T1 corrected Fast T2 Mapping Using Partially Spoiled SSFP

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Introduction. The width of transition of steady-state free precession (SSFP) to RF-spoiled SSFP is inversely proportional to the transverse relaxation time T_2 (1), which has been used to derive quantitative T_2 maps from two partially spoiled SSFP-FID signals (T2-pSSFP) (2). Signal analysis based on an approximate solution being independent on the longitudinal relaxation time T_1, but with sensitivity to the partial spoiling increment (ϕ), the flip angle (α), the repetition time (TR) and to T_2. This approximation is valid for tissues with

$$T_1/T_2 >> 0.5(1+\cos\alpha)/(1-\cos\alpha) \qquad [1]$$

In the limit of large flip angles ($\alpha \sim 70°$) and for tissues with $T_1/T_2 >> 1$, estimation of T_2 was shown to be accurate whereas for liquids or for smaller flip angles, T_2 is underestimated. In this work, we abandon the constraint formulated in Eq. [1] and solve the more complex signal equation as given by C. Ganter in Eq. [35] (1),

$$m_{xy}(\phi) \propto \frac{[\sigma^2\delta^2+\xi^2\phi^2]^{1/2}}{\sigma^2\delta^2+\xi^2\phi^2-\eta\sigma\delta^2} \qquad [2]$$

that depends now on T_1, as well. We will show that an analytic expression to Eq. [2] can be found that can be used to assess T_2 using T2-pSSFP in combination with T_1 measurements.

Theory. Suppose we know $\lambda := T_2/T_1$. Eq. [2] leads to a cubic equation of form $z^3+a_2z^2+a_1z+a_0=0$, where $\sqrt{z} := TR/T_2$. Thus

$$z = s_+ + s_- - a_2/3, \text{ where } s_\pm = [r+(q^3 \pm r^2)^{1/2}]^{1/3}$$
$$\text{and } q := a_1/3 + a_2^2/9, \quad r := (a_1a_2 - 3a_0)/6 - a_2^3/27 \qquad [3]$$

with

$$a_0 = (1-S_{12})^{-1}(b_1c_2^2 - S_{12}b_2c_1^2)$$
$$a_1 = (1-S_{12})^{-1}(2b_1c_2 + c_2^2 - S_{12}[2b_2c_1 + c_1^2]) \qquad [4]$$
$$a_2 = (1-S_{12})^{-1}(b_1 + 2c_2 - S_{12}[b_2 + 2c_1])$$

and definitions

$$b_i := \xi^2\phi_i^2/[1+\nu]^2, \quad c_i := b_i/\nu, \quad \nu := \sqrt{1+\eta\lambda} \qquad [5]$$
$$\eta := (1+\cos\alpha)/(1-\cos\alpha)$$

The quantity ξ depends on α and is determined via a continued fraction expansion (see Eq. [34] in Ref. (1)) and $S_{12} = S_1^2(\phi_1)/S_2^2(\phi_2)$ refers to the measured quadratic signal ratio with partial spoiling increments ϕ_1 and ϕ_2, respectively.

Materials & Methods. All simulations, data analysis and visualizations were done using Matlab 2007b. Human brain scans were performed in 3D at 1.5T with 1.33mm isotropic resolution (192x192x144 matrix) for α ranging from 20° to 70°. The *TR* was set to 5.4ms and a hard RF pulse of 600µs duration was used. Partial spoiling increments were 1° and 9° and T_1 information was acquired using DESPOT1 (*TR* = 15ms with $\alpha_{1,2}$ = 4°, 23°) with essentially identical matrix size and FOV.

α (TR ~ 5)	T2/T1 ≤ 1/2			T2/T1 ≤ 1/5			T2/T1 ≤ 1/10		
	ϕ1	ϕ2	δ(**)	ϕ1	ϕ2	δ(**)	ϕ1	ϕ2	δ(**)
20°(*)	--	--	--	0	7	2	0	6…7	1
30°	2	10	1.5	1	10	1	1	9…10	3/4
40°	1	7…10	5/4	1	7…10	3/4	1	6…10	1/2
50°	1	6…10	1	1	6…10	1/2	1	5…10	1/3
60°	1	5…10	3/4	1	5…10	1/3	1	5...10	1/5
70°	1	5…10	1/2	1	5…10	1/5	1	5...10	1/10
90°	1	5…10	1/3	1	5…10	1/10	1	5...10	1/20

Table 1: Error in the estimation of T2 according to Eqs. [3-5] is less than 10% within the stated range of ϕ values and is given as a function of α and T_2/T_1. The sensitivity on T_1 of the estimated T_2 is given by $\Delta T_2/T_2 = \delta \cdot \Delta T_1/T_1$.

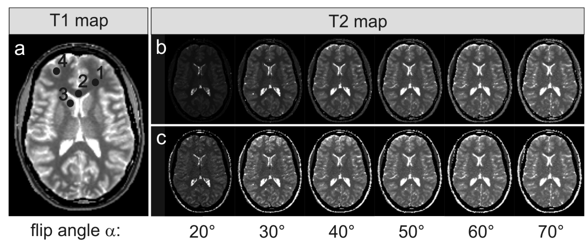

Fig. 1: T2 maps from 3D T2-pSSFP with and without T_1 correction as a function of α with ROIs in white (1,2) and gray (3,4) matter.

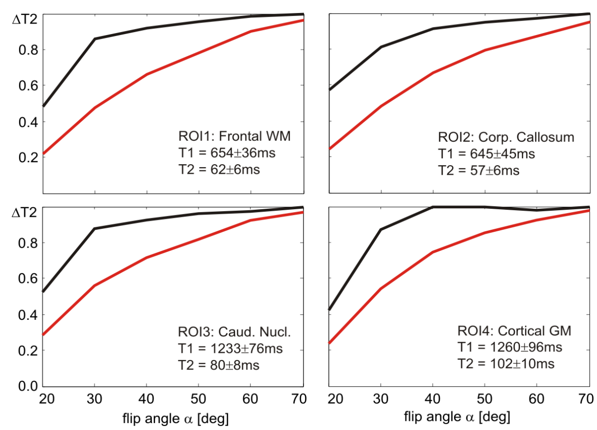

Fig. 2: Deviation from T2 as a function of flip angle for ROIs as indicated in Fig. 1 (red curve: derived T2 without T1 correction, i.e. according to ref (2); black line: T1 corrected derived T2 value using Eqs. [3-5]). As expected (see Table 1), derived T2 values from pSSFP can be corrected using T1 information approximately down to 30°.

Results & Discussion. Using the full analytic signal description of partially spoiled SSFP, the accuracy in the estimation of T_2 from Eqs. [3-5] can be analyzed as a function of λ and α (Table 1). Deviation in T_2 is typically less than 10% for tissues ($T_2/T_1 \sim 0.1$) down to $\alpha \sim 30°$ provided T_1 is known. As expected, sensitivity on T_1 is low for large flip angles ($\alpha > 70°$), but T_1 information becomes increasingly important with decreasing α, as indicated by the parameter δ in Table 1. For evaluation, in-vivo 3D T2-pSSFP brain scans were performed on a healthy volunteer and results are shown in Fig. 1. As expected, sensitivity of T_2 on α is reduced upon T_1 correction, but breaks down for low flip angles ($\alpha \sim 30°$). Observed residual T_2 modulations between α = 30°–70° are most likely either due to B_1 field inhomogeneities which become increasingly important with lower α, or due to inconsistencies between derived T_1 values from DESPOT1 and true T_1 values (an underestimation in T_1 results in an underestimation of T_2) which become less and less important with increasing flip angles.

Conclusion. Provided that T_1 is known, the constraint on high flip angles for the assessment of T_2 values using T2-pSSFP can be abandoned and accurate T_2 values can be derived with flip angles down to 30°. This offers the possibility for acquisitions with higher SNR, but requires guessed or additional measured T_1 values.

References. (1) Ganter, C. MRM 2006; 55:98-107; (2) Bieri O, Ganter C, Scheffler, K. Proc. ISMRM Hawaii (2009), p. 2634