IR TrueFISP: Analytical expressions for calculation of T_1, T_2 and spin density and investigation of off resonance influences

P. Schmitt[1], M. A. Griswold[1], V. Gulani[1,2], M. Kotas[3], M. Flentje[3], A. Haase[1], P. M. Jakob[1]

[1]Experimentelle Physik 5, Universität Würzburg, Würzburg, Germany, [2]Department of Radiology, University of Michigan, Ann Arbor, Michigan, United States, [3]Klinik und Poliklinik für Strahlentherapie, Universität Würzburg, Würzburg, Germany

Introduction The signal recovery during continuous TrueFISP imaging after spin inversion and initial $\alpha/2$-preparation depends on both T_1 and T_2 [1]. In this work, a complete set of analytical solutions is provided for the direct calculation of T_1, T_2 and spin density from the signal recovery curve which is described by a three parameter monoexponential function. Furthermore, the influence of off resonance frequency effects is analyzed with numerical simulations and the feasibility of the technique for fast acquisition of parameter maps of the human brain is demonstrated.

Theory The signal time course of an IR TrueFISP experiment may be described in good approximation by monoexponential behavior. For magnetization at or close to on-resonance which evolves along the $\alpha/2$-cone, the recovery curve is determined by an apparent relaxation time (derived from [2] for $TR \ll T_1, T_2$)

$$T_1^* = \left(\tfrac{1}{T_1}\cos^2\tfrac{\alpha}{2} + \tfrac{1}{T_2}\sin^2\tfrac{\alpha}{2}\right)^{-1}.., \qquad \text{(eq1)}$$

where α denotes the flip angle. After spin inversion and subsequent $\alpha/2$-preparation, the initial TrueFISP signal value corresponds to

$$S_0 = M_0 \sin\tfrac{\alpha}{2} \quad , \qquad \text{(eq2)}$$

with the spin density M_0. The signal evolves towards a steady state signal S_{stst} which may be written (for $TR \ll T_1, T_2$) as

$$S_{stst} = \frac{M_0 \sin\alpha}{(T1/T2+1) - \cos\alpha \cdot (T_1/T_2 - 1)} \qquad \text{(eq3)}$$

Consequently, three parameters are needed for a complete description of a corresponding exponential IR time course from S_0 to S_{stst}, e.g. using the fit function:

$$S(nTR) = S_{stst}\left[1 - INV \exp\left(-\tfrac{nTR}{T_1^*}\right)\right] \qquad \text{(eq4)}$$

Here, the inversion factor INV indicates the ratio between S_0 and the steady state signal S_{stst}. Using eqs.2 and 3, INV can be expressed as

$$INV = 1 + \frac{S_0}{S_{stst}} = 1 + \frac{\sin(\alpha/2)}{\sin\alpha}\left[\left(\tfrac{T_1}{T_2}+1\right) - \left(\tfrac{T_1}{T_2}-1\right)\cos\alpha\right] \qquad \text{(eq5)}$$

Thus, INV only depends on the flip angle and on the ratio T_1/T_2, approaching INV=2 for the limit of a small flip angle. Together with Eq.2, the following expressions are obtained so that T_1 and T_2 can be directly calculated from measured fit parameters T_1* and INV:

$$T_1 = T_1^*\left[\cos^2\tfrac{\alpha}{2} + (A \cdot INV + B)\sin^2\tfrac{\alpha}{2}\right] \qquad \text{(eq6)}$$

$$T_2 = T_1^*\left[\sin^2\tfrac{\alpha}{2} + (A \cdot INV + B)^{-1}\cos^2\tfrac{\alpha}{2}\right] \qquad \text{(eq7)}$$

with

$$A = 2\cos\tfrac{\alpha}{2}(1 - \cos\alpha)^{-1} \qquad \text{(eq8)}$$

and

$$B = (1 + 2\cos\tfrac{\alpha}{2} + \cos\alpha)(\cos\alpha - 1)^{-1}. \qquad \text{(eq9)}$$

When relaxation effects between the inversion pulse and the imaging sequence is neglected, the relative spin density M_0 may be estimated directly from:

$$M_0 = S_{stst}(INV - 1)\sin^{-1}\tfrac{\alpha}{2} \quad . \qquad \text{(eq10)}$$

Methods The accuracy of the approximate description given above as well as potential errors induced by off resonance at various flip angles were analyzed by comparison to numerical simulations on the basis of the Bloch equations. The technique was employed in a volunteer brain study on a 1.5T whole body scanner (Vision, Siemens Medical Solutions). A segmented IR TrueFISP imaging sequence was used (TR=6.46ms, 38 images, 21 phase encoding steps (i.e. 136ms) per segment, 8mm slice, FOV 256mm, matrix 252x256). Thus, the recovery curve was sampled for more than 5s with a train of 38 image segments. A sinc-shaped RF pulse was used, which had been optimized for a rectangular flip angle profile. With a delay of 5s before the next inversion, the total scan time was 2:05min. T_1, T_2 and M_0 maps were obtained by pixelwise fitting measured IR time courses to eq4 and direct calculation according to eqs6-9.

Results The given analytical descriptions correspond to the results of the Bloch simulation very closely. In the in-vivo studies, reproducible results were obtained. In Fig1, representative parameter maps of a human brain are shown, acquired at a flip angle of 50°. For better visualization, the T_1 and T_2 map color scales were truncated at 3500ms and 250ms, while the M_0 map was normalized to 1 for the maximum value (in CSF). The parameter values obtained in different compartments are given in table 1. The spin density of CSF is underestimated because of partial volume effects and incomplete recovery during the 5s waiting delay. The values obtained for the other parameters are in close agreement with the literature [3-6]. In Fig2, expected errors introduced by off resonance are plotted against the off resonance angle. For example at an off resonance angle of $\pi/3$, which corresponds to a frequency offset of 26Hz for TR=6.46ms at 1.5T, the measured T_1 is about 5% too large while T_2 is underestimated by 20%.

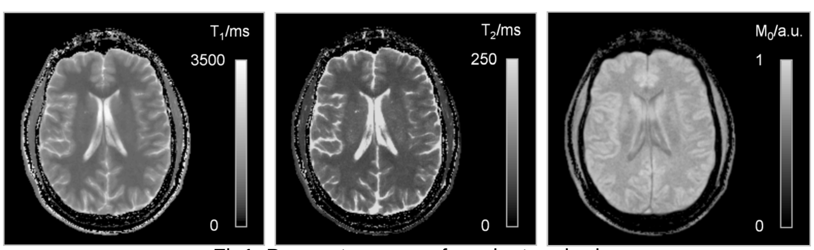

Fig1: Parameter maps of a volunteer brain

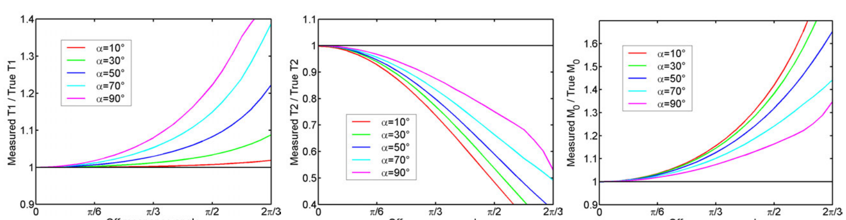

Fig2: Errors caused by off resonances at different flip angles

	T_1 / ms	T_2 / ms	M_0 / a.u.
White matter	719 ± 33	73 ± 6	0.81 ± 0.03
Gray matter	1165 ± 88..	92 ± 11	0.98 ± 0.07
CSF	3337 ± 111	2562 ± 123	1.00 ± 0.07
Muscle	963 ± 78	60 ± 12	0.79 ± 0.05

Table1: Measured parameter values

Discussion: It is possible to calculate T_1, T_2 and M_0 parameter maps directly from the signal obtained via a single IR TrueFISP measurement. Thus, it is also possible to derive multiple synthetic images mimicking different weighted contrasts of certain sequences, e.g. T_1- or T_2-weighted spin echo or FLAIR sequences. These computed images originate from the same experiment and thus are perfectly aligned. The accuracy of the technique is diminsihed in the presence of off resonance frequencies, as seen in Fig2. This may be a limitation for in-vivo applications in regions with poor B_0 homogeneity. However, in our experience, this has proved not to be a problem in our studies on the human brain.

Acknowledgments Support by Siemens Medical Solutions (Erlangen, Germany) is gratefully acknowledged

References [1] Schmitt P, Griswold M, Fidler F et al. 2002. Proceedings ESMRMB. #469. [2] Scheffler K. Mag Reson Med 2003;49:781-783. [3] Breger RK, Rimm AA, Fischer ME et al. Radiology 1989;171:273-276. [4] Poon CS, Henkelman RM. J Magn Reson Imaging 1992;2:541-553. [5] Whittall KP, MacKay AL, Graeb DA et al. Magn Reson Med 1997;37:34-43. [6] Vymazal J, Righini A, Brooks RA et al. Radiology 1999;211:489-495.