Denoised diffusion spectrum imaging of white matter tracts in the brain stem

C. Granziera[1.2.3.4], A. Daducci[3,5], Samuel St-Jean[6], G. Krueger[7] and M. Descoteaux[5].

1. Martinos Center for Biomedical Imaging, Massachusetts General Hospital and Harvard Medical School, Chalestown, MA, United States.
2. Neuroimmunology Unit, Neurology, Department of Clinical Neurosciences, Centre Hospitalier Universitaire Vaudois (CHUV) and University of Lausanne (UNIL), Lausanne, Switzerland.
3. Signal Processing Core, Centre d'Imagerie BioMédicale (CIBM), Lausanne, Switzerland
4. Advanced Clinical Imaging Technology (HC CMEA SUI DI BM PI), Siemens Healthcare AG, Lausanne, Switzerland.
5. Sherbrooke Connectivity Imaging Laboratory (SCIL), University of Sheerbrooke, Canada
6. Image Sciences Institute, University Medical Center Utrecht, Utrecht, Netherlands
7. Siemens Medical Solutions USA, Inc., Boston, MA, United States

Synopsis: High-angular resolution diffusion (HARDI) MRI, like diffusion spectrum imaging-DSI, provides an attractive tool to investigate the complex white matter structure in the brainstem. However, due to the application of high b-values in the HARDI image acquisition, the raw images are SNR limited (SNR<10). In this study, we applied a novel denoising alogorithm to low-SNR DSI data. Our results showed that Generalized Anisotropy maps and tractography seeding the periacqueductal grey matter, a small structure in the mesencephalon, match more accurately the underlying anatomy when applying the denoising algorithm.

Introduction: The brainstem is a mixed grey-white matter structure, which plays a pivotal role in controlling consciousness, respiration, sleep, respiratory and cardiovascular function as well as sensory-motor communication between the brain and the spinal cord[1]. Diffusion Magnetic Resonance Imaging (MRI) in the brainstem might help understanding in vivo physiology as well as pathophysiological mechanisms in neurological and neuropsychiatric diseases (i.e. multiple sclerosis[2], migraine[3], stroke[4] ect). DSI as other high angular resolution diffusion MRI techniques might be highly advantageous to study the complex white matter structure characterizing the brainstem. Yet, diffusion MRI in the brainstem is prone to susceptibility,motion artifacts due to cardiac pulsation and respiratory activity and is located in the area of lowest coil sensitivity[5].

In this work, we applied a new non-local denoising method[6,7] to diffusion spectrum imaging (DSI) data. Using denoised and original DSI data, we then evaluated the qualitative parametric and tractography appearance of large white matter bundles in the mesencephalon, pons and medulla oblongata.

Methods: We retrospectively evaluated two DSI datasets obtained from a cohort of multiple sclerosis patients and healthy subjects (repetition time [TR]/echo time [TE]=8,600/144 msec, field of view [FOV]=212x212 mm, 48 slices, 2.2x2.2x3 mm resolution, 258 diffusion directions, b=8,000 s/mm^2). Each subject was scanned at clinical 3T MRI (Magnetom Trio a TIM System, Siemens, Germany) using a 32 channel head-coil array. MP2RAGE uniform images (TR/TI1/TI2=5000/700/2500 ms, vs=1.0x1.0x1.2mm[3)8] were used for anatomical reference. A prototype of the non local spatial and angular block matching (NLSAM) technique was used to denoise the raw DSI data. Probabilistic Identification and Estimation of Noise (PIESNO)[9] was used to automatically correct for the variable non-central Chi distributed noise and then NLSAM was performed with a spatial neighborhood of 3x3x3 and 5 angular q-space neighbors. Generalized fractional anisotropy (GFA) maps were calculated as in[10]. White matter tracts in the mesencephalon, pons and medulla oblongata of GFA maps from denoised and original volumes were qualitatively compared to the Duvernoy atlas of the brainstem[11].

The periacqueductal grey matter (PAG) was manually delineated based on the Duvernoy atlas (PAG is a gray matter structure located around the mesencephalic aqueduct, which extends for about 14mm and is approximately 4–5mm wide). PAG was used as seed to perform streamline tractography using trackvis (www.trackvis.org). Tractography-derived fibers trajectories from the PAG were qualitatively evaluated based on anatomical knowledge and previous studies[12].

Results and Discussion: *Figure 1* shows the comparison of GFA maps in the mesencephalon at the level of the PAG: GFA maps from denoised images evidenced the presence of the medal lemniscus and spinothalamic tract, which were not visible in the original maps. *Figure 2* shows the comparison of GFA maps in the pons: also at this level, GFA maps from denoised data show the presence of the medial and lateral lemniscus, in addition to the pyramidal and

spinothalamic tract that are evident also in the original images. No clear white matter tract differences were observed between the denoised and the original datasets in the medulla oblongata. *Figure 3* shows the tractography result of seeding the PAG in the mesencephalon. The PAG is a key structure in the brainstem as it plays a major role in pain modulation, anxiety, reproductive behavior and in the integration of information from the periphery and the brain[13]. Therefore, the PAG is directly highly connected to the prefrontal and insular cortex, thalamus, hypothalamus, brainstem and deep layers of the spinal cord[14]. In addition, it is connected to the cerebellum through the inferior olive in the medulla oblongata. *Figure 3* show the tractographic appearance of PAG connection in denoised and original DSI data, highlighting the advantages of using denoised data to perform tractographic analysis of a small brainstem structure like the PAG.

Conclusion: NLSAM applied to high-angular resolution diffusion DSI data provided clear advantages to visualize WM bundles in the brainstem using both GFA maps and streamline tractography. Future investigations in patients affected by pathologies alternating WM bundles in the brainstem will highly benefit of denoising techniques such NLSAM.

Figures:

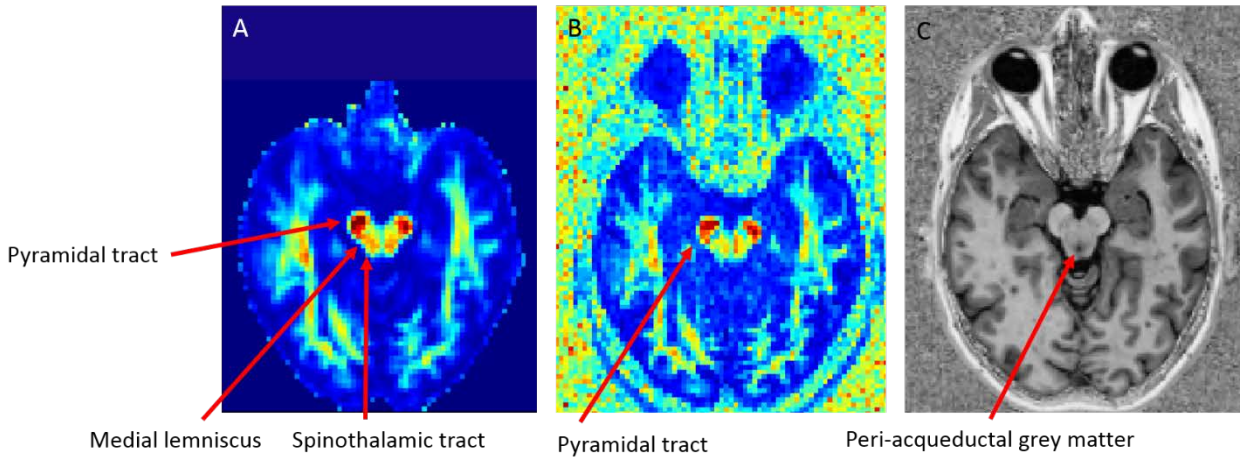

Figure 1: At the mesencephalon level, axial Generalized Fractional Anisotropy maps in denoised (A) and non-denoised DSI data (B). Axial T1-weighted MP2RAGE uniform image (C). Arrows indicate the medial lemniscus and the spinothalamic tract in the denoised DSI image (A) that appear better delineated in the denoised images and the periacqueductal grey matter region in the uniform MP2RAGE image.

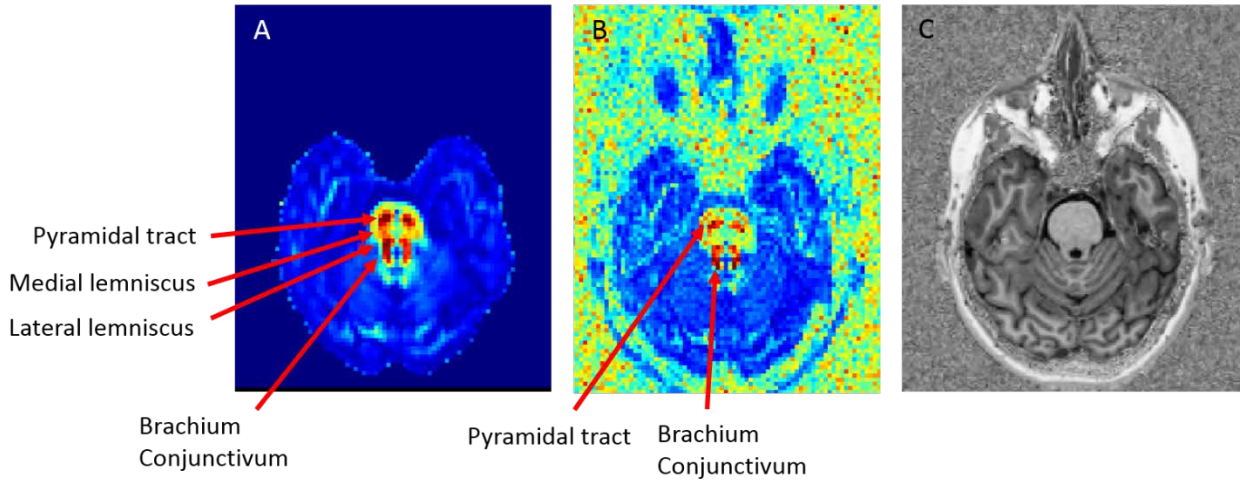

Figure 2: At the pons level, axial Generalized Fractional Anisotropy maps in denoised (A) and original DSI data (B). Axial T1-weighted MP2RAGE uniform image (C). Arrows indicate the medial and lateral lemniscus in A and the spinothalamic tract and the pyramidal tract in A and B. All structures appear better delineated in the denoised images.

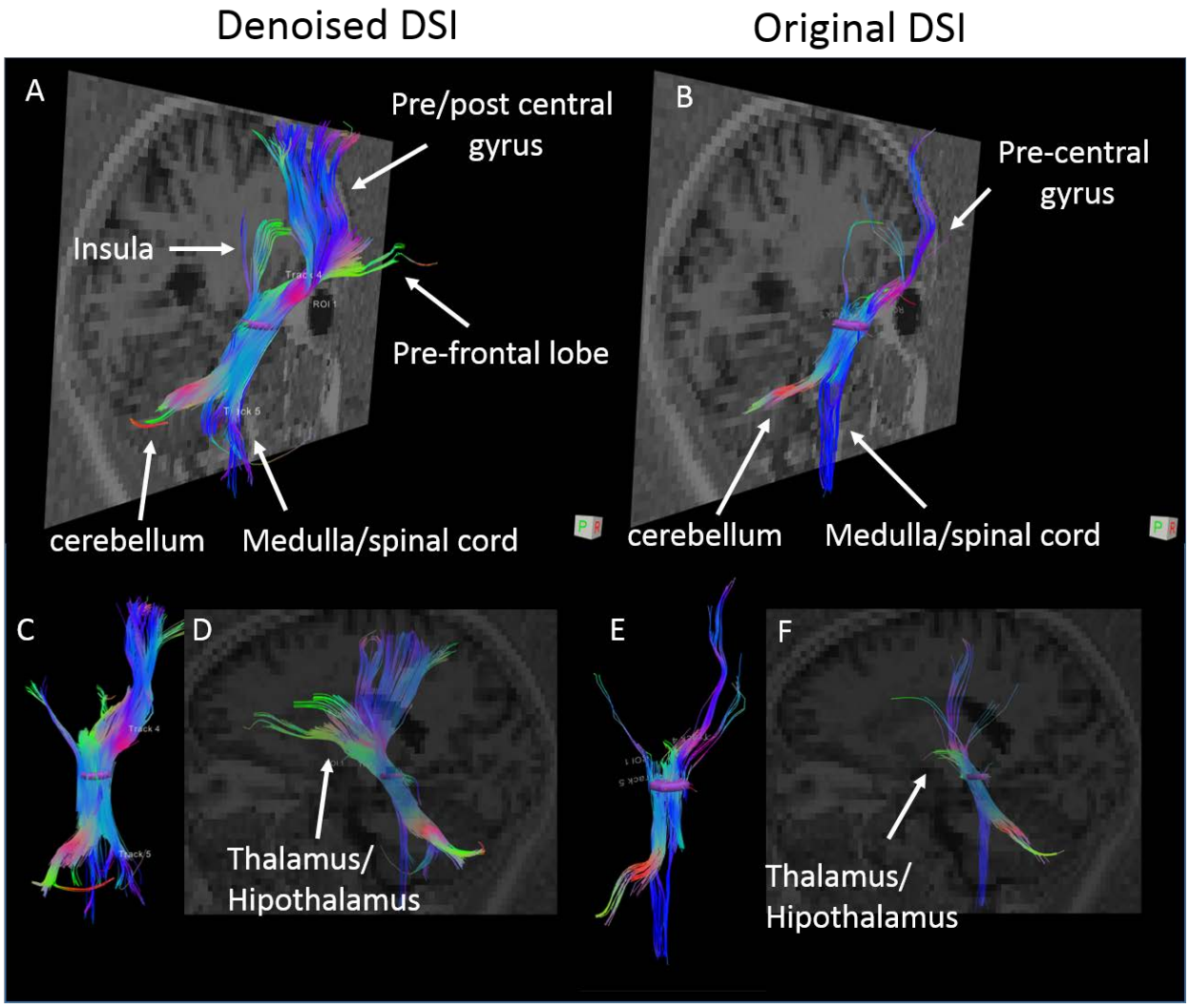

Figure 3: Tractography results obtained seeding form the PAG (violet ROI). A, C and D denoised PAG tractography and B, E and F PAG tractography on original DSI data.

References:

1. Nicholls JG, Paton JF. Brainstem: neural networks vital for life. *Philos Trans R Soc Lond B Biol Sci.* 2009;364(1529):2447-2451.
2. Papadopoulou A, Naegelin Y, Weier K, et al. MRI characteristics of periaqueductal lesions in multiple sclerosis. *Mult Scler Relat Disord.* 2014;3(4):542-551.
3. DaSilva AF, Granziera C, Tuch DS, Snyder J, Vincent M, Hadjikhani N. Interictal alterations of the trigeminal somatosensory pathway and periaqueductal gray matter in migraine. *Neuroreport.* 2007;18(4):301-305.
4. Byeon J, Kim JY, Cho AH. Readout-segmented echo-planar imaging in diffusion-weighted MR imaging of acute infarction of the brainstem and posterior fossa: comparison of single-shot echo-planar diffusion-weighted sequences. *Clin Imaging.* 2015;39(5):765-769.
5. Wiggins GC, Triantafyllou C, Potthast A, Reykowski A, Nittka M, Wald LL. 32-channel 3 Tesla receive-only phased-array head coil with soccer-ball element geometry. *Magnetic resonance in medicine : official journal of the Society of Magnetic Resonance in Medicine / Society of Magnetic Resonance in Medicine.* 2006;56(1):216-223.
6. St-Jean S, Coupé P., Descoteaux M Non Local Spatial and Angular Matching : a new denoising technique for diffusion MRI. Paper presented at: Proceeding of: International Society of Magnetic Resonance in Medicine (ISMRM)2014; Milano, Italy.
7. St-Jean S. GG, Descoteaux M. . Connectome-like quality diffusion MRI in 13 minutes - Improving diffusion MRI spatial resolution with denoising. Paper presented at: International Society of Magnetic Resonance in Medicine (ISMRM)2015; Toronto, Canada.
8. Marques JP, Kober T, Krueger G, van der Zwaag W, Van de Moortele PF, Gruetter R. MP2RAGE, a self bias-field corrected sequence for improved segmentation and T1-mapping at high field. *NeuroImage.* 2010;49(2):1271-1281.
9. Koay CG, Ozarslan E, Pierpaoli C. Probabilistic Identification and Estimation of Noise (PIESNO): a self-consistent approach and its applications in MRI. *Journal of magnetic resonance.* 2009;199(1):94-103.
10. Tuch DS. Q-ball imaging. *Magnetic resonance in medicine : official journal of the Society of Magnetic Resonance in Medicine / Society of Magnetic Resonance in Medicine.* 2004;52(6):1358-1372.
11. Naidich TP DH, Delman BN, Sorensen AG, Kollias SS, Haacke EM. . *Duvernoy's Atlas of the Human Brain Stem and Cerebellum High-Field MRI: Surface Anatomy, Internal Structure, Vascularization and 3D Sectional Anatomy.* Springer Vienna; 2009.
12. Linnman C, Moulton EA, Barmettler G, Becerra L, Borsook D. Neuroimaging of the periaqueductal gray: state of the field. *NeuroImage.* 2012;60(1):505-522.
13. Behbehani MM. Functional characteristics of the midbrain periaqueductal gray. *Prog Neurobiol.* 1995;46(6):575-605.
14. Mantyh PW. Connections of midbrain periaqueductal gray in the monkey. II. Descending efferent projections. *Journal of neurophysiology.* 1983;49(3):582-594.