Simultaneous T1 and T2 mappings using partially Spoiled Steady State Free Precession (pSSFP)

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Introduction: A fast 3D T2 mapping technique based on two partially Spoiled Steady State Free Precession (pSSFP) gradient echo acquisitions has recently been proposed by Bieri et al. [1]. Analytical expression for the estimated T2 as a function of the experimental parameters (TR, the RF flip angle α and the RF spoiling increments φ) assumed that the condition T2 < T1/2 was respected, where η = 0.5(1+cosα)/(1-cosα) [1]. For the most of human soft tissues, this condition could only be attained using RF flip angles between 70° and 100°. Such flip angles could lead to SAR concerns for fast 3D mapping in particularly at high fields (≥ 3T). In this work (i) we examined numerical dependence of the estimated values of T2 (T2_estim) upon the parameter T2/Tr/η; (ii) we described an empirical analytical expression relating T2_estim and the “true” T2; (iii) we verified experimentally the validity for this expression. By extension we demonstrated that using two α and two φ simultaneous T1 and T2 extraction was possible even when the η < T2/Tr condition was not fulfilled. These findings allowed us to introduce a novel fast 3D simultaneous T1 and T2 mappings method with low SAR deposition.

Theory: In [2] an analytical description of SSFP with RF spoiling is given. For small φ, the solution to the steady-state signal as function of α, φ, TR, T1, and T2 can be written as:

\[ S = A \delta \sqrt{1 + \phi^2} / (a^2 + \phi^2) \]  

A is a scale factor, which depends on the receiver sensitivity and the proton density (ρ). φ only depends on the flip angle α and must be determined numerically. Typical values are given in [2]. T1 = sin²/(1-cosα), δ = TR/T1, λ = TR(x/x0)(1 + 1/κ) and κ = (1 + 2κ T2/T1)². If η << T2/Tr, κ ≈ 1 and Equation (1) can be reduced to an expression independent of T1. In this case, T2 estimated from two pSSFP acquisitions with different linear increments φ1 and φ2 is [1]:

\[ T2_estim = 2 TR \sqrt{S_1^2 - S_2^2 \delta} / \sqrt{S_1^2 \phi_1^2 - S_2^2 \phi_2^2} \]  

Methods: (Simulation) Numerical simulation was performed using Equations (1) and (2) to calculate the error in the T2 estimation for different values of T1, T2 and α. Linearly spaced values for T1, T2 and α were generated in the range [T1: 100ms to 10s], [T2: 20ms to T2=T1] and (α: 10 to 90°). φ1 and φ2 were set to 1 and 10 degrees. TR was set to 10ms. S1 and S2 were calculated for each T1, T2 and α values using Equation (1). T2_estim was calculated using Equation (2). The last equation could be fitted with an empirical logistic curve: y = (x/κ1)(1 + x/κ2) where y = T2_estim/T2, x = T2/T1 and κ1 = κ2. With such an expression T2_estim and the “true” T2 can be related by a simple analytical expression: \( T2 = T2_estim (1 + \beta \eta) \), where \( \beta = \sqrt{2} (T1/T2) \). An important consequence of this simplification is that T2 and T1 can be accuracy obtained from four pSSFP acquisitions, using two different linear increments φ1 and two different flip angles αi and completing a simple system of two equations with two unknowns.

(Experimental) Experimental data were acquired on a 3.0 T whole-body scanner (Tim Trio, Siemens Healthcare, Erlangen, Germany) using a Circularly Polarized coil (CP Extremity). 3D pSSFP experiments were carried out using a doped agarose phantom with 1.2mm³ isotropic voxel volume and 300µs hard pulse excitations, with φ1, φ2, and TR set like in the numerical simulation. Twelve different flip angles were used, ranging from 30° to 90°. T2_estim was calculated for each flip angle value using Equation (2). Phantom T1 and T2 were independently measured using an inversion recovery sequence (11 T1 values ranging from 110 to 8000 ms, TR = 8 s) and a 2D multi-spin echo sequence (31 TE values, ranging from 25.8 to 412.9 ms, TR = 8 s), respectively.

Results: (Simulation) Figure 1 (up) shows the result for the numerical simulation (black circles). Simple empirical fit was represented by the red line. Figure 1 (bottom) shows the residual plot for the fitting. The logistic curve fits accurately (less than 5% error) the numerical data for the range (T1/T2)/η > 2.

(Experimental) Using the phantom T1 and T2 values independently obtained (T1 = 1560 ms, T2 = 130 ms), experimental data (blue squares) are superposed to the numerical data and the fitted curve. On Figure 2 an example of this simultaneous T1 and T2 mapping can be seen. T1 and T2 were derived from four pSSFP experiments, using φ1 = 1°, φ2 = 10°, αi = 45° and αi = 90°. Results for T1 and T2 obtained from this method agree very well with independent measurements.

Discussion: This new method allowed us to estimate T2 alone with 2 pSSFP acquisitions or T1 and T2 with 4 pSSFP acquisitions and gave accurate results on phantoms for (T1/T2)/η > 2. It looks promising in terms of flexibility with regard to T1/T2 ratios of biological tissues and for use at lower flip angles compatible with high magnetic field SAR limitations. In contrast to other 3D SSFP based T1 and T2 mapping techniques, such as segmented IR-TrueFISP [3] or DESPOT1/DESPOT2 [4], T1-T2-pSSFP method does not suffer of banding artifacts due to off-resonance. Future work will aim at the demonstration of the analytical equation used and the optimization of φ1 and φ2 increments for 3D T1 and T2 mapping of the skeletal muscle. References: [1] Bieri et al, ISMRM 2634 (2009), [2] Ganter C., MRM 2006;55:98-107, [3], Schmitt et al, MRM 2004; 51:661-667, [4] Deoni et al, MRM 2003;49:515-526.