Balanced spin-lock preparation for $B_1$-insensitive and $B_0$-insensitive quantification of the rotating frame relaxation time $T_{1p}$

Maximilian Gram$^{1,2}$ | Michael Seethaler$^{2,3}$ | Daniel Gensler$^{1,3}$ | Johannes Oberberger$^1$ | Peter M. Jakob$^2$ | Peter Nordbeck$^{1,3}$

1Department of Internal Medicine I, University Hospital Würzburg, Würzburg, Germany
2Experimental Physics 5, University of Würzburg, Würzburg, Germany
3Comprehensive Heart Failure Center, University Hospital Würzburg, Würzburg, Germany

Correspondence
Peter Nordbeck, Department of Internal Medicine I, University Hospital Würzburg, Oberdürrbacher Str. 6, Würzburg, DE D-97080, Germany.
Email: nordbeck_p@ukw.de

Funding information
Federal Ministry for Education and Research of the Federal Republic of Germany (BMBF 01EO1504, MO.6)

Purpose: Accurate and artifact-free $T_{1p}$ quantification is still a major challenge due to a susceptibility of the spin-locking module to $B_0$ and/or $B_1$ field inhomogeneities. In this study, we present a novel spin-lock preparation module (B-SL) that enables an almost full compensation of both types of inhomogeneities.

Methods: The new B-SL module contains a second 180° refocusing pulse to compensate each pulse in the preparation block by a corresponding pulse with opposite phase. For evaluation and validation of B-SL, extensive simulations as well as phantom measurements were performed. Furthermore, the new module was compared to three common established compensation methods.

Results: Both simulations and measurements demonstrate a much lower susceptibility to artifacts for the B-SL module, therefore providing an improved accuracy in $T_{1p}$ quantification. In the presence of field inhomogeneities, measurements revealed an increased banding compensation by 79% compared with the frequently used composite module. The goodness of the mono-exponential $T_{1p}$ fitting procedure was improved by 58%.

Conclusion: The B-SL preparation enables the generation of accurate relaxation maps with significantly reduced artifacts, even in the case of large field imperfections. Therefore, the B-SL module is suggested to be highly beneficial for in vivo $T_{1p}$ quantification.

KEYWORDS
artifacts correction, quantitative MRI, relaxation, spin-locking, $T1rho$, $T1p$
1 | INTRODUCTION

Relaxation processes that take place under the influence of a continuous-wave RF pulse (the so-called spin-lock pulse) differ fundamentally from the common spin-spin and spin-lattice relaxation. This was first described in the context of solid-state NMR in 1955 and is now referred to as the spin-lattice relaxation time in the rotating frame T1ρ. In the last decade, T1ρ-based imaging and quantitative techniques such as T1ρ mapping and dispersion measurements have become increasingly popular imaging methods, enabling additional improved contrast mechanisms, as shown in several clinical studies. The T1ρ relaxation mechanism shows high sensitivity for slow motional processes at the molecular and cellular level, and therefore is a useful tool for achieving new specific tissue contrasts. Prominent examples include cartilage imaging in the knee, the detection of myocardial fibrosis, hepatic fibrosis, or applications in the brain. As demonstrated in prior work, the information provided by T1ρ cannot be obtained by conventional spin-lattice or spin-spin relaxation techniques. However, accurate and artifact-free T1ρ quantification is a major challenge with problems specifically arising from the spin-lock (SL) preparation module itself, because its primary implementation shows a high susceptibility to B0 and B1 field inhomogeneities. To date, several improved SL preparation modules have been introduced, such as the rotary echo and the composite SL modules, which overcome some existing limitations. However, the proposed methods cannot compensate all kinds of field imperfections, as the rotary echo module is prone to B0 inhomogeneities and the composite module does not work sufficiently for all needs. Hence, new improved techniques are required to enable robust and artifact-free imaging, potentially increasing routine clinical applications.

Here, we present a new preparation module that features further improvements for compensating B0 and B1 inhomogeneities. The new module is supposed to be completely balanced, meaning that every pulse is compensated by a corresponding pulse with opposite phase.

2 | THEORY

2.1 | Basics of the SL preparation method

The general structure of a SL preparation module (standard spin lock) consists of a 90° excitation pulse, tilting the magnetization by convention to the x'-axis in the rotating frame. Subsequently, a continuous-wave SL pulse is applied on-resonant and in phase to the magnetization with the amplitude fSL, leading to a decay of the SL component with the relaxation time T1ρ. A second 90° flip-back pulse stores the prepared magnetization on the z'-axis. After crushing the residual transverse magnetization, imaging is performed, such as using a spin-echo acquisition. Different T1ρ weightings are generated by variation of the spin-lock time tSL. For quantitative T1ρ mapping, a series of images using different tSL is acquired. The calculation of a T1ρ map is done by fitting the data pixel by pixel to a mono-exponential model.

\[ M_z(t_{SL}) = M_0 \cdot e^{-t_{SL}/T_{1\rho}} \]  

2.2 | Influence of B0 and B1 field imperfections

The main challenge of accurate and artifact-free T1ρ mapping is the susceptibility against field imperfections. Inhomogeneities in the B1 field result in an incorrect execution of excitation and refocusing pulses and change the effective SL field strength. An inhomogeneous B0 field equals an off-resonant application of the SL pulse. The effect on the preparation process can be described in the rotating frame by tilting the effective SL field Be toward the z'-axis direction by the angle θ.

\[ B_e = B_{SL} + \Delta B_0 \]  

\[ \omega_{SL} = 2\pi f_{SL} = \gamma B_{SL}, \Delta \omega_0 = 2\pi \Delta f_0 = \gamma \Delta B_0 \]  

\[ \omega_e = \sqrt{\omega_{SL}^2 + \Delta \omega_0^2} \]  

\[ \theta = \tan^{-1} \left( \frac{\Delta \omega_0}{\omega_{SL}} \right) \]

Both B0 and B1 imperfections result in an unsatisfactory SL condition, with the locked magnetization precessing around the direction of Be (Figure 1A,B). This phenomenon is responsible for the emergence of banding artifacts in the acquired images and leads to a disturbed contrast of mixed T1ρ and T2ρ weighting.

2.3 | Approaches of field compensation

In the past decade, several methods have been proposed to compensate for field imperfections, thus ensuring a more robust SL preparation. In this context, the use of adiabatic excitation pulses and adiabatic spin locking is often discussed as an effective method. In this work we focus on improving the on-resonant spin-lock technique, which concerns the spin-lock block of the pulse sequence itself. The first approach for optimizing the SL block was introduced by Charagundla et al and is known as rotary echo (RE-SL).
FIGURE 1  A,B, Spin-lock (SL) process in rotating frame (x’ y’ z’) and tilted rotating frame (x’’ y’’ z’’) coordinates. The graphs show 3D trajectories of magnetization during the SL process in the presence of a B1 (A) and B0 (B) field imperfection. The SL component decays according to an exponential function with $T_{1ρ}$. The envelope of the oscillating spin-tip components decays with $T_{2ρ}$. The schematics (C-F) show pulse sequences of SL preparation modules that use different strategies for the compensation of field imperfections: rotary echo (RE-SL) (C), composite (C-SL) (D), and paired self-compensated (PSC-SL) (E). F, Pulse-sequence schematic of the presented balanced SL module, consisting of three SL pulses and two refocusing pulses using opposite phases for maximum symmetry.

(Figure 1C). Here, the SL pulse is separated into two pulses with equal duration and opposite phases. This method aims at compensation of B1 inhomogeneities, but does not provide a suppression of artifacts caused by B0 imperfections. For this purpose, Witschey et al introduced an extension known as composite SL (C-SL) (Figure 1D). In this case, a 180° refocusing pulse is applied between the SL pulses, resulting in an additional compensation for B0 imperfections. A further extension of this method was presented by Mitrea et al, which again divides the two SL pulses. This paired self-compensated module (PSC-SL) (Figure 1E) consists of four SL pulses of alternating phases and one 180° refocusing pulse. As shown in Mitrea et al, the PSC-SL module offers lower artifact susceptibility compared with the C-SL module in the particular case of small $f_{SL}$ and large inhomogeneities.

2.4 | Concept of balanced spin locking

The addition of a 180° refocusing pulse is designed specifically to compensate for B0 inhomogeneities. However, a fatal error occurs if the refocusing pulse is misapplied due to B1 imperfections. In this case, even an increase in artifact formation is possible. For this reason, a second refocusing pulse has been included in our novel SL preparation module (Figure 1F). Here we use an opposite phase (-x) according to the rotary-echo principle. Refocusing issues caused by B1 imperfections during application of the refocusing pulses will therefore be balanced. The spin locking itself has been subdivided into three pulses also using alternating phases. Consequently, the B-SL module uses maximum symmetry, in which each pulse is compensated by a complementary pulse of opposite phase, ensuring an optimized B0 and B1 inhomogeneity compensation with minimal artifact formation.

3 | METHODS

To analyze the susceptibility of our new B-SL module to field inhomogeneities, various comparisons with the established SL modules described before have been performed. The comparisons were performed in three different ways. First, detailed analytical calculations of the SL trajectories were examined for pure B1 and B0 imperfections. Second, extensive numerical simulations were performed, which compare the $T_{1ρ}$ quantification accuracy and artifact susceptibility. In the final step, the theoretical results were
validated on a 7T small animal imaging system in phantom experiments.

### 3.1 Analytical comparison

The analytical comparison of the preparation modules was based on an approach for calculating spin-lock trajectories using matrix propagators. The formalism is described in detail in Supporting Information S1. Dependencies of banding and relaxation behavior can be derived from the solution functions in the case of only B₀ and only B₁ inhomogeneities.

### 3.2 Numerical Bloch simulations

The numerical simulations take the simultaneous occurrence of B₀ and B₁ field inhomogeneities into account and were performed in MATLAB (R2017a; The MathWorks, Natick, MA). The simulations reflect the effect on the T₁ρ quantification experiment. Instead, as in most in vivo experiments, the range of ±600 Hz (2 ppm at 7 T) and for the B₁ imperfections the range of ±50% was observed. Here, 100 × 100 cases were distinguished for each module. Using the matrix propagator formalism, the prepared magnetization Mₑ was calculated for different SL times using N = 2000 linearly spaced sampling points (ΔtSL = 0.1 ms) in the range 0 … 2T₁ρ. These nearly continuously sampled trajectories were used to analyze the banding susceptibility by calculating the residual sum of squares (RSS) in relation to a mono-exponential fit. In contrast, the quantification accuracy was not determined from the global fit (2000 sample points), as this does not correspond to the realistic conditions of a T₁ρ experiment, which was calculated from the fitted value T₁ρ,fit and the value T₁ρ,true = 100 ms, which was actually defined in the simulation. For the selection of random sampling points, the range 0 … 200 ms was divided into eight equally sized areas from which uniformly distributed samples were drawn. This ensures a sufficient sampling of the exponential decay. The comparison of the different modules was always based on identical random numbers. The simulation was repeated and evaluated for various fSL (100 Hz … 4 kHz) and various T₁ρ:T₂ρ ratios (1:5 … 5:1) to finally compare and rate the performance of the preparation modules.

### 3.3 Experimental validation

For experimental validation, the preparation modules (RE-SL, C-SL, PSC-SL, and B-SL) were implemented on a 7T small animal imaging system (Bruker BioSpec 70/30, Bruker BioSpin MRI, Ettlingen, Germany) based on a turbo spin-echo acquisition. In contrast to the numerical simulations, the experiment cannot be based on the quantification accuracy. This is because an equivalent procedure cannot be carried out in any realistic measurement time, and the true T₁ρ relaxation time of a phantom is not known due to the lack of a gold-standard method for a definitely determined. Therefore, the simulation results were validated by a comparative study analyzing the banding susceptibility and the quality of the mono-exponential fit (RSS) in a large number of phantom measurements. The phantom in use consisted of a homogeneous cylindrical sample tube filled with an aqueous solution of agar (2%). The T₁ρ-weighted images were taken in a transverse slice (FOV = 32 × 32 mm², matrix = 96 × 96, thickness = 2.5 mm). Further imaging parameters were TE = 7.3 ms, TR = 5000 ms, and turbo factor = 4.

To compare the preparation modules in different cases of B₀/B₁ field inhomogeneities, targeted disorders of the SL process were carried out in addition to the natural inhomogeneities of the selected slice. The natural inhomogeneities were obtained by B₀/B₁ mapping and determined to be ΔB₁,max ≈ 10.6% and ΔB₀,max ≈ 0.11 ppm. An additional disorder of the B₁ field was caused using incorrect flip angles (up to −25%) of the excitation and refocusing pulses within the preparation modules. Furthermore, B₀ imperfections were increased using specific off-resonances (up to +1 ppm) for the SL pulses. Both cases lead to a violation of the SL condition and cause distinct banding artifacts in the T₁ρ-weighted images. Measurements were performed for all modules at different tSL (4, 12, 20, 28, 36, 44, 52, and 60 ms), fSL (500, 1000, 1500, and 2000 Hz), B₁ (0, −5, −10, −15, −20, and −25%), and B₀ (0, 0.2, 0.4, 0.6, 0.8, and 1.0 ppm) disorders. With 1536 measurements in total, a high coverage of an experimentally relevant parameter scope was achieved. As a measure of artifact susceptibility, the SD σ of the signal intensities has been determined within a circular region of interest. The quality of mono-exponential fitting
was specified by the mean observed RSS. To compare the overall performance of the different modules, the SDs $\sigma$ and the RSS values of identical experiments were each normalized on a scale of $0 \ldots 1$. With this procedure it was possible to compare a large number of individually different experiments on an equal basis and to statistically evaluate the overall result.

4 | RESULTS

4.1 | Analytical comparison

The analytical calculations of SL trajectories provide information about the susceptibility of the SL pulses to artifact formation and the influence of the excitation and refocusing pulses as well as off-resonance effects. The results show that perfect compensation of field inhomogeneities is not possible with any module (Supporting Information Table S1). However, clear differences can be identified. In contrast to RE-SL and PSC-SL, the B-SL module shows neither banding terms for $B_0$ nor $B_1$ imperfections. Compared with PSC-SL and C-SL, B-SL is not dependent on the quality of the refocusing pulse.

4.2 | Numerical Bloch simulations

The concept for evaluating the simulation results is shown in Figure 2. Comparing C-SL and B-SL for a special $B_0/B_1$ scenario, it appears that B-SL exhibits a lower oscillation level (lower RSS) and leads to fewer quantification errors (lower $\Delta Q$), yielding a higher accuracy in the synthetic experiments (Figure 2C).

The quantitative indicators $\Delta Q$ (Figure 3A) and RSS (Supporting Information Figure S2A) were calculated on a grid of $100 \times 100$ different field constellations and are visualized as heat maps. The RE-SL module appears to offer an effective compensation mechanism for $B_1$ inhomogeneities, as expected. Both indicators rise rapidly with increasing $B_0$ imperfections. In the case of C-SL, PSC-SL and B-SL, the compensation mechanism for $B_0$ is clearly visible for both indicators. The B-SL module provides the best $B_1$ compensation. The results of the $f_{SL}$ analysis are depicted in Figure 3B and Supporting Information Figure S2B. Here, a lower susceptibility to bandings and a better quantification accuracy in the case of high amplitudes can be identified for all modules. Figure 3C and Supporting Information Figure S2C show the results of the detailed analysis of the relaxation-time ratio influence. The best behavior is reached for the case of $T_{1p}:T_{2p} \approx 1$. Comparing the overall performance of the modules, B-SL achieves the best result for both indicators, various amplitudes, as well as various relaxation-time ratios. The average performance is outmatched by a factor of 3.58 (RE-SL), 2.04 (C-SL), and 2.87 (PSC-SL).
4.3 | Experimental validation

The measurements with no additional $B_0$ or $B_1$ imperfections show the same $T_1\rho$ quantification for all preparation modules. The B-SL module achieves the values $T_{1\rho,500\text{ Hz}} = 48.05 \pm 0.66 \text{ ms}$, $T_{1\rho,1000\text{ Hz}} = 49.69 \pm 0.67 \text{ ms}$, $T_{1\rho,1500\text{ Hz}} = 50.57 \pm 0.66 \text{ ms}$, and $T_{1\rho,2000\text{ Hz}} = 51.69 \pm 0.69 \text{ ms}$ with the four spin-lock amplitudes used. The modules indicate the same dispersion behavior, with the highest deviation between the modules being 0.77%. Figure 4 shows exemplary $T_1\rho$-weighted images, $T_{1\rho}$ maps, and RSS maps of the four different preparation modules. In Figure 4A, in which a $B_1$ disorder for the excitation and refocusing pulses has been used, C-SL and PSC-SL exhibit slight artifacts. The RE-SL and B-SL modules provide the most reliable $T_1\rho$-weighted images, as proven by the corresponding $T_1\rho$ and RSS maps. Figure 4B shows images with off-resonant SL pulses. Here, the occurrence of banding artifacts is clearly visible for all modules. The RE-SL module, without any $B_0$ compensation, exhibits the highest banding intensity. Comparing the remaining three modules, B-SL achieves a substantial improvement.

The statistical analysis of the 1536 individual experiments using the normalized indicators $\sigma$ and RSS are depicted in Figure 5. As expected from theory, RE-SL yields good banding and RSS performance in the case of $B_1$ imperfections, but achieves the worst overall results in the case of $B_0$ imperfections. The C-SL module shows the opposite behavior to RE-SL. We found poor banding and RSS performance in the case of $B_1$ disorders and good performance in the case of $B_0$ disorders. The PSC-SL module shows an anomaly for $B_1$ disorders, with a high banding susceptibility and good RSS performance at the same time. This effect occurs when the $T_1\rho$-weighted images show distinct artifacts, which decay mono-exponentially. In the case of $B_0$ disorders, a medium banding susceptibility and a good RSS performance could be determined. The results of B-SL show good banding and RSS performance for both $B_1$ and $B_0$ imperfections. This is also evident in the combined statistics of both scenarios. Compared with the established modules, the banding performance could be increased by 84% (RE-SL), 79% (C-SL), and 86% (PSC-SL). The RSS performance was increased by 70% (RE-SL), 58% (C-SL), and 30% (PSC-SL).
In the present work, a new spin-lock preparation module has been presented. The new method has been validated and compared in analytical, numerical, as well as experimental studies, showing a superior behavior to other previously published SL preparation techniques. The results of the three investigation methods are consistent and demonstrate an improved robustness as well as a much less artifact formation for combined $B_0/B_1$ inhomogeneities. This confirms that the concept of a second complementary refocusing pulse within the B-SL module provides further stabilization of the spin-lock process.

When interpreting the simulation results, it must be considered that spin relaxation and spin dynamics under the influence of the SL pulse are highly complex processes. It is known from relaxation theory that $T_{1\rho}$ and $T_{2\rho}$ depend on both amplitude and off-resonance of the locking field. The simulation examines the influence of spin dynamics on the accuracy of a $T_{1\rho}$ mapping experiment. Therefore, we studied banding artifacts leading to quantification errors. The influence of $T_{1\rho}$ dispersion, which is described in the theory of spin relaxation, was not considered. Furthermore, matrix propagators were used for the Bloch simulation, which represent efficient modeling of a preparation module. Using this approach, however, the influence of the pulse shape and pulse amplitude of the excitation and refocusing pulses is not taken into account. As a result, the $B_0$ susceptibility of these pulses is not considered in the simulation results. Low amplitude pulses are expected to increase artifact formation. Furthermore, the simulation is based on the single pool model. Influences of the excitation and refocusing pulses on

**FIGURE 4** Examples of experimental results based on phantom measurements with agar. For each preparation module, four $T_{1\rho}$-weighted images ($t_{SL} = 12, 28, 44,$ and $60$ ms) and the corresponding $T_{1\rho}$ and RSS maps are listed for $f_{SL} = 1500$ Hz. A, We set a specific $B_1$ deviation of $-15\%$. B, An off-resonance of the SL pulses of $0.4$ ppm was used. The banding artifacts (SD of intensity) of the $T_{1\rho}$-weighted images and the RSS values of the mono-exponential fits are used as quantitative indicators for statistical analysis in Figure 5.
the multipool situation were therefore not examined. The results of the simulation using matrix propagators are nevertheless clear and indicate a significantly improved quantification accuracy for B-SL in the context of strong B₀/B₁ field inhomogeneities. Compared with the C-SL module, which has been used in numerous studies, an increase in absolute performance by a factor of 2.04 could be observed.

The simulation results were validated using a large series of measurements, in which the different modules were compared directly for identical experiments. The dispersion behavior of T₁ρ could be observed equally for all modules in the case of no additional field imperfections. Using the simultaneous analysis of the banding intensity and the RSS value, both the image quality and the goodness of the mono-exponential T₁ρ mapping were validated in the statistical evaluation. This prevents a result showing good RSS but high spatial artifact formation (and vice versa) from being incorrectly rated as a high performance. It could not be proven that the B-SL module delivers the best result in every single combination of B₀/B₁ inhomogeneity. However, B-SL shows a significantly increased performance in the evaluation of the entire series of measurements. Above all, an increased robustness against banding artifacts could be determined, which leads to a significant improvement in image quality and quantification accuracy. Compared with C-SL, the banding performance was increased by 79% in the combined B₀/B₁ evaluation. Under the same conditions, the goodness of mono-exponential T₁ρ fitting, which was determined through the RSS performance, was improved by 58%.

The results of the phantom experiments show a lower increase in performance than predicted by the simulation. However, the absolute performance values are not directly comparable and depend on the choice of simulation and measurement parameters. In the simulation, very large parameter spaces were used, whereas in the experimental setup parameters were selected that are most relevant for T₁ρ-based imaging.

The presented work only considers on-resonant spin-lock techniques. The use of adiabatic excitation pulses enables the spin-lock preparation to be further stabilized, as previous studies have already shown. Furthermore, the new balanced spin-lock technique was not compared with fully adiabatic methods. This or a combination of B-SL with a constant amplitude technique is interesting for future studies.

Due to its high robustness against field imperfections, B-SL is particularly suitable for the use at high field strengths or for cardiac applications. A drawback of our new method is the increased specific absorption rate, due to the additional refocusing pulse. In the worst case, the rise in specific
absorption rate for the $T_{1\rho}$ mapping experiments carried out in this work was in the lower single-digit percentage range. However, this increase is negligible if high spin-lock amplitudes or adiabatic excitation pulses are used for the preparation. Hence, compared with composite modules that use a single adiabatic refocusing pulse, our method even offers a reduction in specific absorption rate.

6 | CONCLUSIONS

The new B-SL module is a consequent extension and optimization of the popular C-SL module. To the best of our knowledge, B-SL currently provides the most stable $T_{1\rho}$ preparation using on-resonant pulse sequences. The implementation of B-SL is simple and straightforward, and therefore simplifies the reproducibility on different scanners. This might enable its everyday use in clinical routine for a variety of applications.

ACKNOWLEDGMENTS

This work was supported by the Federal Ministry for Education and Research of the Federal Republic of Germany (BMBF 01EO1504, MO.6). Open access funding enabled and organized by Projekt DEAL.

ORCID

Maximilian Gram https://orcid.org/0000-0003-2184-3325
Peter Nordbeck https://orcid.org/0000-0002-2560-4068

REFERENCES

1. Redfield AG. Nuclear magnetic resonance saturation and rotary saturation in solids. Phys Rev. 1955;98:1787-1809.
2. Bull TE. Relaxation in the rotating frame in liquids. Prog Nucl Magn Reson Spectrosc. 1992;24:377-410.
3. Wang YJ, Zhang Q, Li X, Chen W, Ahuja A, Yuan J. $T_{1\rho}$ magnetic resonance: Basic physics principles and applications in knee and intervertebral disc imaging. Quantitative Imaging in Medicine and Surgery. 2015;5:858-885.
4. Spear JT, Gore JC. New insights into rotating frame relaxation at high field. NMR Biomed. 2016;29:1258-1273.
5. Gilani IA, Sepponen RE. Quantitative rotating frame relaxometry methods in MRI. NMR Biomed. 2016;29:841-861.
6. Duvvuri U, Goldberg AD, Kranz JK, et al. Water magnetic relaxation dispersion in biological systems: The contribution of proton exchange and implications for the noninvasive detection of cartilage degradation. Proc Natl Acad Sci. 2001;98:12479-12484.
7. Mäkelä H, Gröhn OHJ, Kettunen ML, Kauppinen RA. Proton exchange as a relaxation mechanism for $T_1$ in the rotating frame in native and immobilized protein solutions. Biochem Biophys Res Comm. 2001;289:813-818.
8. Akella SVS, Regatte RR, Wheaton AJ, Borthakur A, Reddy R. Reduction of residual dipolar interaction in cartilage by spin-lock technique. Magn Reson Med. 2004;52:1103-1109.
9. Wheaton AJ, Borthakur A, Kneeland JB, Regatte RR, Akella SVS, Reddy R. In vivo quantification of $T_{1\rho}$ using a multislice spin-lock pulse sequence. Magn Reson Med. 2004;52:1453-1458.
10. Heckelman LN, Smith WAR, Rofio AD, et al. Quantifying the biochemical state of knee cartilage in response to running using $T_{1\rho}$ magnetic resonance imaging. Sci Rep. 2020;10:1870.
11. Witschey WRT, Pilla JJ, Ferrari G, et al. Rotating frame spin lattice relaxation in a swine model of chronic, left ventricular myocardial infarction. Magn Reson Med. 2010;64:1453-1460.
12. Han Y, Liimatainen T, Gorman RC, Witschey WRT. Assessing myocardial disease using $T_{1\rho}$ MRI. Current Cardiovascular Imaging Reports. 2014;7:9248.
13. Qi H, Bustin A, Kuestner T, et al. Respiratory motion-compensated high-resolution 3D whole-heart $T_{1\rho}$ mapping. J Cardiovasc Magn Reson. 2020;22:12.
14. Koon C-M, Zhang X, Chen W, et al. Black blood $T_{1\rho}$ image acquisition may diagnose early stage liver fibrosis: A proof-of-principle study with rat biliary duct ligation model. Quant Imaging Med Surg. 2016;6:353-363.
15. Chen W, Chan Q, Wáng YJ. Breath-hold black blood quantitative $T_{1\rho}$ imaging of liver using single shot fast spin echo acquisition. Quant Imaging Med Surg. 2016;6:168-177.
16. Sharafi A, Baboli R, Zibetti M, et al. Volumetric multicomponent $T_{1\rho}$ relaxation mapping of the human liver under free breathing at 3T. Magn Reson Med. 2020;83:2042-2050.
17. Barajas RF, Villanueva-Meyer J, Perry A, Berger M, Cha S. Biologically aggressive regions within glioblastoma identified by spin-lock contrast $T_1$ relaxation in the rotating frame ($T_{1\rho}$) MRI. Radiol Case Rep. 2017;12:827-832.
18. Menon RG, Sharafi A, Windschu J, Regatte R. Bi-exponential 3D–$T_{1\rho}$ mapping of whole brain at 3T. Sci Rep. 2018;8:1176.
19. Sepponen RE, Pohjonen JA, Sipponen JT, Tanttu JI. A method for $T_{1\rho}$ imaging. J Comput Assist Tomogr. 1985;9:1007-1011.
20. Chen W. Errors in quantitative $T_{1\rho}$ imaging and the correction methods. Quant Imaging Med Surg. 2015;5:583-591.
21. Charagundla SR, Borthakur A, Leigh JS, Reddy R. Artifacts in $T_{1\rho}$-weighted imaging: Correction with a self-compensating spin-locking pulse. J Magn Reson. 2003;162:113-121.
22. Zeng H, Daniel G, Gatenby C, Zhao Y, Avision M, Gore JC. A composite spin-lock pulse for $\Delta B_0 + B_1$ insensitive $T_{1\rho}$ measurement. In: Proceedings of the 14th Annual Meeting of ISMRM, Seattle, Washington, 2006. p 2356.
23. Witschey WRT, Borthakur A, Elliott MA, et al. Artifacts in $T_{1\rho}$-weighted imaging: Compensation for B1 and B0 field imperfections. J Magn Reson. 2007;186:75-85.
24. Moran PR, Hamilton CA. Near-resonance spin-lock contrast. Magn Reson Imaging. 1995;13:837-846.
25. Schuenke P, Koehler C, Korzowski A, et al. Adiabatically prepared spin-locking pulse. J Magn Reson. 2007;186:75-85.
26. Chen W. $T_{1\rho}$-weighted imaging: Correction with a self-compensating spin-locking pulse. J Magn Reson. 2003;162:113-121.
27. Zeng H, Daniel G, Gatenby C, Zhao Y, Avision M, Gore JC. A composite spin-lock pulse for $\Delta B_0 + B_1$ insensitive $T_{1\rho}$ measurement. In: Proceedings of the 14th Annual Meeting of ISMRM, Seattle, Washington, 2006. p 2356.
28. Mitrea BG, Krafft AJ, Song R, Loeffler RB, Hillenbrand CM. Paired self-compensated spin-lock preparation for improved $T_{1\rho}$ quantification. J Magn Reson. 2016;268:49-57.
SUPPORTING INFORMATION
Additional Supporting Information may be found online in the Supporting Information section.

S1 Calculation of SL trajectories
FIGURE S2 Comparison of the preparation modules using numerical Bloch simulations. In (A) the indicator RSS is shown as heat maps depending on $B_0$ and $B_1$ imperfections in the case $f_{SL} = 500 \text{ Hz}$ and $T_{1p} : T_{2p} = 1$. In (B) the proportions of indicators that meet the criteria $RSS < 0.01$ is shown for various SL amplitudes and $T_{1p} : T_{2p} = 1$. In (C) the proportions for various relaxation time ratios and $f_{SL} = 500 \text{ Hz}$ is shown. The RSS scale was normalized by the number of sampling points 2000

TABLE S1 Propagator matrices $B$ of the different preparation modules (A). The propagator describes the entire operation that the preparation module makes on the effective magnetization. In the simplified case of pure $B_1$ (B) and pure $B_0$ (C) inhomogeneities, the prepared magnetization can be represented exactly by analytical means. To simplify matters, $M_0 = 1$ was used. The check boxes indicate which external disruptive factors the respective modules are able to compensate for

How to cite this article: Gram M, Seethaler M, Gensler D, Oberberger J, Jakob PM, Nordbeck P. Balanced spin-lock preparation for $B_1$-insensitive and $B_0$-insensitive quantification of the rotating frame relaxation time $T_{1p}$. Magn Reson Med. 2021;85:2771–2780. https://doi.org/10.1002/mrm.28585