Robust implementation of 3D Bloch Siegert B1 mapping

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Target Audience: Engineers and Scientists who are interested in mapping the B_{1+}-field.

Introduction: Accurate in-vivo mapping of the RF-field (B_{1+}) is important for different aspects in MRI at high field strengths; in particular for the calibration of parallel transmit systems. In a recent publication [1] a fast and accurate method was proposed for this purpose, which exploits the phase shift caused by an off-resonant RF-pulse (Bloch-Siegert (BS) shift). In comparison to other B_1 mapping methods it was shown in [2] that reliable results can be achieved over a wide range of flip angles with a good suppression of tissue heterogeneity in-vivo. However, for 3D applications we observed inconsistencies and non-negligible errors due to phase instabilities between the positive and negative BS encoding. This work reports an investigation of the described errors and a robust 3D implementation that provides stable and consistent B_{1+} maps for the same configuration.

Theory: B_{1+} mapping using the BS shift makes use of the shift in resonance frequency by an off-resonant RF-pulse, which is proportional to the square of the B_{1+} magnitude. By applying an off-resonant RF-pulse over a certain time an additional phase is accumulated according to Eq. 1. The calculation of the actual B_1 field is described in [3] (see Eq. 2).

$$\varphi_{BS} = \int_0^T \frac{\gamma^2 B_{1+}(t)^2}{2\omega_{BS}} dt = K_{BS} \cdot \left(B_{1+,peak}\right)^2 \quad (1) \qquad |B_{1+}| = \sqrt{\left(\varphi_{BS,+\omega_{BS}} - \varphi_{BS,-\omega_{BS}}\right)/(2K_{BS})} \quad (2)$$

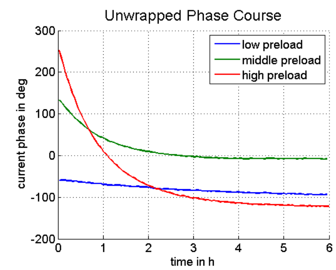

Fig. 1: Phase drift measured at the end of 3 regular masurement days over a time period of 6h.

To suppress phase influences from B_0, chemical shift or excitation the data has to be acquired with positive and negative resonance offset $\pm\omega_{BS}$ of the BS pulse. The difference of those two phase images is proportional to $2B_{1+}^2$ (Eq. 2). In the conventional implementation these acquisitions are performed sequentially, whereas in this work we exploit the advantage of an interleaved acquisition pattern.

Methods: All measurements were performed on a clinical Siemens Magnetom Skyra 3T system (Siemens, Erlangen, Germany). The BS method was implemented by adding an off-resonant Gaussian shaped BS pulse with a duration of 10ms, a calibration constant K_{BS} of 53.4rad/gauss^2 and scaled to a flip angle of 1000° into a GRE sequence. The off-resonance frequency to encode the BS shift was set to +4kHz and -4kHz respectively. The phase drift was measured over 6 hours at the end of three regular measurement days with different preloads of the scanner using the sequence described above. The B_{1+} maps were acquired with a FOV of 250mm, a matrix size of 128x76, a TE of 13.4ms and a TR of 150ms which is near the lower limit due to SAR restrictions. The 3D maps were acquired for a slab with 16 slices using both sequential and interleaved acquisition. The reference was measured using the Double Angle (DA) method [4] using a $TR > 5 \cdot T_{1max}$. To enable a direct comparison to the reference measurement the B_{1+} maps were normalized such that the nominal applied flip angle appears at one. The error maps show the deviation of a specific B_{1+} map compared to the reference measurement in percent.

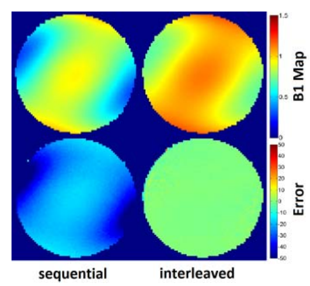

Fig. 2: Comparison between seq. and interleaved acqusition of a 16 slice 3D acquisition.

Results: In Fig. 1 the phase variation is shown over 6 hours for three different scanner preloads. The changing rate is different but the phase stabilizes and reaches a steady state after about 3-4 hours independent of the initial slope. Fig. 2 shows a comparison between the calculated B_{1+} maps (center slice) of two 3D scans acquired with sequential (left) and interleaved acquisition (right) and the corresponding error maps in comparison to the reference scan shown in Fig. 3 (top left). Fig. 3 further shows several 2D BS acquisitions with increasing delay between both BS encodings and the corresponding error maps.

Discussion: The resonance frequency is not stable within the scanner and behaves like an exponential decay. We assume that thermal effects within the hardware are the reason for that. Extending the sequential BS-acquisition to 3D for i.e. 16 slices there is a time difference of more than 3 minutes between both BS-encoding steps. If the resonance frequency drifts within that time, as shown by the red line in Fig. 1, causing an additional phase accumulation, this leads to a substantial error in the acquired B_{1+} map as shown in Fig. 2. Even if the drift lies within the hardware specifications (0.1ppm/h) an error of about 15-20% occurs. We found that an interleaved acquisition scheme is capable to suppress those phase effects. A comparison between DA reference and the achieved results show that the error is lower than 2% over the whole FOV for the interleaved acquisition, whereas the error for the sequential case varies from 17% to more than 50%, depending on the absolute value of B_{1+} (Fig 2). Because of the square root dependency between phase and RF-field the error increases in low B_{1+}-field regions. To show that only the phase drift is responsible for the quantification error, some sequential 2D acquisitions with different delays between both BS-encodings are shown in Fig. 3. The error increases substantially with increasing delay. The 200s delay is about the time required the acquisition of the 16 slices in the 3D case and the error is approximately the same. In an actual 2D scan this effect is negligible due to the comparable low acquisition time.

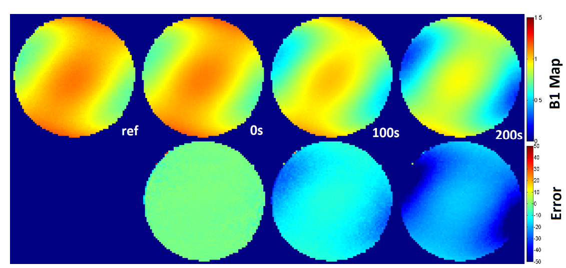

Fig. 3: DA reference measurement and 2D Bloch-Siegert maps acquired with different delays (0, 100 and 200s) between positive and negative BS-encoding and an the deviation to the reference map.

Conclusion: We showed that the phase drift within the scanner is responsible for substantial errors occurring in the BS mapping in 3D. Furthermore, an interleaved acquisition scheme is effective to suppress this influence on Bloch-Siegert B_{1+}-mapping and makes the measurement robust and independent from the operating grade of the system.

References: [1] Sacolick et al. MRM 63:1315-1322 (2010), [2] Pohmann, Scheffler NMR Biomed. 26: 265-275 (2013), [3] Khalighi et al. Proc. ISMRM18:2831 (2010), [4] Stollberger, Wach MRM 35:246-251 (1996)

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