

Improved Model for Physiological Fluctuations in fMRI

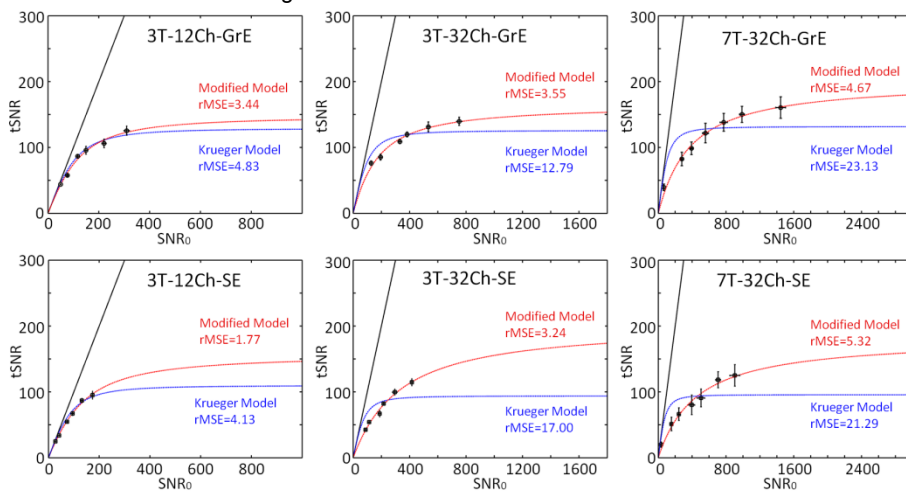
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Introduction: Sensitivity in BOLD fMRI is characterized by the time-series SNR (tSNR), which contains fluctuations from thermal and physiological noise sources. Previous studies [1-2] have examined the relationship between tSNR and the image SNR (SNR_0) using a model where the physiological noise standard deviation (SD) is proportional to signal. Although single channel acquisitions fit this model well, a re-examination of recent high- SNR_0 acquisitions from 32-channel array coils at 3T and 7T, shown noticeable deviations from this model. With this in mind, we re-examine the noise characteristics at 7T in both gradient echo and spin echo EPI acquisitions from highly parallel array coils, and suggest a modified model which includes a constant term in the physiological noise SD which does not scale with signal strength and is not present in the image noise. Our findings demonstrate that the relationship between tSNR and SNR_0 is well described by the Krueger model [2] for small count of channels, however for higher field strengths and higher channel arrays, the proposed modified model better fits the data for both spin echo and gradient echo acquisitions.

Theory: Following previous studies [1-2] the total noise, σ_t , for a voxel in the fMRI time-series is modeled as the sum of the Gaussian thermal image noise (σ_0) and the physiological signal fluctuations (σ_p) (cardiac, respiratory and hemodynamic induced signal modulations); $\sigma_t^2 = \sigma_0^2 + \sigma_p^2$. Krueger modeled the physiological noise as proportional to MR signal amplitude (S) $\sigma_p = \lambda S$. The model predicts that the relationship between tSNR and SNR_0 is given by: $tSNR = SNR_0 / (1 + \lambda^2 SNR_0^2)^{1/2}$; for large SNR_0 , tSNR is asymptotically limited to $1/\lambda$. In this study we introduce a modified version of the Krueger model. We assume the total SD of the fMRI time-series, σ_t , includes an additional term σ_k which corresponds to signal independent physiological fluctuations; $\sigma_t^2 = \sigma_0^2 + \lambda^2 S^2 + \sigma_k^2$. Then, the relationship between tSNR and SNR_0 is described by $tSNR = SNR_0 / (1 + [\lambda SNR_0 + \sigma_k/\sigma_0]^2)^{1/2}$. The additional noise contribution eliminates the asymptotic nature of the tSNR at high SNR_0 values.

Methods: Four subjects were scanned at both 3T and 7T after approval of the institutional review board and informed consent. The Siemens 7T system (Siemens Healthcare, Erlangen Germany) used a head gradient insert (AC84) and a 32Ch receive-only array coil [3]. At 3T, a Tim Trio system (Siemens Healthcare, Erlangen Germany) with product head coils (1Ch birdcage, 12Ch and 32Ch) was used. Resting state EPI images were collected using single-shot gradient echo (GrE) and spin echo (SE) EPI, at six in-plane resolutions (1x1mm², 1.5x1.5mm², 2x2mm², 3x3mm², 4x4mm² and 5x5mm²) using TR=5.4s, 60 measurements, and twenty 3mm thick slices. For the 7T data an additional high spatial resolution (1mm isotropic) was acquired to sample a resolution where thermal noise dominates. The TE was chosen to optimize BOLD contrast at each field strength: 30ms and 20ms for GrE at 3T and 7T and 75ms and 55ms for SE. Other imaging parameters, such as echo spacing, partial Fourier etc were optimized for each acquisition and field strength. No acceleration was used. Images without RF excitation were also obtained to determine the thermal image noise (σ_0). The 3T acquisitions were also performed in a loading phantom.



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All EPI images were reconstructed offline with custom software. Array data was combined using the root Sum-of-Squares method. Temporal SNR maps (tSNR) were estimated from the motion corrected and detrended EPI time-series, as the ratio of the mean pixel intensity across time points to their temporal standard deviation. To directly compare the array SNR_0 and tSNR, SNR_0 was calculated using the method of Kellman and McVeigh [4]. The cortical SNR_0 and tSNR for an acquisition were evaluated by taking the mean of a cortical gray matter ROI placed over the SNR maps. We then plotted tSNR as a function of SNR_0 for the

different in-plane resolutions, receive coils, field strengths and acquisition type (SE or GrE) and fit the tSNR vs SNR_0 relationship to the Krueger model and the new model using a non-linear least squares algorithm available in Matlab.

Results and Discussion: The figure shows tSNR as a function of SNR_0 for GrE (top) and SE (bottom) at 3T and 7T for a given coil. The points represent the different spatial resolutions. The blue line is the fit to the Krueger model, and red is the new model. The goodness of fit was characterized by an rMSE for each model (also printed on the graphs.) For the small coils (1Ch and 12Ch) the data are well parameterized by the Krueger model. For example, rMSE was 1.04 and 0.45 for the Krueger and modified models respectively for the 1Ch 3T SE acquisition and

| | σ_k/σ_0 | |
|---------|---------------------|------|
| | GrE | SE |
| 3T 1Ch | 0.11 | 0.27 |
| 3T 12Ch | 0.22 | 0.38 |
| 3T 32Ch | 0.74 | 1.42 |
| 7T 32Ch | 1.70 | 2.30 |

0.93 and 0.63 for the 1Ch 3T GrE data. As we move to higher number of channels and higher field strength the rMSE increased substantially for the Krueger noise model, while the modified model retains a very low rMSE (values printed on the graphs). Thus, the total noise in the time-series appears to contain both a signal dependent term (Krueger model) and a contribution that is independent of the signal intensity but not present in the image noise. This second source of noise is present in both SE and GrE acquisitions and appears to become important for high sensitivity studies (either by higher field strengths and/or bigger array coils). Neither physiological noise term is significant in the phantom acquisitions, suggesting a physiological noise source for the new term. The estimated ratio of σ_k/σ_0 from the fit (see Table) shows a higher ratio for the SE contrast.

Conclusion: We demonstrated that when highly parallel arrays are used at field strengths of 3T and 7T, the GrE and SE fMRI time-course SNR can be better modeled by a modified version of the Krueger model which includes an additional source of physiological noise in the EPI time-series. Further investigation is needed to ascertain the origin of this noise source.

References: 1) Triantafyllou C, et al. NeuroImage, 26(1):243-50, 2005, 2) Krueger G, et al. MRM, 46:631-7, 2001, 3) Keil B, et al. ISMRM 2010, Abst. 6960, 4) Kellman P, et al. MRM, 54(6):1439-1447, 2005.