Motion-insensitive sequence for single-voxel determination of B_1^+ by Bloch-Siegert shift in moving organs including the human heart

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INTRODUCTION: Determination of the B_1^+ field based on Bloch-Siegert (BS) shift as suggested by Sacolick et al.[1] uses the fact that an off-resonance RF pulse shifts the resonance frequency of a nucleus. The aim of this study was to develop and test a single-voxel sequence for a B_1^+ determination based on the BS shift that can be used in moving organs like the heart. Since motion during the application of gradients also leads to phase shifts, a major target was the reduction of motion-induced phase shifts during a single-shot sequence which had to be applied twice (including one reference scan without and one scan with BS).

METHODS: A PACE/ECG-triggered PRESS sequence (Fig. 1) with motion-compensated crusher gradients[2,3] and two 8ms Fermi pulses (symmetrically applied around the water resonance, selectable at offsets of ±2 kHz, ±4 kHz, or ±8 kHz, respectively) was developed for a 3T MR-system (VERIO, Siemens, Erlangen Germany). Following validation in a spherical phantom with and without motion, the sequence was applied on skeletal muscle, liver, and heart in 12 young, healthy, normal-weight volunteers (28 ± 4y, 6 volunteers for heart and 6 for muscle and liver). Informed consent was obtained from all volunteers and the study was approved by the Institutional Ethical Committee. A variety of coils was used to evaluate potential coil specific problems: the phantom was measured in a transmit/receive (Tx/Rx) volume coil ($^1H/^{31}P$ head coil, RAPID Biomedical) and a Tx/Rx surface coil ($^1H/^{31}P$, RAPID Biomedical), while skeletal muscle and liver were measured with the surface coil (see above) and the heart with a Tx body coil together with Rx body and spine matrix arrays. The phantom (TE 64.2ms, TR 1500ms, voxel size: 20x20x20mm) was measured at rest and during different types of motion (variation of amplitude and speed) generated by a home-built, MR-compatible, motor-driven device. While skeletal muscle was obviously static, liver was measured PACE-triggered and in breath-hold (TE 64.2ms, TR 1500ms), the heart (ROI in cardiac septum) was recorded with double triggering (PACE navigator for respiratory, ECG-triggering for cardiac motion, TE 64.2ms, TR 800ms, 16 repetitions, total ~2mins, voxel size: 12x25x20mm). B_1^+ was calculated from the phase difference of two single acquisitions with and without the application of Fermi pulses. B_1^+ maps from a work-in-progress (WIP) B_1-mapping package (Siemens, based on the stimulated vs. spin echo responses for a 3 pulse sequence, duration 17s) were obtained for comparison in all cases except for the heart where the measurement was not feasible for the lack of double-triggering of the WIP sequence.

RESULTS: The agreement of the BS sequence with theory was excellent for the phantom at rest and with motion (Fig.2, points horizontally shifted for better visibility). The BS shift follows the theoretical curve (voltage^2/offset) almost perfectly even with motion. At rest, the BS sequence and the B1 mapping WIP sequence agreed very well; however, with increasing motion (Fig.3), the BS sequence produced the same values consistently (10 repetitions each) while the variations and the bias increased dramatically in the WIP imaging sequence. In vivo, the Concordance Correlation Coefficient (CCC) was 0.98 for the muscle measurements between the BS and WIP with a mean flip angle difference of 1.3°. In the liver, the CCC was 0.92 between triggered and breath-hold BS measurements with a mean difference of 0.5°. Mean difference between the triggered BS and WIP measurements was 10.2°. In the heart, the suggested BS sequence showed an excellent stability over 16 repetitions of the single shot measurements (Fig.4, green curve at a B_1^+ that would result in a 90 degree pulse for a 0.5ms long rectangular pulse, blue 150%, red 50% of this amplitude). Average coefficient of variation over 16 identical repetitions in the heart of 6 volunteers was 4.5 %.

DISCUSSION & CONCLUSION: The suggested PACE/ECG-triggered PRESS sequence reveals reliable measurements of B_1^+ with single-shot acquisitions (applied twice - once without BS, once with BS). It is almost immune against motion related perturbations and can even be applied in the beating heart. The sequence has been validated in vitro and in vivo in various organs and with different coil arrangements. Results suggest that the new BS shift based PACE/ECG-triggered modified PRESS sequence is a robust, fast, and easily applicable method for B_1^+ determination in moving organs.

REFERENCES: 1. Sacolick LI, et al, MRM, 63:1315 (2010). 2. Bernstein MA et al, Chapter 10, Handbook of MRI Pulse Sequences (2004) 3. Duan Q et al, NMR Biomed. 26:1070 (2013).

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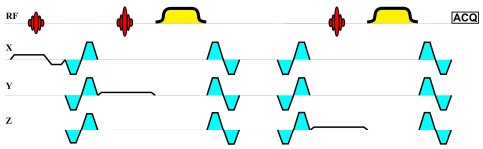

Fig.1: Sequence diagram: The Fermi pulses are indicated in yellow while the motion-compensated crusher gradients are shown in cyan

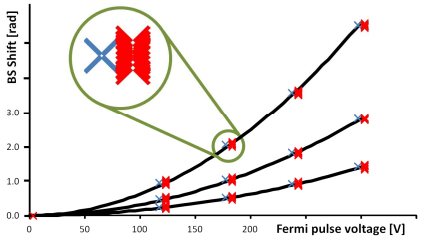

Fig. 2: In vitro voltage and frequency dependence of the BS shift with (red) and without (blue) motion. Black curves show the theoretical fit (voltage^2/offset)

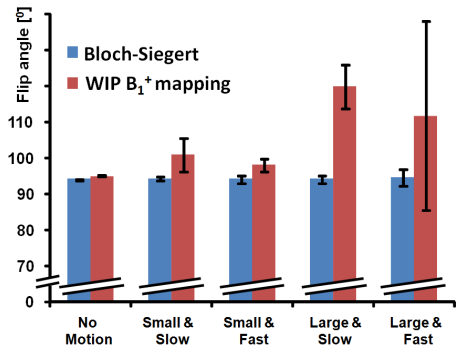

Fig.3: Comparison of the BS sequence with WIP at rest and with increasing motion in a phantom

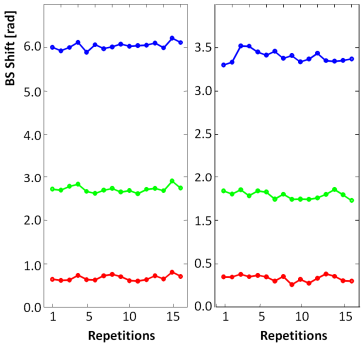

Fig.4: B_1^+ measurements (BS shift) in the human heart by double-triggered BS sequence in 2 subjects with 3 different voltages of the Fermi pulse