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

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Introduction

Recently, a de-noising technique referred to as 'AWESOME' has been proposed that reduces noise by 'averaging' of complex 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 weighted fMRI.[3-6]

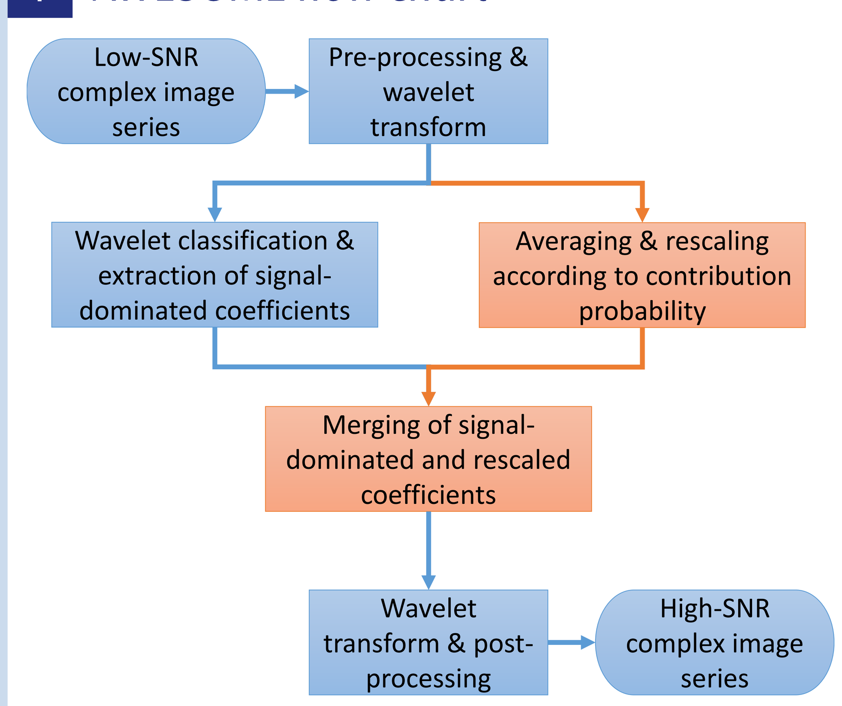
Methods

- Two datasets acquired at 7T (MAGNETOM 7T, Siemens Healthcare, Germany), 32-channel head coil (Nova Medical, Wilmington, MA, USA):

i) Resting-state BOLD-based fMRI data, 3D GRE-EPI scans in healthy subject: 1.5×1.5mm² in-plane resolution, 0.25/0.5/1/2mm slice thickness, 12 slices, TR=3s, TE=22ms, in-plane GRAPPA 2, 50 repetitions.[3]

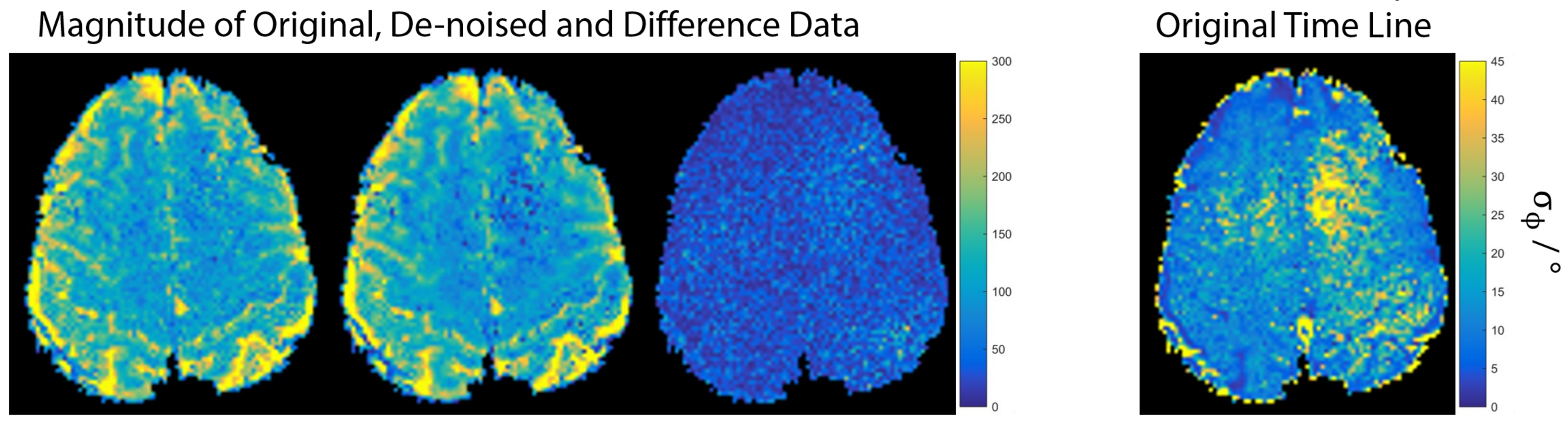
ii) Task-based fMRI data: CBV and BOLD contrasts were recorded, 3D slice-saturation slab-inversion VASO (SS-SI-VASO) sequence: 0.75×0.75mm² in-plane resolution, 1.8mm slice thickness, 8 slices, TR=3s, TE=22ms, in-plane GRAPPA 2.[3]
Paradigm: unilateral finger-tapping task (block design; 13-min total acquisition time).

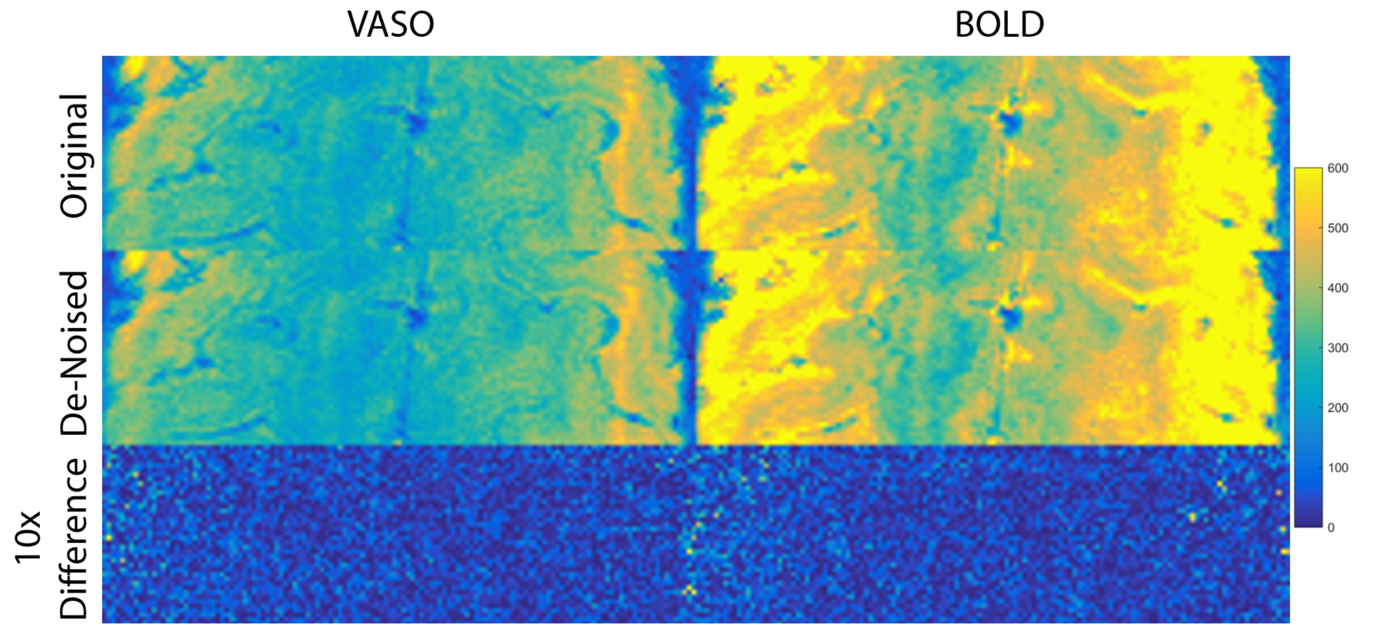
1 *AWESOME flow chart*



Adaptive **W**avelet-based **E**nhancement of **S**ignal **O**ver **M**ultiple **E**xperiments (AWESOME)

2 *Processing Pipeline*



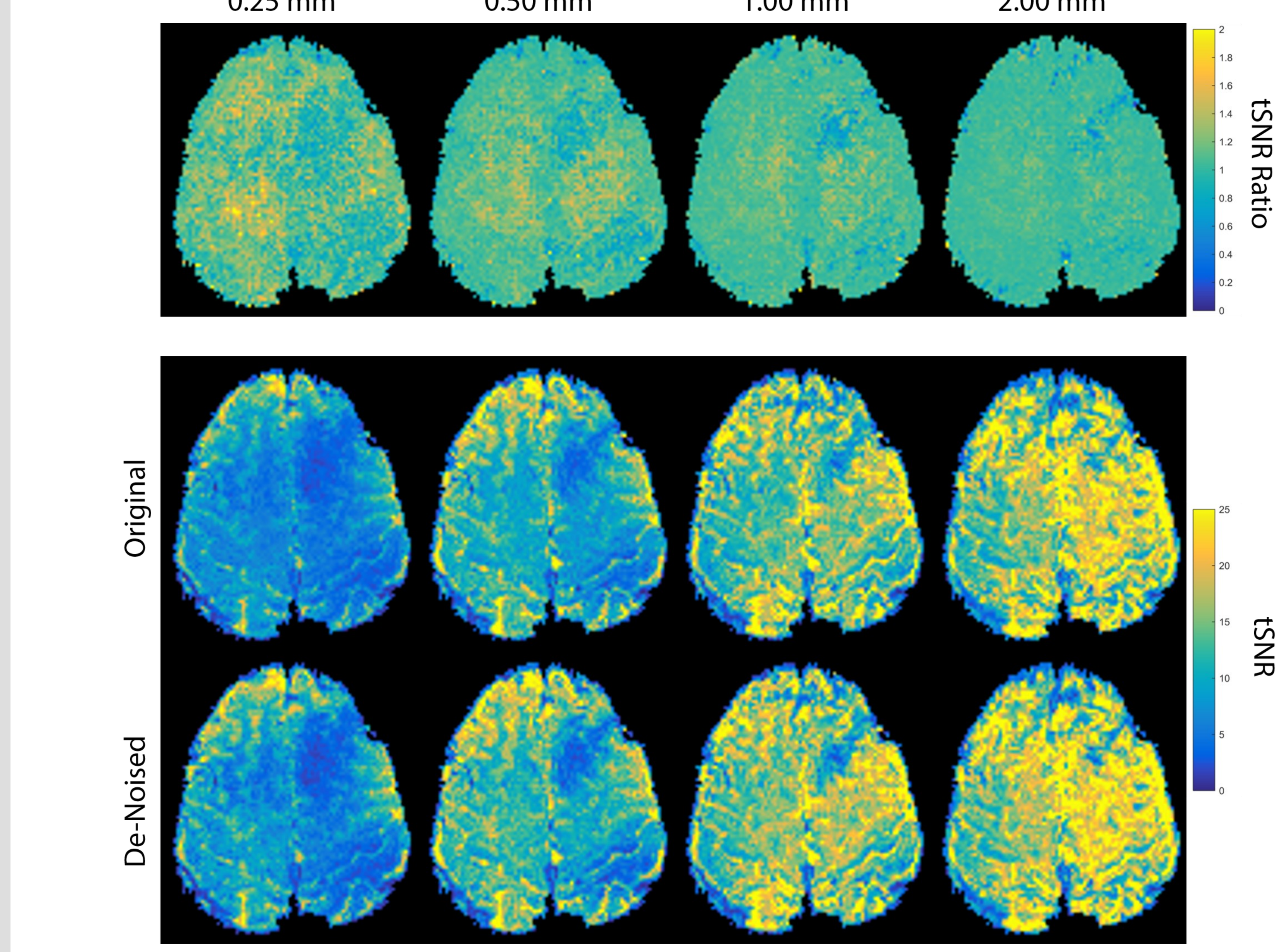


i) The 10th time step/central slice for 0.25mm slice thickness of the original, de-noised and difference rs-fMRI data. The removed noise is mostly free of structure, except of the pattern of phase variation.
ii) Magnitude VASO and BOLD images show little contribution of thermal noise in original images. Removal of this contribution enabled subtle improvements in quantification (Figure 4).

- Preprocessing: motion correction, background phase correction via a total variation based algorithm[7], noise-level normalization by noise estimation from 1D wavelet transformation of the time line for each voxel.
- AWESOME[1,2] algorithm modification: The magnitude estimation was modified to compensate for non-zero phase variation of signals (despite phase correction).
Estimation of the magnitude correction is performed by analyzing the probability distribution of ideal signals (varying in phase by measured phase variation for each time line), superimposed with white noise.
The modification can be applied to all or just rescaled wavelet coefficients by user choice.
- AWESOME de-noising parameters are determined via global optimization, reducing the mean-squared difference of de-noised output images to a high-SNR target version of the same images.
- Ideal target images are obtained via simulation of equivalent measurements by artificial neural network (ANN) driven approximation of the current measurements.
- ANNs are trained to estimate the voxel-wise intensity changes over the image series by learning the underlying behavior from randomly selected voxels. Noise is not reproducible by ANNs, yielding a "smooth" approximation of the measurements.
- Simulated "noisy" measurements for AWESOME optimization are obtained by adding complex white noise to the noise-free simulations.

Results & Discussion

3 *rs-fMRI (i)*

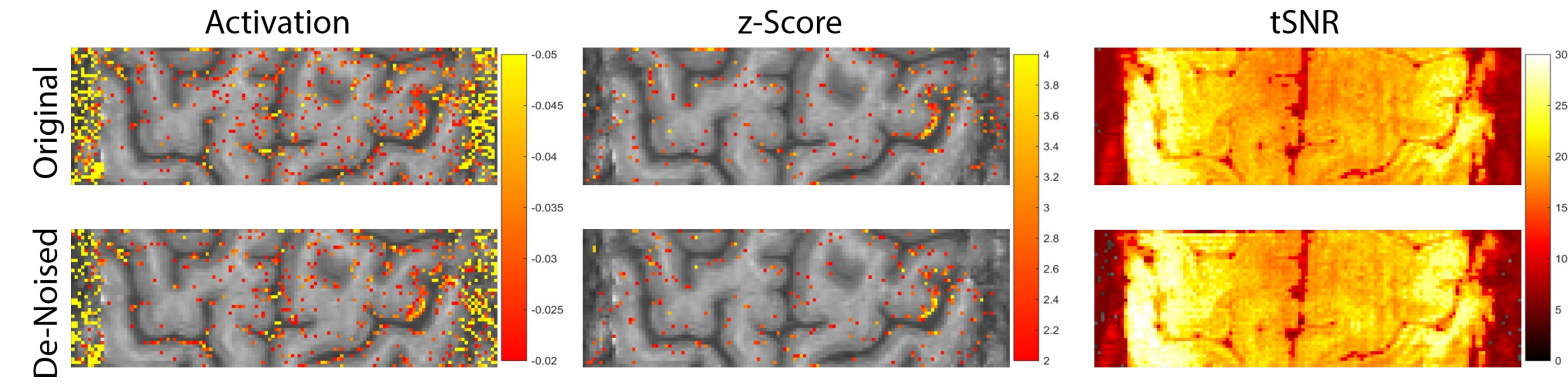


tSNR ratio as obtained after individual de-noising per slice thickness. tSNR ratio is the ratio after de-noising to the original. A subtle checkerboard-like pattern in the tSNR maps appears after de-noising due to limitations in precision of the estimation of original noise-free signals in the wavelet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

rs-fMRI:

In Figure 2a, the result of AWESOME-based de-noising is demonstrated for the acquisition with the minimal slice thickness (0.25 mm). De-noising of rs-fMRI data resulted in an up to four fold SNR improvement per volume as compared to original SNR. As a consequence, the time-series SNR (tSNR) is almost doubled (Figure 3). Most notably, this is obtained without visible loss in image detail. The results for all rs-fMRI data are summarized in Figure 3.

4 *Task-based fMRI (ii)*



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.

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 2b. 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). Also, the corresponding cortical profiles of VASO signal change are not significantly altered.

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.

References

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Acknowledgments

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