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

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Introduction: A fast 3D T_2 mapping technique based on two **p**artially **S**poiled **S**teady **S**tate **F**ree **P**recession (pSSFP) gradient echo acquisitions has recently been proposed by Bieri *et al*. [1]. Analytical expression for the estimated T_2 as a function of the experimental parameters (TR, the RF flip angle α and the RF spoiling increments ϕ) assumed that the condition $\eta << T_1/T_2$ was respected, where $\eta = 0.5(1+\cos\alpha)/(1-\cos\alpha)$ [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 T_2 (T_2^{estim}) upon the parameter $T_2/T_1/\eta$; (ii) we described an empirical analytical expression relating T_2^{estim} and the "true" T_2; (iii) we verified experimentally the validity for this expression. By extension we demonstrated that using two α and two ϕ simultaneous T_1 and T_2 extraction was possible even when the $\eta << T_1/T_2$ condition was not fulfilled. These findings allowed us to introduce a new fast 3D simultaneous T_1 and T_2 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, T_1 and T_2 can be written as:

$$S = A\frac{\Gamma\delta}{\xi}\frac{\sqrt{\lambda^2+\phi^2}}{\kappa\lambda^2+\phi^2} \qquad (1)$$

A is a scale factor, which depends on the receiver sensitivity and the proton density (M_0). ξ only depends on the flip angle α and must be determined numerically. Typical values are given in [2]. $\Gamma = \sin\alpha/(1-\cos\alpha)$, $\delta = TR/T_1$, $\lambda = TR/(\xi\cdot T_2)(1+\kappa)$ and $\kappa = (1 + 2\eta\, T_2/T_1)^{1/2}$. If $\eta << T_1/T_2$, $\kappa \rightarrow 1$ and Equation (1) can be reduced to an expression independent of T_1. In this case, T_2 estimated from two pSSFP acquisitions with different linear increments ϕ_1 and ϕ_2 is [1]:

$$T_2^{estim} = \frac{2TR}{\xi}\sqrt{\frac{S_1^{\,2}-S_2^{\,2}}{S_2^{\,2}\phi_2^{\,2}-S_1^{\,2}\phi_1^{\,2}}} \qquad (2)$$

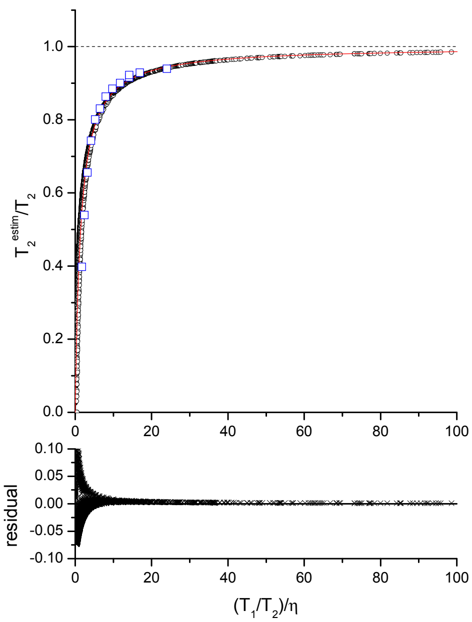

figure 1: ***(Up)*** *Numerical simulation data (black dots), fitted curve (red line) and experimental data (blue squares).* ***(Bottom)*** *residual plot for the fitting model.*

Methods: (Simulation) Numerical simulation was performed using Equations (1) and (2) to calculate the error in the T_2 estimation for different values of T_1, T_2 and α. Linearly spaced values for T_1, T_2 and α were generated in the range [T_1: 100ms to 10s], [T_2: 20ms to T_2=T_1] and [α: 10 to 90°]. ϕ_1 and ϕ_2 were set to 1 and 10 degrees. TR was set to 10ms. S_1 and S_2 were calculated for each T_1, T_2 and α values using Equation (1). T_2^{estim} were calculated using Equation (2). The last equation could be fitted with an empirical logistic curve: $y = (x/x_0)/(1 + x/x_0)$ where $y = T_2^{estim}/T_2$, $x = T_1/T_2/\eta$ and $x_0 = \sqrt{2}$. With such an expression T_2^{estim} and the "true" T_2 can be related by a simple analytical expression: $T_2 = T_2^{estim}(1 + \beta\cdot\eta)$, where $\beta = \sqrt{2}\,(T_2/T_1)$. An important consequence of this simplification is that T_2 and T_1 can be accuracy obtained from four pSSFP acquisitions, using two different linear increments ϕ_i and two different flip angles α_i 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 1.2mm^3 isotropic voxel volume and 300µs hard pulse excitations, with. ϕ_1, ϕ_2, and TR set like in the numerical simulation. Twelve different flip angles were used, ranging from 30° to 90°. T_2^{estim} was calculated for each flip angle value using Equation (2). Phantom T_1 and T_2 were independently measured using an inversion recovery sequence (11 TI 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 $(T_1/T_2)/\eta > 2$.

(Experimental) Using the phantom T_1 and T_2 values independently obtained (T_1 = 1560 ms, T_2 = 130 ms), experimental data (blue squares) are superposed to the numerical data and the fitted curve. On Figure 2 an example of this simultaneous T_1 and T_2 mapping can be seen. T_1 and T_2 were derived from four pSSFP experiments, using $\phi_1 = 1°$, $\phi_2 = 10°$, $\alpha_1 = 45°$ and $\alpha_2 = 90°$. Results for T_1 and T_2 obtained from this method agree very well with independent measurements.

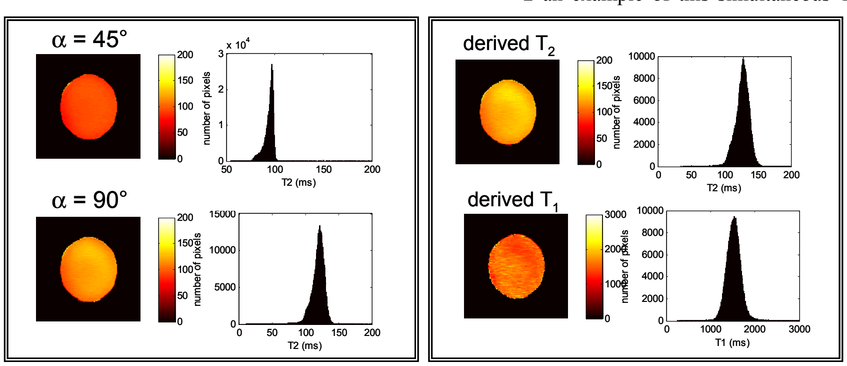

figure 2 (left) *Axial view of the 3D T_2 maps and corresponding histograms obtained such a pSSFP experiments with α=45° and α=90°.* ***(right)*** *derived T_2 and T_1 maps and corresponding histograms, combining experimental data from pSSFP acquisitions with α=45° and α=90° as described in Discussion.*

Discussion: This new method allowed us to estimate T_2 alone with 2 pSSFP acquisitions or T_1 and T_2 with 4 pSSFP acquisitions and gave accurate results on phantoms for $(T_1/T_2)/\eta > 2$. It looks promising in terms of flexibility with regard to T_1/T_2 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 T_1 and T_2 mapping techniques, such as segmented IR-TrueFISP [3] or DESPOT1/ DESPOT2 [4], T_1-T_2-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 α_i and ϕ_i increments for 3D T_1 and T_2 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.