Single-Shot Spiral Based Bloch-Siegert $B_1^+$ Mapping

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Purpose: $B_1^+$ mapping has a variety of applications in high field MRI such as designing parallel transmit RF pulses or correcting quantitative relaxometry maps such as those produced by DESPOT [1]. Bloch-Siegert $B_1^+$ mapping was recently introduced as a fast and accurate $B_1^+$ mapping method [2], however, due to the long high-amplitude Bloch-Siegert off-resonant RF pulse, this method suffers from high RF power deposition (SAR) at high field, and this limitation leads to long TR and scan time. We have implemented a Bloch-Siegert $B_1^+$ mapping method with a single-shot spiral acquisition to minimize SAR and scan time, with the goal of whole brain $B_1^+$ mapping at 7T in seconds rather than minutes.

Methods: An optimized off-resonant Bloch-Siegert (BS) pulse [3] with 4 ms pulse width and frequency offset of $\Delta \omega_{\text{res}}=4000 \text{ Hz}$ was added to a spiral-out sequence, with the BS pulse placed after the excitation pulse and before the readout gradient. The refocusing part of the slice select gradient was moved after the BS pulse to act as a crusher for any direct excitation caused by the BS pulse. Fig. 1 shows the complete pulse sequence. The BS-spiral combination was repeated with BS pulse shifted symmetrically above and below resonance by $\pm \Delta \omega_{\text{res}}$ for phase difference processing [2]. On each scan, an additional frame was collected at a longer TE (differing by 2ms) for $B_0$ mapping. The phase difference between the 2nd frames of the two scans was obtained as the BS phase shift. Due to high sensitivity of the optimized off resonance pulse, the BS phase is more than 2$\pi$ so we used a Fourier based phase unwrapping method [4]. Using the BS phase shift map and the $B_0$ map in a full Bloch equation solution, we calculated the $B_1^+$ map. We compared spiral BS $B_1^+$ maps with those produced by a conventional gradient echo based BS $B_1^+$ mapping sequence using the same off-resonant BS pulse.

Results: A multi-slice $B_1^+$ map of a head-neck phantom was acquired by spiral and GRE based BS sequences on a 7T scanner (GE Healthcare, Waukesha). The scan parameters for the GRE sequence were selected as: TE=8.7 ms, TR=50 ms, FOV=24, slice thickness=5 mm, matrix 128×128, FA=40, NEX=1, bandwidth=15.6 kHz, readout=4.096 ms, which led to a 33 s scan time. The scan parameters for the spiral sequence were selected as: TE=8.7 ms TR=80 ms, FOV=24, slice thickness=5 mm, bandwidth=65 kHz, readout=39.708 ms, # interleaves= 1, Freq= 96, kmax=0.5, variable density [5], 128×128 reconstruction matrix, which led to 0.48 s scan time. The BS pulse amplitude was set to the excitation pulse and before the readout gradient. The refocussing part of the slice select gradient was moved after the BS pulse to act as a crusher for any direct excitation caused by the BS pulse. Fig. 1 shows the complete pulse sequence. The BS-spiral combination was repeated with BS pulse shifted symmetrically above and below resonance by $\pm \Delta \omega_{\text{res}}$ for phase difference processing [2]. On each scan, an additional frame was collected at a longer TE (differing by 2ms) for $B_0$ mapping. The phase difference between the 2nd frames of the two scans was obtained as the BS phase shift. Due to high sensitivity of the optimized off resonance pulse, the BS phase is more than 2$\pi$ so we used a Fourier based phase unwrapping method [4]. Using the BS phase shift map and the $B_0$ map in a full Bloch equation solution, we calculated the $B_1^+$ map. We compared spiral BS $B_1^+$ maps with those produced by a conventional gradient echo based BS $B_1^+$ mapping sequence using the same off-resonant BS pulse.

Discussion: This novel single-shot spiral BS sequence is a fast $B_1^+$ mapping method with minimum RF deposition. We have shown here that it can be used for whole brain $B_1^+$ mapping at 7T in a 10 s timeframe, which makes it a good candidate for time-efficient whole-brain $B_1^+/B_0$ calibration for multi-transmit applications. It could also be used as part of prescan to optimize transmit gain quickly and accurately, even in single-transmit applications. Comparison between spiral and GRE sequences shows that the spiral method has a better ANR than GRE method because of its higher sensitivity due to higher BS pulse amplitude (which was not possible with GRE because of SAR limit) but suffers slightly from $B_0$ artifacts in the area with low $B_1^+$. Due to the slow variation in $B_1^+$ maps in the brain, these high frequency artifacts can be easily suppressed by filtering. In addition, the application of improved higher order $B_0$ shimming may reduce these artifacts. The spiral method is easily adaptable to lower field strengths, where the artifacts and overall performance should be even better.


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