Improved accuracy of variable flip angle T_1 measurements using optimal radiofrequency and gradient spoiling

V. L. Yarnykh[1]

[1]Department of Radiology, University of Washington, Seattle, WA, United States

Introduction. A variable flip angle (VFA) method is widely used for in vivo T_1 mapping due to its time efficiency and easy 3D implementation with a large anatomical coverage. Practical implementations of VFA measurements are typically based on a radiofrequency (RF) spoiled gradient echo (GRE) sequence (1). A recent study (2) identified incomplete spoiling as a critical source of errors in the VFA method. Such errors are caused by the dependence of the optimal phase increment in the RF spoiling scheme on T_2 of the object. This study demonstrates the way to overcome this problem by using a combination of RF and gradient spoiling and also presents a general methodology for theoretical analysis of spoiling phenomena.

Theory. A standard approach to analyze spoiling effects in the GRE sequence is based on the isochromat summation method (1-4), where the role of spoiling gradients is to create a phase distribution of isochromats. An additional spoiling mechanism caused by diffusion, therefore, cannot be analyzed within this approach. To incorporate the diffusion effect, a combined isochromat summation and diffusion propagator model (5,6) was adopted and applied to the RF and gradient-spoiled GRE sequence. Within this model, a distribution of isochromats after each RF pulse is convolved with the propagator of the Bloch-Torrey equation. The evolution of an isochromat with the spatially dependent phase ψ_l on jth TR interval is described as follows:

$$\mathbf{m}_{j+1}(\psi_l) = \sum_q \mathbf{E}(\psi_l, \psi_q)\mathbf{m}_j(\psi_q) + (1-E_1)\mathbf{m}_0$$

where the summation is performed for all isochromats. The propagator in the matrix form is given by

$$\mathbf{E}(\psi_l, \psi_q) = \begin{bmatrix} P(\psi_l - \psi_q)E_D E_2\cos((\psi_l+\psi_q)/2) & P(\psi_l - \psi_q)E_D E_2\sin((\psi_l+\psi_q)/2) & 0 \\ -P(\psi_l - \psi_q)E_D E_2\sin((\psi_l+\psi_q)/2) & P(\psi_l - \psi_q)E_D E_2\cos((\psi_l+\psi_q)/2) & 0 \\ 0 & 0 & P(\psi_l - \psi_q)E_1 \end{bmatrix}$$

where $E_{1,2}$=exp(-TR/$T_{1,2}$), the diffusion term E_D=exp(-1/12$\gamma^2 A_G^2 t_G D$), A_G is the spoiler gradient area, t_G is the time when a gradient is turned on, D is the diffusion coefficient and the terms

$$P(\psi_l - \psi_q) = (4\pi D\mathrm{TR})^{-1/2}(\gamma A_G)^{-1}\exp[-(\psi_l - \psi_q)^2 / 4D\mathrm{TR}\gamma^2 A_G^2]$$

describe the Gaussian probability of magnetization exchange between isochromats due to diffusion. RF pulses are described by the standard rotation matrix dependent on the flip angle (FA) and phase. Similar to the traditional isochromat summation technique, the computational procedure is iterated until the total magnetization (vector sum of isochromats) achieves the steady state.

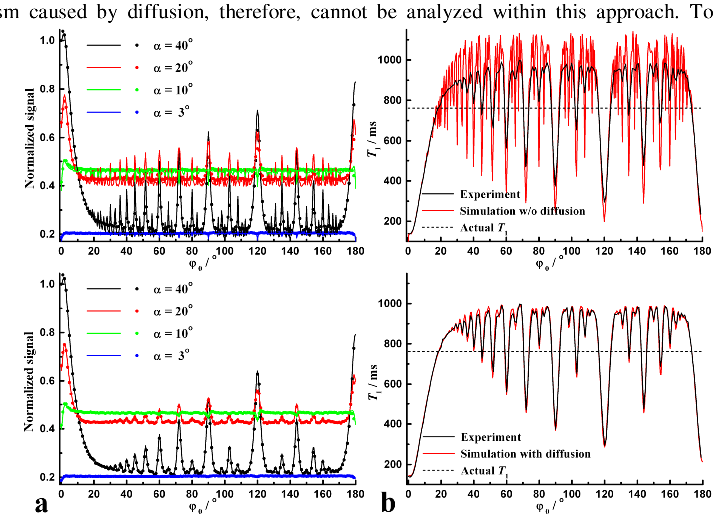

Fig. 1. Comparison between the standard isochromat summation (**top**) and diffusion propagator (**bottom**) models. **a:** Experimental signal measurements (points) are superimposed with simulations (lines). **b:** Experimentally determined T_1 (black lines) are superimposed with simulations (red lines). Sequence parameters: TR=20 ms, A_G=23.4 mT*ms/m. Object: T_1/T_2=784/662 ms, D=2.2x10^{-3} mm^2/s.

Methods. ***Simulations.*** The above algorithm was implemented in a custom-written C program. T_1 measurement process was simulated by generating signal intensities corresponding to a set of FA α=40, 20, 10, and 3º and phase increment values ranging from 0 to 180º. For each phase increment, simulated variable FA signal intensities $S(\alpha)$ were processed by the linear fit in coordinates ($S(\alpha)/\sin\alpha$ vs. $S(\alpha)/\tan\alpha$) to yield T_1.

Experiments. Experimental measurements were obtained on a 3T Philips Achieva whole-body scanner with a body coil used for transmission. A phantom containing 5 small tubes with variable T_1 (1.0, 0.5, and 0.2 mM solutions of Gd-DTPA, 0.3 mM solution of $MnCl_2$, and water) was scanned using the 3D GRE sequence. A series of measurements was obtained with a variable phase increment φ_0 in a range 0-180º. For each φ_0 value, four images with FA of 40, 20, 10, and 3º were acquired. The measurement procedure was repeated for several settings of the spoiling gradient area A_G. The described above linear fit method was used to obtain T_1 values from experimental measurements. Control T_1, T_2, and diffusion coefficient (D) measurements were obtained in the same scanning session.

Results. ***Agreement between simulations and experiments.*** The role of diffusion in the model of spoiling phenomena is illustrated by Fig.1. The standard isochromat summation (Fig. 1) does not adequately represent the signal behavior over a range of phase increments and flip angles. On the other hand, the model with diffusion provides close agreement between simulated and experimental spoiling patterns (Fig. 1).

Analysis of T_1 measurements. Depending on the gradient areas, sequence timing, T_2, and D, the spoiling patterns of the GRE sequence can be classified into three regimes termed here as weak, intermediate, and strong spoiling. The examples are shown in Figs. 1 and 2. In the weak spoiling regime, the signal has a multi-peak dependence on the phase increment, which translates into a complex dependence of measured T_1 on φ_0 with multiple sharp inverted peaks (Fig. 1,2). Although optimal spoiling (i.e. correct T_1 measurements) is possible at multiple φ_0, the dependences are steep and their shape is sensitive to T_2 and diffusion properties. If sufficiently large spoiling gradients are used, the GRE sequence is characterized by the strong spoiling regime (Fig. 2), where the dependence of the measured flip angle on φ_0 has a smooth shape and all peaks are eliminated. The intermediate regime is characterized by wide major peaks, while minor peaks disappear. The translation between regimes may also take place due to relaxation and diffusion properties of the object as seen in Fig. 2. For the sample with short T_2, intermediate regime occurs at the same sequence parameters, which correspond to the weak regime observed in the sample with long T_2. In general, T_1 measurement can be independent of T_2 and diffusion only in the strong spoiling regime (Fig. 2). The choice of the phase increment in the strong spoiling regime is rather flexible, while the values in a range150-160° will provide the best accuracy and immunity against the residual diffusion effect (Fig. 2).

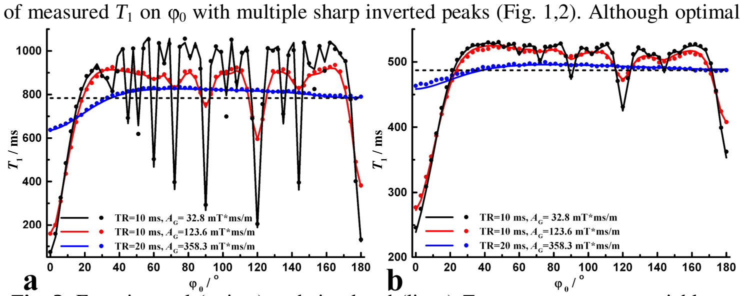

Fig. 2. Experimental (points) and simulated (lines) T_1 measurements at variable φ_0 in the weak (black), intermediate (red), and strong (blue) spoiling regimes. **a:** Long T_2=662 ms (0.2 mM Gd). **b:** Short T_2=34 ms (0.3 mM Mn). Dash lines correspond to actual T_1. D=2.2x10^{-3} mm^2/s in both solutions.

Discussion and conclusions. This study shows that the effect of diffusion should to be taken into consideration to adequately describe the spoiling behavior of the GRE sequence. Excellent agreement between experiments and simulations allows using the presented theoretical model for the GRE sequence optimization. The strong spoiling regime is recommended to improve accuracy of T_1 VFA measurements. With typically available 20-25 mT/m gradient strength on most MR systems, this regime requires the TR=20-30 ms, while the sequence design should allow the spoiler gradients to be applied at the maximal available strength and duration.

References: 1) Zur Y, et al. *MRM* 1991; 21:251. 2) Yarnykh VL. ISMRM 2007, #1796 3) Epstein FH, et al. *MRM* 1996; 35:237. 4) Ganter C. *MRM* 2006; 55:98. 5) Gudbjartsson H, Patz S. MRM 1995;34:567. 6) Kiselev VG. JMR 2003; 164:205.