acquisition needs to be repeated only for one rf channel, resulting in scan time savings that increases with the number of rf transmit channels (33% for 2 channels, 45% for 8 channels). At 7T, B₀ maps are routinely acquired for parallel transmit rf pulse design and can be used to remove any residual errors, which are normally subtracted out in the symmetric BS method.

Methods: All experiments were performed on GE 3T and 7T scanners, the latter employing 2 rf transmission channels. At 7T, the asymmetric BS B₁⁺ maps were compared to two-sided BS maps on a custom-made head-neck phantom. Twenty repeat acquisitions with both sequences were used to determine mean, SD and angle-to-noise ratio (ANR). SAR was monitored using the power monitor supplied by the vendor. Human subjects were scanned at both field strengths after obtaining informed consent. At 3T, where SAR was not a limitation, 3D mapping was done using the two-sided 3D BS acquisition. Sequence parameters: 32x32x32 matrix, 5 mm thick, 24 cm FOV, 15-32 KHz BW, TR=35-40ms at 7T (16ms at 3T). The new BS pulse was 4 ms long and played at an offset of 1940 Hz. Scan times were 32s at 3T and 50/70s at 7T (ABS method with same SAR, shorter TR versus lower SAR, same TR).

Results: Figure 1 shows 3D B₁⁺ maps obtained from a human brain at 3T in 30sec. Figure 2a compares mean B₁⁺ map from a phantom at 7T using a two-sided BS (left, SAR=1.6 W/kg), the proposed ABS method (center, SAR =0.8 W/kg) and the error scaled by a factor of 100 (right), validating the accuracy of the ABS method. The angle-to-noise ratio (mean B₁⁺/SD noise) is shown in Figure 2b. There is a reduction in sensitivity due to the elimination of the second BS acquisition but the overall ANR is high due to the 3D acquisition. Figure 3 compares B₁⁺ maps of a representative slice (out of a 32 slice 3D slab) from a human head at 7T using two-sided BS (left), ABS with lower SAR same scan time (center), ABS with same SAR shorter scan time (right)). The error maps (3X) are shown below verifying the accuracy of the proposed method *in vivo*. The two-sided BS method had a scan time of 103s and SAR was 2 W/kg, while the ABS method with the same TR had a scan time of 72s and SAR of 1.3 W/kg. Trading off to reduce the TR and maintain a SAR of 1.9 W/kg reduced the total scan time to 50s (Fig 3c).

Discussion: We have demonstrated fast 3D Bloch-Siegert B₁⁺ mapping in the human brain at both 3T and 7T (scantimes: 30s at 3T, 50s at 7T). At 7T where BS B₁⁺ mapping is SAR limited, we used a new asymmetric BS scheme. By eliminating one of the BS acquisitions, SAR could be halved and scan time reduced by 33% (for 8 channels, this would increase to 45%). SAR can also be traded off for shorter TR/scan times. The phase errors from coil, sequence and B₀-inhomogeneity are still suppressed resulting in accurate B₁⁺ maps. Magnetization transfer effects were not an issue as BS is a phase-based method.

References: [1] Sacolick et al. MRM 63:1315-1322 (2010) [2] Yarnykh et al. MRM 57:192-200 (2007) [3] Hornak et al. MRM 6:158-163 (1988) [4] Khalighi et al. Proc ISMRM 18:2842 (2010). **Acknowledgments:** GE Healthcare

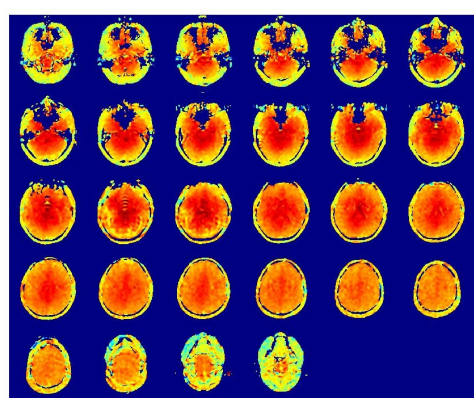


Figure 1. Whole brain 3D BS B₁⁺ maps (in μ T) from a human volunteer at 3T obtained in 32s.

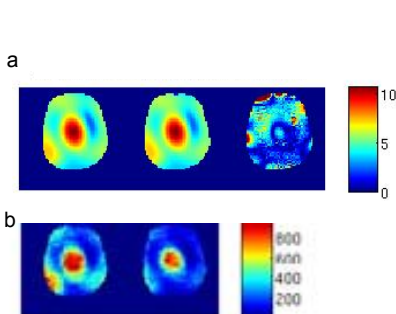


Figure 2. (a) Mean B₁⁺ map (in μ T) from a representative slice using two-sided BS (left) vs. proposed asymmetric BS (center) and the error (x100, right) on a phantom (b) The ANR maps for two-sided BS (left) and asymmetric BS (right)

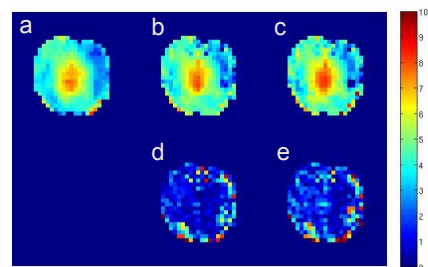


Figure 3. One slice human brain B₁⁺ map (in μ T) from a two-sided 3D BS acquisition (a), an asymmetric BS acquisition with same scan time, lower SAR (b) and lower scan time, same SAR (c). Corresponding error maps are shown (3X) in (d-e). Scan times were 103s, 70s and 50s respectively.