Simultaneously Refocused Turbo Spin Echo Sequence

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Introduction: In Turbo Spin Echo (TSE) at field strength of 3T or higher the acquisition time (TA) is often limited by SAR. A number of techniques reduce SAR by variable flip-angle schemes. An alternative approach is the simultaneous echo refocusing (SER)-TSE sequence [1]. It refocuses m adjacent excited slices simultaneously and thereby reduces SAR by approximately a factor m. SER-TSE eliminates some of the pathways which emerge from stimulated echoes with a special crusher scheme to avoid mixing of the signals from different slices. The authors demonstrate the usefulness of SER-TSE for T1-weighted imaging with short echo trains. However, SER-TSE fails to sustain a long echo train required for the more important T2 contrast. In this work we introduce a TSE sequence, which also refocuses m adjacent excited slices simultaneously. The new sequence, called mTSE, refocuses signals of different slices in temporally separated readout windows. m-1 of the m slices do not fulfill the CPMG condition. Signal pathways of a non-CPMG slice that would interfere destructively are also separated. This results in 2m-1 readout windows per refocusing pulse. The mTSE sequence utilizes the signal of all pathways and is able to sustain a long echo train required for T2 weighted imaging.

Methods: Figure 1 shows a m=2 variant of mTSE. The most important differences to a CPMG-TSE sequence with excitation pulse α2 and echo spacing Tβ are:

1. A second excitation pulse α1 is added Tα before α2, which excites a different slice.
2. The width of the refocusing slice is broadened, such that it covers both excited slices.
3. The m-TSE generates 2m-1 echoes with temporal distance Tα per refocusing pulse. To readout these echoes in separate non-overlapping acquisition windows either the echo spacing Tβ is prolonged or the duration of one acquisition window is shortened by decreasing the readout dwell time by a factor x≥2m-1 and by increasing the readout gradient by the same factor x.
4. Between the slice selection gradients of α1 and α2 a gradient in slice select direction is inserted such that the 0th-moment acquired between the isodelay points of α1 and α2 is zero.
5. Between α1 and α2 another gradient in readout direction is inserted. The 0th moment of this gradient is equal to the moment acquired by the readout gradient between successive echoes.

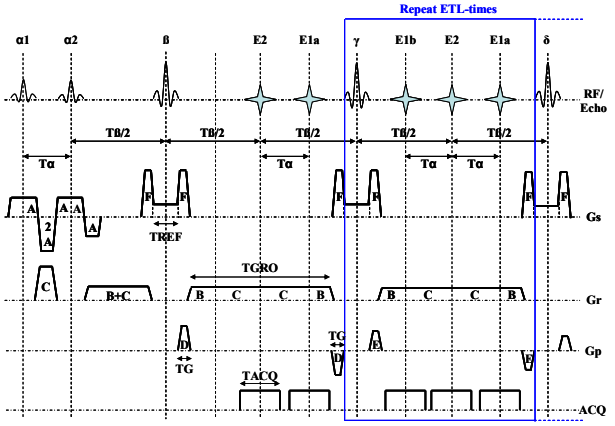

Figure 1: Sequence diagram for two simultaneously refocused slices.

How the sequence works: First consider the spins of slice 2 (S2) excited by the last excitation pulse α2. These spins are unaffected by α1 since the resonance condition is not fulfilled and as longitudinal magnetization are also unaffected by the gradients prior to α2. Therefore, for the spins of S2 mTSE is a conventional CPMG sequence: All echoes of S2 are formed in the middle between successive refocusing pulses and signal following different pathways add constructively. Next consider the spins of slice 1 (S1) which are excited by α1. These spins are not affected by α2 since the resonance condition is not met but, as transverse magnetization, accumulate phase due to the slice selection gradient of α2. However, this phase is exactly compensated by the negative gradient between both slice selection gradients (difference 4). The broad 1st refocusing pulse β refocuses part of the signal excited by α1 and produces a 1st spin echo (SE) at time Tβ/2+Tα after β. At this time the phase accumulated by the gradients in readout direction before and after β is exactly equal (due to difference 5) so that gradient and spin echo coincidence and can be readout in echo group E1a. At this time the signal which forms the 1st SE of S2, at time Tβ/2 after β, is already dephased by a gradient moment C. Vice versa at the time of the 1st SE of S2 the signal which later forms the 1st SE of S1 is still dephased by a moment C. Part of the signal with form the 1st SE of S1 is refocused by the second refocusing pulse γ and produces a 2nd SE Tβ/2-Tα after γ. The moment B acquired between the 1st SE and γ and between γ and the 2nd SE due to the readout gradients is exactly balanced so that the 2nd SE can be readout in echo group E1b. The 1st stimulated echo (STE) of S1 is formed Tβ/2+Tα after γ. The spins which contribute to this STE were in longitudinal direction between β and γ and hence did not see the 1st readout gradient. At the time of the 1st STE of S1 the moment B+2C accumulated before β is exactly equal to the moment accumulated by the 2nd readout gradient after γ and hence the 1st STE can be readout in E1a. If higher pathways of S1 are considered the following is valid: Pathways, which produce echoes in echo group E1a have spent a time interval 2Tα+oTβ in the transverse plane, were o is an odd integer. For pathways that produce echoes in echo group E1b the corresponding time interval is eTβ, were e is an even integer. Hence, due to the spin echo principle, the signals from different pathways in the same group add constructively and need not to be separated. Here there is some similarity between mTSE and SPLICE [2]. Please note, that in mTSE spin echoes and gradient echoes coincide due to the temporal arrangement of the RF-pulses.

Image reconstruction: After encoding all data needed for image reconstruction an image of S2 can be reconstructed conventionally using data set E2. For S1 two complete data sets E1a and E1b are obtained. Two magnitude images of S1 can be calculated using the data sets E1a and E1b, respectively. These images can be combined to a single image with better SNR using the sum of squares algorithm, for example. In our BLADE version of mTSE, called mBLADE, the data of echo group E1a and E1b are first phase corrected blade-wise and then added directly in the complex before gridding.

Inter-slice homogenization: Slices acquired in CPMG mode have better SNR than the non-CPMG slices. This leads to a fluctuating image impression. mBLADE solves this problem by acquiring the data in m-revolutions. In each revolution every mth blade is acquired. The sequence permutes the slice acquired in CPMG mode between revolutions.

Results: Figure 2 shows T2w brain images acquired in a female volunteer with a Siemens MAGNETOM Verio. Images in the same row show the same slice. The images of the 1st column are separately refocused and serve as reference. The images of column 2 and 3 are simultaneously refocused (m=2). In column 2 all blades of slice 1 were acquired in CPMG mode and all blades of slice 2 were acquired in non-CPMG mode. The images of column 3 were acquired in two revolutions with permutation of the CPMG slice between revolutions. The ES of the reference and m=2-BLADE was adjusted by increasing the readout bandwidth (407 Hz/pixel versus 130 Hz/pixel). TR of the reference was doubled to 6000 ms due to SAR. All other parameters are equal (Matrix=256, FoV=220 mm, 28 slices, TH: 4 mm, gap: 1.2 mm, ETL: 23, 18 blades, TE: 123ms, FA: 140°).

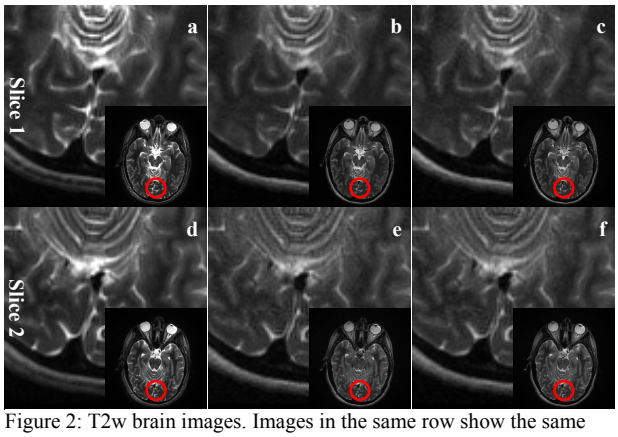

Figure 2: T2w brain images. Images in the same row show the same slice. a,d (reference): separated refocused using twice TR,TA; b,e: simultaneously refocused, b acquired in CPMG mode; c,f: simultaneously refocused with inter-slice homogenization.

Discussion: Intra-row comparison of Figure 2 shows that the separation of the slices is perfect. TR was chosen such that all scans were SAR limited. Hence, TA was halved by mTSE. The significant higher SNR of the reference is explained by the longer acquisition window. To reveal the true SNR loss due to the separation of pathways a different setup is needed. mTSE is able to sustain a long echo train needed for T2w images. The brighter CSF signal of the reference is explained by the longer TR. The extension of mTSE to three and more simultaneously refocused slices is straightforward. The main drawback of mTSE is the longer echo spacing.

References: [1] Guenther et al. MRM 54:513 (2005); [2] Schick, MRM 38:638 (1997).