Multi Bloch-Siegert B_1^+ mapping in a single experiment

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Introduction

A new method for phase-based B_1^+ mapping based on the Bloch-Siegert (BS) shift (ϕ_{BS}) was presented in 2010 by Sacolick et al. (1,2). Recent studies have shown that BS-B_1^+ mapping can be extended to CMPG multi/turbo-spin-echo sequences (3,4). Furthermore, it was shown that the necessary phase information for B_1^+ mapping can be obtained in a single experiment by using an adapted BS-phase encoding scheme (4). Importantly BS-B_1^+ mapping shows only small dependency on TR, T_1, flip angle, chemical shift, background field inhomogeneity and magnetization transfer effects (1). However, being a phase-based method, the maximal ϕ_{BS} can be restricted since phase wraps cannot easily be removed for all given situations (e.g. not connected areas with a wrap in between). This can be critical for BS B_1 mapping using surface coils. Thus, to also obtain high quality B_1 data in insensitive areas phase wraps in more sensitive areas cannot always be prevented.
To reduce this problematic, a method is proposed which allows variation of ϕ_{BS} in a single echo train. Consequently, by combining the information of the various obtained ϕ_{BS} it is possible to remove phase wraps.

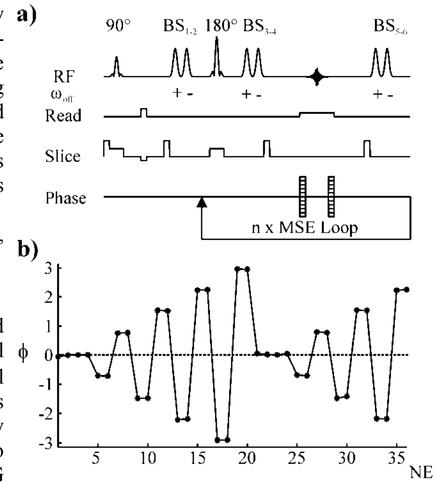

Fig.**1a)** Sequence diagram of the used BS-CPMG-MSE sequence. **b)** Phase values obtained in one echo train using the modified BS phase encoding scheme.

Theory

It was recently shown that it is possible to vary the encoded BS phase at readout time in a single CPMG-based MSME-/TSE-sequence (4). This was enabled by pre-encoding the BS phase with a "bipolar" BS pulse (two identical BS pulses with opposite off-resonance frequencies (ω_{off})) before the initial refocusing pulse (Fig.1a, BS_{1-2}). To fulfill CPMG conditions, it is necessary to generate the initial BS phase twice between the following refocusing pulse pairs (3,4). This was reached in Reference 4 by applying each of the initial BS pulses two times in each echo interval. By permuting the succession of the BS pulses, it was thus possible to acquire all BS phase information necessary to calculate a B_1^+ map in a single echo train. Prior to these findings it was shown that it is possible to fulfill CPMG conditions by scaling the amplitudes of the applied BS-pulse in the echo train by $\sqrt{2}$ (3). In the present study, pre-encoding with the "bipolar" BS pulse (4) was combined with the amplitude scaling of the BS pulses (3). Thus, it was possible to acquire B_1^+ maps for different BS pulse amplitudes in a single experiment. The following condition had to be fulfilled for both BS off-resonances:

$$\sum \phi_{BS} = \frac{\omega 1_{BS_{3/4}}^{2} t_{BS}}{2(+/-\omega_{off}+\omega_{B_0})} + \frac{\omega 1_{BS_{5/6}}^{2} t_{BS}}{2(+/-\omega_{off}+\omega_{B_0})} = 2\phi_{BS1/2}$$

The value of the BS phase at readout is defined by the BS pulses 3&4. After readout, the amplitude $\omega 1_{BS5/6}$ of the BS pulses is adapted to restore the corresponding initial phase state $\phi_{BS1/2}$. Due to CPMG properties two subsequent echoes with the same BS phase encoding were always acquired.

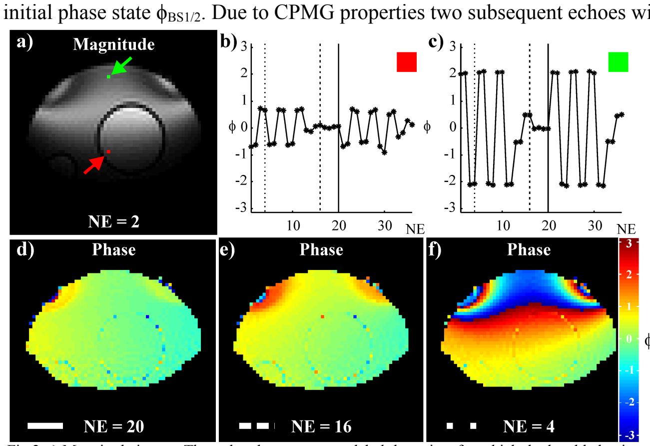

Fig.2 **a)** Magnitude image. The red and green arrows label the points for which the local behavior of the phase in the echo train is displayed in **b** (red) & **c** (green). **d)** Phase image with $\phi_{BS} = 0$ (NE = 20). **e)** Phase image with small ϕ_{BS} (NE = 16). **f)** Phase image with large ϕ_{BS} (NE = 4).

Materials and Methods

The modified BS encoding scheme was implemented on a 7T small animal scanner. A surface coil with 20mm diameter was used for imaging. Gaussian-shaped off-resonant pulses were used for BS encoding. The BS pulse duration was set to 1ms and the off-resonance of the BS pulses was set to = ±16kHz.
A single slice of the phantom was imaged (Echo time/ repetition time (TE/TR) = 14/2000ms; echo images (NE) = 36; matrix size (MTX) = 64x64; field-of-view (FOV) = 30x30mm^2; slice thickness (ST) = 2mm; number of dummy scans (NDS) = 2, T_{exp} = 2min8s). Two different BS experiments were performed. In the first, the amplitudes of the BS pulses were adapted to obtain linear increasing BS phase states. In the second, two defined BS phase states were acquired. All acquired phase states were an equal combination of BS phases produced by BS pulses at both off resonance frequencies. The negative BS phase was thereby produced by commuting the amplitudes of $BS_{3/4}$. The B_1 maps were calculated according to reference 3.

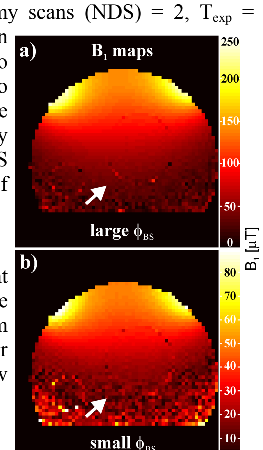

Fig.3) B_1^+ maps calculated from the two-step experiment. **a)** Large ϕ_{BS} (Fig.2f) and **b** small ϕ_{BS} (Fig.2e).

Results

In Fig.1b, the phase behavior of one exemplary spatial point in the phantom is shown for the multi-step experiment. Starting from zero BS phase (NE = 1-4), the BS phase state was ramped up in the subsequent echoes (NE = 5-20). The procedure was successfully repeated for the latter echoes (NE = 21-36). Fig.2 shows the results from the BS experiments using two different BS encoding strengths. While no phase wraps were present in the phase images with no (Fig.2d) or small ϕ_{BS} (Fig.2e), phase wraps were present when a large ϕ_{BS} was introduced (Fig.2f). The corresponding B_1^+ maps (Fig.3a&b) show similar patterns but different B_1^+ values according to the applied BS-pulse amplitudes.

Discussion and Conclusion

As shown the modified BS encoding scheme allowed acquisition of multiple BS phase states in one echo train while maintaining CPMG conditions. A possible application of this modification is B_1^+ mapping with inhomogeneous coils. In such situations multiple phase wraps are unavoidable as enough ϕ_{BS} must be reached for BS-B_1^+ mapping in insensitive areas of the coil. For such applications, a large ϕ_{BS} is of special interest to improve the B_1^+ map quality in regions of low B_1^+ (Fig.3a and b, arrows). At regions of high B_1^+, however, phase wraps might occur with a large ϕ_{BS} (Fig.2f). Since phase wraps are not always easily removed, the presented technique might thus avoid errors due to phase wraps.

References

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