Equivalent T2-Contrast for Fast Spin Echo Sequences with Low and Variable Flip Refocusing

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Varying the flip angle of the refocusing RF pulses in a RARE (Fast/Turbo Spin Echo) pulse sequence has been demonstrated as a means to address high RF power deposition [1,3,5,7-10] and MTF distortion due to relaxation [4,6,7]. However, because magnetization is not purely transverse, decay occurs more slowly than T2, altering image contrast if not accounted for. In circumstances where T2 contrast is desirable, the effective echo time must be extended, or the contrast will be less than expected. The purpose of this work is to demonstrate a method to directly calculate an equivalent TE of each echo in an echo train and thus be able to select which echo should be used for the zero-order phase encode to achieve the desirable T2 contrast, nearly equivalent to that produced by 180° refocusing.

Methods

Given a sequence of refocusing flip angles, α_i, signal at each echo, s_i, may be calculated by the extended phase graph (EPG) algorithm [2]. If the refocusing flip angle sequence is designed to maintain pseudo steady state (PSS) conditions, then the signal may be regarded in terms of two separable functions [8]

$$s(i) = s_0\, f_{coherence}(i)\, f_{relaxation}(i) \qquad (1)$$

where s_0 is the signal generated by 180° refocusing pulses in the absence of relaxation (which we'll consider equal to unity from this point), $f_{coherence}$ describes what fraction of the magnetization forms a coherent echo, and $f_{relaxation}$ describes how much relaxation has taken place since excitation. The coherent echo fraction is a function of refocusing flip angle, and is well approximated by [5, 10]

$$f_{coherence}(i) = \left(\sin\frac{\hat{\alpha}_i}{2}\right)^{1/2} P_{-1/2}\left[\sin\frac{\hat{\alpha}_i}{2}\left(1+\frac{\sin^2\hat{\alpha}_i}{8\sin^4\frac{\hat{\alpha}_i}{2}}\right)\right] \qquad (2)$$

$$\text{where} \quad \hat{\alpha}_i \approx \alpha_i + \tfrac{1}{4}\left(\alpha_{i+1} - \alpha_{i-1}\right) \qquad (3)$$

If this dependence is removed from the signal, the relaxation function remains. We define TE_{equiv} as the "equivalent echo time" in which as much relaxation will have taken place due to pure T2 decay.

$$f_{relaxation}(i) = \frac{s(i)}{f_{coherence}(i)} = \exp\frac{-TE_{equiv}(i)}{T2} \qquad (4)$$

TE_{equiv} is determined at each echo by choosing a representative T1 and T2 value, calculating (by means of the EPG algorithm) the signal at each echo, and accounting for the signal reduction due to reduced flip angle ($f_{coherence}$):

$$TE_{equiv}(i) = -T2\,\ln\left(\frac{s(i)}{f_{coherence}(i)}\right) \qquad (5)$$

Once the equivalent TE is known for each echo in the train, the echo with TE_{equiv} closest to the desired effective echo time is chosen as the zero-order phase encode, and the phase encode schedule designed accordingly.

A RARE (SSFSE) sequence was used at 1.5T (GE Twinspeed Excite) to acquire data of a phantom containing materials with known T1 and T2 values: 892ms/137ms, 597ms/95ms, and 455ms/53ms. An RF train of 180° pulses or with flip angles designed to reduce signal modulation and increase mean signal level, as shown in Fig. 1, was used. TE_{equiv} values were determined for each echo using T1/T2 = 1000/100ms as the representative values. Phase encode gradients were disabled in order to measure signal at each echo in a first experiment and enabled to generate images in a second experiment. For the imaging experiment, the zero-order phase encode was played at echo 22 (TE=92ms, TE_{equiv}=57ms) or at echo 37 (TE=155ms, TE_{equiv}=92ms).

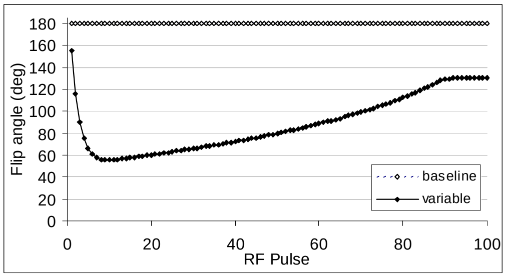

Fig 1: Refocusing flip angle schedules

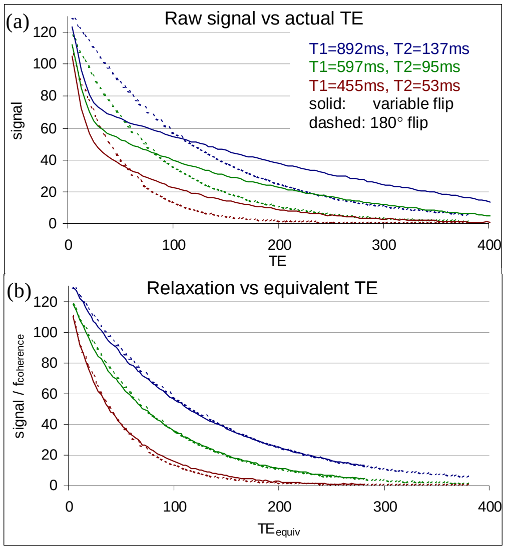

Fig 2: (a) raw signal vs actual TE, (b) relaxation vs TE_{equiv}

Results

The first experiment (Figure 2) demonstrated that after removing the effect of coherence fraction on signal level, relaxation as a function of TE_{equiv} was nearly identical to the baseline (180°) case. Part (a) shows raw signal vs. actual TE. Varying the flip angle (solid lines) caused an initial drop in signal, but decay throughout the remainder of the train was much slower than baseline (dashed lines), as desired. Part (b) shows relaxation (coherence fraction corrected signal) vs. TE_{equiv}. The relaxation curves are nearly identical, indicating TE_{equiv} is an accurate and consistent parameter for specifying T2 weighting.

The second experiment (Figure 3) demonstrated that assigning the zero-order phase encode based on TE_{equiv} preserves image contrast. The top row (a) shows the three vials imaged using 180° refocusing and echo 22 as the zero-order phase encode. Significant blurring due to signal modulation during the readout train is observed. The middle row (b) shows the vials using the variable flip schedule and echo 22 as the zero-order phase encode. Increased stimulated echo contribution causes alteration in contrast. The bottom row (c) shows the vials using the variable flip schedule and echo 37 as the zero-order phase encode, maintaining the same TE_{equiv} as the 180° refocusing case. Now contrast is nearly identical, as expected, and resolution is notably improved because the signal modulation through the echo train is considerably reduced.

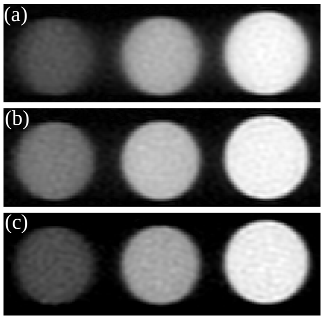

Fig 3: (a) 180° refocusing, TE=92ms (b) variable refoc., TE=92ms, TE_{equiv}=57ms (c) variable refoc., TE=155ms, TE_{equiv}=92ms

Discussion

A method to calculate equivalent TE for each echo in an echo train has been described. This method enables an appropriate echo to be selected for the zero-order phase encode to generate T2-contrast nearly equivalent to 180° refocusing. Previous publications have suggested that TE must be increased to preserve contrast [5], and means have been suggested to determine the increase by computing the fraction of time spent in transverse pathways [8]. This method is more direct and, because it does not assume infinite T1, has been found to be more accurate. Perfect equivalence is not possible as T1 and T2 both affect relaxation, but representative T1 and T2 values used to compute TE_{equiv} need not be identical to any materials imaged while still approximating contrast due purely to T2, as demonstrated by these experiments.

References: 1. Glover, Proc SMRM 1991, p1242; **2**. Hennig, Concepts in MR 3:125 (1991); **3**. LeRoux, MRM 30:183 (1993); **4**. Schäffter, Proc SMR 1994, p27; **5**. Alsop, MRM 37:176 (1997); **6**. Mugler, Proc ISMRM 2000, p687; **7**. Busse, Proc ISMRM 2001, p1790; **8**. Hennig, MRM 49:527 (2003); **9**. Hennig, MRM 51:68 (2004); **10**. Busse, MRM 51:1031 (2004)