Effect of the phase increment on the accuracy of T1 measurements by the variable flip angle method using a fast RF spoiled gradient echo sequence

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Introduction: An increasing popularity of T_1 relaxation measurements by a variable flip angle (VFA) technique is motivated by fast acquisition and easy 3D implementation with a large anatomical coverage. A number of studies (1-3) investigated the accuracy of the VFA method and factors affecting potential errors, such as the noise, B_1 non-uniformity, and suboptimal sampling. However, all previous methodological analyses have relied on the ideal spoiling approach, which may not hold at the experimental conditions. Such techniques make use of an appropriate RF phase cycle (4) to eliminate the residual transverse magnetization, if the TR of the sequence is insufficient to warrant complete T_2 decay, i.e. TR<3T_2. Several RF spoiling schemes (4,5) based on a general principle of linear incrementing of the phase of the excitation RF pulse were proposed. However, none of these schemes was tested with respect to the accuracy of T_1 measurements by the VFA method. The situation is even worse, because the default spoiling schemes implemented by major vendors of MR equipment are different and, typically, unknown to the user. For instance, according to the authors' experience, General Electric (GE) scanners operate with the 115.4º increment for the 3D SPGR sequence. A T_1-weighted gradient echo sequence by Philips employs the 150° phase increment. These values are also considerably different from optimal phase increments suggested in literature, e.g. 117, 123 (4), and 84° (5),

Purpose: To evaluate the effect of the phase increment on T_1 measurements by the VFA method with an RF spoiled gradient echo sequence.

Methods: *Simulations:* T_1 measurement process was simulated by generating signal intensities corresponding to a set of flip angles (FA) of 40, 20, 10, and 3º and phase increment values ranging from 0 to 180º. For each dataset, Bloch equations were iteratively solved until achieving the steady state. The intensities were generated as the modulus of the transverse magnetization after vector summation of 200 isochromates uniformly distributed over the 4π phase dispersion range. 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 (1-3).

Experiments: Experimental measurements were obtained on a 1.5T clinical scanner (GE Signa) with a transmit-receive head coil. A phantom containing 5 small tubes with variable T_1 (1.0, 0.5, and 0.1 mM solutions of gadolinium, 0.3 mM solution of $MnCl_2$, and water) was scanned using the 3D SPGR sequence with TR/TE=10/1.8 ms. A series of measurements was obtained at variable phase increment values in a range 0 to 180º with the step of 3º. A more detailed tracing of the phase increment dependence with the step of 1º was performed in the vicinity of the 117º value (range 114-120º). The setting of phase increments was performed by the "seed" control variable, which corresponds to the phase increment converted into the 16-bit integer range in the scanner's software. Also, measurements were obtained for a default "seed" value of 21001 corresponding to the phase increment of 115.37º. For each phase increment, four images with FA of 40, 20, 10, and 3º were acquired. The described above linear fit method was used to obtain T_1 values from experimental measurements. Control T_1 and T_2 measurements were obtained in the same scanning session by the inversion-recovery and spin echo techniques, respectively.

Results: Theory predicts a strong dependence of T_1 measured by the VFA method on the phase increment (Fig. 1). The multi-peak shape of this dependence resembles previously reported simulations for signal intensities (4,6) with the difference that maximums for the spoiled signal correspond to minimums for T_1. Detailed analysis shows that there is no unique phase increment value, which could guarantee the accuracy of VFA T_1 measurements for a variety of relaxation properties. As seen from Fig. 2, the position of the crossing point between the VFA T_1 curve and the true T_1 line depends on T_2, because the widths of inverted peaks are determined by T_2. This effect is also in agreement with earlier signal simulations (6). Although the optimal phase increment varies within a small range of ~1º for a physiologically reasonable T_2 range, the errors in T_1 estimates can be quite significant (up to 10%) due to the steep nature of the T_1 dependence. Experimental measurements confirm the noted multi-peak structure of the measured T_1 as a function of the phase increment (Fig. 3). In agreement with theoretical predictions, the 117º increment value minimizes but not completely eliminates systematic errors (Fig. 4). It is of practical interest also to look at some phase increment values suggested in literature or implemented in commercial pulse sequences. As seen in Fig. 4, at the 115.4º increment (GE default value), the T_1 values are systematically overestimated by 10-20% for relatively short T_2 corresponding to those observed in tissues (<200 ms) and up to 40% for longer T_2 values. Severe overestimation (20-50%) also occurs for the phase increments of 150º (default for Philips) and 84º (5). The behavior of the measured T_1 in the vicinity of 123º is similar to that around 117º due to the symmetry of the inverted peak at 120º.

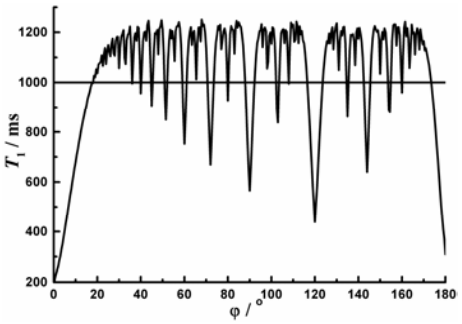

Fig. 1. Simulated dependence of T_1 measured by the VFA method on the phase increment for actual T_1=1000 ms (horizontal line), T_2=100 ms, and TR=10 ms.

Conclusions: Researchers should be aware of the effect of the RF spoiling phase increment on VFA T_1 measurements as a potential source of large systematic errors. Commercial implementations of a spoiled gradient echo sequence by GE and Philips are not suitable for VFA T_1 measurements because of inappropriate default phase increment values. Careful standardization of the VFA method with respect to the default phase increment and accuracy of its hardware setting is required for quantitative T_1 clinical studies.

References: 1) Wang HZ, et al. MRM 1987;5:399. 2) Venkatesan R, et al. *MRM* 1998;40:592. 3) Cheng HL, Wright GA. *MRM* 2006;55:566. 4) Zur Y, et al. *MRM* 1991; 21:251. 5) Epstein FH, et al. *MRM* 1996; 35:237. 6) Ganter C. *MRM* 2006; 55:98.

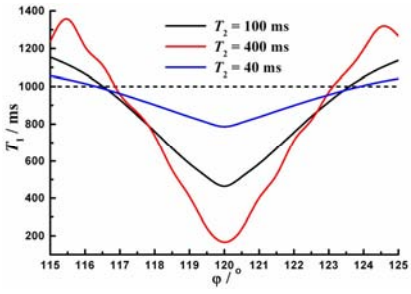

Fig. 2. Simulations of the effect of T_2 on the optimal value of the phase increment for VFA T_1 measurements. Depending on T_2, the optimal phase increment varies in ranges 116-117º and 123-124º. For all plots, the actual T_1=1000 ms (horizontal line), and TR=10 ms.

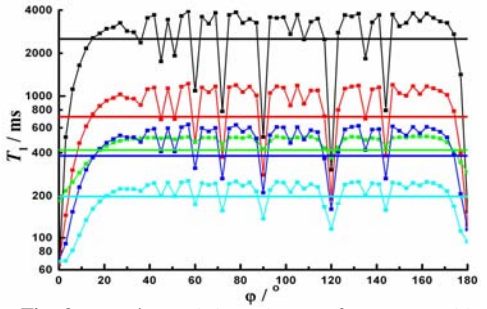

Fig. 3. Experimental dependences of T_1 measured by the VFA method on the phase increment for media with T_1/ T_2= 2515/1029 ms (black), 716/568 ms (red), 419/47 ms (green), 381/330 ms (blue), and 198/173 ms (cyan), Horizontal lines correspond to T_1 measured by inversion-recovery.

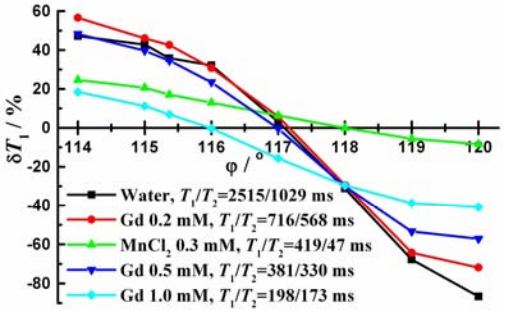

Fig. 4. Experimental dependences of the relative error of T_1 measurements (δT_1=(T_1-T_1^{ref})/T_1^{ref}, where reference values T_1^{ref} were measured by inversion-recovery) on the phase increment in the vicinity of the optimal increment value of 117°.