Slice-Accelerated Inversion Recovery T_1 Mapping

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Purpose

Parametric T_1 mapping using inversion recovery (IR) has competing requirements for speed, signal-to-noise ratio (SNR), spatial resolution, anatomical coverage, and adequate sampling of the longitudinal magnetization recovery. A technique with very fast sampling of the magnetization recovery consists of an inversion pulse followed by a series of rapid single-slice low flip-angle pulses (i.e. Look-Locker; LL) and EPI readout, which can sample inversion times (TI) every 50-100 ms depending on the spatial resolution. This technique is referred to here as LL-IR-EPI. Such rapid TI sampling allows the modeling of multi-exponential T_1 recovery, and can be fast enough (<3 seconds) to support dynamic T_1 mapping during contrast injection [1]. For some applications, EPI can be limited by image distortions, ghosting, and susceptibility artifacts, in which case TurboFLASH [2] (TFL) may be preferred (referred to here as LL-IR-TFL). Although TFL has better image quality than EPI, it is slower and can only achieve TI measurements spaced every ~250-500 ms. Both of these single-slice approaches have low SNR because of the small flip-angles required for the short repetition times (TR) used.

For many applications, full coverage of the anatomy of interest is more important than rapid TI sampling and scan time. One approach involves a non-selective IR pulse followed by 2D multi-slice echo-planar imaging (EPI), which is repeated with the EPI slice acquisition order permuted each time such that each slice experiences a different effective TI within each repetition [3,4] (referred to here as shuffled-IR-EPI). This can achieve T_1 maps with 16-64 slices having 16-64 TI points in 3-10 minutes. The SNR is high because a large flip-angle excitation pulse (90°) can be used with the typically long TR.

Slice-accelerated (SliceAcc) multi-slice techniques (sometimes referred to as "multiband") utilize RF pulses which excite multiple 2D slices simultaneously [5-8]. As all of k-space is still measured, SliceAcc has the benefit of acquiring more slices per unit time without the SNR penalty associated with parallel imaging or partial Fourier approaches. Recent advances in acquisition schemes (such as CAIPIRINHA [6]) and image reconstruction (such as slice-GRAPPA [8]) have made SliceAcc practical. Here, we describe the implementation and application of simultaneous multi-slice techniques to accelerate quantitative T_1 mapping, providing increased slices and/or TI points acquired in a given measurement time.

Methods

Slice-acceleration was implemented for LL-IR-TFL, LL-IR-EPI, and shuffled-IR-EPI. First, a separate calibration scan to be used later for the SliceAcc image reconstruction is acquired without an inversion pulse using standard 2D excitation slices. This calibration scan takes less than 10 seconds for EPI, and less than 40 seconds for TFL. Next, a non-selective IR pulse inverts the magnetization throughout the imaging volume, and is followed by the primary imaging kernel (either single-shot EPI or TFL) which is repeated N_{TI} times. This is followed by a magnetization recovery period before another IR pulse is applied. In the case of LL-IR-EPI, the slice ordering is permuted relative to the IR pulse for each repetition. To provide optimal SliceAcc reconstruction, the TFL imaging kernel employed RF-CAIPI FOV-shifting [6], and the EPI imaging kernel employed blipped-CAIPI [8], which both introduce an inplane image shift between the simultaneously acquired slices to improve image reconstruction. Measurements were performed on a Siemens MAGNETOM 7T using a Nova Medical 24-channel head coil. Representative protocol parameters are summarized in Table 1. Images were reconstructed using the slice-GRAPPA algorithm. The series of magnitude images were then fit voxel-wise to the model $S(TI) = M_0*|1-2*\exp(-TI/T_1)|$ (with appropriate noise correction) to create quantitative T_1 and M_0 maps. Images were masked with an empirically determined intensity threshold to remove regions containing low signal (i.e. air) prior to T_1 fitting to reduce processing time.

Results and Discussion

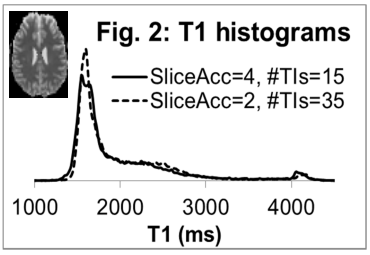
Representative T_1 mapping results for IR-TFL are seen in Fig. 1A, and for shuffled-IR-EPI in Fig. 1B, showing high quality T_1 maps in agreement with previously reported results [1,9]. Each figure depicts three simultaneously acquired slices (SliceAcc=3). In general, slice leakage artifacts between simultaneously excited slices were similar to what has been reported in fMRI and DTI applications, not exceeding 5%. Fig. 2 shows the T_1 histograms of shuffled-IR-EPI for the same slice acquired with GRAPPA=2 and SliceAcc = 2 & 4, demonstrating comparable results even with high acceleration. Similar results were obtained with IR-TFL and IR-EPI.

Table 1 demonstrates the added flexibility possible when using SliceAcc in combination with 2D IR T_1 mapping. The IR-EPI and IR-TFL approaches enable 3-4 slices in the same time as a conventional single-slice experiment. The additional slices can also be useful when an arterial input function is needed. Note that the rapid IR-TFL and IR-EPI T_1 maps are typically run repeatedly for 1-2 minutes during bolus passage in DCE experiments, therefore the additional scan time needed for the SliceAcc calibration data has minimal impact on the total measurement time. The shuffled-IR-EPI technique benefits from the extra flexibility that SliceAcc provides in the number of measured slices and TI samples possible in a given scan time, which makes it more appealing than previous approaches.

In conclusion, we demonstrate that T_1 relaxometry benefits significantly from SliceAcc techniques in scan time, slice coverage, and TI sampling, with the potential of making quantitative T_1 mapping much more feasible and clinically practical.

References [1] Labadie, MRM early-view doi:10.1002/mrm.24670. [2] Haase, MRM 13(1):77-89 (1990). [3] Clare, MRM 45:630-634 (2001). [4] Grinstead, Proc. ISMRM 16:3084 (2008). [5] Larkman, JMRI 13:313–317 (2001). [6] Breuer, MRM 53:684–691 (2005). [7] Moeller, MRM 63:1144-1153 (2010). [8] Setsompop, MRM 67:1210-1224 (2012). [9] Rooney, MRM 57:308–318 (2007).

Table 1	#slices	resolution (mm^3)	Flip angle (°)	TR (ms)	#TI; range (ms)	GRAPPA factor	SliceAcc factor	scan time	
IR-TFL	3	2x2x10	6	5.3	8; 305-4532	1	3	0:06	see Fig. 1A
IR-EPI	4	2x2x2	10	100	64; 21-6400	1	4	0:08	
shuffled-IR-EPI	45	2x2x2	90	10000	15; 32-6000	2	3	2:30	see Fig. 1B
shuffled-IR-EPI	60	2x2x2	90	10000	15; 32-6000	2	4	2:30	see Fig. 2
shuffled-IR-EPI	50	2x2x2	90	10000	25; 32-6000	2	2	4:10	
shuffled-IR-EPI	70	2x2x2	90	10000	35; 32-6000	2	2	5:50	see Fig. 2



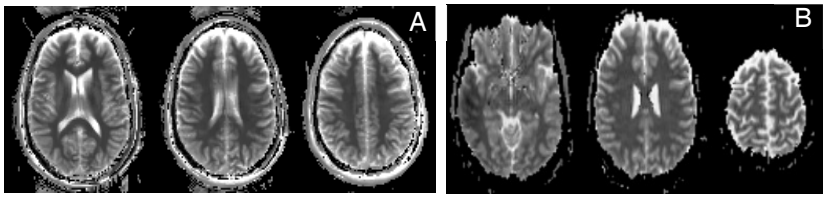


Fig 1. T_1 maps calculated from IR-TFL (**A**) and shuffled-IR-EPI (**B**) with SliceAcc=3.