Single-Shot Multi-slice T1 Mapping at High Spatial Resolution – Inversion-Recovery FLASH with Radial Undersampling and Iterative Reconstruction

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Introduction: Rapid quantitative T1 mapping is very useful in clinical MRI. However, low spatial resolution and long acquisition time have been the two major limitations for its routine application. Recently several image space and k-space based reconstruction methods have been proposed to estimate T1 maps from undersampled data, most of them dealing with single-shot single-slice T1 mapping. In [1], a radially sampled single-shot multi-slice T1 mapping has been proposed, however, the spoke-interleaved acquisition strategy corrupts the temporal consistency when the number of radial spokes or number of slices is increased. In this work, a sequential multi-slice acquisition scheme together with a new relaxation model is proposed to solve this problem, our contribution facilitates accurate, high-resolution multi-slice T1 mapping.

Materials and Methods: Single-shot T1 mapping employs an inversion recovery (IR) prepared Look-Locker sequence [2, 3], the signal evolution can be described as $M(t) = M_0^* - B \cdot e^{-t/T1^*}$, with M_0^* the observed steady-state magnetization and $B = M_0^* - M_{ini}$ the difference to the initial magnetization M_{ini}. Assuming $TR \ll T1^*, T1$, $T1$ can be calculated by $T1 = T1^* (B / M_0^* - 1)$. The sequential 3-slice acquisition scheme is demonstrated in Fig.1: the IR time course interleaves the aforementioned $T1^*$ relaxation process with periods of true $T1$ relaxation which prevails during the recording of images from neighboring slices. For this RF-free region, the relaxation is $M(t) = M_0 - D \cdot e^{-t/T1}$, with M_0 the equilibrium magnetization and $D = M_0 - M_{ini}$. The combination of both processes yields an explicit expression for the magnetization of one slice after a total number of j RF excitations. Here the j low-flip angle pulses correspond to the acquisition of $l = \lfloor j / (n_{sp} \cdot n_{sl}) \rfloor$ frames each slice, where n_{sp} is the number of radial spokes per frame and n_{sl} the total number of slices. The resulting longitudinal magnetization reads

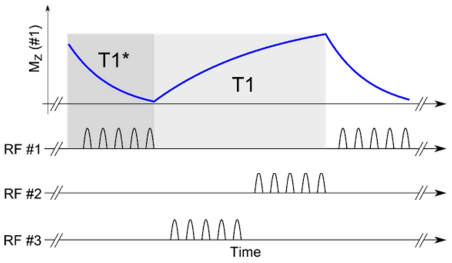

Fig. 1: Schematic representation of a small part of the dynamic inversion-recovery MRI signal for sequential 3-slice T1 mapping

$$M_{l,k} = M_0^* - \frac{\beta(1-\gamma^l)}{1-\gamma} + \gamma^l \cdot M_{ini} \cdot e^{-kTR/T1^*}$$

with $\beta = M_0\left(1 - e^{-\frac{n_{sp}(n_{sl}-1)TR}{T1}}\right) + M_0^* e^{-\frac{n_{sp}(n_{sl}-1)TR}{T1}}\left(1 - e^{-\frac{n_{sp}TR}{T1^*}}\right)$, $\gamma = e^{-\frac{n_{sp}TR(n_{sl}-1)}{T1} + 1/T1^*}$ and $k = j \bmod (n_{sp} \cdot n_{sl})$. For a specific slice, only $(M_0, M_0^*, T1^*)$ are unknowns which need to be estimated, T1 then can be calculated by $T1 \approx T1^* \cdot M_0 / M_0^*$.

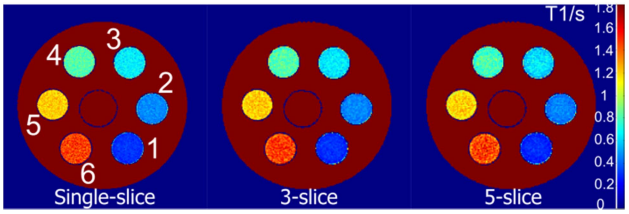

Fig 2: T1 maps obtained for a T1 reference phantom.

Table 1. T1 values (s) of a T1 reference phantom.

ROI	1-lice	3-slice	5-slice	SE-MRI
1	0.32 ± 0.03	0.31 ± 0.03	0.30 ± 0.03	0.33 ± 0.01
2	0.48 ± 0.04	0.46 ± 0.04	0.46 ± 0.04	0.50 ± 0.01
3	0.66 ± 0.06	0.65 ± 0.05	0.64 ± 0.06	0.68 ± 0.01
4	0.83 ± 0.07	0.82 ± 0.06	0.80 ± 0.07	0.86 ± 0.01
5	1.22 ± 0.07	1.22 ± 0.06	1.20 ± 0.07	1.25 ± 0.01
6	1.49 ± 0.09	1.48 ± 0.08	1.47 ± 0.10	1.50 ± 0.01

All our studies were performed at 3 T (Magnetom Prisma, Siemens Healthcare, Erlangen, Germany). Phantom and brain studies both employed the standard 64-channel head coil. The signal was acquired by highly undersampled radial FLASH with complementary sets of spokes within one slice [4] (FOV: 192x192 mm^2, Resolution: 256x256 (384x384, single-slice (SS)), slice thickness = 5 mm, TR/TE = 2.64/1.76 (3.37/2.25, SS) ms, α = 4°, 15 (19, SS) spokes/frame). The coil profiles were first estimated from the data close to full recovery using nonlinear inversion (NLINV) with its extension to real-time MRI [5]. The coil sensitivities were then fixed and the resulting linear SENSE-like reconstruction problem was solved using an iteratively regularized conjugate gradient (CG) method. Fitting of the 3 parameter maps to the reconstructed images was then performed using the Levenberg Marquard algorithm in MATLAB (MathWorks, Natick, MA).

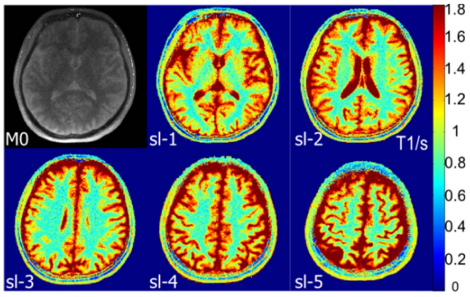

Fig. 3: (Top left) Single-shot proton density (first section) and (top middle to bottom right) simultaneous multi-slice T1 maps at 0.75 mm resolution.

Results & Discussion: Fig. 2 depicts T1 maps of a T1 reference phantom (Diagnostic Sonar LTD., Scotland, UK). They were obtained at 0.5 mm resolution for a single-slice acquisition as well as 0.75 mm resolution for 3-slice and 5-slice acquisitions. In all cases the maps correspond to the same section. The numerical results summarized in Table 1 reveal accurate T1 determination when compared to a reference measurement using an IR spin-echo MRI sequence at long TR (7.2 s). Multi-slice acquisitions show a mild tendency toward lower T1 relaxation times with increasing number of sections, while all values remain within one standard deviation. Fig. 3 shows all simultaneously acquired T1 maps of a transverse 5-slice acquisition of the brain at 0.75 mm resolution. The measured T1 values are in good agreement with literature findings. In conclusion, the combination of a conventional IR radial FLASH sequence with pronounced radial undersampling and iterative NLINV/CG image reconstruction allows for robust and efficient single-shot T1 mapping at high spatial resolution for up to 5 simultaneous sections.

References: [1] Zhang S, et al., Proc ISMRM 21:3700 (2013), [2] Look D, et al., Rev Sci Instrum, 41:250 (1970), [3] Deichmann R, et al., J Magn Reson 96:608-612 (1992), [4] Zhang S, et al., J Magn Reson Im 31:101-109 (2010), [5] Uecker M, et al, NMR Biomed 23:986-994 (2010).