BOLD sensitivity in multiecho sequences

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Introduction: Maximum BOLD sensitivity is obtained if the echo time of a T2* weighted sequence is equal to the T2* of the region of interest, and this sensitivity can be increased by weighted addition of the signals from a multi-echo sequence [1]. This abstract aims to determine the optimal echo times for BOLD sensitivity in a multi-echo sequence and to determine how sensitivity varies between regions with different relaxation rates. It also aims to determine the effect of imaging bandwidth on the optimum echo time for fMRI. It assumes that activation causes a constant change in R2* rather than T2* [1] for a given change in CBV and blood oxygenation.

Theory: Let N be the total number of echoes, let j denote the j^{th} echo (1<j<N) and let δ be the initial echo time so that subsequent echo times are given by $TE_j = (2j-1)\delta$, rather than being spaced by simply jδ. Let ΔR_2^* be the change in R_2^* of the tissue on activation, S_o be the signal in equilibrium at zero echo time and σ_o be the noise in an image. The signals from the different echoes are combined by weighted summation, where signals are combined with a weighting factor $w_j = (2j-1)e^{-\delta(2j-1)R_{2*}}$, and contrast in the combined signal is given by

$$\frac{S_o}{\sigma_o}\Delta R_{2*}\delta\sqrt{\sum_{j=1}^{N}(2j-1)^2 e^{-2(2j-1)\delta R_{2*}}}$$

. It is assumed that the noise is either constant thermal noise or that it scales with bandwidth which is related to available image acquisition time, so that the noise is proportional to $\sigma_o/\sqrt{(2\delta)}$.

Method: The BOLD sensitivity, given by the equation above, was calculated using the symbolic algebra package, Maple (Maplesoft Canada). It was assumed that $S_o=\sigma_o=\Delta R_2^*=R_2^*=\delta=1$ initially, with the parameters varied over the ranges N=1 to 4, δ = 0 to $3T_2^*$ and $T_2^* = 0$ to 2δ, In this way, the echo time interval is normalized with respect to T_2^*, and the results scale with σ_o/S_o and $\Delta R_2^*/R_2^*$.

Results: Figure 1 confirms that with weighted summation, increasing the number of echoes always increases the final CNR. However for increasing numbers of echoes the optimum echo interval δ decreases. Figure 2 shows that increasing the number of echoes increases the variation in CNR with T2*. Figure 3 shows the CNR obtained if the image bandwidth decreases (and hence signal to noise increases) with increasing δ. For the single echo case the optimum echo time interval and hence sampling period is shifted from T2* to 1.5 T2* and the relative advantage of multi-echo imaging at shorter δ is reduced. In practice at short δ the sampling period is inevitably constrained by the echo time interval, whereas at long δ it is constrained by the need to minimize image distortion; this means that Figure 3 is most relevant to the left of δ~1, whereas Figure 1 is most relevant to the right. This implies that for the single echo case, it is optimal to extend the sampling period as far as distortion artifacts will allow, up to a maximum of 3 T2* and to use δ with the shortest accessible value in the range 1.0- 1.5 T2*, since the reduction in noise due to the reduced bandwidth, compensates for the reduction in contrast at longer echo time.

Discussion: If the noise can be assumed to be normally distributed and uncorrelated between echoes and the T2* decay is exponential, then in the single echo case, the imaging bandwidth should be as narrow as possible (sampling time as long as possible) given the limitation of image distortions, up to a maximum echo time of 1.5 T2*. However a multi-echo sequence should be used if available. If multiple echoes are combined by weighted summation, the optimum echo interval is reduced according to Figs. 1 or 3 (depending on whether image distortions limit the image acquisition time). Finally if it is assumed that BOLD effects cause a constant ΔR_2^* independent of tissue R_2^*, then Fig. 2 indicates that the multi-echo sequence will cause considerable variation in sensitivity to BOLD depending on the underlying tissue T2*, so that even if the sequence is optimized for maximum sensitivity for given tissue it will always be more sensitive to BOLD signal changes in tissues with shorter T2*s and less sensitive to changes in tissues with longer T2*s. If similar BOLD sensitivity is required across regions of interest with different T2*s, the echo time should generally be set equal to the longer T2*s. Further work is underway to investigate the effect of physiological noise, and non exponential signal decays.

References: [1] Posse et al, Magn. Res. Med., 42, 87-97, 1999. This work was funded by the MRC UK.

Figure 1

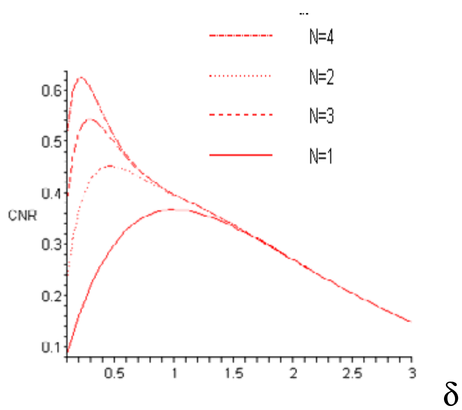

Figure 2

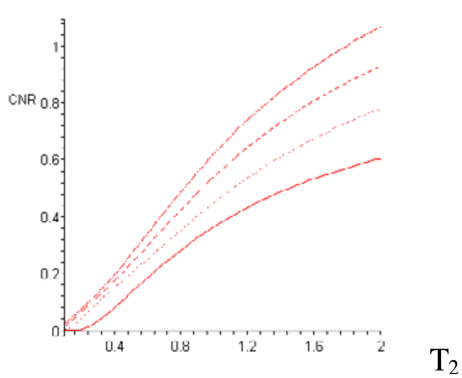

Figure 3

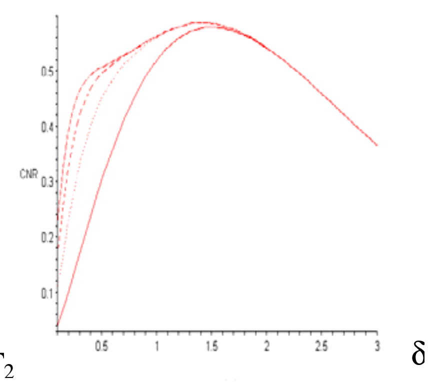

Figure 1 shows the variation of contrast with echo interval. **Figure 2** shows the variation of contrast with T2. **Figure 3** shows the variation of contrast with echo interval, if the noise is assumed to scale with imaging bandwidth, and hence echo time.

This abstract aims to determine the optimal echo times for BOLD sensitivity in a multi-echo sequence and to determine how sensitivity varies between regions of different relaxation rates, taking into account the interaction between imaging bandwidth and echo time. For a single echo acquisition, the bandwidth should be as narrow as possible given the limitation of image distortions, up to a maximum echo time of 1.5 T2*. In a multi-echo sequence if the signals are combined by weighted summation, the optimum echo interval is reduced, and the variation in BOLD sensitivity to the underlying tissue T2* is increased.