Rapid 2D variable flip angle (VFA) T1 mapping using sharp slice profiles

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Target audience: Basic MR researchers, imaging scientists, clinical scientists, radiologists, applications specialists interested in parametric T_1 mapping.

Purpose: 2D variable flip angle (VFA) T_1 mapping has been proposed for fast T_1 quantification of the brain [1]. To obtain accurate T_1 values, knowledge of the flip angle distribution over the slice is essential. RF pulse imperfections evoke inhomogeneous excitation flip angle distributions in the slice selection direction that inevitably lead to deformations of the slice profile, alter the resulting signal, and hence bear the potential to deem T_1 quantification with 2D VFA inaccurate. Sharp and uniform slice excitations could render considerations on complex slice profile corrections obsolete and could afford a direct T_1 calculation using gradient echo signal equations. To achieve this goal, impractically long and specific absorption rate (SAR) intensive high bandwidth SINC pulses are conventionally used. In this study, we aim at a reduction of the RF pulse duration using variable rate selective excitation (VERSE, [2]) while maintaining a high slice profile fidelity at the expense of a moderate SAR increase with the ultimate goal of achieving 2D VFA T_1 mapping in phantom studies and in vivo.

Materials and Methods: A Matlab implementation of the Shinnar-Le-Roux (SLR) [3] algorithm was used to design a SINC RF pulse (slice thickness=10mm, time-bandwidth-product=34, pulse duration=20ms, bandwidth=1.7kHz, 8 side lobes) to achieve a sharp and uniform spin excitation profile throughout the slice. To shorten the pulse duration and to lower SAR while maintaining the high quality excitation profile, the minimum-time VERSE algorithm was employed. The slice selection gradient strength was used to control the duration of the pulse and to mitigate the characteristic dip in the center of the gradient for improving the off-resonance behavior [4]. A FLASH sequence was modified to accommodate VERSE RF pulses and gradients and to measure slice profiles. Slice profiles were obtained from a cylindrical phantom (T_1≈100ms, T_2≈80ms). All measurements were conducted on a 3T MR scanner (Verio, Siemens Healthcare, Germany) equipped with a 32 channel Rx head coil with the exception of the slice profile measurements, where the body coil was used for reception. Simulated and measured slice profiles were compared. VFA T_1 mapping (voxel size=(2x2x10)mm³; TE=5.4ms, TR=9ms, total acquisition time=5.4s) was conducted on a cylindrical manganese doped water phantom (T_1≈500ms, T_2≈50ms, d=10cm) at adjusted flip angles (α_1=4°, α_2=22°,[5]). To correct for B_1^+ non-uniformities, Bloch-Siegert B_1^+ mapping [6] was incorporated (voxel size=(4x4x10)mm³, acquisition time=1.6s). For comparison, an inversion recovery (IR) fast spin echo (SE) technique (voxel size=(2x2x10)mm³; TE=5ms, TR=10s, TI=60/120/240/480/750/1000/3000/5000ms, turbo factor=5, GRAPPA R=2) was used as a reference. 2D VFA T_1 mapping (α_1=2°, α_2=13°) was conducted in an axial slice of the brain of a healthy volunteer. Mean T_1 values for gray and white matter were derived for both techniques.

Results: The VERSE algorithm shortened the pulse duration from 20ms to 5ms with the excitation profile being identical to the profile achieved with the high bandwidth SINC pulse of 20ms duration. To maintain the RF pulse integral, the four-fold reduction in pulse duration was compensated by an increase in the peak RF amplitude by a factor as low as 2.5 (Figure 1). The simulated slice profile using the SINC pulse matched the slice profile using the VERSE pulse as well as the measured slice profile. Figure 2 shows phantom measurements using the reference IR-SE approach (A) and the proposed B_1^+ corrected 2D VFA T_1 mapping approach (B), and the absolute difference between the two (C). Mean T_1 values derived from a ROI covering an axial slice of the phantom were 474±2ms for IR-SE and 469±9ms for 2D VFA T_1 mapping. Measurement time was 17.3min for the reference and 7s for 2D VFA. In vivo IR-SE T_1 mapping showed T_1 values of 1544±188ms in gray matter and 892±66ms in white matter. Measurement time was ≈17min. 2D VFA T_1 mapping showed T_1 values of 1596±212ms and 1017±90ms in white matter with a measurement time of 7s.

Discussion: We demonstrated rapid 2D variable flip angle T_1 mapping using improved slice profiles at 3T in phantom experiments and in vivo. For this purpose we combined Shinnar-Le-Roux pulses with the VERSE approach. For the proposed approach, no extra corrections for imperfect slice excitation were needed. The standard deviation of T_1 in 2D VFA phantom studies was less than 2% of the mean T_1 value. VERSE allows for further shortening of the pulse at the expense of stronger slice selection gradients or deterioration of the slice profile fidelity. The low scan time and low computational effort makes the proposed method attractive, since T_1 maps are calculated within a few milliseconds. We anticipate extending our explorations into balancing SAR, off-resonance behavior, and slice profile fidelity using VERSE guided numerical RF pulse design [7].

Conclusions: 2D VFA T_1 mapping using sharp and uniform excitation profiles is feasible and represents a valuable alternative for rapid T_1 mapping of the brain.

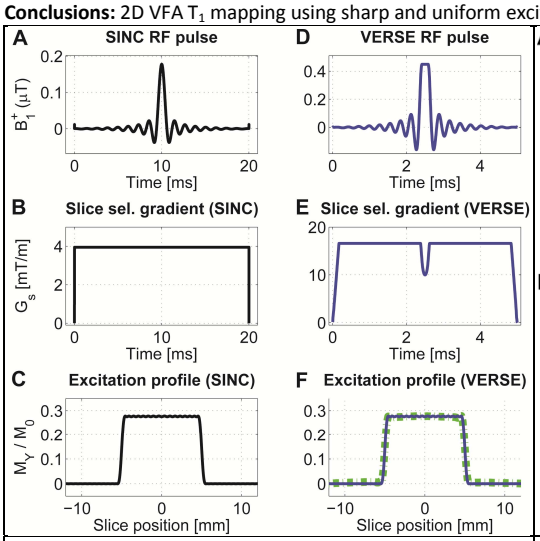

Figure 1: (A) SINC pulse (time-bandwidth product=34, duration=20ms, bandwidth=1.7kHz) to achieve a sharp and uniform slice excitation; **(B)** corresponding slice selection gradient for 10mm slice thickness; **(C)** simulated slice profile using Bloch equations; **(D)** variable rate selective excitation (VERSE) representation of the SINC pulse; **(E)** corresponding VERSE gradient; **(F)** simulated (blue line) and measured slice profile (green dashed line) showing excellent agreement.

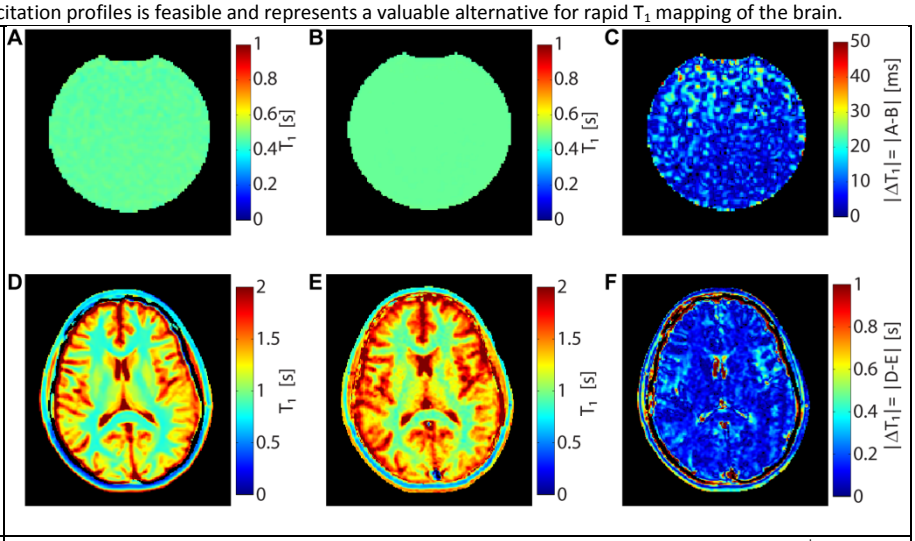

Figure 2: (A) Reference T_1 map derived from IR-SE in a phantom (T_1=474±2ms). **(B)** B_1^+ corrected variable flip angle T_1 map using flip angles of 4° and 22° (T_1=469±9ms). Measurement time was ≈17min for the reference measurement and 5.2s for the VFA T_1 map including B_1^+ mapping. **(C)** The absolute mean difference was as low as 6±6ms. **(D)** Reference T_1 map of the brain derived from IR-SE in a healthy volunteer. T_1 in gray matter was 1544±188ms and 892±66ms in white matter. Measurement time was ≈17min. **(E)** B_1^+ corrected variable flip angle T_1 map using flip angles of 2° and 13°. T_1 in gray matter was 1596±212ms and 1017±90ms in white matter. Measurement time was 7s. **(F)** Absolute difference map between the reference IR-SE T_1 measurement and 2D VFA T_1 mapping.

References: [1] Dieringer et al., ESMRMB 2013, p.122; [2] Hargreaves et al., Magn Reson Med 52:590 –597 (2004), Matlab implementation by Brian Hargreaves and Chuck Cunningham; [3] Matlab implementation NIH P41 RR023953 (PI: Michael W. Weiner); [4] Norbeck et al., ESMRMB 2013, p.48; [5] Deoni et al., Magn Reson Med 51:194–199 (2004); [6] Sacolick et al., Magn Reson Med 63:1315-22 (2010); [7] Grissom et al, Magn Reson Med 67:353-62 (2012)