AWESOME-Based De-Noising of Complex-Valued fMRI Time Series

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Synopsis

In this study we investigate possible benefits of an application of 'AWESOME' de-noising on fMRI. The application in a high-SNR finger tapping experiment showed a reduction of the already low thermal noise contribution and therefore improvement of tSNR and reduction of false positives; no adverse effects in the form of smoothing or suppression of 'true' activation was observed. A second investigation of the scalability of tSNR improvement on a resting state experiment with variable slice thickness / SNR showed that thermal noise can be reliably reduced and the tSNR proportionally improved without visible reduction of detail sharpness / resolution.

Purpose

Recently, a de-noising technique referred to as 'AWESOME' has been proposed that reduces noise by 'averaging' of complex MRI data in wavelet space.[1] It permits to use an image series acquired with varying contrast as input without the need for repeated acquisitions. Application to relaxation studies[1] and diffusion-weighted MRI[2] experiments demonstrated that quantitative information is well preserved in the de-noised images while object features initially covered by noise are regained. Here, we investigate a novel application of the AWESOME algorithm to de-noise high-resolution 3D gradient-echo (GRE) EPI and 3D VASO time series used for BOLD and cerebral blood volume (CBV) weighted fMRI.[3-6]

Methods

Acquisition: Two data sets acquired at 7T (MAGNETOM 7T, Siemens Healthcare, Germany) with a 32-channel head coil (Nova Medical, Wilmington, MA, USA) were analyzed. (i) resting-state BOLD-based fMRI data consisting of 3D GRE-EPI scans in a healthy subject employing the following parameters: 1.5x1.5mm^2 in-plane resolution, varying slice thickness of 0.25/0.5/1/2 mm, 12 slices, TR=3s, TE=22ms, in-plane GRAPPA 2, 50 repetitions.[3] (ii) task-based fMRI data: CBV and BOLD contrasts were recorded using a 3D slice-saturation slab-inversion VASO (SS-SI-VASO) sequence: 0.75x0.75mm^2 in-plane resolution, 1.8mm slice thickness, 8 slices, TR=3s, TE=22ms, in-plane GRAPPA 2.[3] The paradigm was a unilateral finger-tapping task (block design; 12-min total acquisition time).

Preprocessing: Data were corrected for motion. Subsequently, the background phase in the data was corrected using an algorithm based on total variation de-noising.[7] The AWESOME algorithm requires a normalized noise-level map that was calculated from the highest frequency band of the 1D wavelet transformation of the time line for each voxel.

AWESOME de-noising: AWESOME[1,2] operates in the wavelet space of complex MR images. In the wavelet space, signals (i.e. brain structures) and noise are well separated in multiple frequency bands, with thermal noise mostly represented in high frequency bands. From the complex noise distribution, a filter is derived to separate noisy and mostly meaningful data in the wavelet space. A mean wavelet data set is calculated over the image series. From this high SNR mean data set, the original signal contributions are estimated based on phase-weighted rescaling using the fraction of total signal energy per voxel over the series and each single voxel signal in the wavelet space. The thereby estimated signals replace noisy signals in the original wavelet data. The inverse wavelet transformation of the new data results in a de-noised MR image series.

The calculation of the mean wavelet data set was performed differently in both time series, because data containing *alternating* contrasts (i.e. CBV-weighted VASO and BOLD contrasts acquired with the SS-SI-VASO sequence) can suffer from cancellation of meaningful data in the complex mean. Thus, (i) the mean of rsMRI data is calculated from the complex wavelet coefficients; (ii) the mean of the task-based-fMRI data is calculated from the mean imaginary part and the mean absolute real part, which is then bias-corrected for the background noise.

FSL was used for statistical fMRI analysis and estimation of smoothness in the VASO data set.

Results

rs-fMRI: In Figure 1, the result of AWESOME-based de-noising is demonstrated for the acquisition with the minimal slice thickness (0.25 mm). De-noising of rsMRI data resulted in an SNR improvement per volume by up to four times as compared to the original SNR. As a consequence, the time-series SNR (tSNR) is almost doubled (Figure 2). Most notably, this is obtained without visible loss of image detail. The results for all rs-fMRI data are summarized in Figure 2.

Task-based fMRI: Although the voxel size was rather small, the SNR was already relatively high. Therefore, the effect of de-noising is not readily visible in Figure 3. Yet, fMRI analysis showed a reduction of false-positives in the statistical maps of the VASO signal changes (Figure 4). On the other hand, the areas of activation appear unchanged (cf. Figure 4). This can be seen as well in the VASO signal time course (Figure 5). Also, the corresponding cortical profiles of VASO signal change are not significantly altered.

Discussion & Conclusion

The multi-contrast data suggest that the de-noising preserves the temporal and spatial signature of "true" activation while reducing false positives. In conclusion, application of AWESOME to fMRI may offer the potential to produce meaningful results from lower SNR data, such as acquisitions at very high resolutions or with reduced paradigm length.

Acknowledgements

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References

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Figures

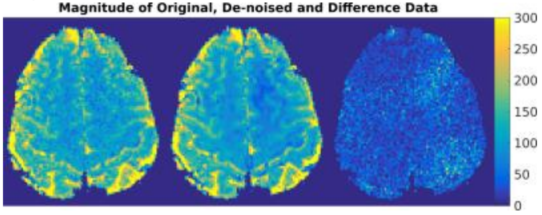

Figure 1: The central time step/central slice for 0.25 mm slice thickness of the original, de-noised and difference rs-fMRI data. The removed noise is mostly free of structure, except the pattern of non-uniform noise amplitude over the volume.

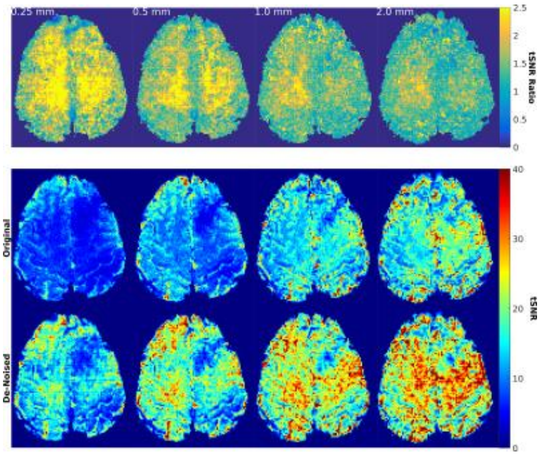

Figure 2: tSNR ratio as obtained after de-noising with identical pre-processing per slice thickness. tSNR ratio is the ratio of tSNR after de-noising to the original. A subtle checkerboard-like pattern in the tSNR maps appears after de-noising due to limitations in the precision of the estimation of original noise-free signals in the wavelet space.

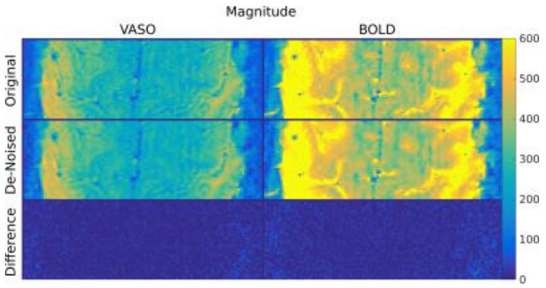

Figure 3: Magnitude images of both VASO and BOLD contrast show already little contribution of thermal noise in original images. Removal of this contribution (difference data) by de-noising enabled subtle improvements in quantification as shown in Figure 4.

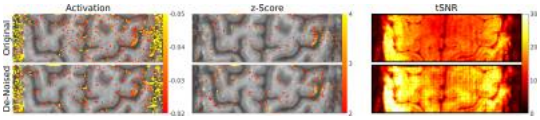

Figure 4: Activation maps of VASO ((S_{act}-S_{rest})/S_{rest}), z-score and tSNR maps of a finger-tapping experiment with alternating acquisition of VASO and BOLD contrasts; Besides the improved tSNR, false positive activations are reduced while keeping the activation pattern.

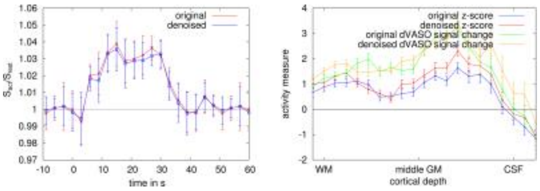

Figure 5: (Left) Trail-averaged, BOLD-corrected VASO time course (S_{act}/S_{rest}) of a ROI in the left primary motor cortex during right-hand finger tapping. Stimulus onset was at 0s and stimulus offset was at 30s. (Right) Tapping-induced fMRI signal changes as a function of cortical depth. The time course was not altered by de-noising nor were the activation profiles across cortical layers broadened or distorted.