Theoretical and Experimental Efficiency and Optimization of Flip Angle Mapping Techniques

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Introduction: Transmit B1 inhomogeneity is a major problem at higher field strengths. The RF wavelength decreases with increasing field strength and at 3T and above begins to approach the same scale as the human body. This leads to destructive interference and non-uniform excitation of tissue. Methods exist for correcting this non-uniformity, but mapping the flip angle field is a prerequisite. A number of $B1^+$ mapping methods exist; we specifically looked at the saturated double angle based methods (satDAM) [1], actual flip angle imaging (AFI) [2] and the newly introduced, non-inverted double angle Look-Locker (niDALL) technique.[3]. The flip angle inhomogeneity is a spatially smooth 3D phenomenon, and there is an unmet need for a rapid, efficient and accurate 3D method of mapping the flip angle, especially important for transmit arrays. We set an arbitrary scan time restriction of one minute, for a 3D volume $B1^+$ map with approximately 1000 total phase encodes (approximately 32x32 or 42x24 in k_y x k_z).

Theory: The three above mentioned methods each take a different approach to mapping the flip angle. In order to optimize and then compare them, we introduce here a metric of imaging efficiency (Eq 1). This is based on a dimensionless noise propagation factor, b, which is based on the propagation of signal-to-noise ratio from the input images to the derived flip angle maps (Eq 2). Γ is thus proportional to the flip angle to noise in the flip angle ratio (ANR), normalized by the sequence scan time (T_{exam}), assuming equivalent image acquisition techniques for each method. If T_{exam} is set constant across the different imaging methods, then the efficiency will depend on T_{seq}, where T_{seq} is a measure of effective sequence time given by $T_{exam}=N_{ex}N_{pe}T_{seq}$. b can be derived analytically by applying noise propagation theory to the signal and fitting equations used to derive the flip angle from the input signals. Comparison of any flip angle mapping method can then be made on a rigorous and fair basis by evaluating Gamma, which only requires the derivation of b and T_{seq} for each method.

$$\Gamma = \frac{1}{b}\frac{1}{\sqrt{T_{seq}}} \propto \frac{ANR}{\sqrt{T_{exam}}} \quad (1) \qquad b = \frac{\alpha/\sigma_\alpha}{S_0/\sigma_0} \quad (2)$$

	Tseq	Parameters	Optimum
satDAM	$2T_{SR}$	α, T_{SR}	96°, 30 ms
AFI	TR_1+TR_2	α, TR_1, TR_2	116°, 5ms, 55ms
niDALL	$2N_{TI}\tau$	α, τ, N_α	4.8°, 3.7ms, 328

Table 1: Effective sequence time and parameters optimized for each of the flip angle imaging techniques, including the parameters for an optimized one minute scan

Methods: Each of the methods was optimized over the relevant free imaging parameters (see Table 1) for an assumed T_1=1500 ms. These parameters were varied to find the combination that would give the maximum imaging efficiency for a range of effective sequence times (T_{seq}). The theoretical noise propagation analysis was then validated in a phantom (12 cm diameter) with T_1's ranging from 150 to 2950 ms. Experimental ANR was calculated using multiple repeats of the AFI and niDALL methods (no 3D satDAM method was available), for a range of nominal flip angles using an imaging matrix 42x42x24, FOV =12 cm, slice thickness = 1cm, to cover the entire volume of the phantom in a one minute scan(T_{seq}=60 ms).

Results: The optimized efficiency as a function of T_{seq} is shown in Figure 1. The efficiency of the satDAM and AFI methods strongly depends on Tseq, which is fundamentally different than the flat niDALL efficiency vsTseq. Thus the satDAM and AFI methods are only fully optimized for relatively long 3D scan times ($T_{seq} \sim T_1$). .For a scan time of one minute and a T_1 of 1500 ms, T_{seq}/T_1~0.04. Below approximately this point, Figure 1 shows that the niDALL method has the highest efficiency which becomes a major advantage for Tseq/T1<0.01. The ANR measurements in Figures 2 and 3 indicate that the propagation of noise analysis does predict the measured value reasonably well, and also that the optimization does appear to work, and predict the correct optimum flip angle to use for AFI and niDALL.

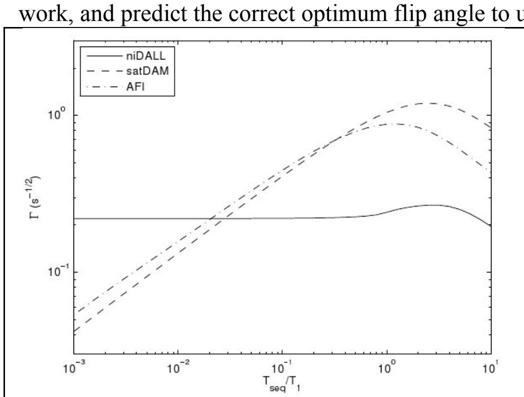

Figure 1: Efficiency vs the available effective sequence time.

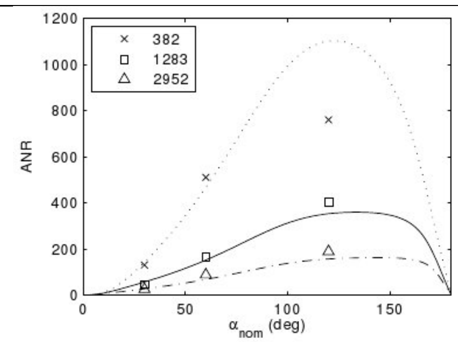

Figure 2: ANR for a range of T1 values acquired using the AFI technique, compared to the ANR predicted from the propagation of noise analysis

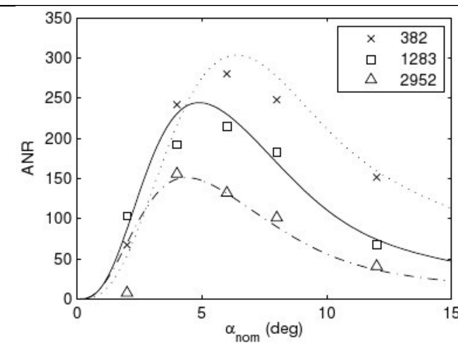

Figure 2: ANR for a range of T1 values acquired using the niDALL technique, compared to the ANR predicted from the propagation of noise analysis.

Discussion and Conclusion: The optimized imaging parameters predicted by the efficiency analysis differ slightly from those typically used for the satDAM and AFI techniques. In particular the optimum flip angles predicted are greater than 90°. Imaging in this regime would require that image phase be maintained and used, but may also lead to improvements in ANR. Imaging in this regime, particularly with short repetition times and large flip angles poses additional challenges, especially with regards to spoiling the transverse magnetization. These effects were not investigated here. It is also interesting to note that this efficiency optimization suggested that the AFI TR_1 should be minimized. More commonly the ratio TR_2/TR_1 is set to be in the range 4 to 6. The noise propagation theory and new efficiency metric introduced here allows both the optimization of imaging parameters within a given B_1^+ mapping method, but also allows direct comparison of efficiency between methods. Application of this method to three different methods shows that the niDALL method has efficiency advantages for high-speed B_1^+ mapping.

References:[1] Cunningham C, Pauly J, Nayak K, *Magn Reson Imag*, 2006; 55:1326 [2] Yarnykh, V.L., *Magn Reson Imag*, 2007; 57:192–200.[3] Wade T, McKenzie C, Rutt B, In: Proceedings of the 18th Annual Meetings of ISMRM, Sweden, 2010. Abstract 3732.