

Multi Echo GRE for Thermal Imaging

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Purpose: MR-guided Focused Ultrasound (MRgFUS) is used to treat brain disorders including, among others, essential tremor and neuropathic pain. The thermometry sequence used is multi-slice gradient echo. Long TE gives higher temperature accuracy, peaking at $TE = T_2^*$. Therefore to lengthen TE and reduce noise a low receiver bandwidth is used. However, lower bandwidth increases the sensitivity to B_0 inhomogeneity and increases spatial shifts in the images. This is unacceptable for brain applications where the max allowed spatial shift is ≤ 1 mm. To overcome this limitation, i.e. retain low temperature noise while reducing spatial shift, we propose a multi-echo GRE sequence where $N > 1$ echoes are acquired in each TR. For each echo the bandwidth is high thereby reducing spatial shifts. The temperature signal to noise ratio (TSNR) is preserved by combining signals from all the echoes to generate a temperature image. In this work we compare the TSNR and spatial shift of our conventional single-echo low-bandwidth thermal sequence to the new multi-echo sequence and optimize the parameters of the new sequence.

Method: The polarity of the readout gradient G_r in a multi echo GRE sequence alternates, generating $N > 1$ echoes in each TR. The TE of echo n ($n = 1$ to N) is TE_n . The echoes may be acquired during the positive polarity of G_r or during both positive and negative polarities. The phase difference $\Delta\Phi_n$ of echo n between a "cold" image and a "hot" image acquired during heating is measured for all the echoes. To improve accuracy we fit $\Delta\Phi_n$ vs. TE_n to a straight line using Ahn algorithm (1). The temperature T_n of echo n is calculated from $\Delta\Phi_n$ using Eq. [1] where the constant K is $0.01 \text{ ppm} \cdot 2\pi / ^\circ\text{C}$. The overall T is a weighted sum of the T_n 's (Eq. [2]) and the weights are proportional to the inverse of the variance δT_n^2 of T_n (2) as in Eq. [3]. From Eq. [1] δT_n^2 is proportional to the variance of $\Delta\Phi_n$, which is proportional to BW/ρ_n^2 (3) where ρ_n is the signal amplitude of echo n and BW is the receiver bandwidth. The spatial shift Δx for a given frequency shift Δf due to B_0 inhomogeneity is $\Delta x = \Delta f \cdot \text{FOV} / (2 \cdot BW)$, showing that Δx is inversely proportional to BW . Our goal is to minimize Δx while maximizing TSNR.

$$T_n = \frac{1}{K} \cdot \frac{\Delta\Phi_n}{TE_n} \quad n = 1 \text{ to } N \quad [1] \quad T = \sum_n w_n \cdot T_n \quad [2] \quad w_n \propto \frac{1}{\delta T_n^2} \propto \frac{(TE_n \cdot \rho_n)^2}{BW} \quad [3]$$

Results: Sequence optimization was done by measuring T (Eq. [2]) and the variance of T , $\text{var}(T)$, by scanning a 17 cm diameter spherical phantom on a 1.5T GE system. The correctness of [1] to [3] was verified by shifting the central frequency of the scanner (equivalent to a temperature change of the phantom) and calculating T and its variance $\text{var}(T)$. The spatial shift Δx was measured with a thin water filled test tube after changing the central frequency by Δf . In all cases we calculate Δx and $\text{var}(T)$ relative to our standard single-echo GRE sequence. The parameters of the standard sequence are: matrix 256×128 , 1 echo, BW 5.68 kHz, $TR = 26$ msec, RF flip 30° , slice 3 mm, $FOV = 26$ cm. In all the multi-echo scans we used the same parameters, but varied the number of echoes N , the TE 's and the bandwidth BW so that the TR (26 msec) was retained. The relative TSNR is simply $1/\sqrt{\text{var}(T)}$. Fig. 1 and 2 show the relative TSNR and the relative spatial shift Δx vs. the number of echoes N . Results are shown for positive readout GRE sequence (full circles) and alternate readout GRE sequence (open circles). Based on this simulation we use $N = 5$ echoes with BW of 36 kHz. The echoes are acquired during the positive polarity of the readout gradient. Excellent thermometry results were obtained with the new sequence at 1.5T and 3T on a phantom and a pig skull.

Conclusion: Compared to the standard GRE sequence the new multi-echo sequence provides identical or better TSNR with a 5 – 8 fold reduction in spatial shifts due to B_0 inhomogeneity.

References: (1) C. Ahn et. al. IEEE Trans. Med. Imag. MI-6(1), p. 32 (1987). (2) W. H. Press et. al., "Numerical Recipes" 3rd edition, p. 776 – 779 (2007). (3) Eq. [7] to [11] in A. R. Pineda et. al., Mag. Res. Med. 54, 625 – 635 (2005).

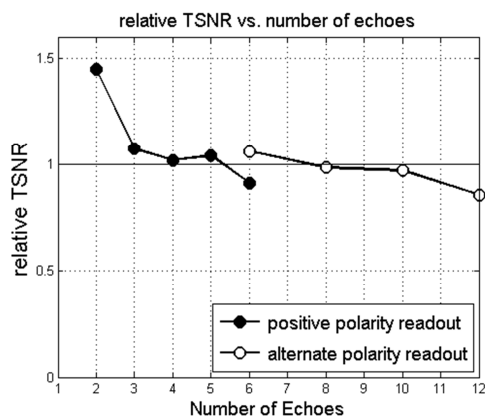


Fig. 1: Relative TSNR vs. number of echoes.

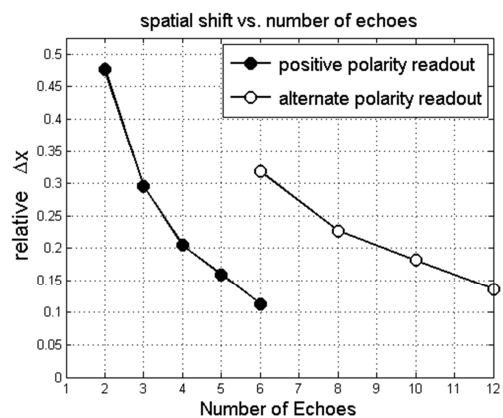


Fig. 2: Relative Spatial shift vs. number of echoes.