Effect of physiological noise on densely sampled multi-echo fMRI data

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Introduction Blood oxygenation level dependent (BOLD) signals are intrinsically weak. In recent years, multi-echo fMRI methods have provided significant contrast-to-noise ratio (CNR) enhancement by acquiring multiple images at varied echo times during a single RF excitation [1,2]. Alongside the development of whole-brain multi-echo echo planar or spiral gradient echo imaging techniques, restricted field-of-view methods offering many more echoes per excitation have emerged as a tool for providing improved enhancement over select regions of interest [3]. However, as echoes become more finely spaced, and with the ever-increasing push for higher MRI field strengths, the effect of correlated physiological noise must be considered in the assessment of CNR gains provided by multi-echo fMRI strategies. Here, using Monte Carlo simulations and experimental data, the relative CNR gain (rCNR) of densely sampled multi-echo fMRI data is assessed in response to varying levels of physically realistic inter-echo noise correlations. These data can be useful in determining the optimal echo spacing for multi-echo fMRI acquisitions, as well as demonstrating the characteristics of multi-echo fMRI noise across subjects.

Theory Correlated noise affects multi-echo fMRI data analysis because echo amplitudes are typically combined in weighted summation to obtain an improved BOLD signal. Signal-to-noise ratio (SNR) or CNR normally increases with $\sqrt{N}$, where N is the number of samples. However, this benefit is an upper bound on the maximum CNR increase, obtained when the N samples are completely independent. With an underlying noise correlation, less "new" information is conferred with the additional samples, and CNR benefit is reduced. This is compounded by weights that are assigned to different echo times (TE) prior to summation. There are various different weighting schemes; here CNR weighting [2] and principal component analysis (PCA) weighting [4] are explored.

In contrast to thermal or electronic sources of noise, variance arising from physiological mechanisms such as motion or respiration causes coherent fMRI signal fluctuations across image time series acquired at different echo times. If the timescale of the fluctuation is larger than the inter-echo spacing, correlated noise will be present in the measured time series. The effect is anticipated to worsen as magnetic field strength increases.

Methods A Monte Carlo simulation was developed in MATLAB to generate 1000 simulated multi-echo datasets with additive correlated Gaussian noise at a number of different noise correlation levels. These simulated datasets were individually analyzed and combined using both the CNR and PCA weighting methods, and a mean estimate of rCNR relative to a single-echo acquisition at TE=T2* was performed using a simple general linear model estimator. Signals were generated from the convolution of a hemodynamic response function with a boxcar waveform, and TE-dependent noise variance was generated using an established physiological noise model [5]. Correlations were introduced by convolving the noise matrix with a Gaussian kernel, whose time width determined the degree of correlation across echoes. A wider kernel width would introduce noise correlations across a larger time window, and vice versa. Multi-echo data were simulated at an echo spacing of Δt = 1 ms, with a total sampling window of 150 ms.

Experimental data were collected using a 1.5 T Signa GE MRI system, on 5 healthy young volunteers (4 male) who gave informed consent with approval of the Research Ethics Board at Sunnybrook Health Sciences Centre. A total of 20 scans were acquired using a prototype multi-echo pulse sequence [3] with TR = 1000 ms, 256 echoes with an echo spacing of Δt = 1.024 ms. The subjects performed a simple 20 s on/20 s off boxcar design hand clenching task, and data from a single (5 x 20 x 20 mm^3) voxel was chosen for analysis. Subsequent processing was identical to that used for the simulations. An equivalent noise correlation kernel width (KW) was calculated from the experimental data, using the multi-echo correlation matrix after removal of the task related BOLD signal.

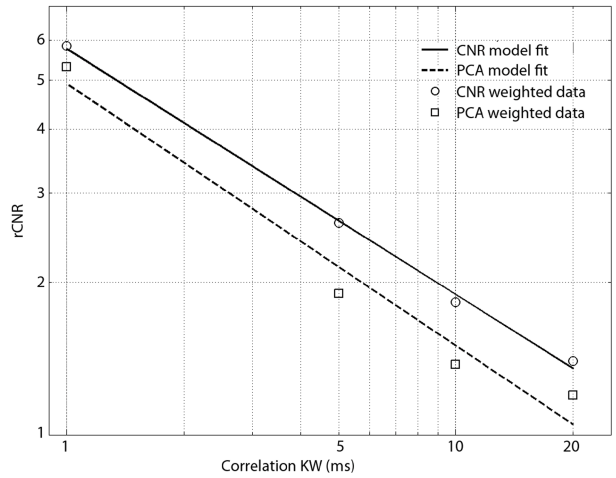

Figure 1 - Simulated rCNR vs. noise correlation (KW)

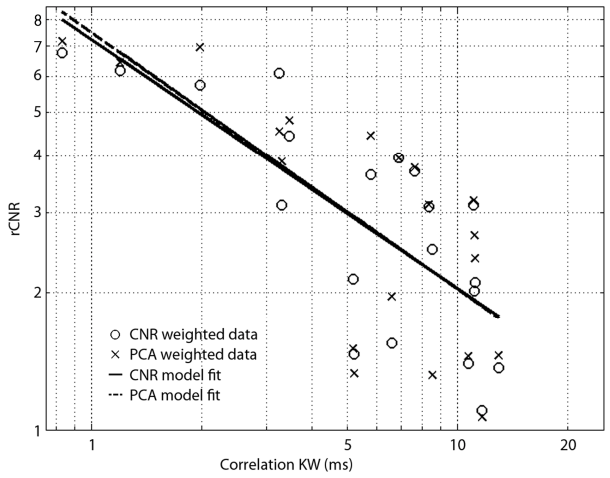

Figure 2 - Experimental rCNR vs. noise correlation

Discussion Figure 1 shows the results of simulated rCNR over a range of correlation kernel widths from 1-20 ms. Overlaid in the solid and dashed lines are KW^x model fits, where x = -0.48 and -0.52 for the CNR and PCA weighting methods respectively. Figure 2 displays rCNR for the 20 experimental datasets, plotted against equivalent KW. The solid and dashed lines again represent KW^x model fits, this time with x = -0.55 and -0.57 for CNR and PCA weighting respectively. All fits are significant with $p < 0.05$. The decreases observed are consistent with an inverse square-root dependence, and are not strongly dependent on the method of multi-echo signal combination. As correlation increases to the point where the noise is 100% correlated, rCNR approaches 1 and no sensitivity gains are realized. The KW value, or correlation timescale observed in the experimental data was less than 15 ms for all subjects (see Fig. 2, x-axis), well within the regime modelled and indicating substantial rCNR benefit in many cases. The 15ms cutoff also explains why techniques employing more sparse echo sampling strategies do not observe CNR degradation due to physiological noise correlation [6], as inter-echo spacing is longer than typical correlation timescales. These simulation and experimental results illustrate the decreasing contrast sensitivity relationship with increasing noise correlation in densely sampled multi-echo fMRI, and highlight the heterogeneity of noise across subjects and across scans. These data will be useful in the the investigation of optimal fMRI echo spacings for multi-echo techniques, and may lead to development of individually optimized fMRI acquisitions.

References

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