High Angular Resolution Diffusion Imaging of the Complex White Matter Architecture of the Human Brainstem: A 3T Study using Parallel Imaging

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INTRODUCTION: Diffusion tensor imaging (DTI) cannot resolve multiple fiber orientations within a single voxel. High angular resolution diffusion imaging (HARDI) overcomes this limitation through the acquisition of large numbers of diffusion directional measurements at diffusion-weighting factors (*b* values) greatly exceeding 1000 s/mm^2. In this study, 3T HARDI with parallel imaging using an 8-channel head coil is employed to visualize the complex white matter architecture of the human brainstem, including intravoxel crossing fibers where DTI is inadequate.

METHODS: HARDI was performed on three adult volunteers using a 3T EXCITE scanner (General Electric, Milwaukee, WI). The 8-channel EXCITE head coil was employed for parallel imaging using the Array Spatial Sensitivity Encoding Technique (ASSET) with an acceleration factor of 2. A multislice interleaved axial HARDI acquisition encompassing the entire brainstem was performed with a single-shot echoplanar spin echo pulse sequence (TR=6s, TE=93ms, NEX=1) with 131 diffusion-encoding directions (uniformly distributed over the surface of a sphere using an electrostatic repulsion model) at b = 3000 s/mm^2 and 1.6 mm isotropic spatial resolution. In two of the subjects, an additional HARDI acquisition covering only the medulla was performed with 282 diffusion-encoding directions at b = 3000 s/mm^2 and 1.5 mm isotropic spatial resolution. The orientation distribution function (ODF) was constructed for each voxel using Q-ball (Tuch DS, et al. *Neuron*, 2003; 40:885-895) and spherical deconvolution (Tournier JD, et al. *NeuroImage*, 2004; 23:1176-1185) methods. The resulting ODFs were compared with DTI analysis, including directionally-encoded color fractional anisotropy (FA) maps.

RESULTS & DISCUSSION: Parallel imaging at 3T using a multi-channel phased array head coil provided unprecedented spatial resolution for diffusion imaging in the human brainstem, without the strong warping artifacts usually encountered in the posterior fossa with single-shot echoplanar imaging at high-field and ultra-high diffusion-weighting factors. In all subjects, both the Q-ball and spherical deconvolution ODFs generated reconstructions of intravoxel crossing fiber tracts in the brainstem that are consistent with known white matter anatomy. These included (1) craniocaudally oriented projection fibers of the pyramidal tract that intersect with transversely oriented pontocerebellar fibers in the pons (*Fig. 1*); and (2) crossing fibers of the pyramidal decussation in the core of the medulla (*Fig. 2*). To our knowledge, this is the first noninvasive *in vivo* demonstration of the pyramidal decussation in humans. In contradistinction, tensor analysis of this HARDI data provided no useful fiber orientation information in these regions of complex white matter architecture.

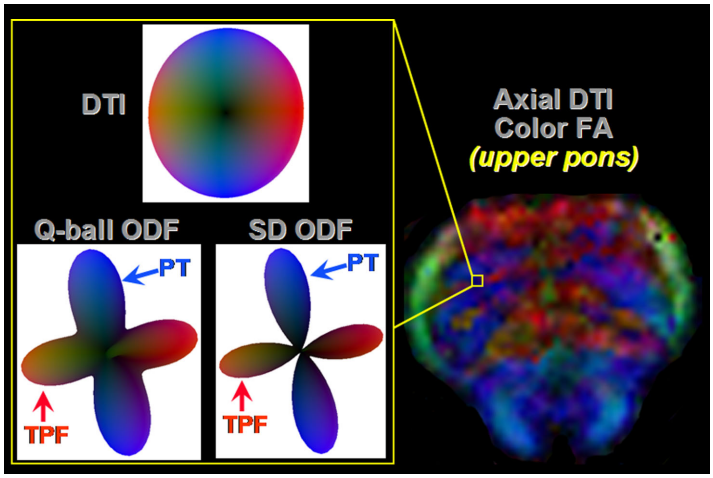

Figure 1. High angular resolution diffusion imaging reveals intravoxel crossing fibers in the upper pons, which cannot be visualized with DTI. The directionally-encoded color fractional anisotropy (FA) image (*right*) is an axial slice through the upper pons at 1.6 mm isotropic voxel resolution, based on tensor analysis of 131 diffusion-encoding directions at b = 3000 s/mm^2. Fiber orientation is indicated in red for left-right, green for anteroposterior, and blue for up-down. The brightness is modulated by the FA in each voxel. The 3D ADC profile (DTI, *top left*), Q-ball orientation distribution function (Q-ball ODF, *bottom left*), and spherical deconvolution orientation distribution function (SD ODF, *bottom right*) are from a single 1.6-mm cubic voxel (*yellow boxed inset*). The Q-ball ODF and SD ODF both show crossing fibers of the pyramidal tract (*PT*), oriented up-down, and the transverse pontine fibers (*TPF*), oriented left-right, which cannot be resolved by DTI.

CONCLUSION: 3T HARDI with parallel imaging enables visualization of the white matter architecture of the human brainstem in unprecedented detail, including intravoxel crossing fibers where DTI fails.

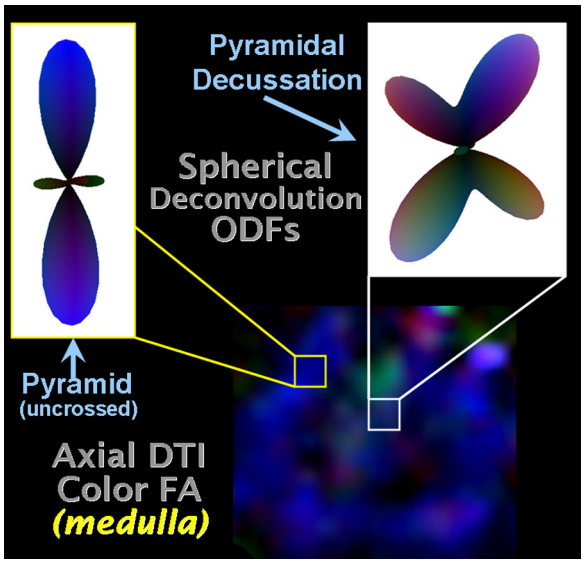

Figure 2. High angular resolution diffusion imaging reveals intravoxel crossing fibers of the pyramidal decussation in the lower medulla. The directionally-encoded color fractional anisotropy (FA) image (*bottom*) is an axial slice through the lower medulla at 1.5 mm isotropic voxel resolution, based on tensor analysis of 282 diffusion-encoding directions at b = 3000 s/mm^2. Fiber orientation is indicated in red for left-right, green for anteroposterior, and blue for up-down. The brightness is modulated by the FA in each voxel. Note that the greatest FA is in the periphery of the medulla, which contains craniocaudally oriented white matter tracts without fiber crossings (SD ODF at *left* from the *yellow boxed inset*), whereas the core of the medulla has low FA, in part due to the crossing fibers of the pyramidal decussation (SD ODF at *right* from the *white boxed inset*). Each ODF is from a single 1.5-mm cubic voxel (*yellow boxed inset*).