

Effective TE for Radial FID Sequences

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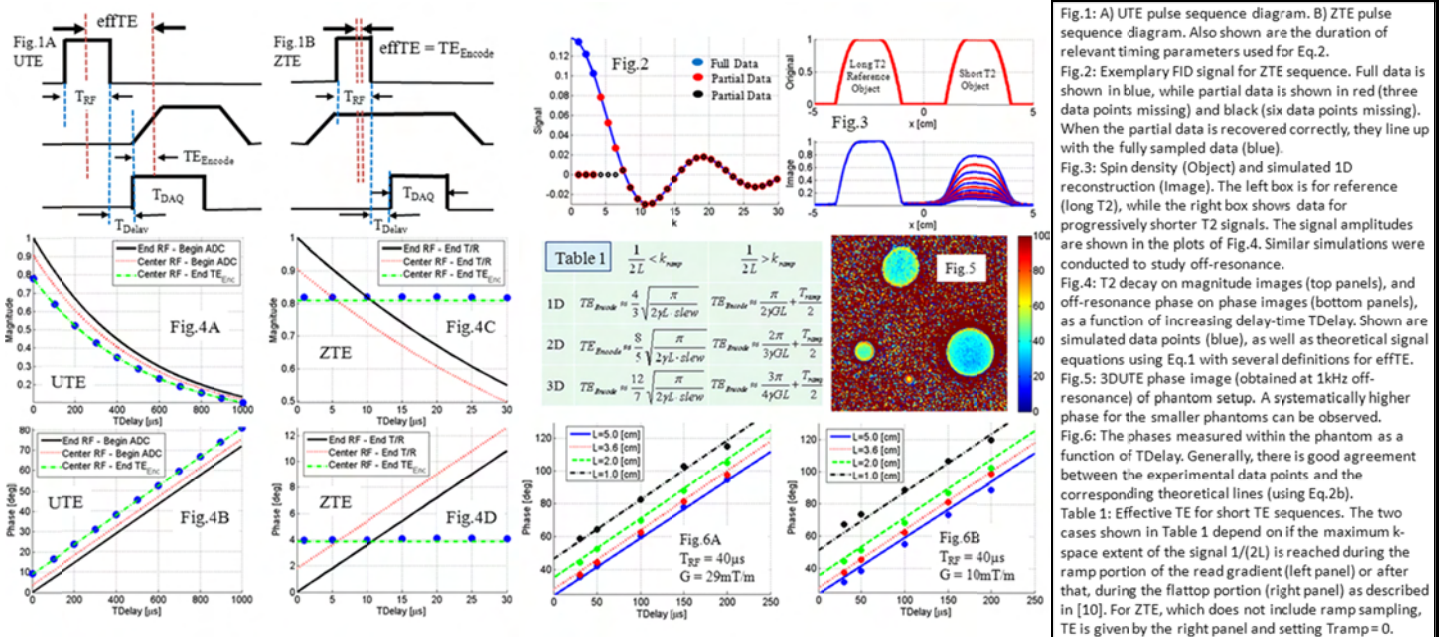
Introduction: Imaging very short T2 tissues frequently encountered in the musculoskeletal system using MRI requires specialized pulse sequences with very short echo times (TE). TE is an important sequence parameter which, coupled with the tissue relaxation rate, $R_2 = 1/T_2$, and off-resonance, f_{off} , determine T2 contrast on magnitude images or phase contrast on phase images, respectively. There exists a variety of inconsistent definitions of TE for short echo time sequences throughout the literature. For 3D UTE (where the read gradient is ramped up after the application of the excitation RF pulse), TE is often defined as the duration from the end of the RF pulse to the beginning of the read gradient ramp-up [1,2], or the duration from the center of the RF pulse to the beginning of the read gradient ramp-up [3], while for other FID based sequences, such as WASPI [4], RUFIS [5], ZTE [6], or PETRA [7], (where the read gradient is already ramped up before the application of the excitation RF pulse), TE is defined as either the dead-time during transmit-receive (T/R) switching [7], or simply zero [6]. Here we investigate via theoretical analysis, Bloch simulations, and phantom experiments an appropriate definition of TE for either kind of short echo time FID sequences.

Theory: With a standard gradient echo (GRE) sequence (Fig.1A), TE is a well-defined quantity, starting at the center of the RF pulse and ending at the center of the data acquisition (DAQ) window where $k = 0$. The image intensity reduction due to T2, and phase evolution due to $\omega = 2\pi f_{\text{off}}$ is given by: $S(TE) \sim e^{-R_2 TE} e^{i\omega TE}$ [1] A typical UTE and RUFIS/ZTE sequence are shown in Fig.1B and Fig.1C, respectively. The effective TE can be subdivided into the time periods (not drawn to scale) during RF excitation (TE_{RF}), frequency encoding during data acquisition (TE_{Encode}), and a time between the two which we will refer to as the delay-time T_{Delay} .

For example, for a GRE sequence (Fig.1A) this means that: $TE_{\text{GRE}} = T_{\text{RF}}/2 + T_{\text{Delay}} + T_{\text{DAQ}}/2$ [2a]

The magnetization trajectory during hard RF excitation in the presence of T2 relaxation is given by [8], while the magnetization trajectory for off-resonance during hard RF pulses is given by [9]. Both can be expanded to first order to yield an effective $TE_{\text{RF}} = T_{\text{RF}}/2$, resulting in $TE_{\text{UTE}} = T_{\text{RF}}/2 + T_{\text{Delay}}$. It was shown in [10] that when imaging an object of size L, the effective equations for T2 decay and off-resonance for radial imaging using a read gradient with amplitude G and slew-rate slew (corresponding to a ramp time T_{ramp}) have contributions during the gradient encoding beyond $k = 0$ that need to be included into the signal model. Expanding these image equations to first order yields effective TEs during the DAQ shown in Table 1. Combining these contributions, we arrive at an effective TE for UTE sequences: $\text{effTE}_{\text{UTE}} = TE_{\text{UTE}} + TE_{\text{Encode}}$ [2b]

where TE_{Encode} is given by Table 1. For ZTE, if the missing data is synthesized/extrapolated correctly (that is it actually represents the signal that would be observed during DAQ with negligible RF and T/R switch time) the fully recovered signal becomes independent of the amount of missing center k-space data (e.g. due to a longer or shorter T/R switch time), as shown in Fig.2. This implies that the effective TE time is independent of the T/R switching time. Since the time points for the center of the RF pulse and readout $k = 0$ coincide, $TE_{\text{ZTE}} = 0$ and the effective TE only contains the effects during gradient encoding: $\text{effTE}_{\text{ZTE}} = 0 + TE_{\text{Encode}}$ [2c]



Simulations: Bloch equation simulations were conducted to study T2 decay and phase evolution during the different parts of the sequences (e.g. RF pulse, DAQ, etc.) shown in Fig. 1. A 1D example of such a Bloch simulation is shown in Fig. 3. The signals for both k-space lines of a 1D UTE/ZTE sequence (or a single full k-space line for 1D GRE) for two simple box objects (one long T2 and on-resonance, the other with progressively shorter T2s and/or higher off-resonances, as shown in blue and red) were simulated, combined, and then Fourier transformed. Fig. 4 shows simulation results (symbols) of the magnitude and phases for the three pulse sequences as the delay-time (T_{Delay}) between the end of the RF pulse and the beginning of the DAQ is increased. Also shown are theoretical lines using the simple exponential in Eq. 1, employing several definitions for the effective TEs. For UTE (shown in Fig. 4A), the correct effective TE is given by the time from the center of RF pulse and ends after the effective TE time during gradient encoding (Eq. 2b). Fig. 4B shows the results for the ZTE sequence, for which the effective TE was found to be independent of the T/R switching time or RF pulse width (consistent with the theoretical argument above), and is solely given by the effective TE during DAQ from Table 1 (which remains constant in the plots for Fig. 4).

Phantom Experiments: Phantom experiments using 3DUTE sequences were conducted to verify the equations for the effective TE. Four water-filled spherical phantoms (diameters $L=5.0, 3.6, 2.0,$ and 1.0cm), shown in Fig. 5 were imaged at 1kHz off-resonance using RF pulses with $T_{\text{RF}} = 40\mu\text{s}$, with read gradient strengths $G = 29\text{mT/m}$ and 10mT/m . The measured phases with each phantom are displayed in Fig. 6A and B) and show good agreement with the corresponding theoretical lines. Note how the phases between the smaller and larger phantoms are farther separated in Fig. 6B (which uses a lower value of G), consistent with Table 1.

Conclusion: We have studied the effective echo time (TE) for short echo time sequences. We found that for UTE and ZTE the echo time is best described by Eq. 2. From our results it follows, that the echo time for ZTE is not given by the T/R switching time, (not the time between the end of the RF to the start of DAQ). Erroneous definitions of TE will underestimate the amount of T2 decay and off-resonance phase evolutions, which may result in errors in assessing T2 and/or resonance frequency of tissues, when the data is fitted using Eq. 1.

References: [1] Rahmer et al. MRM 55 (2006), 1075–1082 [2] Du et al, MRI 29 (2011) 470–482 [3] Springer et al, JMR, 206 (2010) 88–96 [4] Wu et al. MRM 50 (2003) 59–68 [5] Madio et al, MRM 1995:3452–529 [6] Weifer et al, ISMRM 19 (2011), 2612 [7] Grodzki et al, MRM 2011 (Early View) [8] Carl et al, MRM, 2010. 64: p. 481–490 [9] Robin. In vivo NMR spec., 2nd ed. New York: Wiley; 2008. p235 [10] Carl et al, MRM 2011 (Early View)