Implementation and Validation of Fast Whole-Brain B_1 Mapping Based on Bloch-Siegert Shift and EPI Readout

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Introduction

In high field MRI, RF flip angle inhomogeneity due to wavelength effects can lead to spatial variations in contrast and sensitivity. B_1 mapping techniques provide a way to quantify this inhomogeneity for the purpose of mediation and correction, for example through parallel excitation techniques. Recently, the method proposed by [1] based on the Bloch-Siegert (BS) shift effect has been shown to be robust to variations in TR, T_1 relaxation, flip angle, chemical shift, B_0 inhomogeneity, and magnetization transfer. However practical application of whole-brain B_1 mapping may be hampered by long measurement times due to limits on Specific Absorption Rate (SAR), in particular when multiple transmit coils are employed. In this abstract, three modifications to the BS technique are proposed to allow whole brain mapping of B_1 within 40s with 4mm isotropic resolution. The effectiveness of this approach is demonstrated on phantoms and in vivo.

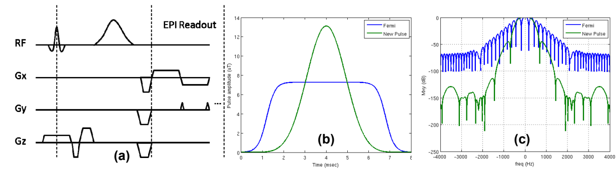

Fig. 1: (a) proposed GE-EPI based Bloch-Siegert B1 mapping sequence diagram. (b) Pulse shape and (c) simulated frequency response of the Fermi (blue) and the new pulse (green).

Methods

Theory:

Substantial reduction of SAR in the BS technique can be achieved by reducing the number of BS pulses per slice, or reducing the energy required for each BS pulse at a given BS phase shift. To reduce the number of BS pulses per slice, rapid scan techniques such as TSE or EPI can be used [2] and [3]. Here we implemented gradient-echo EPI for its low SAR level, and relative insensitivity to flip angle variations of the imaging pulse. To minimize the SAR of the BS pulse at a given B_1 sensitivity (i.e. BS shift), the method proposed in [4] is adopted, with a modified gradient scheme and improved pulse shape, as shown in Fig. 1, which could potentially reduce the power deposition of the BS pulse by four-fold.

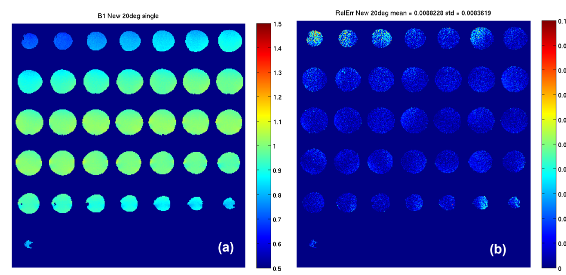

Fig. 2: (a) Relative B_1 map (scaled from 50% to 150%) and (b) relative error map (scaled from 0% to 10%) on the oil phantom scan.

Implementation:

The improved sequence diagram is shown Fig. 1a. Both GE-EPI based sequences with Fermi pulse used in [1] as well as our proposed scheme were implemented in the Siemens Integrated Development Environment for Applications (IDEA) sequence development environments. Both EPI sequences were modified from Siemens product sequences. The BS module was implemented as a stand-alone building block and inserted between excitation and readout blocks. Sequences with positive and negative frequency offsets for the BS pulse were applied in an interleave fashion to minimize unwanted phase effects (such as B_0 heterogeneity induced phase [1]). The original BS pulse (±8kHz Fermi) [1] and our modified pulse (±2kHz) [4] are shown in Fig.1b, with their frequency responses calculated from Bloch simulation shown in Fig.1c. Two 1ms ±40mT/m bipolar crusher gradients sandwich the BS pulse to spoil the direct excitation effect from the BS pulse. In addition, one dummy scan per slice was applied before the actual imaging sequences. The corresponding Siemens Image Calculation Environment (ICE) program was also implemented for online reconstruction on the scanner, with magnitude images, B_1 images, and B_1 images after automated masking, reconstructed in real time. To control the amplitude of the BS pulse, the nominal BS shift was used as the parameter on the user interface, which can be directly translated into (nominal) peak B_1 values. This value was also used to derive the normalization term in calculating the relative B_1 maps as shown in the Results section (Note these B_1 maps can be directly translated to absolute B_1 maps by multiplying the nominal peak B_1 value). In addition, one scaling factor for the magnitude image and one threshold value were added to the user interface for immediate region-of-interest (ROI) analysis. In the initial implementation, phase unwrapping on the resulting BS phase shift was not implemented but planned for future revisions.

Results

The proposed sequence was validated via an oil phantom scan. All experiments were performed using a Siemens Magnetom 7T (Erlangen, Germany) whole body scanner based on an Agilent 7T-830-AS (Oxford, UK) shielded magnet design, with a 32-channel head coil (Nova Medical Inc., Wilmington, MA, USA). Common imaging parameters are FOV 208mm x 256mm, imaging matrix 52x64, flip angle 70^o, slice thickness 4mm, 36 slices, nominal BS phase shift = 20 deg, SAR = 100% of maximum level throughout the whole study.

On the phantom, an average B_1 map acquired with ±8kHz 8ms Fermi pulse with 10 repetitions was used as the reference B_1 map (TR= 10260ms, acquisition time (TA)=31s). Then both sequences were run at TR=3090ms TA=9.3s, with nominal BS shift 20^o for the ±2kHz new sequence and 5^o for the ±8kHz Fermi-based sequence, with 10 repetitions to compute signal-to-noise ratio. The B_1 map from a single scan of the proposed scheme is shown in Fig.2a. The mean and the standard deviation on relative errors (Fig.2b) is 0.88% ± 0.84%. For most of the regions, the relative errors are less than 2% except for the region with extremely low B_1, which is consistent with the findings in [5]. The mean SNRs within the whole 3D ROI in the B_1 maps acquired in 9.3s are 155.38 and 31.14 for the new scheme and Fermi-based scheme, respectively, showing the SNR advantage of our modified sequence.

The effectiveness of the proposed B_1 mapping sequence was also demonstrated in an IRB approved volunteer study. A 3D B_1 map with whole brain coverage acquired with the improved scheme on a volunteer (nominal BS shift 25^o, TR=7520, TA=38s) is shown in Fig.3.

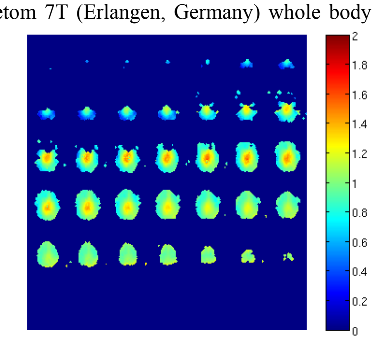

Fig. 3: Relative B_1 map (scaled from 0% to 200%) on a volunteer scan.

Discussions

Initial results are very promising in terms of acquisition time reduction for GE-based B_1 mapping based on the BS shift. On the phantom, at least a three-fold reduction in acquisition time was achieved without sacrificing the accuracy in B_1 estimation. This is very important, especially for applications when multiple transmit channels need to be mapped. The SNR study showed more than four times gain in SNR for B_1 maps if the acquisition time was kept constant as compared to the original scheme. Similar to any other GE-EPI based sequence, geometric distortion can be observed. This can be corrected by post-processing if B_0 map is available, which is already part of standard protocol for neurological applications in our center. Lastly, phase unwrapping can be incorporated into the image reconstruction to increase the allowable maximum nominal BS shift, thereby further increase the SNR in the final B_1 map.

Conclusions

A proposed SAR optimized scheme containing an improved gradient scheme, an improved pulse, and an EPI readout was validated for GE-based Bloch-Siegert B_1 mapping, allowing whole brain B_1 mapping with 4mm isotropic voxel within 40 seconds. The performance of the new scheme was demonstrated in vivo at 7T in comparison with the original BS sequence for at least three-fold reduction in acquisition time while keeping the B_1 sensitivity the same.

References

[1] Sacolick, et al, MRM 2010; 63(5): 1315-22. [2] Nehrke, et al, ISMRM 2011: 4411. [3] Sacolick, et al, ISMRM 2011: 2927. [4]-, et al, ISMRM 2012, submitted. [5] Sacolick, et al, ISMRM 2011: 2926.