Efficient Imaging Parameters for Quantitative 3D T1rho Mapping of the Brain

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PURPOSE: Spin-lattice relaxation in the rotating frame (T1ρ) and its variants are promising quantitative biomarkers for a number of brain diseases such as Alzheimer's disease [1], Parkinson's disease [1,2], multiple sclerosis [3,4], glioma [5,6], and stroke [7]. However, clinical demonstrations of T1ρ brain mapping have often been limited to imaging a single 2D slice due to acquisition time constraints (e.g., Refs. 1, 4, and 5). Whole-brain, high-resolution 3D approaches may greatly improve the potential research and clinical utility of T1ρ mapping. Segmented 3D GRE and FSE sequences have now been developed for volumetric T1ρ mapping that acquire multiple views per spin-lock preparation pulse, greatly improving acquisition efficiency [8,9]. Initial work with these sequences has focused on knee imaging, and the 3D FSE technique has been demonstrated for high-resolution brain imaging [10]. In this work, we aim to further refine 3D T1ρ mapping of the brain using a segmented 3D GRE sequence and a recently-described framework for optimal selection of spin-lock times (TSLs) based on estimation of T1ρ precision (σ) [11]. Tradeoffs between selection of TSLs, longitudinal magnetization recovery time (T_{rec}), views per segment (VPS), and image acceleration (R) are evaluated to yield efficient whole-brain T1ρ maps.

METHODS: ***Theory:*** High-resolution 3D mapping aims to deliver rapid, accurate, and precise quantification of T1ρ. However, these targets are in competition and must be balanced by various imaging parameters. The segmented 3D GRE and FSE sequences share many common elements, including: (i) magnetization saturation pulse with recovery time T_{rec}; (ii) self-compensated T1ρ preparation with adjustable TSL; and (iii) acquisition of multiple views per segment (VPS) with an SNR-efficient elliptical-centric variable flip angle (VFA) scheme. The 3D GRE sequence adds RF cycling [13] to remove T1-dependent effects. Typically, a particular mapping application will require a specific imaging resolution and T1ρ precision (σ), which can be considered fixed parameters. One goal in selecting protocol parameters is to acquire sufficient spatial resolution and precision within the shortest possible acquisition time. Recent work has shown that when assuming a mono-exponential decay model and linear regression fitting of T1ρ, $\sigma \propto 1/[SNR_0 \cdot f(TSLs)]$, where SNR_0 is the base SNR of the sequence when no spin-locking is applied and f(TSLs) is a closed-form function of the TSL sampling schedule [11]. SNR_0 can be expressed using the adjustable parameters of the 3D GRE and FSE mapping sequences: $SNR_0 \propto (\sin\alpha)\left(1\text{-}e^{-Trec/T1}\right)\left(1/g\sqrt{R}\right)$, where α is the first flip angle of the VFA schedule and depends on VPS, R is an optional image acceleration factor (e.g., using sensitivity encoding or elliptical sampling), and g is the acceleration-related noise amplification (i.e., g-factor). The acquisition time (T_{acq}) can in turn be approximated as: $T_{acq} \approx (N_y \cdot N_z)(T_{rec}+TR \cdot VPS)(1/VPS)(1/R)(N_{TSLs})$, where TR is the repetition time for a view and N_{TSLs} is the total number of TSLs acquired including those for RF cycling. Using these expressions for σ and T_{acq}, imaging parameters can be varied to determine which combination yields the shortest T_{acq} for a desired T1ρ precision (σ) threshold and spatial resolution.

Simulations: Sequence parameters (f(TSLs), N_{TSLs}, T_{rec}, VPS with associated α, and R with an estimated g) were systematically varied to determine σ and T_{acq} for a broad search space. Values were calculated assuming the following fixed parameters: N_y=N_z=128, TR=5.6 ms, T1=1200 ms, and maximum SNR_0=500 (T_{rec}>>T1, α=90º, VPS=1, R=1). The best sequences were selected as those that minimized T_{acq} for a given σ threshold. f(TSLs) assumes a range of T1ρ relaxation times of interest, and optimal TSL schedules can be determined based on a cost function. Here we assumed a T1ρ range of 60-120 ms for brain tissue, and optimal TSL schedules were those that maximized the minimum T1ρ SNR (T1ρ/σ) over the T1ρ range [11]. A separate simulation was performed for RF-cycled acquisitions by constraining optimal TSL schedules to only include those with TSL pairs, one with normal magnetization and the other with inverted magnetization.

In Vivo Demonstration: A volunteer was imaged using a segmented 3D GRE sequence with RF cycling and both an acquisition-time-efficient and a typical set of imaging parameters, providing a qualitative comparison of T1ρ maps. Informed consent and IRB approval were obtained. Imaging was performed on a 3T Siemens MRI system using a 12-channel head coil. The time-efficient map used the parameters shown in Table 1 for σ<20 ms (with RF cycling), which represents a particularly rapid acquisition strategy. The typical map used parameters T_{rec}=1500 ms, VPS=64, TSLs=[10,30,50,70,90] ms (×2 for RF cycling), and R=1, which has a comparative precision threshold of σ<4.3 ms. TSL images were sagittally oriented with FOV=22×22×20 cm^2, matrix=128×128×40, and, for the time-efficient map, R=3 GRAPPA applied along the A/P phase-encoding direction. Additional parameters included TR/TE=5.6/2.53 ms, elliptical sampling, and B_1 spin-lock frequency=400 Hz.

Table 1: Simulated acquisition-time-efficient imaging parameters.

Precision (ms)	RF Cycling	T_{acq} (sec)	T_{rec} (ms)	VPS	TSLs (ms)	R
σ < 2.5	No	4400	1600	26	10, 100 (×2), 110	1
	Yes	5635	1500	29	10 (×2), 100 (×4)	1
σ < 5	No	1244	1700	127	10, 100 (×2), 110	1
	Yes	1925	1300	93	10 (×2), 100 (×4)	1
σ < 10	No	481	1100	121	10, 90	1
	Yes	871	800	104	10 (×2), 90 (×2)	1
σ < 20	No	257	1200	119	10, 90	2
	Yes	451	1400	93	10 (×2), 90 (×2)	3

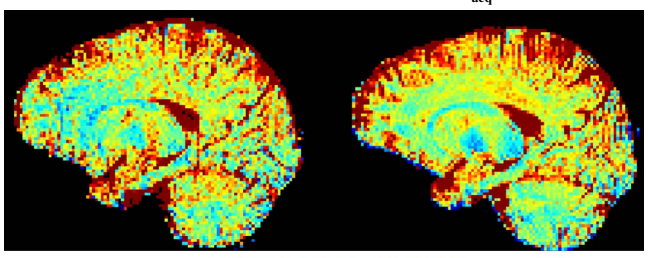

Figure 1: T1ρ maps acquired using (**A**) time-efficient and (**B**) typical imaging parameters. The time-efficient map has relatively low precision but was generated very rapidly.

RESULTS: The simulated sets of imaging parameters to yield target σ thresholds within the shortest possible acquisition times are shown in Table 1 with and without the TSL constraint of RF cycling. Note that σ and T_{acq} can be scaled relative to maximum SNR_0=500 and total number of views (128×128), respectively. Representative sagittal slices of the T1ρ maps generated using the time-efficient and typical imaging parameter sets are shown in Figure 1. The true map acquisition times are indicated.

DISCUSSION: Segmented 3D GRE and FSE sequences for quantitative mapping permit a wide range of possible imaging parameters, and the optimal set is not obvious. Here we provide efficient imaging parameters focused on reducing acquisition time. Such optimizations are an important step toward improving the utility and impact of 3D T1ρ mapping. Parameters must be carefully selected based on the resolution, precision, accuracy, and acquisition time requirements for a particular application.

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