Matched Filter EPI Increases BOLD-Sensitivity in Human Functional MRI

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Introduction

Post processing of MR images is omnipresent: for fMRI in particular, smoothing of the raw images is frequently applied to gain SNR on the spatial scale of the BOLD response ('matched filter'). This shaping of the point spread function (PSF) acts complementary to sampling itself, where the choice of a k-space trajectory imposes an intrinsic filter onto the data. We combine both approaches to pursue SNR optimization through the choice of an optimal acquisition strategy, incorporating the prior knowledge about the target smoothing kernel. Specifically, the implications for temporal SNR and fMRI t-maps in the case of Gaussian weighting are considered for a 2D gradient-velocity modulated EPI.

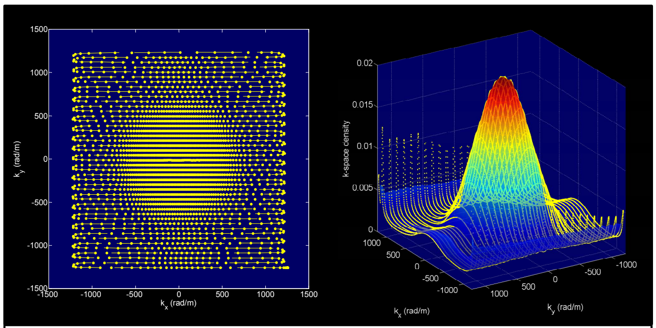

Fig. 1: Measured matched filter EPI trajectory with 2D Gaussian gradient velocity modulation. Sampling positions (left) and 3D plot of k-space density.

Methods

It turns out that the SNR in the final (post-processed) image is optimal, when k-space is acquired with non-uniform density. More precisely, the optimal acquisition k-space weighting d_{acq} (in the presence of white thermal noise and obeying the Nyquist criterion) is the Fourier transform of the desired (or target) PSF in the image domain, i.e. the smoothing kernel $d_{target}(k) = FT[D_{target}(r)]$.

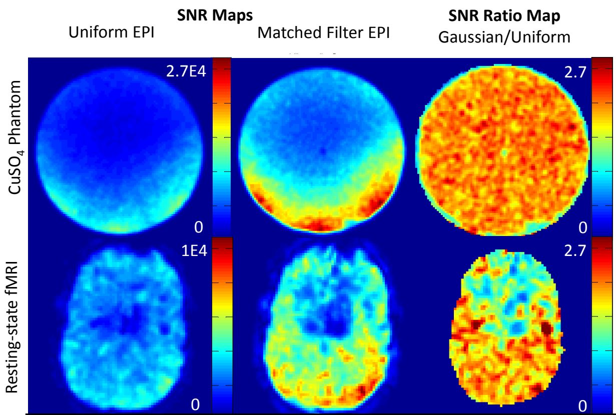

Fig. 2: Temporal SNR maps and SNR ratio map for uniform and Matched Filter EPI

This derives from the fact that k-space density-weighting during acquisition is a type of averaging that scales the noise variance linearly, whereas smoothing during post-processing acts as a scaling factor to the noise and induces a quadratic scaling of the variance. Thus, the noise variance σ^2 in k-space after performing (image-domain) smoothing is given by $\sigma^2(k) \propto \frac{d_{target}(k)^2}{d_{acq}(k)}$ (1) from which $d_{acq}(k) = d_{target}(k)$ follows, when minimizing under the constraint of constant acquisition time [1]. We approximated this ideal Gaussian 'matched filter' using a 2D Gaussian velocity-weighted single-shot EPI (Fig. 1). For a typical fMRI measurement (TR/TE 2000/35 ms, single-shot EPI resolution 2.5mm, SENSE-factor 2, image post-processing by smoothing with a Gaussian kernel of 6 mm FWHM) the matched filter EPI was compared to a uniform EPI of equal duration. Simulations incorporating system gradient constraints were performed to estimate the SNR gain. Measurements were made in a phantom ($CuSO_4$-doped water sphere, n =100 dynamics, TR 1 s, 2 interleaves) and in resting-state in-vivo time series (n =40) on a Philips Achieva 3T system (Philips Healthcare, Best, NL) with an 8-channel receive head coil and transmit body coil. The actual trajectories were concurrently measured using a 3rd order dynamic monitoring setup including 16 ^{19}F-NMR field probes [2],[3] and used for a conjugate-gradient (CG) based iterative image reconstruction [4], also including B_0-correction with multi-frequency interpolation [5].

Temporal SNR ($tSNR_{thermal}$) was assessed via separate noise scans, which were added to a vehicle signal scan for reconstruction: $tSNR_{thermal} = \frac{\mathrm{mean}(smoothed\ signal\ scans)}{\mathrm{std}(smoothed\ noise\ instances)}$. To investigate the additional influence of physiological noise, we conducted an fMRI experiment with block-wise stimulation of either the upper left and lower right visual hemi-fields, or vice versa (flickering colored wedges, 17 s block-length, 3 s fixation, 10 min duration). A general linear model analysis (GLM) was performed in SPM8 (Functional Imaging Laboratory, London) to retrieve peak t-values and cluster sizes of the generated contrast maps after multiple-comparison correction (FWE p=0.05).

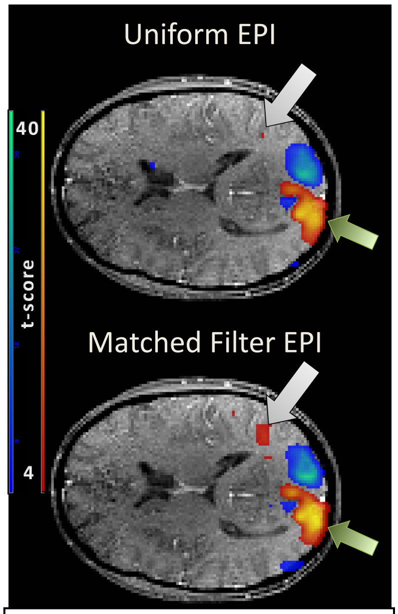

Fig. 3: Higher BOLD-sensitivity of Matched Filter EPI in terms of larger cluster size (gray arrows) and higher peak t-value (green)

Results

Table 1: Mean voxel SNR ratio Gauss/EPI	
Theory	1.81
Simulation	2.27
Phantom	1.88
In vivo	1.62

Given the resolution and smoothing kernel, eq. (1) can be solved analytically in 2D for a perfect Gaussian vs. an ideal uniform density. We found comparable SNR increases in simulations (where EPIs give unfavorable higher-frequency weighting due to their "u-turns") as well as both phantom and in-vivo resting-state measurements (Tab. 1, Fig. 2). Moreover, the sensitivity of statistical analyses in the fMRI paradigm increased for the density-weighted trajectory, observable by larger cluster sizes (red: 30 vs. 2 voxels, blue: 27 vs. 4) and peak t-values (red: t=39.77/35.64, blue: 37.30/32.39) (Fig. 3).

Conclusion

It was shown that by using a suitable trajectory the temporal thermal SNR in post-processed images can be increased by 60-80%. This comes at no cost in terms of measurement time or resolution in the final (smoothed) images. Thereby, also the sensitivity of the BOLD-fMRI acquisition was increased in a visual paradigm enhancing the detection and robustness of smaller clusters – which confirms the significance of thermal contributions to the noise sources at 3T.

References

[1] Kasper et al. *Proc. OHBM 16*, p. 737, 2010. [2] Barmet et al., *Proc. ISMRM. 10*, p. 216, 2010.
[3] Barmet et al., *MRM 60,* 2008. [4] Pruessmann et al. *MRM 46*, 2001. [5] Man et al. *MRM 37*, 1997.