Effect of the Slice Profile on the T_1 Measurement with Steady-State Magnetization

J-J. Hsu[1]
[1]Radiology, University of Miami School of Medicine, Miami, Florida, United States

Introduction. Under continuous application of identical and equally-spaced RF pulses, the magnetization will gradually reaches a steady state, in which the magnitude of the longitudinal magnetization is a constant at the time of each RF pulse application. The magnitude of the steady-state signal S^{SS} depends on the inter-pulse spacing τ, the flip angle (FA) α, and T_1. If τ and α are known, T_1 can be derived from S^{SS}. This is a very simple method for T_1 measurement [1,2], which some authors refer to as DESPOT [3]. It takes time to reach the steady state but, compared with transient-state methods, the constant, steady-state MR signals provide the possibility of time-efficient high-resolution k-space sampling, making the method desirable. When implemented in the 3D mode, the method requires a shorter τ to save the scan time, but τ has to be much longer than T_2 for T_1 measurement accuracy (RF and gradient spoiling do not eliminate the transverse magnetization). In the 2D mode, τ can be longer and scan-time saving can be achieved by multi-slice acquisitions interleaved during τ. The 2D mode and optionally the 3D mode require slice selection. Slice selection uses RF pulses of finite length, which results in a non-uniform FA profile across the slice-thickness dimension (z) and generates serious T_1 measurement error [4–6]. Many researchers have recently recognized that measuring the regional FA inhomogeneity in the volume is essential for accurate T_1 measurement; however, less known is the effect of the FA profile. As revealed by this work, it is important to understand the effect of the FA profile and the valid ranges of the method.

Methods. §***Theory.***—Assuming that the transverse magnetization is fully relaxed during τ, the signal S^{SS} is given by $S^{SS} = c\, M_{eq}\,(1-E)/[1-E\cos(\alpha)]\sin(\alpha)$, where M_{eq} is the magnetization at thermal equilibrium, c a dimension conversion constant, and $E = \exp(-\tau/T_1)$. The equation can be rewritten in a linear form as $S^{SS}/\sin(\alpha) = E\, S^{SS}/\tan(\alpha) + c\, M_{eq}\,(1-E)$. Therefore the basic idea is to measure S^{SS} for two or more values of α and fit the data pairs $[S^{SS}/\tan(\alpha), S^{SS}/\sin(\alpha)]$ to a straight line. The slope of the line is E, from which T_1 can be derived. However, because the FA profile is not uniform, i.e., $\alpha = \alpha(z)$, the observed S^{SS} is actually the integral $S^{SS}|_{obs} = \int S^{SS}\,dz$ and the linear form is no longer valid for $S^{SS}|_{obs}$. Thus the curve-fitting generates error.
§***Computational.***—The symmetrical sinc and Hamming-windowed sinc RF envelopes were considered in this work. By numerically solving the Bloch equation, the transverse magnetization induced by the RF envelope was obtained and then refocused. The simulated $S^{SS}|_{obs}$ was computed by using the Simpson's method of numerical integration. The interval of integration was 4.7 times the slice thickness. The RF envelope amplitude A controlled the FA. The $\alpha|_{obs}$ was determined by solving a trigonometry identity relating the simulated $S^{SS}|_{obs}$ for A and for $0.5A$ [7]. The goal is to examine the effect of the FA profile on the T_1 obtained by the linear curve-fitting from various simulated $S^{SS}|_{obs}$ and $\alpha|_{obs}$. The relaxation during the RF pulse was neglected.

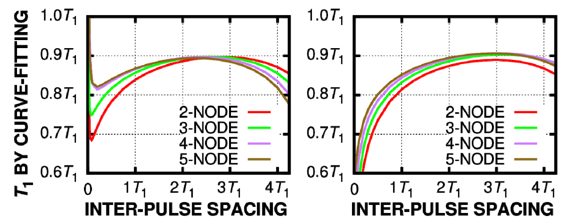

Figure 1 Effect of the FA profile from truncated (left) and Hamming-windowed (right) sinc RF envelope as a function of τ and the number of nodes of each wing.

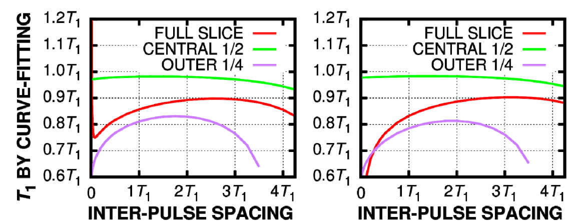

Figure 2 Effect of the FA profile with sub-slicing for truncated (left) and Hamming-windowed (right) sinc RF envelope. Results for the full slice, the central half-slice, and outer quarter-slices combined are shown.

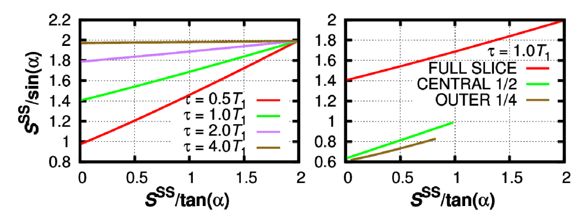

Figure 3 Example of $S^{SS}/\sin(\alpha)$ versus $S^{SS}/\tan(\alpha)$ for the 3-node Hamming-windowed envelope. Both axes are in arbitrary unit. Each curve represents the range of $\alpha|_{obs}$ in [5°, 85°]. The left plot is for full slice.

Results and Discussion. Figure 1 shows that the best result is 10% below the true T_1. Adding number of nodes, which makes the FA profile more squared, does not improve the accuracy. Windowing is known to reduce the slice side lobes and smooth the slice profile, but is irrelevant to the accuracy improvement. For a given RF envelope, there is a value of τ for optimal T_1 accuracy. Figure 2 shows that the T_1 accuracy is significantly improved if only the portion of the signal of the central half-slice is used, indicating that the error is indeed owing to the FA profile. The sub-slicing can be achieved practically as shown in Ref. [6]. Although the linear curve-fitting is theoretically invalid, Fig. 3 shows examples that, in some ranges, the linearity is still preserved (also true for the truncated sinc; not shown). That is, the slope can be expressed as βE such that E is still accurate and the constant β can be predicted as in this work. For example, $\beta = 0.815$ for the full-slice, $\tau = 1.0T_1$ curve in Fig. 3. A systematic formula will be published elsewhere. In conclusion, the present work provides important and essential guidelines for pulse sequence design and scan parameter selection for this popular T_1 measurement method. The FA profile effect is inevitable but, with correction, the linearity can still be used for T_1 measurement.

References: [1] KA Christensen, *et al.*, J Phys Chem **78**, 1971 (1974). [2] RK Gupta, J Magn Reson **25**, 231 (1977). [3] J Homer and MS Beevers, J Magn Reson **63**, 287 (1985). [4] GJM Parker, GJ Barker, and PS Tofts, Magn Reson Med **45**, 838 (2001). [5] BF Coolen, *et al.*, Magn Reson Imaging **27**, 815 (2009). [6] J-J Hsu, G Zaharchuk, and GH Glover, Magn Reson Med **61**, 1319, (2009). [7] EK Insko and L Bolinger, J Magn Reson A **103**, 82 (1993).