Compensating temporal B1 field inhomogeneities using paired self-compensated spin-lock pulses

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Introduction: Spinlock (SL) prepared acquisitions generate a new image contrast that provides molecular-level information from biological systems. An important emerging application of SL is the study of joint damage via mapping of the spin-lattice relaxation time in the rotating frame (T1ρ) [1]. SL preparation is also under investigation as an indirect method to quantify organ oxygen consumption based on T1ρ changes at high and low SL frequencies [2, 3]. In both applications, accurate T1ρ quantification is required. Because SL pulses are usually long, amplitude changes in the B1 field can occur (*e.g.* due to thermal effects of the RF amplifier). Such changes can create imaging artifacts that will introduce errors in the T1ρ quantification. Current methods used to compensate for B0 and B1 field inhomogeneities [4,5] assume a temporally stable B1 amplitude over the course of the SL preparation. Here, we present an improved approach that uses paired self-compensating SL pulses to reduce artifacts from temporal inhomogeneities of the B1 field while preserving the compensation for B0 inhomogeneities.

Methods: Our approach is based on a SL preparation technique described in [5] that employs a self-compensated SL pulse [4] separated by a 180° refocusing pulse (Fig 1a). At the end of this SL preparation the longitudinal magnetization will be:

$$M_Z = \cos^2(90° + \varepsilon_1) \cdot \cos(180° + \varepsilon_2 - \Delta) \cdot e^{\frac{-TSL}{T2\rho}} + \sin^2(90° + \varepsilon_1) \cdot e^{\frac{-TSL}{T1\rho}} \qquad (1)$$

where ε1 and ε2 are flip angle imperfections of the 90° and 180° pulses, respectively, and Δ is the flip angle difference between the first and the second half of the SL pulse. TSL denotes time of SL and T2ρ is spin–spin relaxation time in the rotating frame. To compensate for temporal instabilities of the B1 amplitude, we replaced each half of the SL pulse with a self-compensating SL module that consists of two individual pulses with opposite phases (Fig 1b). Assuming similar temporal B1 imperfections, they are more likely to affect the second self-compensating pulse. In this case the two halves of this pulse will have a flip angle variation of Δ_1 and Δ_2 where $\Delta_1 + \Delta_2 = \Delta$. Because of different phases of the two halves the longitudinal magnetization after the SL preparation will be:

$$M_Z = \cos^2(90° + \varepsilon_1) \cdot \cos(180° + \varepsilon_2 + \Delta_1 - \Delta_2) \cdot e^{\frac{-TSL}{T2\rho}} + \sin^2(90° + \varepsilon_1) \cdot e^{\frac{-TSL}{T1\rho}} \qquad (2)$$

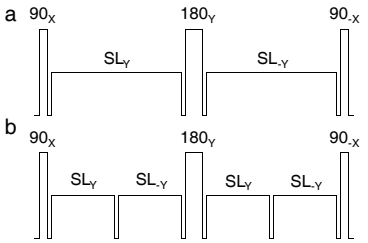

Figure 1: SL preparation with paired self-compensating pulses (b) derived from ΔB0 insensitive composite pulses (a).

We compared the two methods in phantom and *in vivo* experiments on a 7 T animal scanner (Bruker ClinScan). Phantoms containing different agar concentrations ranging from 0.5% to 6% were imaged using a SL prepared fast spin echo sequence. The scan parameters were FOV 55×55 mm, matrix 256×256, TR 1 s, TE 5.3 ms, BW 781 Hz/px, SL frequency 1500 Hz (35.232 μT), and TSL 10-140 ms. For the *in vivo* experiments Wistar rats (body weight about 300 g) were anesthetized with isoflurane. Brain images were obtained with a 2-channel rat head coil and SL prepared sequences with a FOV of 35×35 mm, 128×128 matrix, TR 3 s, TE 5.5 ms, BW 781 Hz/px, SL frequency 1000 Hz (23.487 μT), TSL 10-100 ms. Finally, T1ρ maps were calculated via mono-exponential fitting of the image data acquired with both the original and our modified SL preparation.

Results: The top row of Fig 2 illustrates T1ρ weighted images for TSL = 20 ms at 1500 Hz, recorded on an agar phantom. The original SL preparation (Fig 2a) creates pronounced banding artifacts towards the edges of the phantom (yellow boxes). Paired self-compensating SL pulses remove these artifacts (Fig 2b). Since the frequency of banding is dependent on the TSL, these artifacts will have an impact on the T1ρ quantification as illustrated in the bottom row of Fig 2. The original SL preparation demonstrates large variations in the T1ρ values towards the edge of the phantom (Fig 2c). These variations are considerably reduced when using paired self-compensating SL pulses (Fig 2d). *In vivo* T1ρ weighted images of the rat brain for TSL = 80 ms at 1000 Hz are illustrated in Fig 3 (top row). Similar to the phantom, the original SL preparation produces banding artifacts (yellow boxes in Fig 3a) that are completely removed by the paired self-compensating SL pulses (Fig 3b). The original SL preparation produces a very inhomogeneous T1ρ map in the brain (Fig 3c) which is not expected in a healthy brain. The paired self-compensating SL pulses result in a superior T1ρ homogeneity throughout the brain with values of around 70 ms [6].

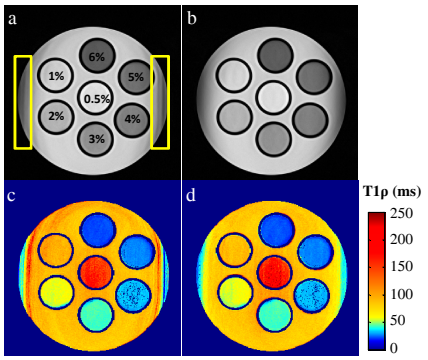

Figure 2: The SL preparation with paired self-compensated SL pulses removes banding artifacts in phantom experiments.

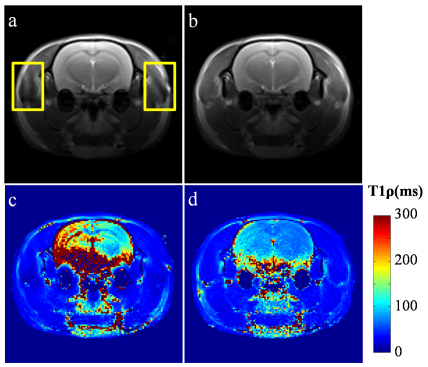

Figure 3: The SL preparation with paired self-compensated SL pulses yields a more homogenous T1rho map by removing banding artifacts *in vivo*.

Discussion: In an ideal situation with a temporally stable B1 field and perfect 90° and 180° pulses, the effect of the two SL preparations should be identical. However, in a real MR system, where spatio-temporal B1 field inhomogeneities are present, we found that paired self-compensating SL preparation performs better in removing imaging artifacts, both *in vitro* and *in vivo*. The paired self-compensating SL modules are shorter, the flip angle difference between the two halves of each pulse is smaller and thereby the SL preparation may be less affected by temporal inhomogeneities of the B1 field. Consequently T2ρ weighting and resulting artifacts are reduced in the final image, which ultimately also improves T1ρ fit accuracy. Using multiple self-compensating pulses might reduce T2ρ weighting even more but this has to be further investigated. We conclude that paired self-compensated SL preparation provides better T1ρ quantification by reducing artifacts due to temporal B1 field inhomogeneities.

References: 1) Regatte RR et al, Radiology 2003;229:269 –274. **2)** Reddy R et al, JMR B 1995;108:276–279. **3)** Tailor DR et al, NeuroImage 2004;22:611–618. **4)** Charagundla SR et al, JMR 2003;162:113–121. **5)** Witschey II WRT et al, JMR 2007;186:75–85. **6)** Tailor DR et al, MRM 2003;49:479–487.