EXPLICIT MODELING OF SPGR SIGNALS USING EXTENDED PHASE GRAPHS IN DESPOT STYLE RELAXOMETRY - A DICTIONARY APPROACH

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Target Audience: Reseachers interested in quantitive MR imaging and the comprehension of some of the main physical properties behind it.

Purpose: The measurement of T1 and T2 is increasingly applied in order to assess brain changes in disorders such as Parkinson's or Alzheimer's diseases and in developmental processes, particularly myelination. Precise and time-efficient T1 and T2, high resolution mapping capabilities are therefore valuable in this context. One possible method is Driven Equilibrium Single Pulse Observation of T1 and T2 (DESPOT)[1], which uses Spoiled Gradient Echo (SPGR) and balanced Steady-State Free Precession (SSFP) sequences over a range of varying Flip Angles (FA) to estimate T1 and T2. A typical estimation framework assumes correct spoiling of the magnetization before each RF-pulse so that the signal evolution follows the linearized Ernst relationship $\frac{S}{\sin(\alpha)} = \frac{S}{\tan(\alpha)}E_1 + M_0(1-E_1)$, where α is the FA, M_0 is the fully relaxed magnetization and $E_1 = \exp(-TR/T1)$. Modern MR sequences aim for TR<<T2 which allows the transverse magnetization to contribute to the final steady state resulting in a steady state which is not only T1 dependent. In order to counteract this issue and allow a T2 independent steady state to be formed, the phase of the applied RF-pulse is incremented at each excitation (RF-spoiling) in combination with gradient spoilers which force the magnetization to interact in a destructive way before each excitation pulse[2]. Correct signal spoiling however, is dependent on the interaction between T1, T2, FA and TR, and may prove to be difficult to obtain for the wide range of relaxation times present in the human brain[4]. A recent study[3], has shown the existence of a T1 estimation bias of the variable nutation angle approach when compared to the gold standard Inversion Recovery technique. We hypothesized that the estimation discrepancies could be due to incorrect signal spoiling and sought to counteract it by exploring the feasibility of a dictionary model fitting approach which doesn't require the assumption of correct signal spoiling.

Methods: The extended phase graph (EPG) framework, which may be interpreted as the Fourier analogy of the Bloch equations, assumes the total magnetization as the linear combination of partition states in order to predict the signal evolution for a given pulse train with high computational efficiency. It was therefore used to generate a signal lookup-table capable of finding the T1 and T2 values responsible for the signal evolution over flip angle at each imaged voxel. A grid of T1 values ranged from 100ms to 4000ms in increments of 30ms and T2 values ranged from 5ms in increments of 10ms until 1500ms and in increments of 25ms until 2100ms was generated. For each T1/T2 combination where T1>=T2 the EPG signal evolution was computed for a number of 6T1/TR excitations in order to guarantee that the steady state was achieved. RF-spoiling was set by incrementing the phase of each RF-pulse at each excitation (n) by $n50^0$ [4]. The value of 50^0 for the phase increment was chosen due to its reported stability [4]. Diffusion effects were taken into account by assuming a diffusion coefficient of 2.3e-9 m^2/s and a total gradient area of 11.45 mT.ms/m applied during 3.3ms. In this work no B_0 or B_1 inhomogeneity effects were considered as this requires further extension of the library and was out of the scope of this abstract. Signal evolution was linearly interpolated to a grid of 0.5ms for both T1 and T2. In order to experimentally validate the method for a range of different relaxation times, six tubes with solutions of manganese chloride ($MnCl_2$) of varying concentrations were imaged on a Phillips Achieva 3T-TX system. Reference T1 and T2 values were previously measured with a IR-TSE and multi-echo SE sequence respectively. The SPGR acquisition was acquired for FA of 2^0,5^0,8^0,15^0 and 20^0 , TR was set to 9ms and RF phase increment to 50^0. The SSFP signal was sampled for FA of 15^0,30^0,45^0 and 60^0 and TR was set to 6ms. All images were had 1.5mm isotropic resolution. Regions of interest were defined inside each tube and the resulting relaxation values are summarized in Table1. In vivo data was acquired on a 28 year old female healthy volunteer with the same protocol as the phantom experiment except the TR of the SSFP was set to 5.3ms. Informed consent was obtained in accordance to local policies. Due to the different acquisition nature between SPGR and SSFP some relative scaling between SPGR and the SSFP measurements was found, in order to counteract this each dictionary and data set from each sequence were normalized by their respective Euclidean norm. The dictionary entry that minimized the residual with the measured data was selected as optimal. In order to ensure correct comparison of the residuals of the fits obtained by the standard DESPOT and the new dictionary approach, each set of signals and each of the fitted solutions were normalized to have unit norm prior to computing the sum of the residuals between fitted model and measured data.

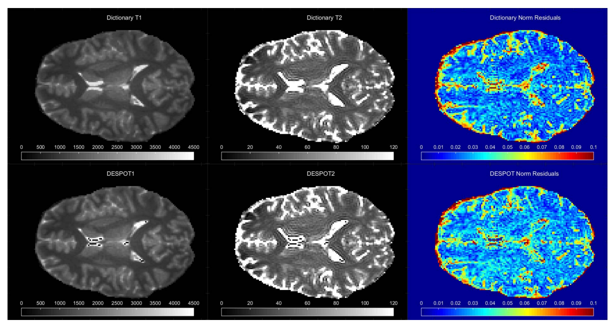

Figure 1

Results/Discussion: Table 1 summarizes the results of the different fit procedures for the phantoms. The average norm of the residuals as defined in the methods section are also listed for each ROI.

Comparing the relaxation times obtained, the bias in the DESPOT1/DESPOT2 results increases with increasing relaxation time. Also an increase in the average norm of residuals can be observed. This is most likely due to incorrect spoiling caused by the larger T2 values, which is consistent with our initial hypothesis. The dictionary approach achieved uniform performance across all the relaxation times, however, the fitted parameters exhibit a systematic offset. This may be due to the fact that no flip angle corrections were incorporated and/or that the reference measurements were not performed on the same day and possibly at a slightly different temperature.

Table 1	T1 ± σT1 (ms)			T2 ± σT2 (ms)			Norm of Residuals	
	Reference	DESPOT1	Dictionary	Reference	DESPOT2	Dictionary	DESPOT	Dictionary
Tube 1	2987±17	3296±58	2808±43	1804±457	2438±440	2240±410	0.033	0.013
Tube 2	2475±33	2631±34	2251±26	600±46	755±20	641±15	0.026	0.012
Tube 3	1442±29	1446±17	1284±13	160±6	173±5	153±5	0.014	0.013
Tube 4	979±16	954±10	878±7	88±2	96±2	88±2	0.009	0.011
Tube 5	620±78	610±6	580±5	50±1	51±3	48±3	0.009	0.010
Tube 6	546±113	534±5	515±5	44±1	39±5	37±5	0.007	0.008

Figure 1 shows the comparison between the relaxation maps obtained with the standard DESPOT approach, no significant difference between the extracted relaxation times was found except for a systematic underestimation (4% for white matter and 6% for gray matter) when compared to the standard DESPOT approach. However, this still represents an overestimation of reported in vivo IR T1 measurements[3]. Careful assessment of the residuals shows a slight overall improvement using the dictionary approach except in CSF areas where the fact that the dictionary was capped to a maximum of 4000ms clearly affected the fitting quality.

Conclusion: This work aimed to explore a possible mechanism to explain the reported discrepancies between T1 estimations based on IR-SE & SE sequences and variable flip angle measurements. It was shown that although using an approach in which the EPG formalism directly modeled the spoiled gradient echo signal forming a dictionary does allow robust fitting of relaxation times, we believe that the range of relaxation times present in the adult brain doesn't justify the use of such dictionaries for this fitting task. On the other hand phantom data suggests that the dictionary fitting procedure may prove beneficial for higher relaxation times which do clearly demonstrate increasing deviation in signal response from the Ernst model. A possible application could be relaxometry of the neonatal brain, which has longer T1 and T2 than adult brain.

References: 1.S. Deoni et al., MRM 2004; 2.Y.Zur, et al., MRM1991; 3.N. Stikoy et al., MRM 2014; 4.C. Preibisch, et al., MRM 2009;

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