Phase accrual during excitation in ultrashort TE (UTE) imaging: an alternate definition of TE for phase measurements

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Introduction

MR imaging of tissues with submillisecond T_2's is possible with UTE (ultrashort TE) sequences that utilize half RF excitation pulses and radial projection readouts (1). For standard pulse sequences that use full symmetric RF excitation pulses and Cartesian readouts, TE (echo time) is defined from the center of the RF pulse to the center of the k-space during readout, and phase accrual (ϕ) for an off resonance source (frequency ω_{off}) is calculated as $\phi=\omega_{off}\cdot TE$. For UTE sequences, TE is customarily defined to be from the end of the half RF pulse to the beginning of radial projection readout (1). We present data here that show phase accrual by off resonance sources in UTE to be significantly in excess of $\phi=\omega_{off}\cdot TE$ using the customary definition of TE. Numerical calculations suggest a major portion of this additional phase is accrued prior to the end of the RF pulse.

Methods

Magnitude and phase images were acquired using a GE 3.0T scanner and UTE sequence with TE=8μs, TR=250ms, FOV=10cm, BW=±62.5kHz, FA=30°, Matrix=512x511. A cadaveric specimen including the Achilles tendon was used for Figure 1, and phantoms containing vegetable oil (fat), dimethylsulfoxide, and acetonitrile were used for the experiments in Table 1.

Results and Discussion

TE=8μs magnitude and phase images are displayed in Figures 1A and 1B. The phase difference between the Achilles tendon and bone marrow (i.e. between water and mainly fat signal) is 0.47 radians, which is significantly greater than the expected phase gain of 0.022 radians at TE=8μs, assuming an off-resonance frequency of 447Hz for fat at 3T. The measured phases for the three phantoms were also greater than expected for TE=8μs (Table 1 Columns 2, 3).

Excitation in 2D UTE sequences uses asymmetric RF pulses and lacks rewinder gradients. We examined numerically whether such a combination might lead to a net phase by the end of excitation – i.e. whether phase accrual effectively begins prior to the end of the half RF excitation pulse. The transverse magnetization after RF excitation can be expressed (in the small tip angle approximation regime) by (2):

$$M_{xy}(T_0) = iM_0\gamma\int_{-\Delta z}^{\Delta z}\int_{-\infty}^{T_0} B_1(t)\cdot e^{-i\left[\int_t^{T_0}\gamma G_z(t')zdt'+\omega_{off}(\tau-T_0)\right]}dtdz \qquad \text{(Equation 1)}$$

where M_0 is the total magnetization, γ is the gyromagnetic ratio, $B_1(t)$ is the excitation RF amplitude, G_z is the slice select gradient amplitude, z is the distance from isocenter in the slice select direction, ω_{off} is the off resonance frequency, T_0 is the time at the end of excitation, and t/t' are integration variables representing time during the RF pulse. By numerical integration of Equation 1, we obtained the net magnetization at the end of RF excitation, and its corresponding phase is given in Table 1 Column 4. The calculated values indicated that off resonance sources are expected to have net phase accumulation by the end of the RF excitation pulse. By comparison with measured values, the calculated phases account for a significant portion of the measured phase, although additional factors (compare the difference between Table 1 Columns 3 and 4) may be important as well.

Our experiments and numerical calculations demonstrate that phase accrual for off resonance sources begins prior to the end of the half RF excitation pulse (schematized in Figure 2). This suggests the definition of an effective TE due to phase accrual during the RF pulse (ϕ_{RF}) given by $TE_{eff} = \phi_{RF}/\omega_{off}$. TE_{eff} and ϕ_{RF} will depend on the exact shape of the RF pulse and slice select gradients used. Note that this effective TE for phase accrual by off resonance sources is different from the effective TE due to T_2 decay during RF excitation discussed previously (3).

Conclusions

Off resonance sources accrue phase in UTE imaging in excess of that expected from the customary definition of TE, a large component of which occurs during the RF pulse. We are investigating additional factors that may contribute to the increased phase.

References

1) Tyler, DJ, et al., JMRI 2007; 25:279-289.
2) Bernstein MA, et al., *Handbook of MRI pulse sequences,* 2004.
3) Robson MD, et al. ISMRM abstract 2004.

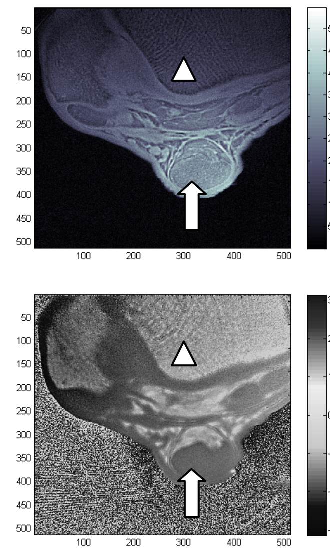

Figure 1 – UTE images acquired with TE 8μs. A) Magnitude and B) Phase images. Arrow – Achilles tendon (water signal). Arrowhead – bone marrow (fat signal)

	Off resonance frequency	Expected phase based on $\phi=\omega_{off}\cdot TE$, TE=8μs	Experimentally measured phase	Calculated phase using Equation 1
Dimethylsulfoxide	278 Hz	0.014 rad	0.41 rad	0.25 rad
Acetonitrile	357 Hz	0.018 rad	0.42 rad	0.32 rad
Fat (vegetable oil)	447 Hz	0.022 rad	0.62 rad	0.4 rad

Table 1 – Phase accrual for fat, dimethyl-sulfoxide, and acetonitrile at TE=8μs in UTE.
Column 1: Frequency
Column 2: Expected phase based on $\phi=\omega_{off}\cdot TE$ with TE 8μs
Column 3: Experimentally measured phase
Column 4: Calculated phase using Equation 1

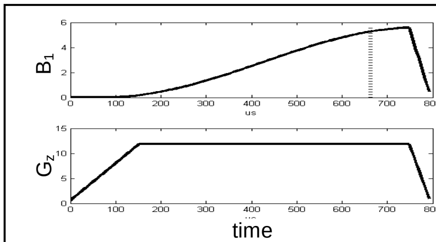

Figure 2 – RF pulse and gradient used for experiments and calculations in Table 1. An effective TE time of 134μs (indicated by dotted vertical line) is calculated for the phase accrual during this RF pulse.