Modeling physiological fluctuations in multi-channel coil fMRI time-series at 7T and 3T

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Target Audience: Clinicians/Researchers/Neuroscientists using functional MRI especially when using multi-channel arrays.

Purpose: Understanding the relationship between time-series SNR (tSNR) and image SNR (SNR_0) in fMRI EPI time-series, is critical because tSNR is a principle determinant of the sensitivity of the fMRI experiment to BOLD contrast (in addition to echo time and ΔR_2*), while SNR_0 is a readily controlled metric (via resolution, flip angle, coil choice or field strength). In this work we investigate the need for a modified model describing the behavior of physiological noise in the fMRI time-series for multi-channel acquisitions and assess the new model's dependence on the physiological noise correlations, tissue class and coil combination methods across field strengths of 3T and 7T.

Theory: Previous studies[1,2] have examined the relationship between tSNR and SNR_0 when single channel coil was used, introducing a model[1] where the physiological noise standard deviation (σ_p) is proportional to the MR signal (S), $\sigma_p=\lambda S$, λ is the proportionality constant. The model predicts that the relationship between tSNR and SNR_0 is given by: $tSNR = SNR_0 / (1 + \lambda^2 SNR_0^2)^{1/2}$ (referred here as *KG-model*). Thus, for large SNR_0, tSNR is asymptotically limited to $1/\lambda$. In this study, we introduce a more general version of the KG-model, to include multi-channel coil acquisitions. Assuming the total SD of the fMRI time-series, σ_t, includes an additional term σ_k which corresponds to signal independent physiological fluctuations, then, the relationship between tSNR and SNR_0 is described by $tSNR = SNR_0 / (1 + \lambda^2 SNR_0^2 + \kappa^2)^{1/2}$, with κ defined as σ_k/σ_0. We propose that the additional noise term (thus κ) corresponds to physiological noise correlations from multi-channel coils[3] and therefore, we extend the *KG-model* to include the Physiological Noise Covariance matrix with non-zero off-diagonal entries *(PNC-model)*.

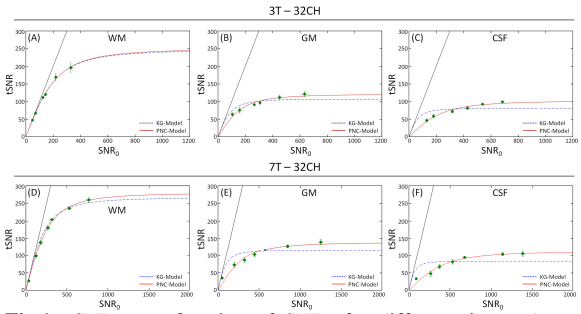

Fig.1: tSNR as a function of SNR_0 for different tissue classes (WM, GM and CSF) for 3T (A, B, C) and 7T (D, E, F) 32Ch array data when image SNR was modulated with voxel size. Each point represents the average over all subjects. The dotted line is the fit to the *KG-model* and solid line corresponds to the *PNC-model*.

Methods: Data from the same 4 subjects were acquired at both 7T and 3T Siemens systems(Siemens Healthcare, Erlangen, Germany); using a custom-built 32Ch brain array coil at 7T[4] and the product 32Ch head coil at 3T. Written informed consent was obtained from all the subjects using an experimental protocol approved by institutional review board. Resting-state EPI data were obtained at six in-plane resolutions (1x1, 1.5x1.5, 2x2, 3x3, 4x4 and 5x5) using TR=5.4s, 60 time-points, and 20 3mm thick slices. For the 7T data an additional high spatial resolution (1mm iso.) was acquired to sample data at a resolution where thermal noise dominates. Phantom data also acquired using same protocols as the human data. Images without RF were obtained to determine the thermal image noise (σ_0). All data reconstructed offline with custom software in Matlab. To explore the origin of the new model's parameter, data from multiple coil elements were combined using different methods: the conventional rSoS (weights derived from measured signal level), a 'Birdcage-like' combination (the complex-valued weight vector, w, is the signal values averaged over a small ROI in the center of the FOV), and single array-element (all weights equal to 0, except one). After motion and drift correction, tSNR maps were generated from the mean pixel values across time-points divided by their temporal standard deviation. The SNR_0 was calculated using the method of Kellman and McVeigh[5]. To evaluate the dependence of the proposed model on tissue component, tSNR and SNR_0 were estimated in regions of CSF, white matter (WM) and gray matter (GM). The relationship between tSNR and SNR_0 was examined by fitting to the data the two different models using a non-linear least squares algorithm in Matlab.

Results: Fig. 1 shows the tSNR dependence on SNR_0 for different tissue classes (WM, GM and CSF) for 3T and 7T. At each field strength, WM is well parameterized by the KG-model, while GM and CSF exhibit better agreement with the proposed PNC-model. The minimum value of κ is observed for the 3T WM data (κ =0.16) and the highest value of κ is found in CSF at 7T (κ =4.16), where we expect the largest physiological noise fluctuations. Fig. 2 shows the different κ obtained from 7T 32Ch GM for three different array channel combination methods (single channel, 'birdcage-like' and rSoS). Single-channel data show a good correspondence to the KG-model while this correspondence is not as strong for the 'birdcage' combination and is weak for the 32Ch rSoS, where the PNC-model shows a substantially better fit to the data. This result suggests that the additional parameter in the proposed model is dependent on the weights chosen to combine the data (as well as the number of channels used). Fig. 3 shows the BOLD signal level matrix (top), the physiological noise covariance matrix (middle) and the thermal noise covariance matrix (bottom) for GM voxels acquired with 3T 32Ch coil. Structural differences are apparent between physiological noise and thermal noise, while signal and physiological noise show more similarities. This suggests that the value of the new parameter (κ) is solely determined by the deviation of the physiological noise covariance matrix from the signal level matrix and can be viewed as a physiological noise source which is independent of signal strength.

Discussion: We propose a general model describing the physiological noise fluctuations in fMRI time-series when multi-channel coils are used, across 3T and 7T. Furthermore, we provide evidence associating the new model parameter with the channel-to-channel noise correlations of the physiological fluctuations in tSNR. We suggest that the covariance matrix describing the physiological noise correlations might be different from both the matrix describing the thermal noise covariance and the signal level matrix. We show that when the physiological noise covariance matrix is simply proportional to the signal level matrix (single channel or volume coils), the proposed model reduces to KG-model. But if the correlations of the physiological noise sources among the array elements are more general then the PNC-model is needed. Experimental data supports the view that the value of κ depends on the coil combination method and number of channels used in the reconstructed image. Fitting the time-series data from different tissue components showed that the largest values of κ were required in the tissue with the highest levels of physiological noise (GM and CSF) and was relatively small for WM and phantom data, supporting further the theory that the new parameter is related to physiological noise correlations.

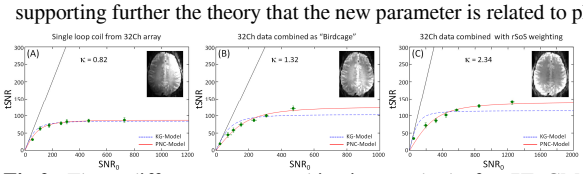

Fig.2: Three different array combination methods for 7T GM showing the effect of the combination weights to the relationship of tSNR vs SNR_0. (A) single loop data from the 32Ch array, (B) birdcage combination and (C) conventional rSoS. Estimated κ values are given on each graph. Dotted and solid lines correspond to *KG-* and *PNC-models*, respectively. Thumbnails with representative images of each combination are also shown.

Conclusion: Our findings demonstrate that the proposed model could be used to characterize multi-channel array acquisitions at high field strengths and ultimately to optimize fMRI protocols towards maximizing tSNR. With the new, more general model, the asymptotic value of tSNR increases beyond the expectations predicted by the KG-model and because this effect increases with the number of channel count, it has implications for future array coils with higher number of elements[6].

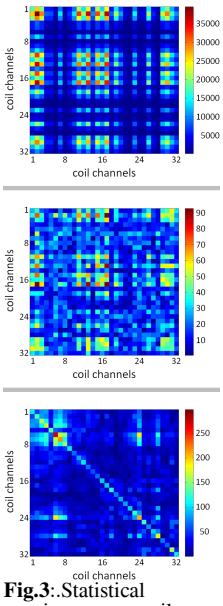

Fig.3:.Statistical matrices across coil channels taken from a single subject (3T, 32Ch array coil) for signal (top) physiological noise covariance matrix (middle), and thermal noise covariance matrix (bottom).

References: 1.Krueger G, et al. MRM, 46:631-7, 2001, 2.Triantafyllou C, et al. NeuroImage, 26(1):243-50, 2005. 5. Polimeni JR, et al. ISMRM 2012, Abst. 1362. 4. Keil B, et al. ISMRM 2010, Abst. 6960. 5. Kellman P, et al. MRM, 54(6):1439-1447, 2005. 6. Keil, et al. Magn Reson Med, 2012.

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