De-noising of diffusion-weighted MRI data by averaging of inconsistent input data in wavelet space

Henrik Marschner, Cornelius Eichner, Alfred Anwander, André Pampel, & Harald E. Möller

Max Planck Institute for Human Cognitive and Brain Sciences, Leipzig, Germany

marschner@cbs.mpg.de

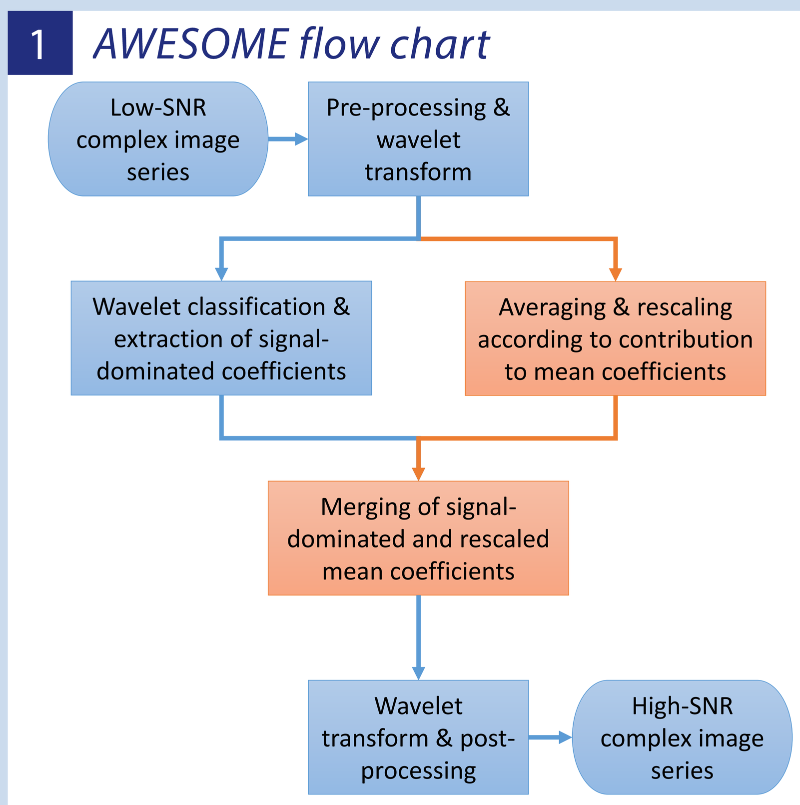
Introduction

Signal averaging can improve the image quality at the cost of substantially prolonged scan times and susceptibility to motion due to the requirement of repeated acquisitions. This is particularly important in diffusion-weighted MRI (dMRI) targeted at high spatial resolutions and/or strong diffusion weighting. 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 image series acquired with different parameters (e.g., echo times) as input without the need for repeated acquisitions. Application to relaxation studies demonstrated that the quantitative information was preserved in the de-noised images while object features initially covered by noise were regained. Here, we investigate if this technique might be beneficial in dMRI.

Methods

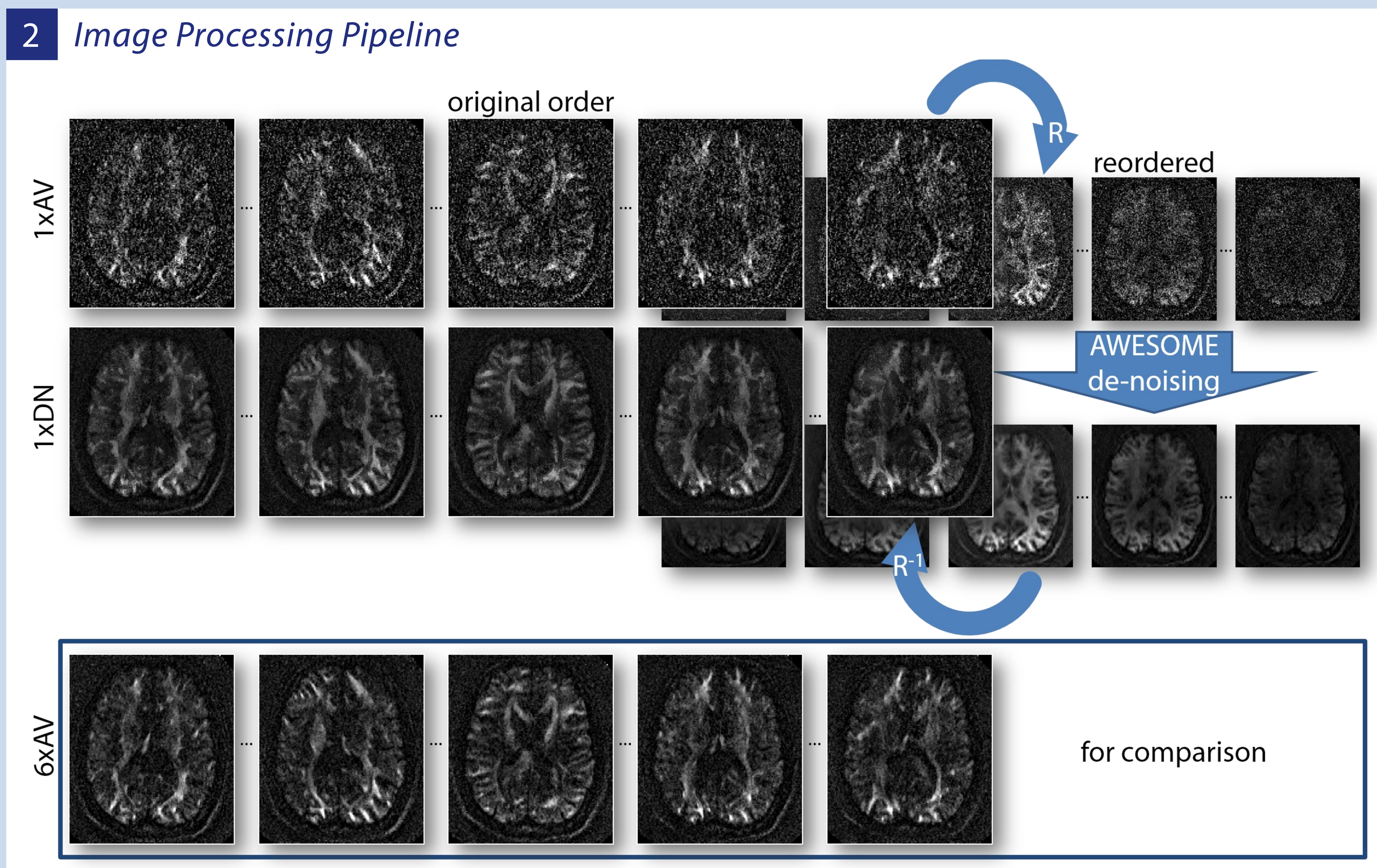
- Previously published data set from healthy subject.[2]
- 3T scanner (Skyra CONNECTOME, Siemens Healthcare, Erlangen); 300mT/m gradient strength; custom-built 64-channel head coil.[3]
- 1.2mm isotropic resolution, FoV=210x210mm, 98 slices, partial Fourier=6/8, TR/TE=4600ms/54ms, GRAPPA=3, SMS=2.[4,5]
- Six repetitions of 128 diffusion directions at b=5000s/mm², 10 interspersed images with b=0.
- Slice-wise background phase maps calculated from complex images after separate total variation (TV) de-noising of real and imaginary parts.[2]
- 6x complex averaging and distortion correction to obtain high-SNR reference data set.[2]

1 *AWESOME flow chart*



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

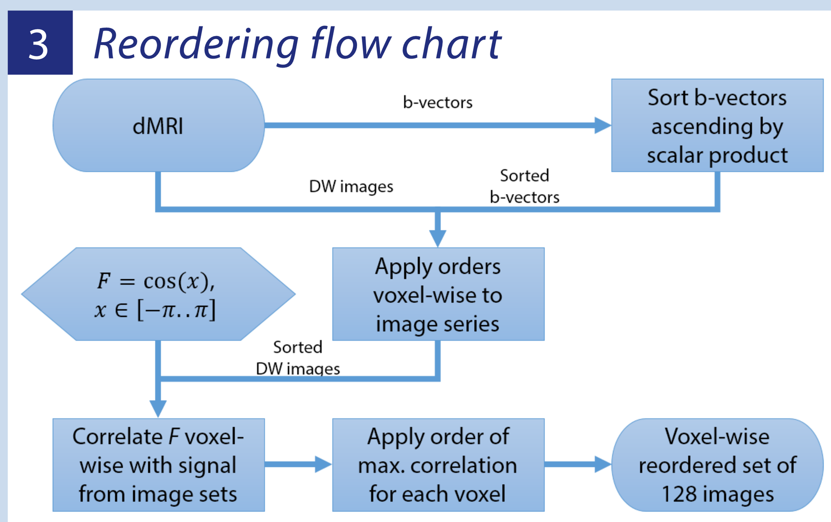
2 *Image Processing Pipeline*



Step 1: Voxel-wise reordering ("R") of image series. Step 2: AWESOME de-noising of reordered image series. Step 3: Reversing voxel-wise reordering ("R^{-1}") of image series. All images shown are real parts of phase-corrected, complex images.

- 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 reproduced 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.

3 *Reordering flow chart*



Reordering yields input images for ANN training.

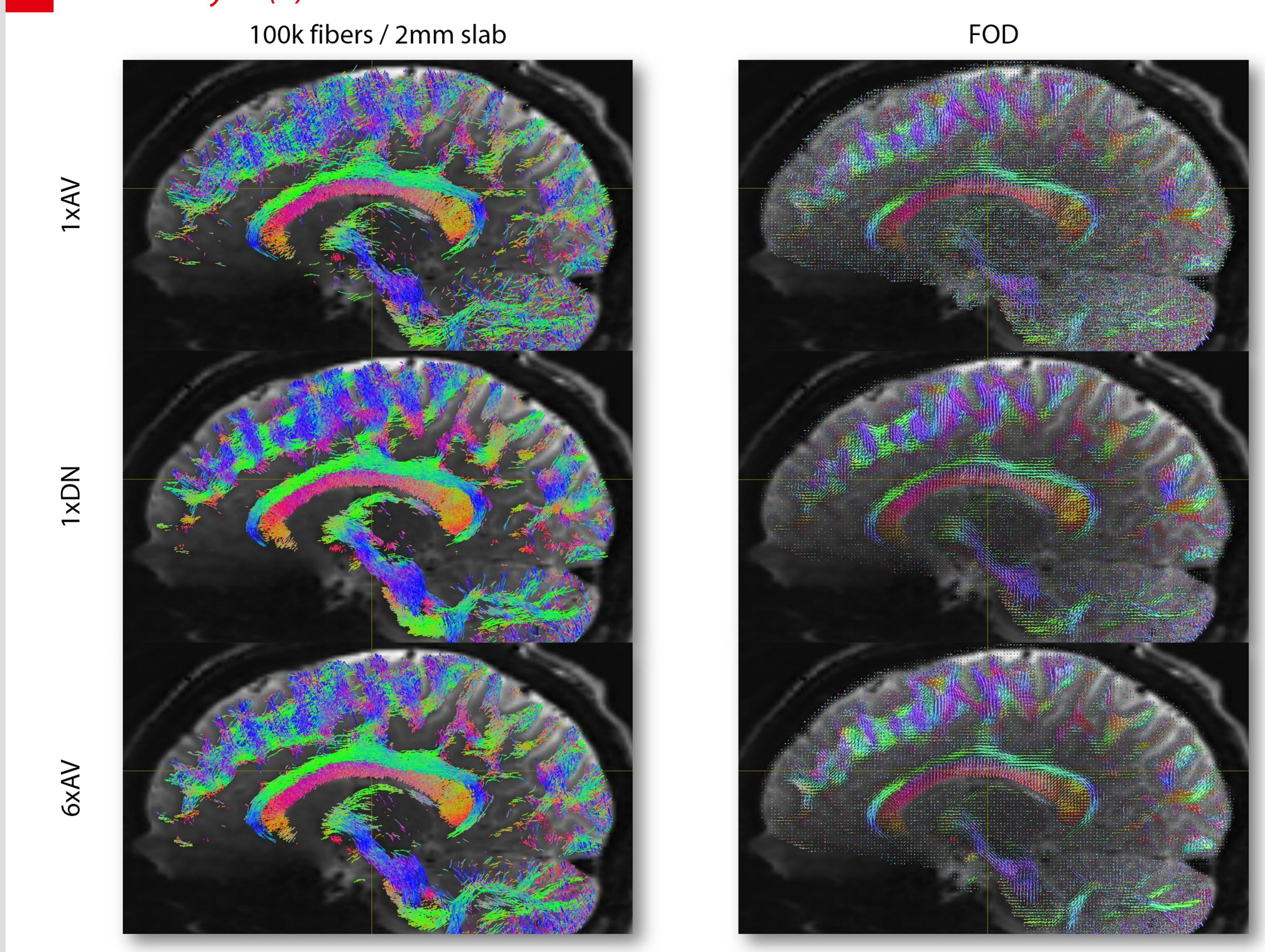
- Here, the input to the ANN training is obtained by a reordering with additional directional information from the applied b-vectors (Fig. 3).
- Optimized de-noising parameters can be applied in AWESOME to de-noise:

a) Reordered image series (Figs. 2 & 4, Table 1);

b) Original order images (direct de-noising).

Results & Discussion

4 *dMRI Analysis (a)*



Fiber tracking (first column) performed for 100k fibers using MRtrix.[6] Spurious responses of the constrained spherical deconvolution are reduced. Improved estimation of FOD supports better fiber tracking.

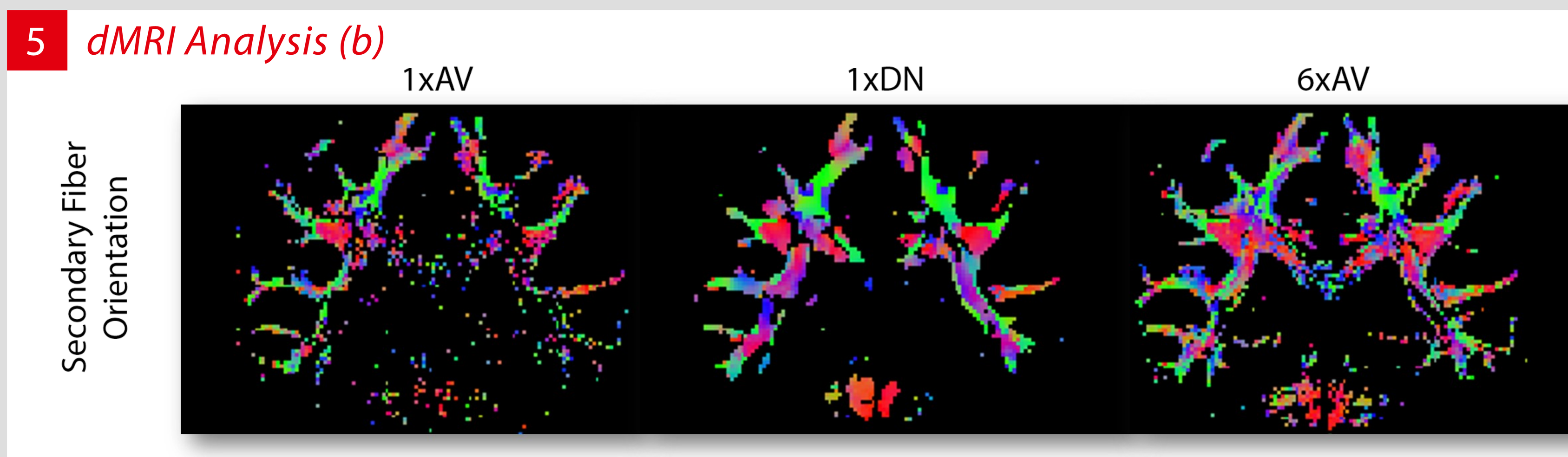
Data sets:

- "Noisy" data from first repetition (1xAV).
- De-noised data from first repetition after application of AWESOME (1xDN).
- Reference data from all six repetitions after traditional (complex) averaging (6xAV).

Discussion:

- AWESOME yields improved SNR for better performance of dMRI analysis.
- De-noising with original order might be beneficial for secondary fiber tract estimations (Fig. 5).

5 *dMRI Analysis (b)*



Secondary fiber orientations for single repetition, de-noised and reference data sets (threshold of 0.05 for anisotropic fiber fraction). De-noising yields comparable definition of secondary fibers as 6x averaging.

Table 1

	1 x AV	1 x DN	6 x AV
"SNR" (WM/GM; b=5000)	1.95 / 1.23	8.42 / 5.41	3.91 / 2.44
Mean Fiber Length / mm	26.84 (±23.05)	40.88 (±31.74)	35.51 (±28.53)

AWESOME de-noising improved SNR 4.4x, compared to a 2.0x gain with 6x averaging. SNR was estimated from the mean brain signal intensity and standard deviation in a ROI outside the head.

Conclusion

The results after AWESOME de-noising were similar or even better than with 6x complex averaging. Information on fiber orientation and presence of crossing fibers were preserved as demonstrated by comparison with the reference data with striking improvements, especially in inferior regions. Application of AWESOME to dMRI may offer the potential to produce reliable quantitative results with low-SNR input data that result from application of very large b-values or high spatial resolution. This is achieved without multiple repetitions yielding a substantial reduction in scan time.

References

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[2] C. Eichner et al.; NeuroImage 2015;122:373-384.
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Acknowledgments

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