Ultrashort TE (UTE) imaging of short T_2 relaxation components: how should the T_2 weighting be described?

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Synopsis:
Time to echo (TE) is an easy parameter to define for long T_2 samples using conventional spin-echo sequences and is a valuable measure of T_2 weighting. The issue is more complicated with FID sequences when no conventional echo is formed and when imaging species with short T_2s comparable in duration to the rf pulses used to excite them. In this paper we consider these issues, present results of simulations and provide a framework for further discussion.

Introduction
Time to Echo (TE) was originally defined as the time from the centre of the radio frequency pulse to the time when the signal was refocussed with a spin echo sequence. It is of fundamental importance in imaging since comparison of TE to the T_2 of the species under study provides a measure of the T_2 weighting of the sequence. For imaging purposes the definition of TE was extended to encompass refocussing by gradient echo sequences [1].
The situation is less clear with pulse sequences in which the FID is collected without the formation of an echo (i.e. fid-csi, gradient echo spirals, centre-out radial etc.). In general, authors have used the term TE as the time to mapping of the center point of k space as the best guide to T_2 weighting. Ultrashort TE sequences using radial imaging of k space are particularly interesting because (i) they use an FID rather than an echo acquisition, (ii) they are mainly used to image short T_2 species which may undergo significant relaxation during the read-out interval producing a T_2 filter effect, finally the short T_2 species may undergo significant relaxation during the excitation pulse so that (iii) the excitation profile will be degraded, and (iv) the centre of the rf pulse may not be an appropriate origin for TE.
Here we only deal with the last of these problems. We define TE as the time between rf pulse action at the centre of k space to that of detection of the center of k space and have performed simulations to examine the consequences of this approach.

Simulations for ultra-short T_2 species
As mentioned the excitation slice profile is dependent upon the T_2 of the sample, to avoid this additional confusion here we have considered just the spins at the center of the slice. This simplification allows us to ignore the effects of the slice selection gradients upon the signal but does assume that pulses are always on-resonance. We have simulated excitation with relaxation in a range of T_2s (7 [blue], 55 [green], 400μs [red], 3 [pale blue] and 22ms [magenta]) for different excitation pulses (square, sinc half pulse [2], sinc).
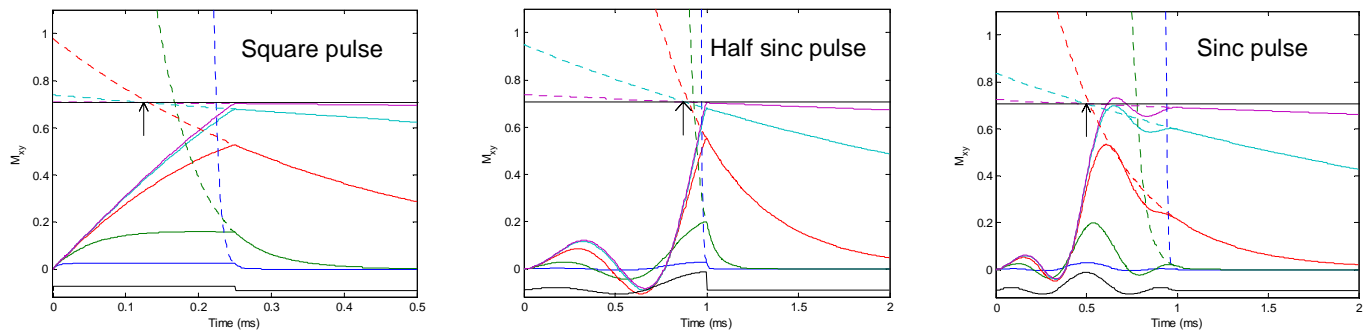
In each case the arrow shows the center of mass of the rf pulse, dotted lines project back the exponential decay for the different T_2 species, and the horizontal line shows the expected level of signal from a 45° excitation. At the bottom of each plot are the shapes of the rf pulses. The point where the dotted line for each T_2 crosses the horizontal line represents the time of pulse action for that T_2.

- For long and intermediate T_2's the time of pulse action is the centre of mass of the rf pulse.
- For short T_2 species this rule collapses, as the spins have very little memory of the beginning of the rf pulse. The time of pulse action becomes later in the excitation pulse as the T_2 decreases (and hence TE decreases).
- The time of pulse action depends on pulse power and pulse shape for short T_2 species.

Conclusion
For short T_2 species we have the situation where TE is dependent on the T_2 of the sample. Consequently no single value for TE is correct for a typical heterogeneous sample but we have a function TE(T_2). Further, the rate of change of TE with T_2 depends on the flip angle and the exact pulse profile. We suggest the following approach:
1) TE (which equals TE(∞)) can be used for the centre-out radial sequences but only for describing the T_2 weighting when the T_2 is long relative to the rf excitation pulse. The TE is measured from the centre of mass of the excitation pulse.
2) For an accurate description of the degree of T_2 weighting when T_2 is short, the parameter TE(T_2) should be used and from this the TE can be referenced to the T_2 of interest (determined via numerical calculation).
3) TE(0) is the TE in the limit where $T_2 \rightarrow 0$ and is equal to the time from the end of the RF pulse to the acquisition of the central k-space point. TE(0) may be a useful characteristic value for describing different MR systems.
The slice selection will be degraded when the time of pulse action differs significantly from the centre of k-space. Tthe half-pulse approach [2] overcomes this. The "true" T_2 weighting can only be determined by careful calculation, but it will always lie between TE(∞) and TE(0). A consensus on these issues would be of value as the usage of UTE pulse sequences increases [3-6].

References: 1) ACR Glossary of MR Terms. 4th Edition 1995; 2) Pauly J M. et al. Proc. SMR 28:1989; 3) Bergin CJ. et al. Radiology 1991; 4) Gold G. et al. MRM 1995. 5) Robson MD. et al. JCAT 2003; 6) Schroeder C, et al. ESMRMB Proceedings 2003; 214